RINA

WARSHIP 2008: NAVAL SUBMARINES 9

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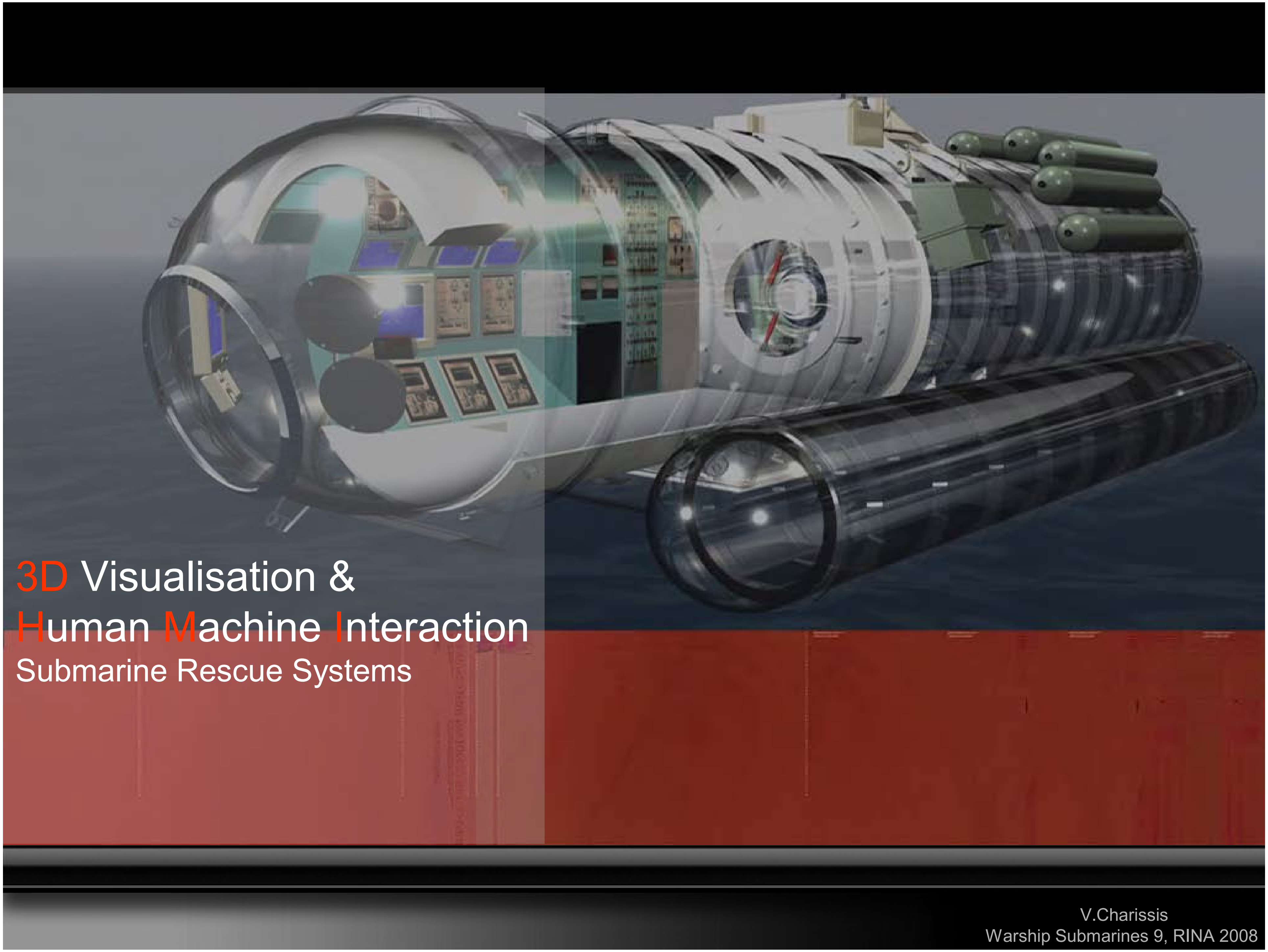
3D Visualisation &
Human Machine Interaction
Submarine Rescue Systems
V.Charissis
Warship Submarines 9, RINA 2008

3D Visualisation of Submarine Rescue Systems and Rescue Mission Simulation

Dr V. Charissis[1], Mr J. Ramsay[2], Mr B. Sharples[2], Dr M. Naef[1] & Prof B. Sherwood Jones[1]

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Glasgow, UK

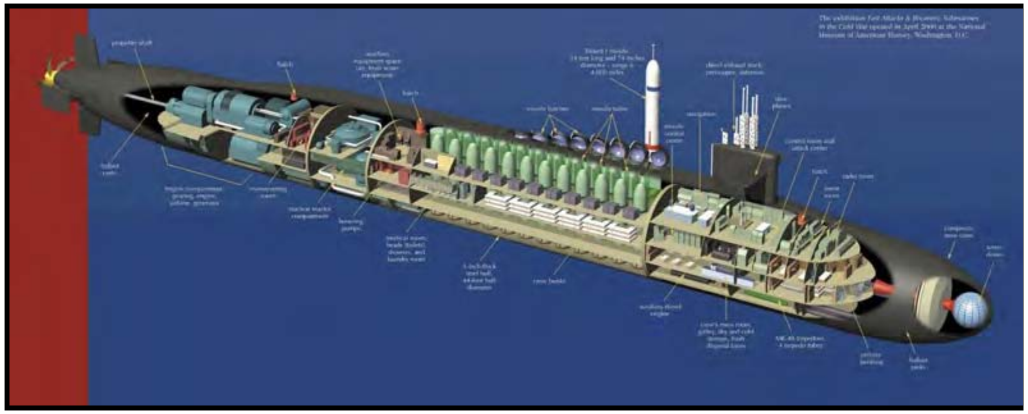
Contemporary CAD

Computer Aided Design (CAD)

- 2D/3D Surface (i.e. pro-engineer, CATIA, etc.)
- Volume development (i.e. solid-works)
- Mechanical Components animation (i.e. inventor)
- Animate operation sequences as non-interactive, off-line rendered video using fixed cameras

Typical CAD Outputs

- 3D format files
- Limited or Non-interactive data (explanatory animations)



Typical Output Constrains

Assess operational aspects in real time

Data Manipulation Study

Solution Under Investigation

- Real-time feedback Human-Computer Interface (HCI)
- VR simulation
- Interactive data manipulation tools
- User-friendly (usage from non-computer specialists)

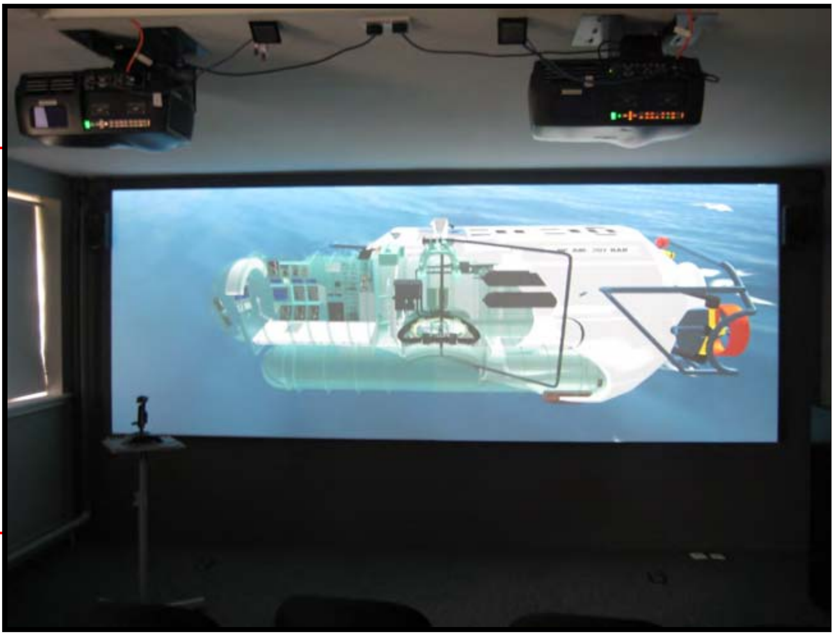
Rationale

1. Design evaluation
2. Explanatory presentations
3. Operation training

Methods

1. Real-Time VR simulation
2. Explanatory Animations / Still images
3. Predetermined simulations and animations

Development of VR Simulation and Animation



3D Visualisation software

- Autodesk Maya 2008

VR Simulation software

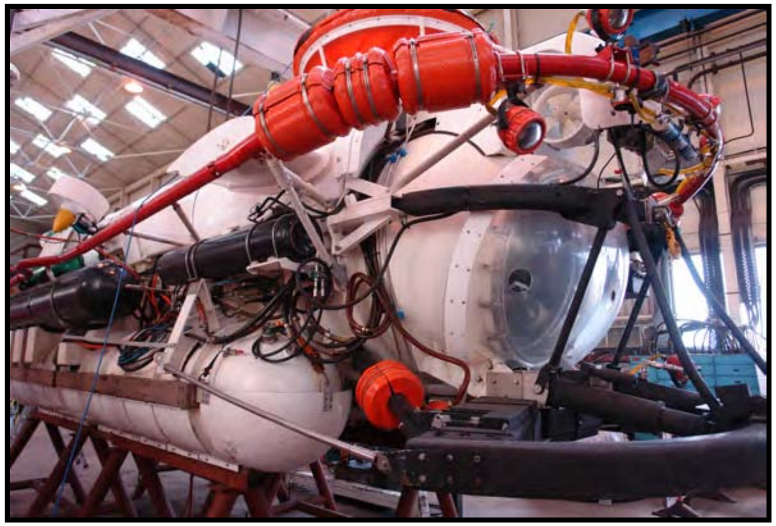
- VEGA

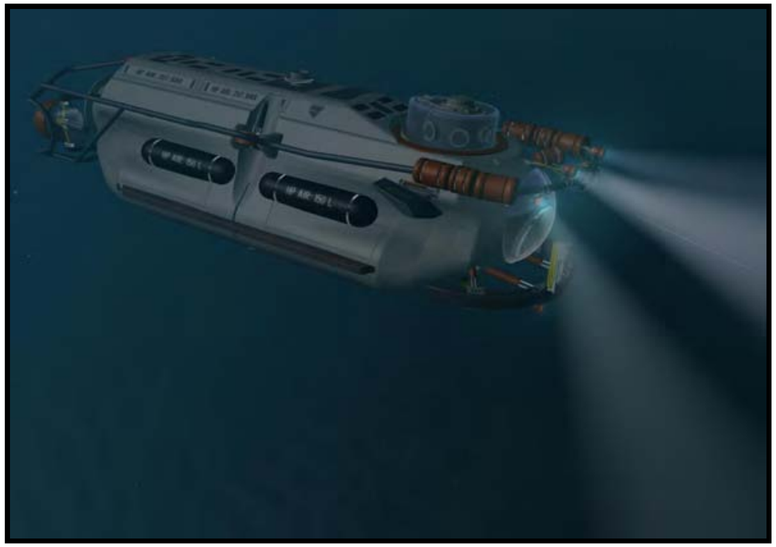
Virtual Reality Simulator hardware

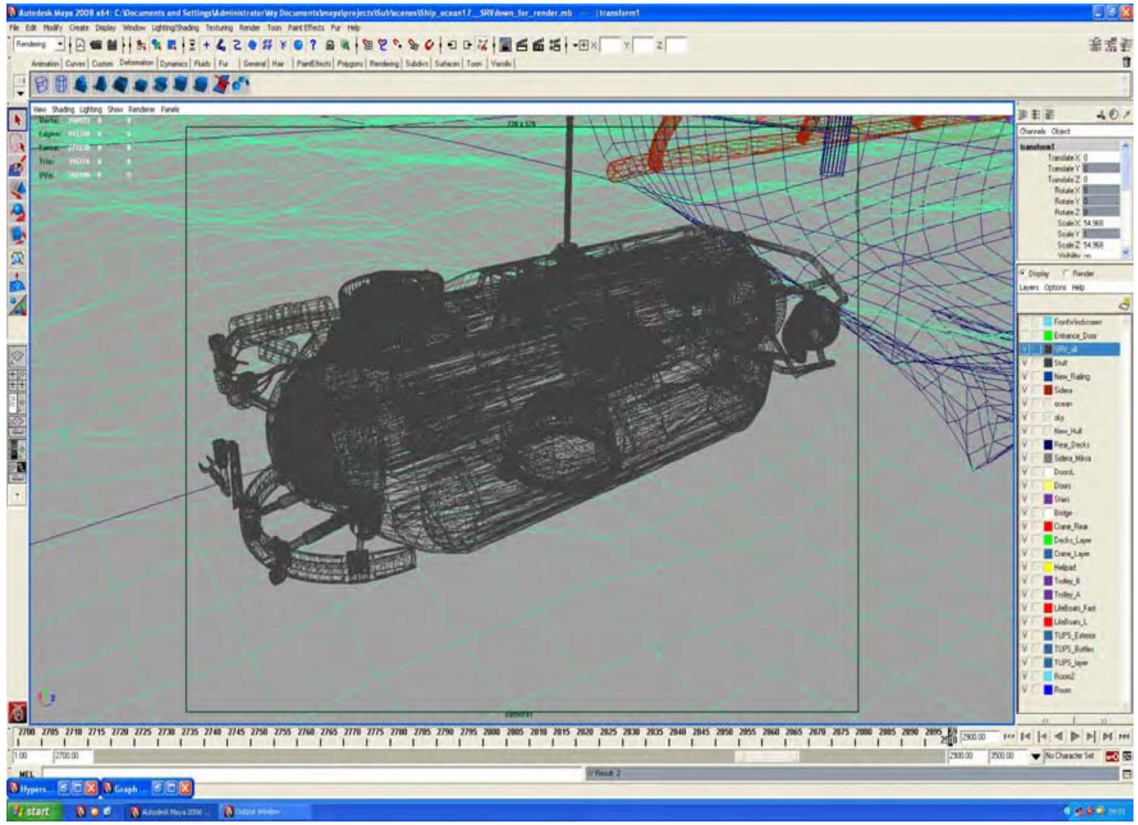
A range of VR display environments for our experiments,

- including stereoscopic projection
  (providing a sense of depth) that enables better understanding of the spatial structure,
- **high-resolution wide screen** (2800 x 1050 pixels on 4.4m x 1.65m)
  to convey a feeling of the actual size of the SRV.
- All our display systems are **driven by PC workstations**
  (with dual Xeon processors and nVidia Quadro FX4400 graphic)

Modelling







Environment Simulation

Environment Simulation

Design Evaluation

Benefits:

- Allowing processes to be:
  (a) repeated
  (b) from multiple viewpoints and
  (c) played back at different speeds

- Including transparency or cutaway views to allow the review of internal mechanisms and processes

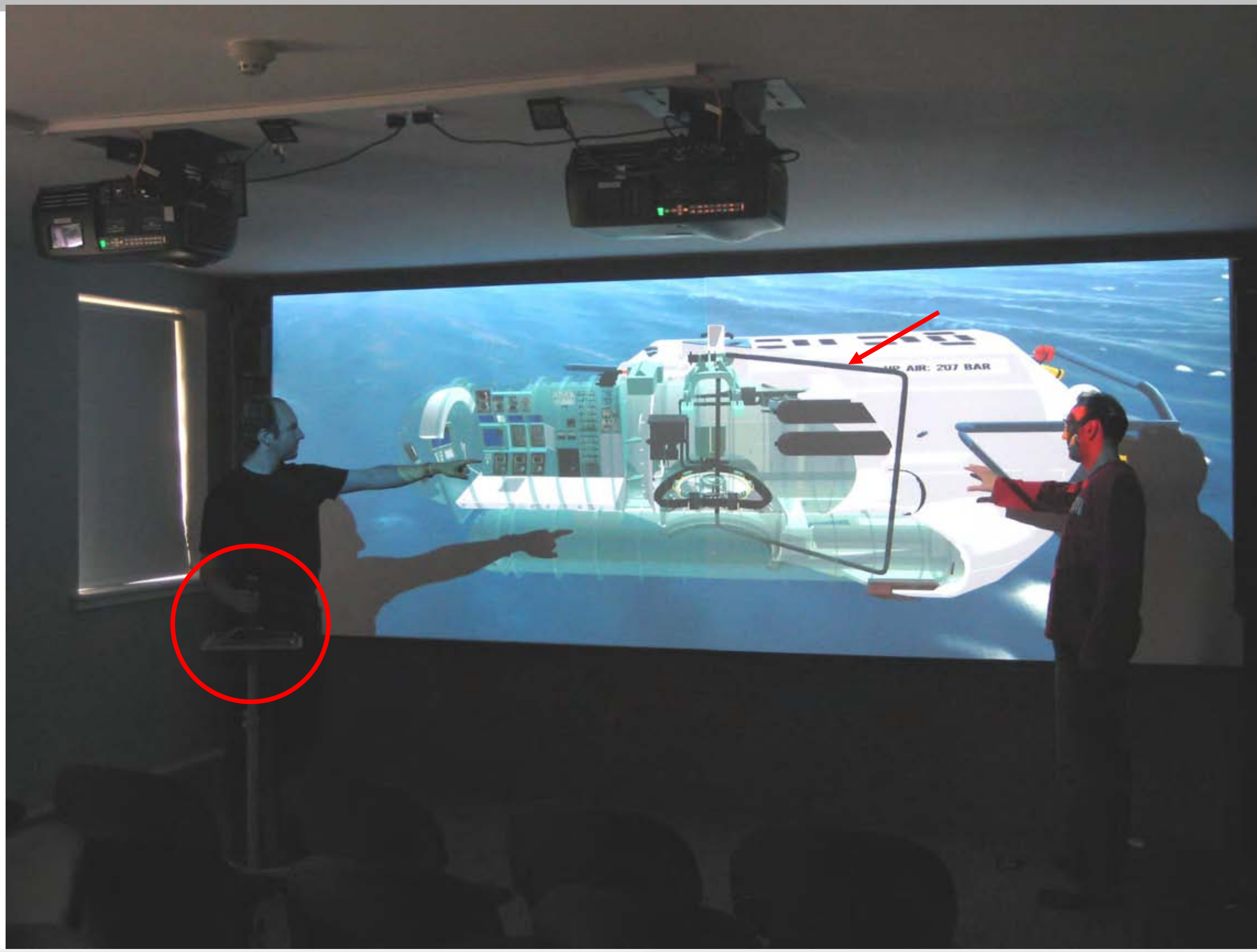
- Allowing team members with a non-technical background, (typically operators or clients), to control and manipulate the 3D environment

Charissis V., and Naef M., (2008), Functionality Simulation of Prototype Products Through Virtual Reality: Automotive Head-Up Display CaseStudy, in Proceedings of the 2nd International Symposium on Systems Research in the Arts and Humanities, part of the 20th Anniversary International Conference on Systems Research, Informatics and Cybernetics, Baden-Baden, Germany.

Naef, M., Interaction and Ergonomics Issues in Immersive Design Review Environments. Proceedings of COMPIT 2007, 23-25 April 2007, Cortona/Italy.

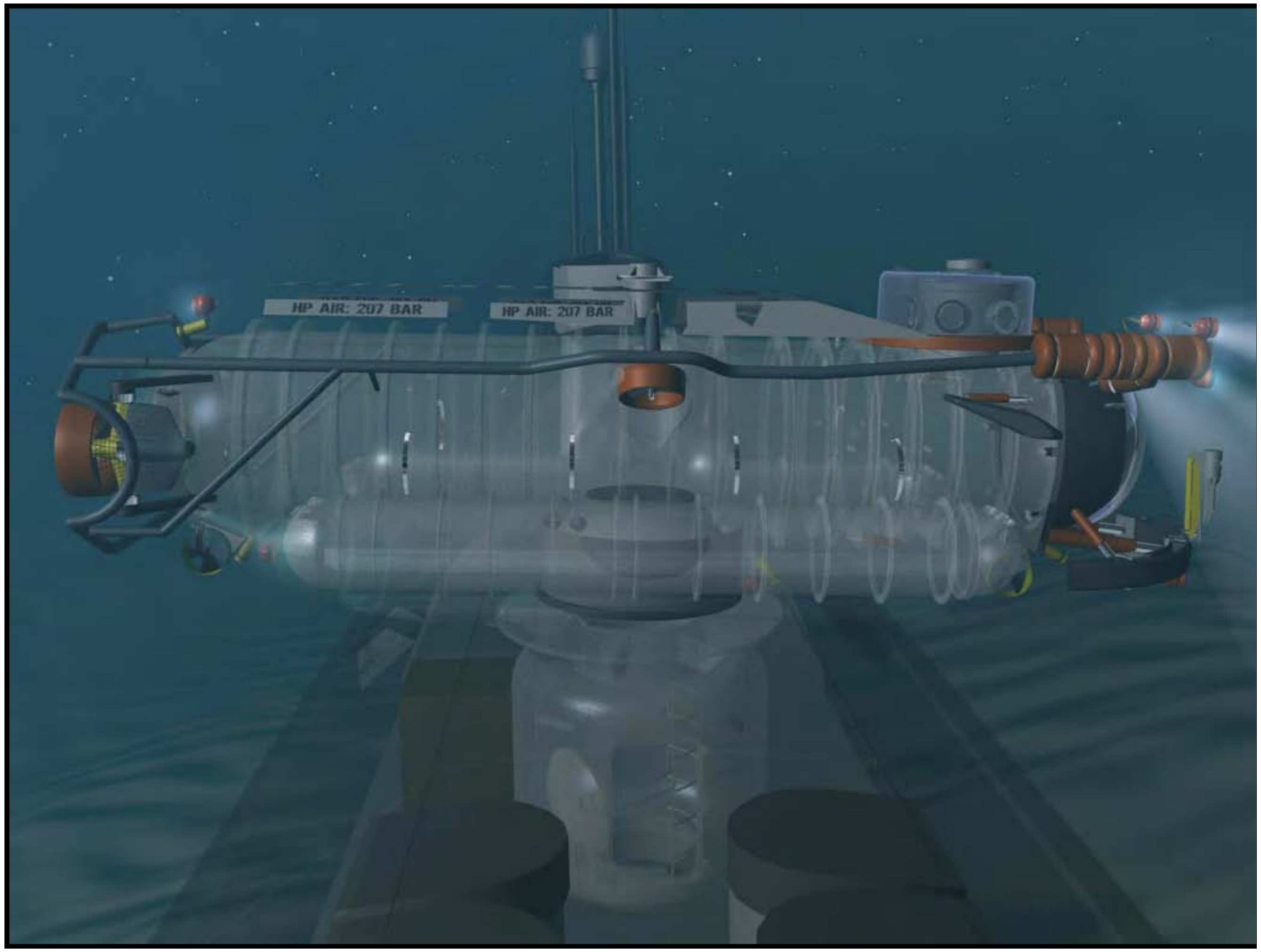
Sherwood Jones, B., Naef, M., McLundie, M.: Interactive 3D Environments for Ship Design Review and Simulation. 5th International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT). Leiden, The Netherlands, May 8-10

Simulation Screenshot



Explanatory Presentations

- Mechanical systems
- Operational procedures



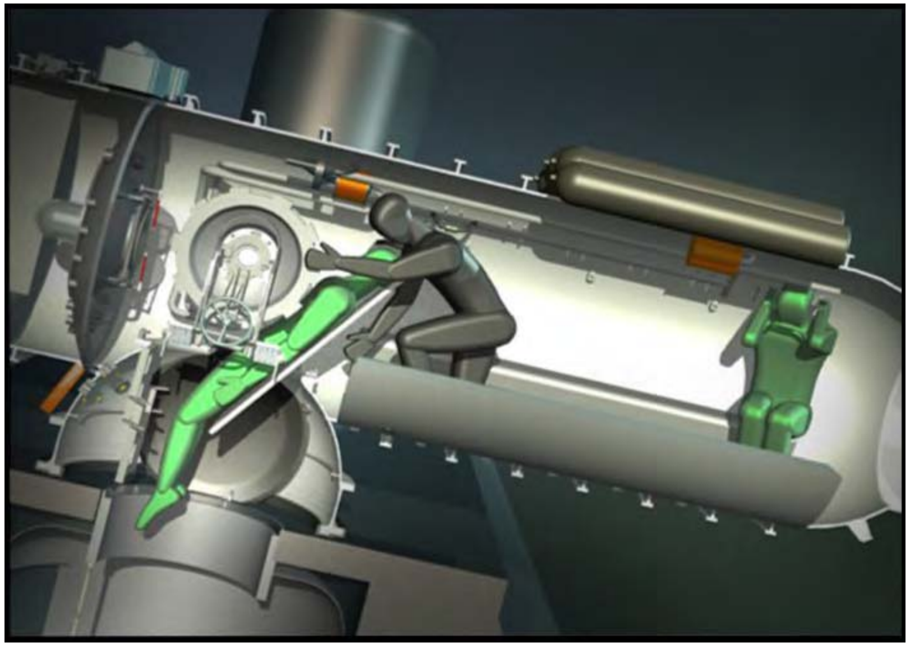
Explanatory Presentations

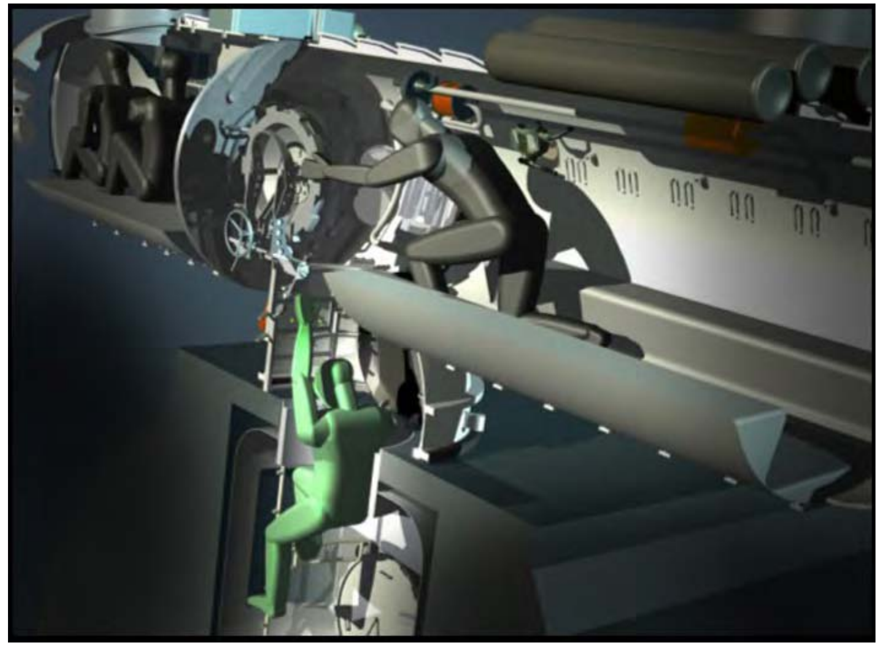
In the SRV Case Study Milestones:

3. The SRV modelling with CAD software
5. Demonstration of the approach procedure with the DISSUB on the seabed,
7. Demonstration of SRV locking onto the DISSUB's rescue seat, (depressurisation of the interlock),
9. The opening of the hatches
11. The transfer of the Rescuees.
13. Visually simulation of the Evacuation of the Rescuees
15. Rescuees transfer from the DISSUB to the SRV
17. Rescuees transfer on to the decompression chambers onboard the MOSHIP.

Operation Training

Simulation of procedures → accurate depiction of the structures onboard



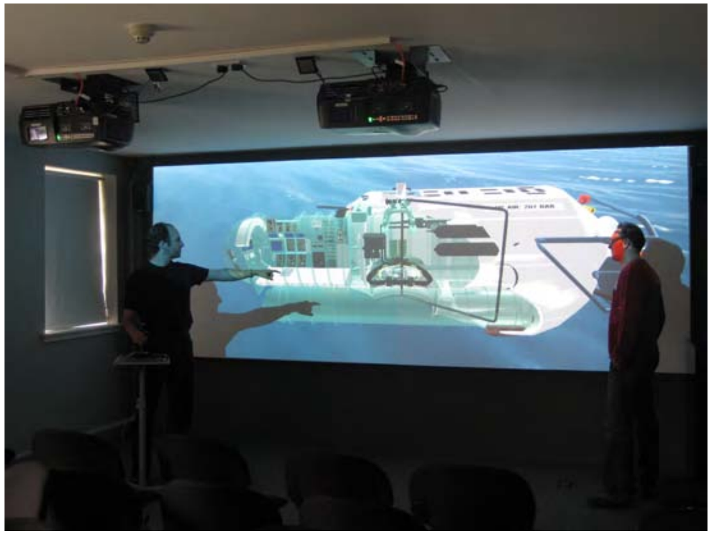


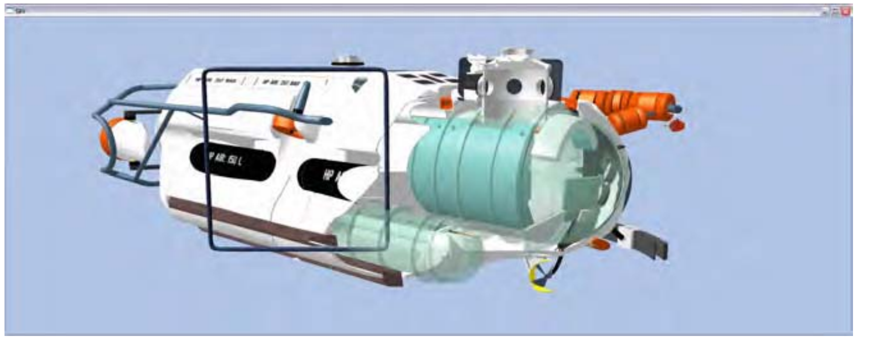
Evacuation of an immobile rescuee

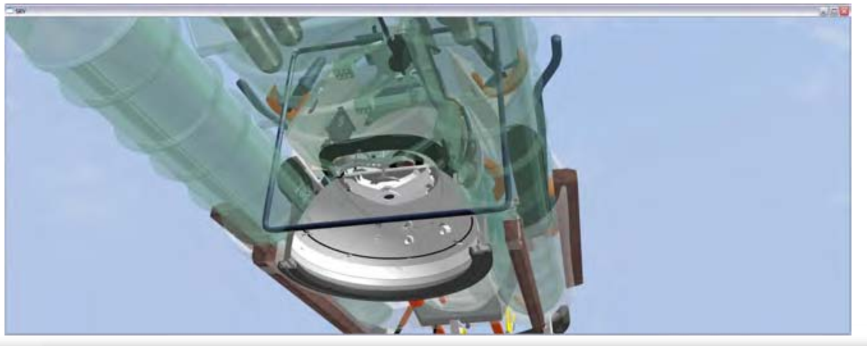
Hatch opening procedure

Human modelling and movements' simulation examples

Simulation Real-Time







Conclusions

Case Study Process & Results

- 3D Visualisation of involved vessels
- Initial Simulation & Animation of procedures
- Environment simulation

Aims

- To Circumvent potential design and ergonomics issues well in advance of the completion stage

Benefits

- Evaluate in Real-Time the structural designs
- Evaluate Human Factors involved in different operations
- Fully controllable environment
- Safe environment (simulated environment)

Future Work

Expand our future work to:

1. The development of the real-time visualisation of the SRV and associated Rescue Equipment.

3. To enable non-expert users in CAD to explore and interact with the 3D environment in real-time

5. Design and development of a virtual-reality-based interface and allowing non-expert users to easily
   a. inspect,
   b. review and
   c. analyse the physical and human interactions

6. To prevent or minimise onboard or procedural accidents

Simulation

- Testing different simulation scenarios (series of simulations for different procedures)

Implementation

- Investigation of various interactivity avenues

Thank you very much

For further information please contact:
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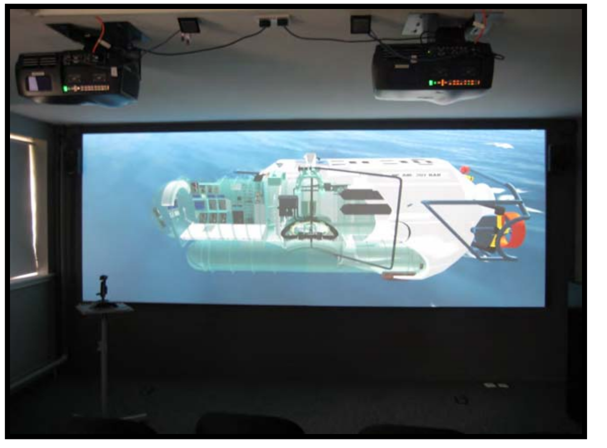

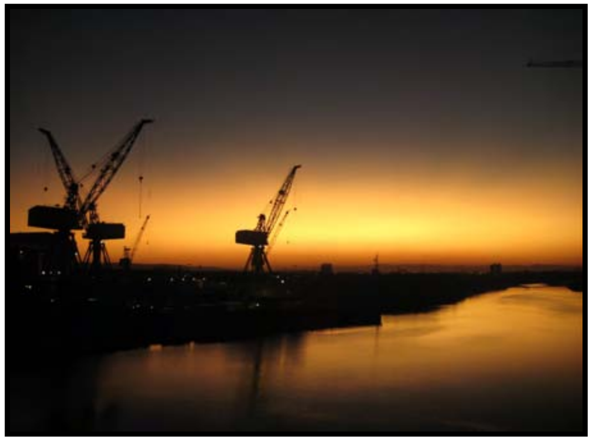

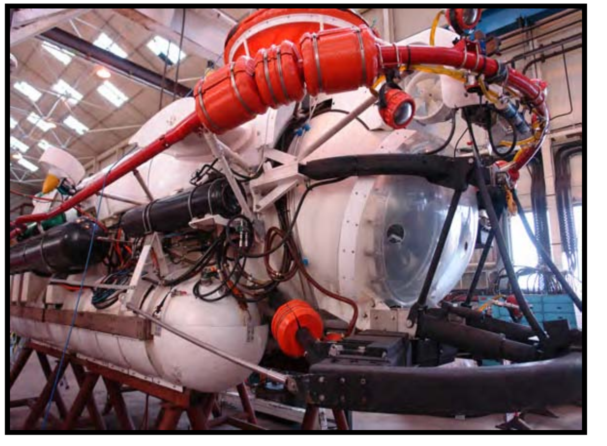

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Warships 2008

An Asset Integrity Management Strategy for Marine Propulsion Tailshafts

Dr Julian Austin, Alexandra Lindsell *Frazer-Nash Consultancy Ltd*
Jim Bentley, *IMES Ltd*
Jon Nicholson, *Maritime Equipment Services, UK MoD*

MINISTRY OF DEFENCE

Agenda

- Introduction
- What is Asset Integrity Management?
- Tailshaft Life Prediction
  - Design Basis
  - Review of Information
  - Reliability-Based Integrity Model
- NDT Inspection System
  - Requirements Capture
  - Technical Development
  - System Qualification
- Asset Integrity Management System

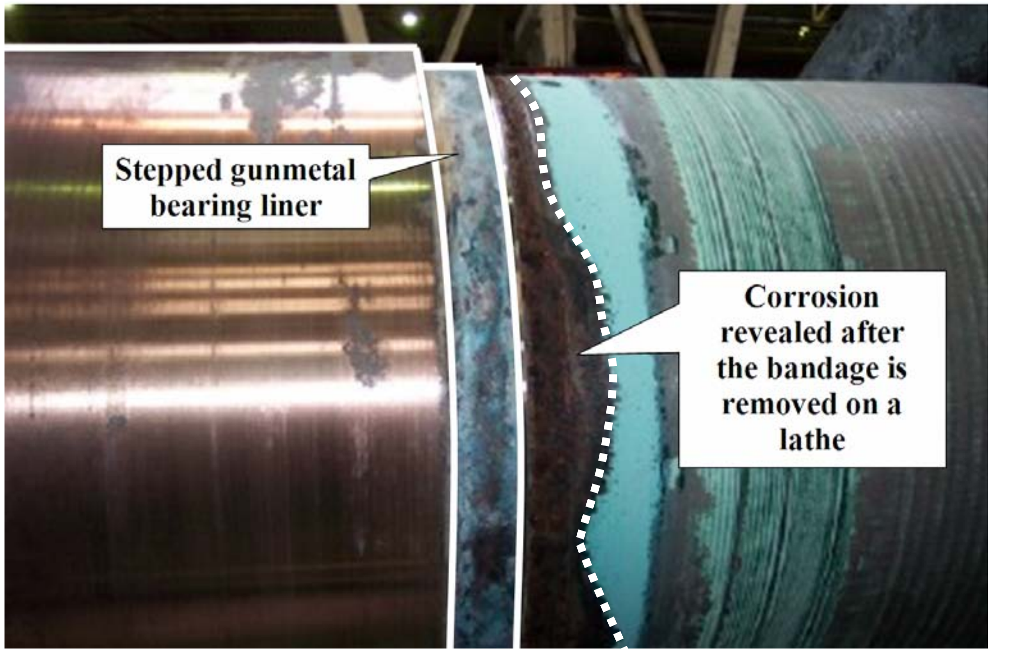
Introduction

- Tailshafts experience millions of revolutions in service
  - Stress concentrations cannot be tolerated due to fatigue
  - Manufactured surface finish is well controlled

- Exposed length between bearing liners covered with epoxy bandage
  - If bandage fails, seawater gets in and corrosion pitting may initiate fatigue cracking

How is shaft integrity controlled?

- Shaft integrity dependent upon DEF-STAN 02-304
  - Surface preparation prior to epoxy bandage application
  - Design loads to remain within guidance
- Despite these controls, several shafts have experienced some cracking



- In order to manage the risk of tailshaft cracking in service an Asset Integrity Management (AIM) strategy has been developed

Asset Integrity Management

- Asset Management
  - *'to ensure that assets deliver the required function and level of performance in terms of service or production, in a sustainable manner, at an optimum whole life cost without compromising health, safety, environmental performance, or the organisation's reputation'* (PAS 55)

- Asset Integrity Management
  - *Management of the integrity of physical assets to deliver the optimum balance of risk / cost / performance throughout the asset lifecycle*

Asset Integrity Management

- Asset Integrity Management requires input from:
  - Current / future design and usage requirements
  - Understanding / criticality ranking of asset degradation processes
  - NDT Inspection / Structural Health Monitoring technologies
  - Human factors / Competency requirements
  - Legislative / Environmental compliance

Planning the future integrity of new to service assets

Managing the ongoing integrity of existing legacy assets

Asset management strategy
Procurement
Construction
Operation
Maintenance
Life extension
Disposal

ASSET LIFECYCLE

Asset Integrity Management

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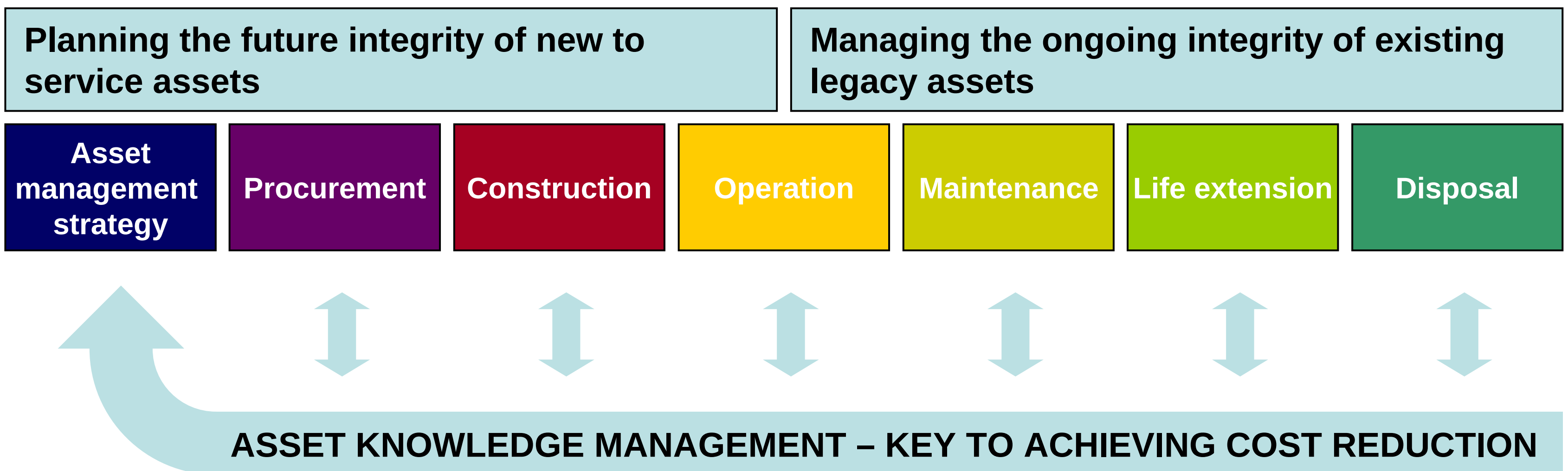

Asset Integrity Management Strategy

- Review the through-life safety drivers and their impact on costs
- Understand the issues that affect shaft integrity
  - Assess how shaft condition is likely to deteriorate over time
- Create a reliability model to predict:
  - When a shaft from new is likely to require inspection
  - When a shaft that has just been inspected should be inspected again
- Capture requirements for an NDT inspection system to find shaft defects before they compromise safety
- Develop the NDT inspection system based on the requirements
- Formally qualify the NDT inspection system
- Manage shaft inspections within a robust data infrastructure

Asset Integrity Management Strategy

Phase 1 Development of Asset Integrity Management Plan

↓

Phase 2. Development of Integrity Management Requirements

↓

Phase 3. Requirements, Feasibility & Demonstration for NDT

↓

Phase 4. Technology Development for NDT

↓

Phase 5. Qualification for NDT and inspection plan

↓

Phase 6. Delivery and Implementation

Tailshaft Life Prediction

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Shaft design intent

- DEF-STAN 02-304 specifies a life between 10^8 and 10^9 cycles
  - Shaft bending stresses dominate fatigue life and should not exceed +/- 20MPa

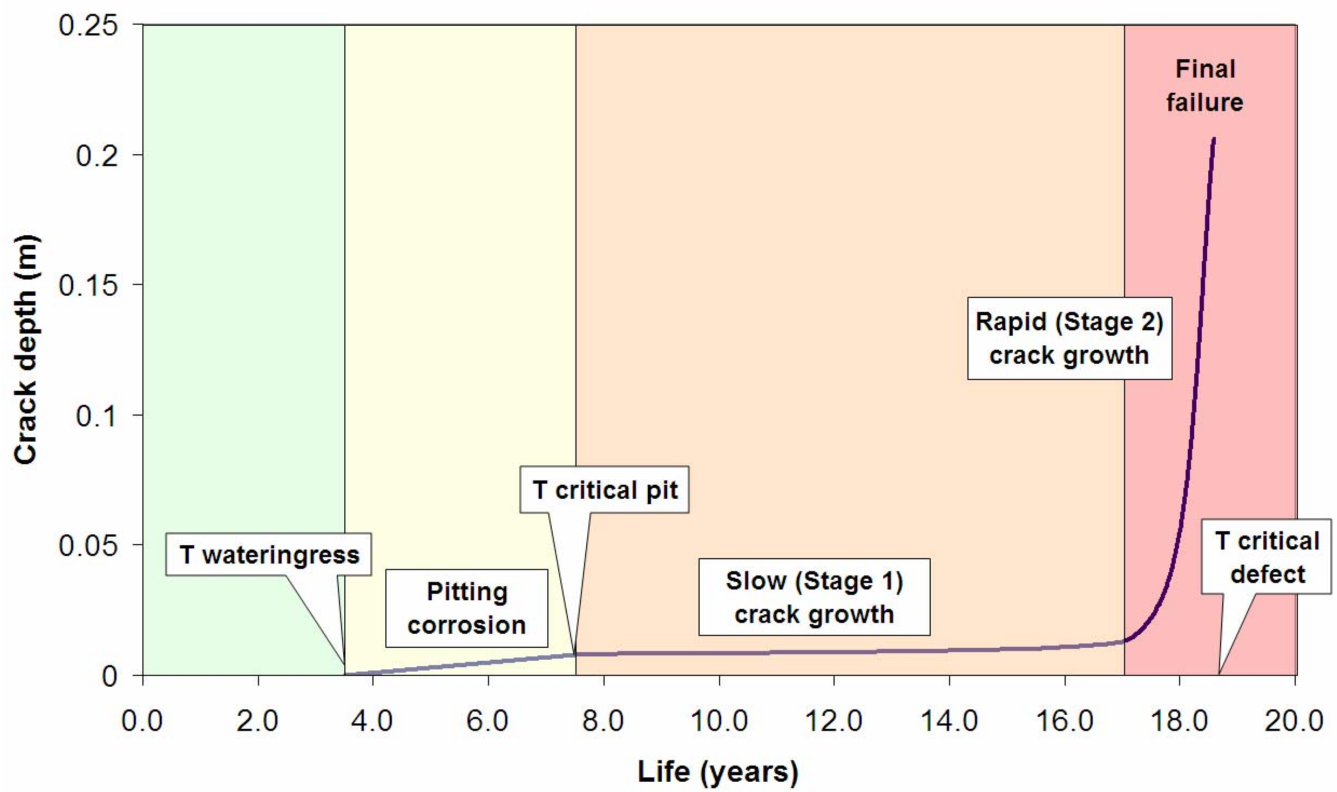
- Shafts must survive at least 7 years between refurbishments (T Class) and possibly even longer (Astute Class)

- If bandage leaks early, deterministic calculations predict shaft failure in about 4 years
  - Not consistent with in-service experience
  - Reliability-based approach provides better shaft life estimates

Review of information

- Various information sources considered
  - Design drawings
  - Material specifications
  - Studies on shaft corrosion
  - Studies on crack propagation
  - Shaft service records and defect reports
  - NDT inspections
  - Shaft alignment studies
- Consensus on primary damage mechanism
  - Bandage leaks at liner terminations
  - Surface corrosion (pitting) occurs
  - Corrosion pits develop into fatigue cracks
- **Very little information on defect mechanics**

Reliability-based shaft integrity model



$$t_{failure} = t_{water\ ingress} + t_{critical\ pit} + t_{critical\ defect}$$

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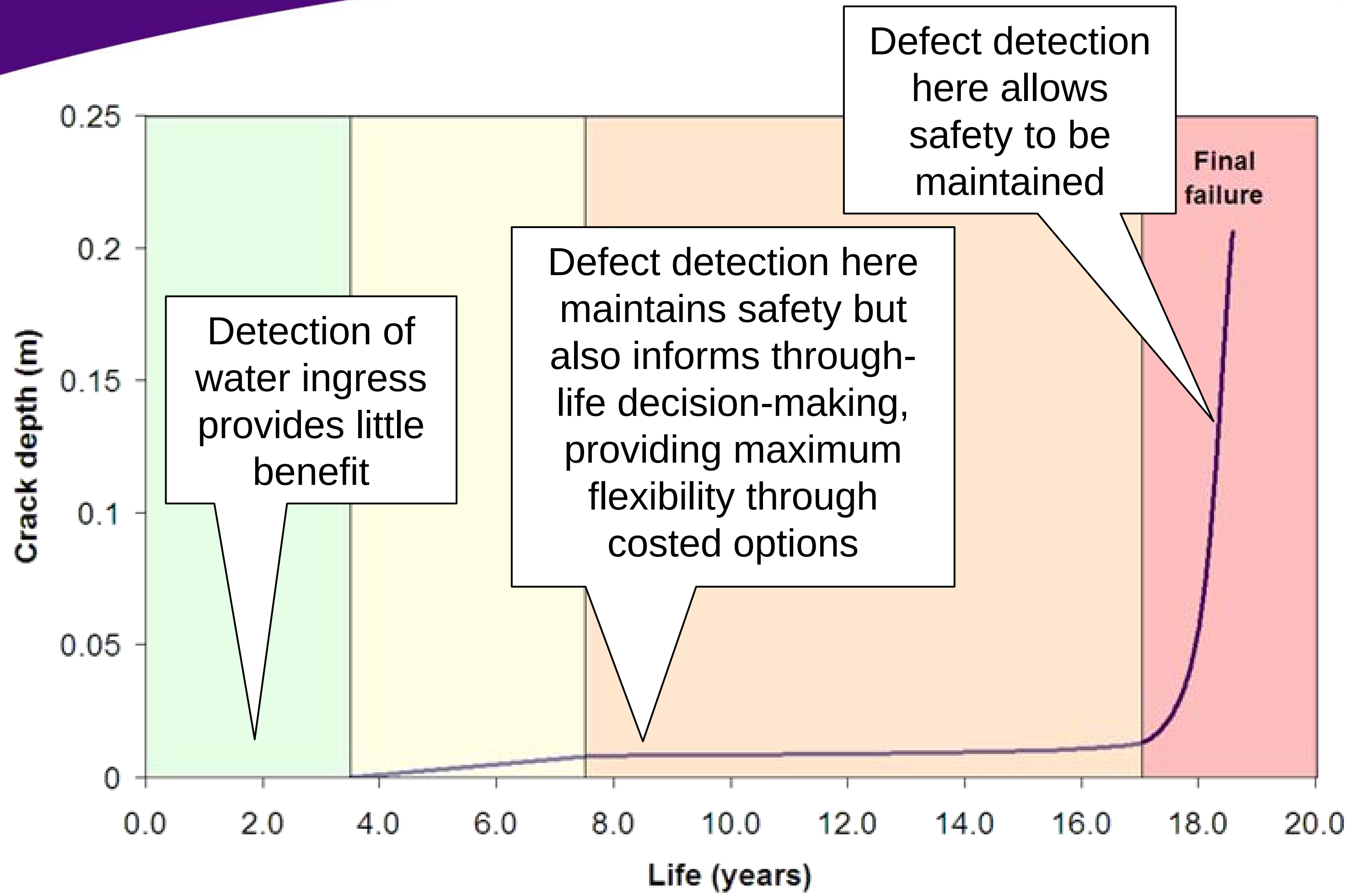
What do we need to know about shaft condition?



Integrity model parameters

- Water ingress impossible to predict
  - Must assume water gets under bandage at start of life
- Corrosion pitting
  - Modelling requires long-term empirical data
  - Shows considerable statistical variation
- Near threshold fatigue crack growth
  - Modelling requires empirical data
  - Shows considerable statistical variation
- Post threshold fatigue crack growth rates so high that life is effectively expired

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Pitting corrosion & crack transition phase

- Several models have gained wide acceptance
  - Maximum pit depth, *c*, increases rapidly initially then slows down (*Hoeppner*)

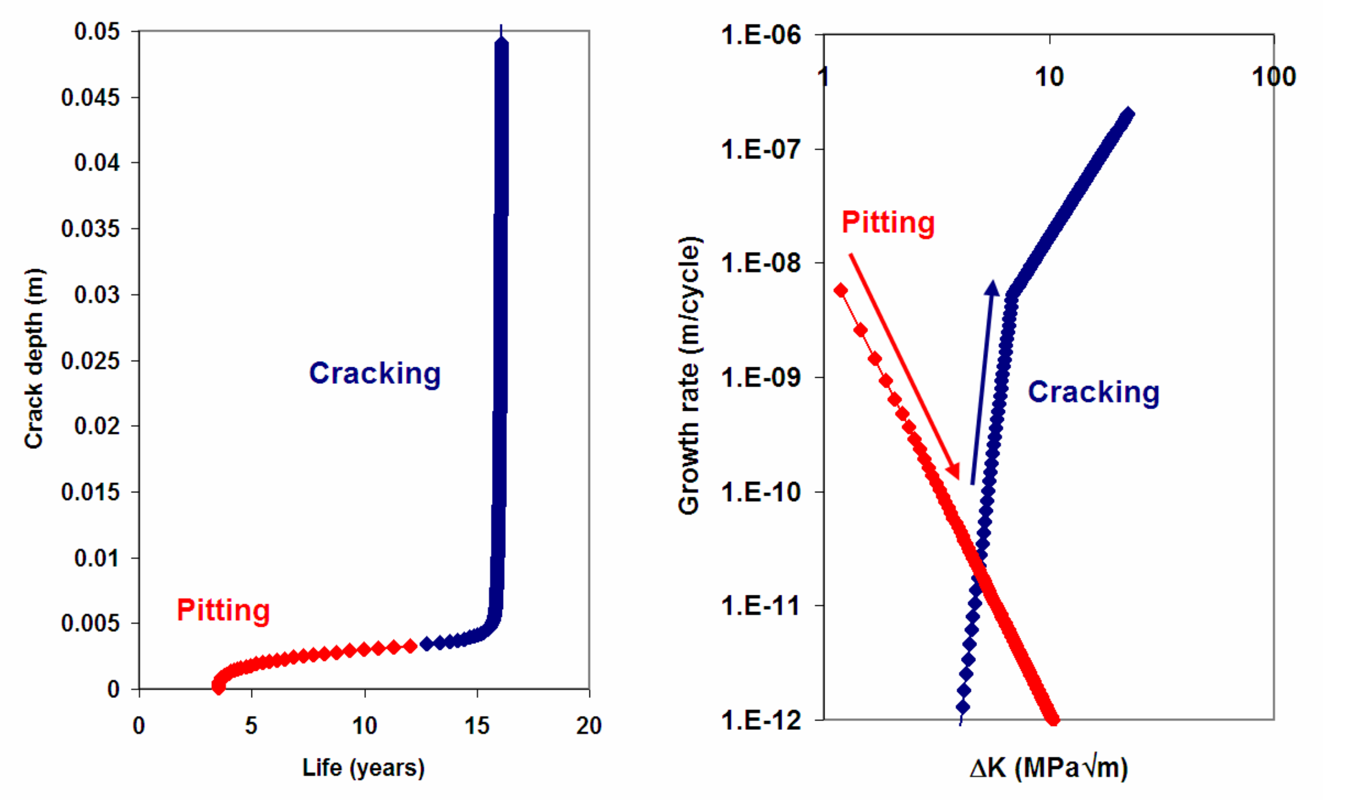
$$c = C_p\, t^{1/3}$$

  - Pitting growth rate as a function of ΔK (*Kondo*)

$$dc/dN = 0.33\, C_p^3 f^{-1} a^2 \pi^2 Q^{-2} (2.24\sigma_a)^4 \Delta K^{-4}$$

- Pit to crack transition occurs when fatigue crack growth rate exceeds rate of pit growth
- Can use this model if we can deduce C_p from observations of depth of pitting over time

Pitting corrosion / fatigue mechanics



- Pits grow until nascent fatigue cracks outrun pits

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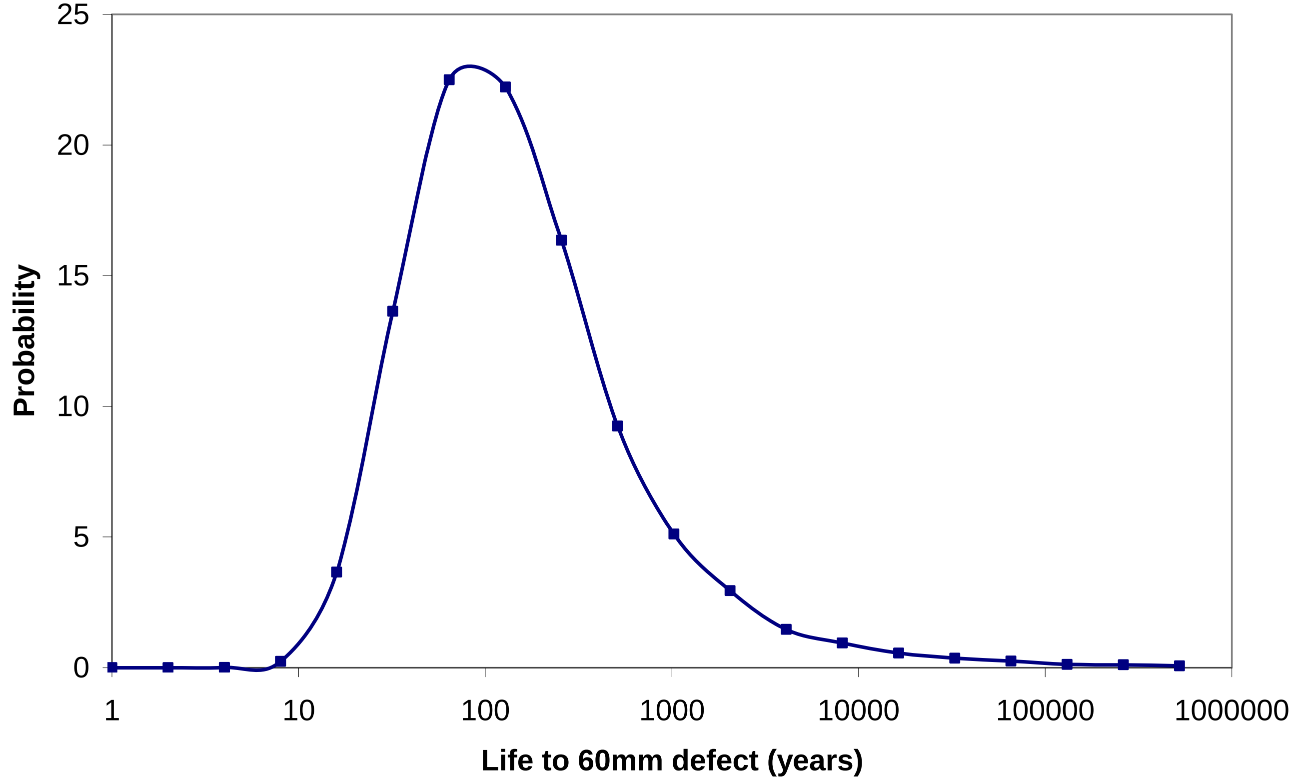
Implementation of integrity model

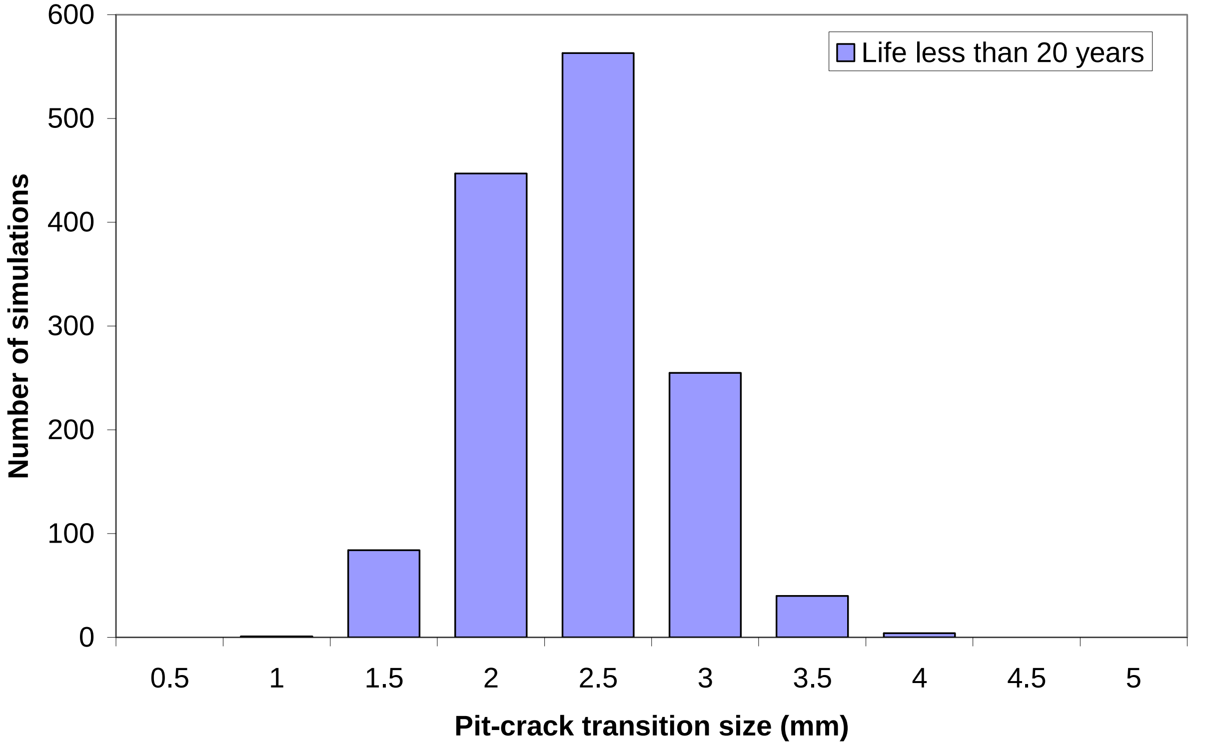
- Monte Carlo reliability model includes pit growth and pit-crack transition mechanics
- 40,000 simulations give adequate resolution of risk
- Output provides statistics for:
  - Pit size at pit-crack transition point
  - Time to develop defects of various sizes
  - Defect populations after various times
- Allows defect detection requirements for NDT system development to be robustly specified

Life to complete shaft failure



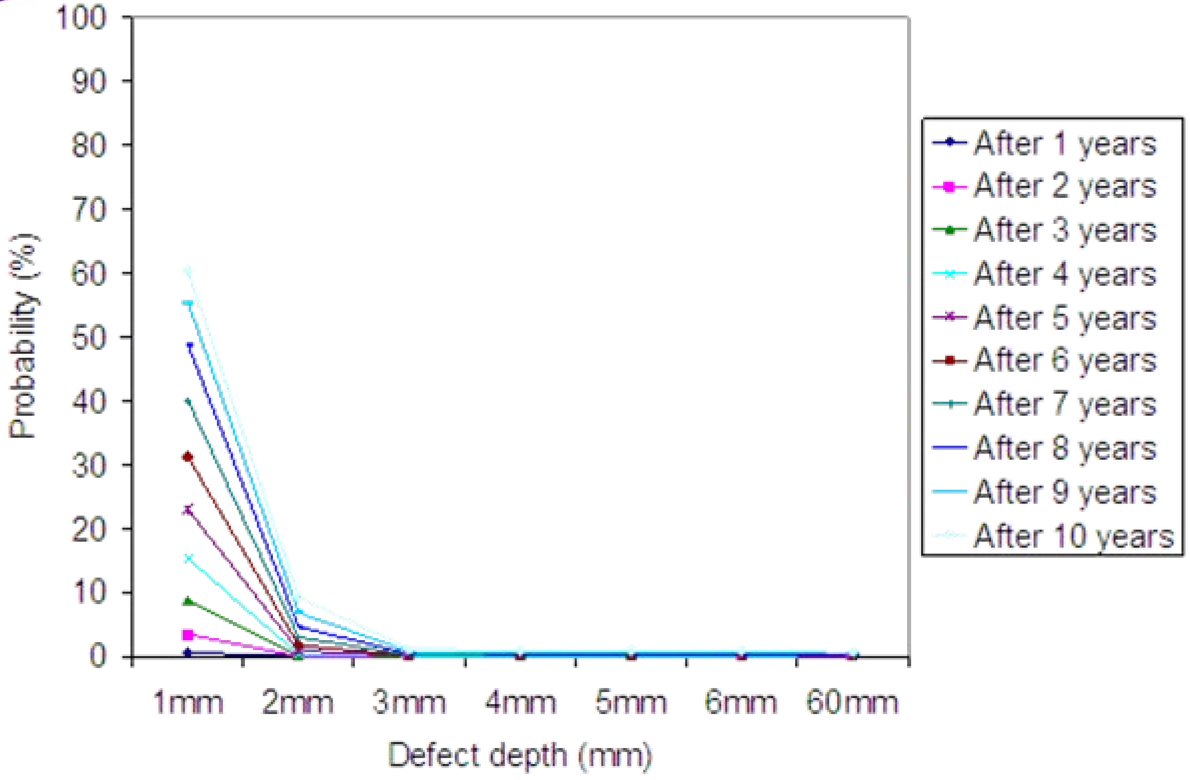
- Confirms that shaft failure is an ‘unlikely’ event within 10 years

Pit-crack transition size



- Pit to crack transition sizes are relatively large (~2-3mm)
- Detection of pits *and* cracks is therefore of interest

Defect populations in new shaft



- High probability of small (<3mm) defects in 10 years if water gets in
- Critical defect size is about 5mm (shock / runaway fatigue)

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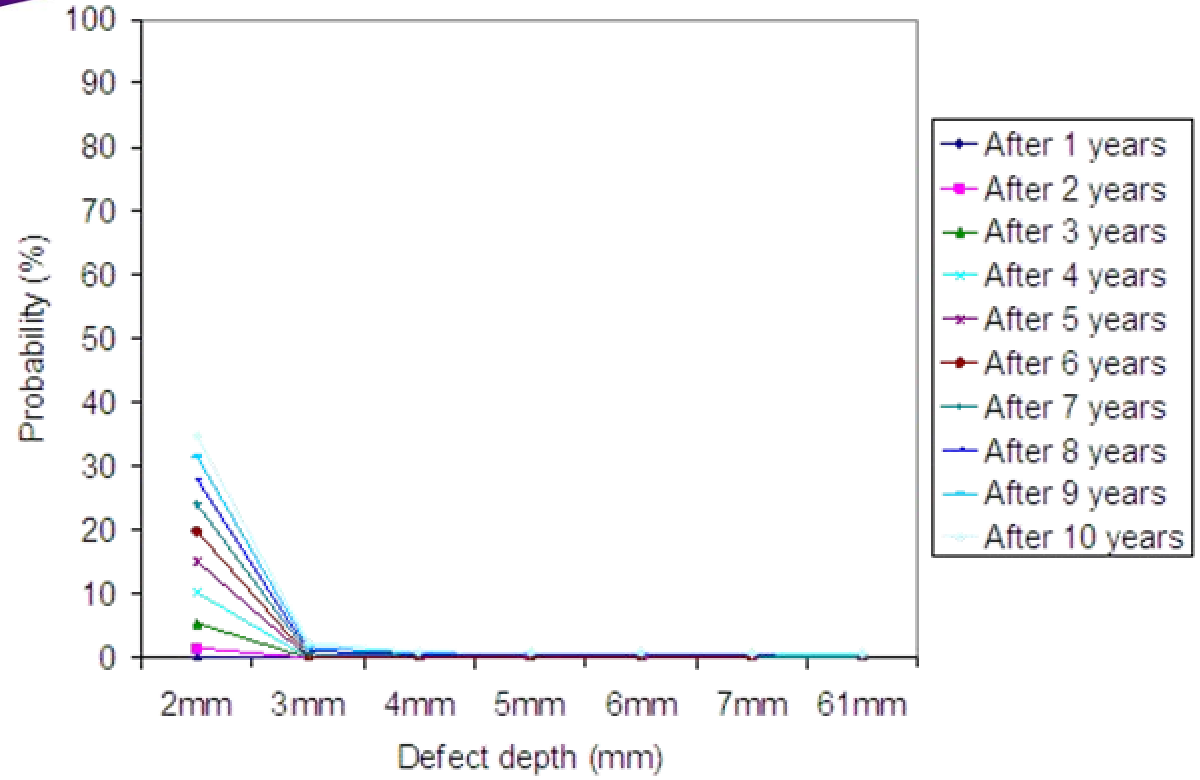
Defect populations in re-used shaft



- Re-used shaft with >2mm defects eliminated by NDT inspection does not develop critical defects within a further 10 years

NDT Inspection System Development

Requirements Capture

- System Requirements fully captured by stakeholder workshop
  - Frazer-Nash, Imes, MoD, Babcock Marine
- Defect detection criteria are demanding
  - 2mm deep defects must be reliably detected
  - Large component dimensions
- Existing commercial systems unlikely to be suitable
  - Sensor technology will dominate success
  - Delivery mechanism of secondary difficulty
- Essential to evaluate sensor technology first

High Level Requirements

The system shall be able to inspect tailshafts of Trafalgar (except HMS Trafalgar), Vanguard and Astute Class submarines.

High Level Characteristics

Detect Defects

- The system shall be able to detect crack-like defects of a minimum depth of 2mm.

  The system must be able to detect pit-like defects of a minimum defect depth and diameter of 1mm x 2mm.
- The system shall be able to assign a confidence level to all inspection data.

Nature of Defect

- The system shall be able to differentiate between crack-like defects and pit-like defects.

  The system shall be able to differentiate between linked pit-like defects and discrete pit-like defects.

Location of Defects

- The system shall be able to determine the orientation of crack-like defects.

  The system shall be able to determine the geometry of the defect.
- The system shall be able to identify and record the absolute location of defects on the shaft.

Access

- The user shall be able to perform the inspection during the RAMP period.

Operating Environment

- The system shall inspect the tailshaft whilst the submarine is in dry dock.

  The system shall be able to be supported on normal staging.

Sensor dependent

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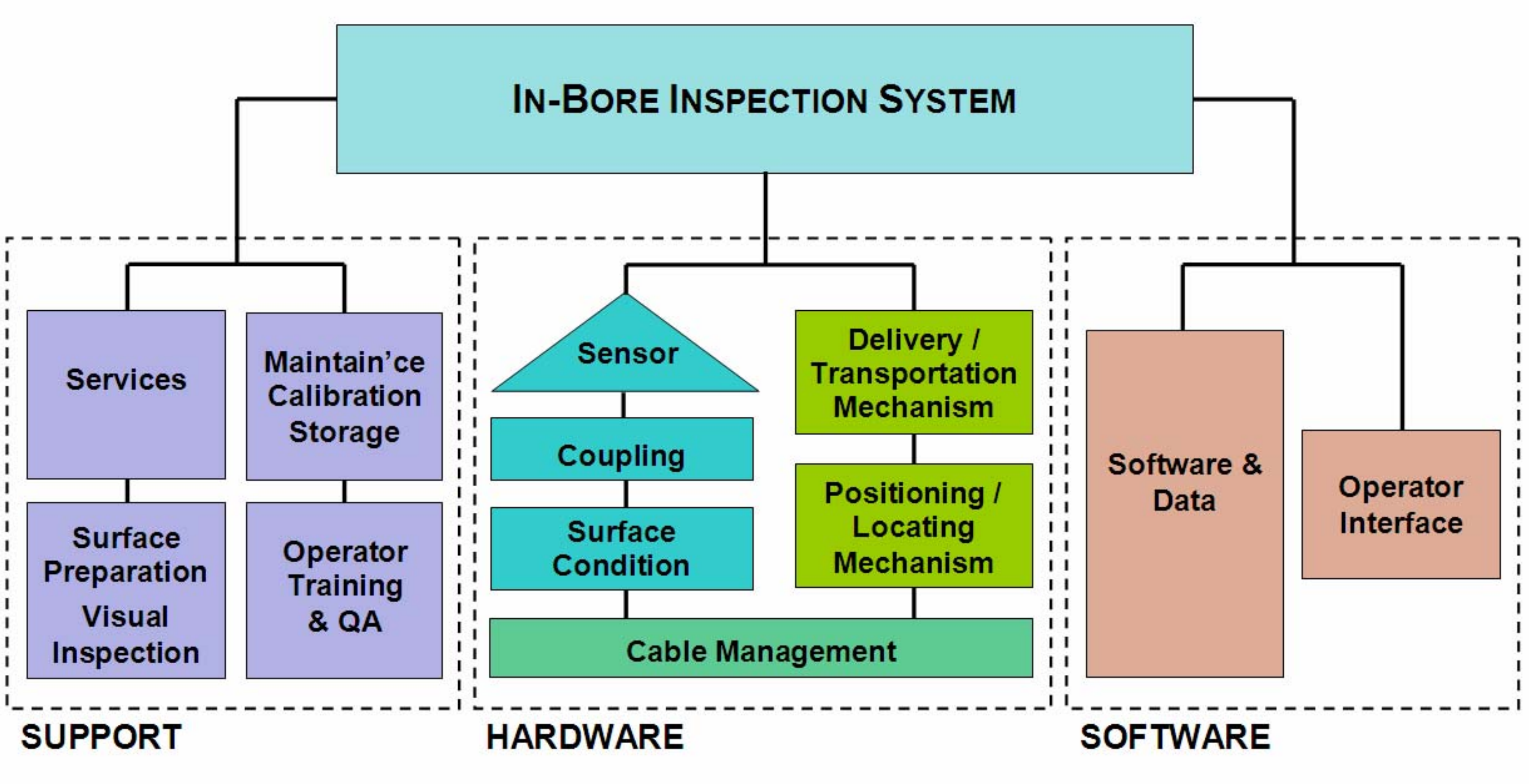
System Functional Diagram



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Sub-system Options

Sub-Systems	Options												
Sensor	Pulse Echo	TOFD	Phased Array	Guided Wave Ultrasonics	Eddy Current	Magnetic Flux Leakage	Alternating Field Current	Magnetic Particle Inspection	Radiographic Testing	Acoustic Emmision	Visual/ Optical Inspection	Magnetic Resonance Imaging	Liquid Penetrant Testing
Coupling	Water	Gel	Grease	Paste									
Coupling Method	Irrigation	Partial flood	Full flood	Transient flood (sealed chamber)	Sprayed	Dry coupled							
Surface Preparation	None	Remote Water Jet Blast	Remote Sand Shot Blast	Remote Manual Wire Brush	Rotating Sandpaper Boring Tool	Cleaning PIG	Remote Needle Gun						
Delivery/ Transport	Manually operated Single Rod	Extendable Rod (Sections, Telescopic)	Mechanical Track operated Rod	Robotic Craw ler	Propelled Inflatable	Automatic bore inspector	Banana Bottle Device						
Location	Sprung concentric circles	Inflatable	Banana Bottle Device	Rollers									
Positioning	Circular sensor array	Helical Scan Sprung Arms											
Data Management	PC Based	Embedded											

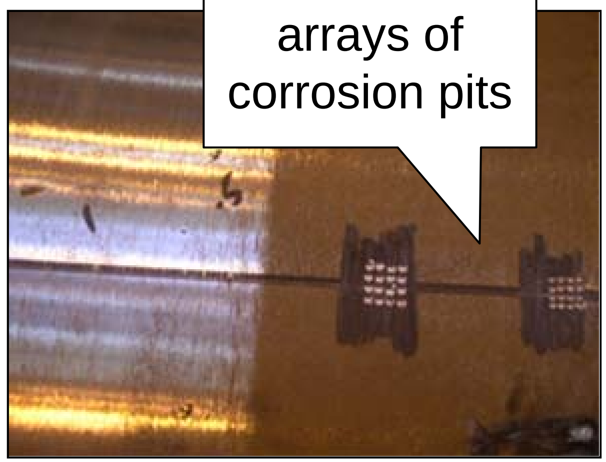
Sensor technologies

Review of requirements

- Initial review - most inspection technologies unsuitable
  - Shaft is covered in epoxy bandage
  - Access to outside surface is restricted
  - Surfaces are curved
  - Defects of interest are very small
  - Detection *and* sizing required
- Conclude that most reliable and technically mature approach was to access from the bore using ultrasonic techniques:
  - Conventional Pulse Echo
  - Time of Flight Diffraction
  - Phased Array
- Initial demonstrations carried out on a full scale test piece

Test Specimen

Simulated isolated corrosion pits



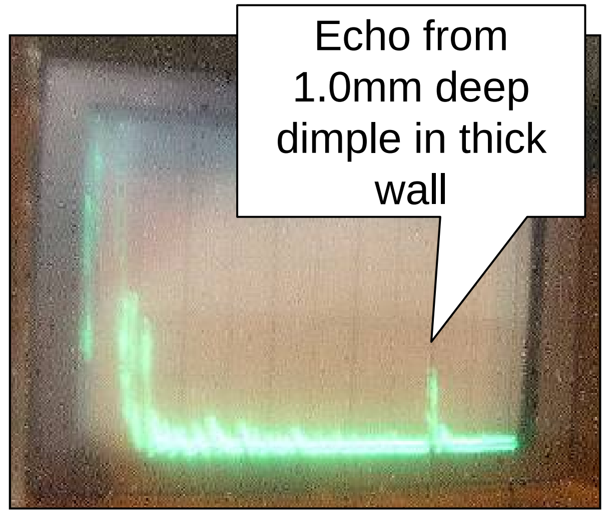
Simulated arrays of corrosion pits

Test specimen defects

- Range of defects in test specimen
- Simulated individual corrosion pits
  - 10, 8, 6, 5, 4, 3, 2, 1mm diameter hemispherical dimples
- Simulated fields of pits
  - 4 x 4 array of 2mm dimples spaced 3mm apart
  - 4 x 4 array of 1.4mm dimples spaced 2mm apart
- Simulated crack
  - 0.7mm deep by 8mm long slot

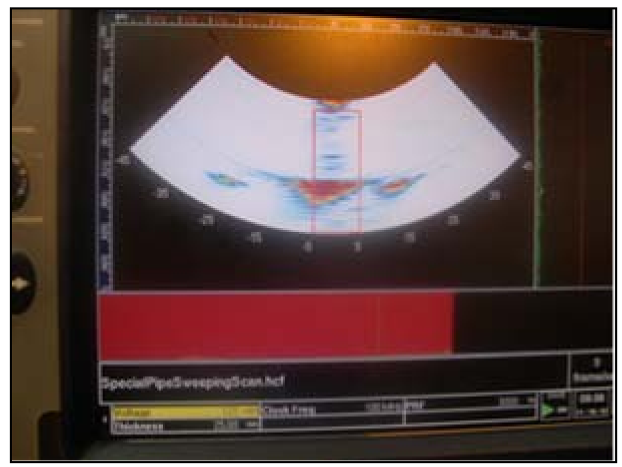
Pulse Echo Demonstration

- 0 degree beam incidence
  - Detection not possible
  - Sizing not possible
- 45 degree beam incidence
  - Thick wall: detection very good
  - Thin wall: detection excellent
  - Sizing not possible without automated manipulator capability



Phased Array Demonstration

- 0 degree incidence
  - Detection poor
- 20 degree incidence
  - Defects could be detected
  - Back wall echo dominates
  - Probe was far from ideal and would need bespoke design
  - Good potential for visualisation



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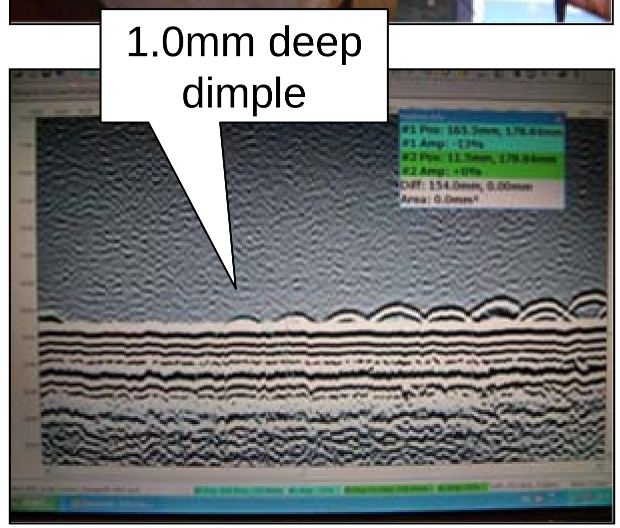
Time of Flight Diffraction Demonstration

- Detection and sizing down to 1mm deep dimple at thick walled end of shaft
- Detection and sizing not quite as good at the thin end due to unusually heavily corroded surface condition
- Shows excellent potential for detection and sizing if optimised



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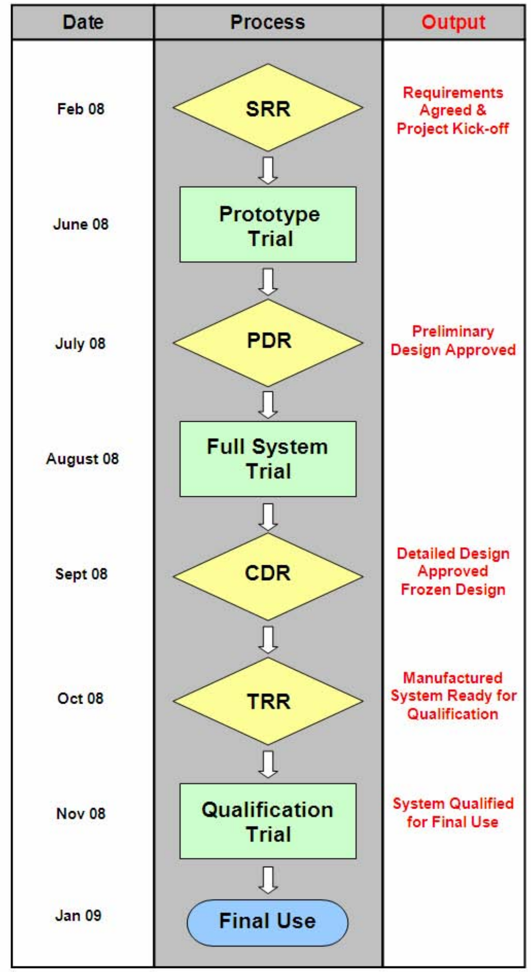
Conclusions from Initial Demonstrations

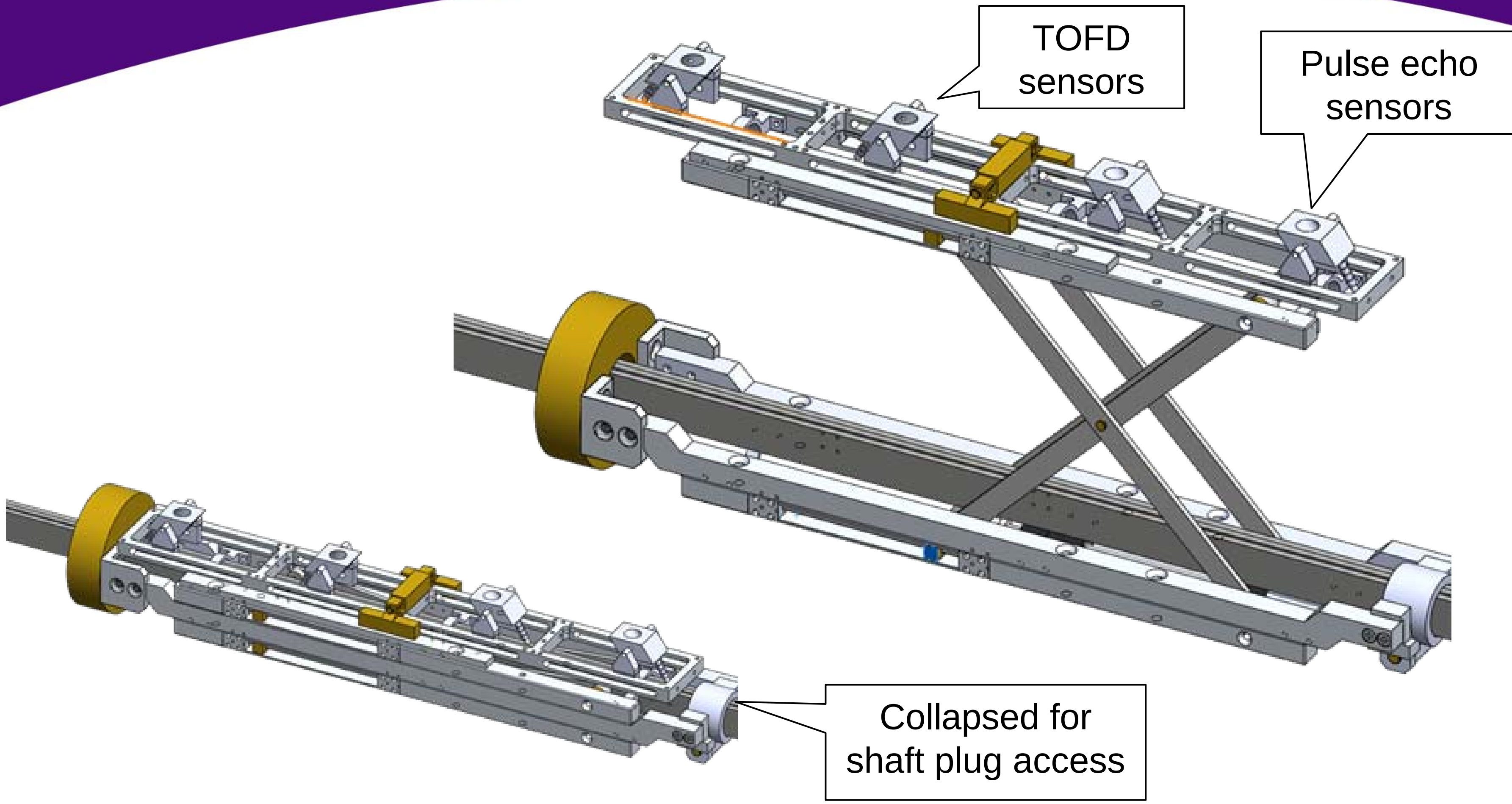
- A combination of TOFD and Pulse Echo Ultrasonics has the capability to meet the defect detection and sizing requirements
- Can use the manipulator system developed for V class gas bottle inspection as the basis of the sensor delivery platform
- Development and qualification programme specified for completion during 2008

Development and Qualification

- Development programme consists of four Design Reviews and Technology Maturity Assessments aligned with physical trials of increasing complexity
- System should be fully qualified by Q4 2008
- First ‘mission’ planned for Q1 2009



Current status of prototype manipulator



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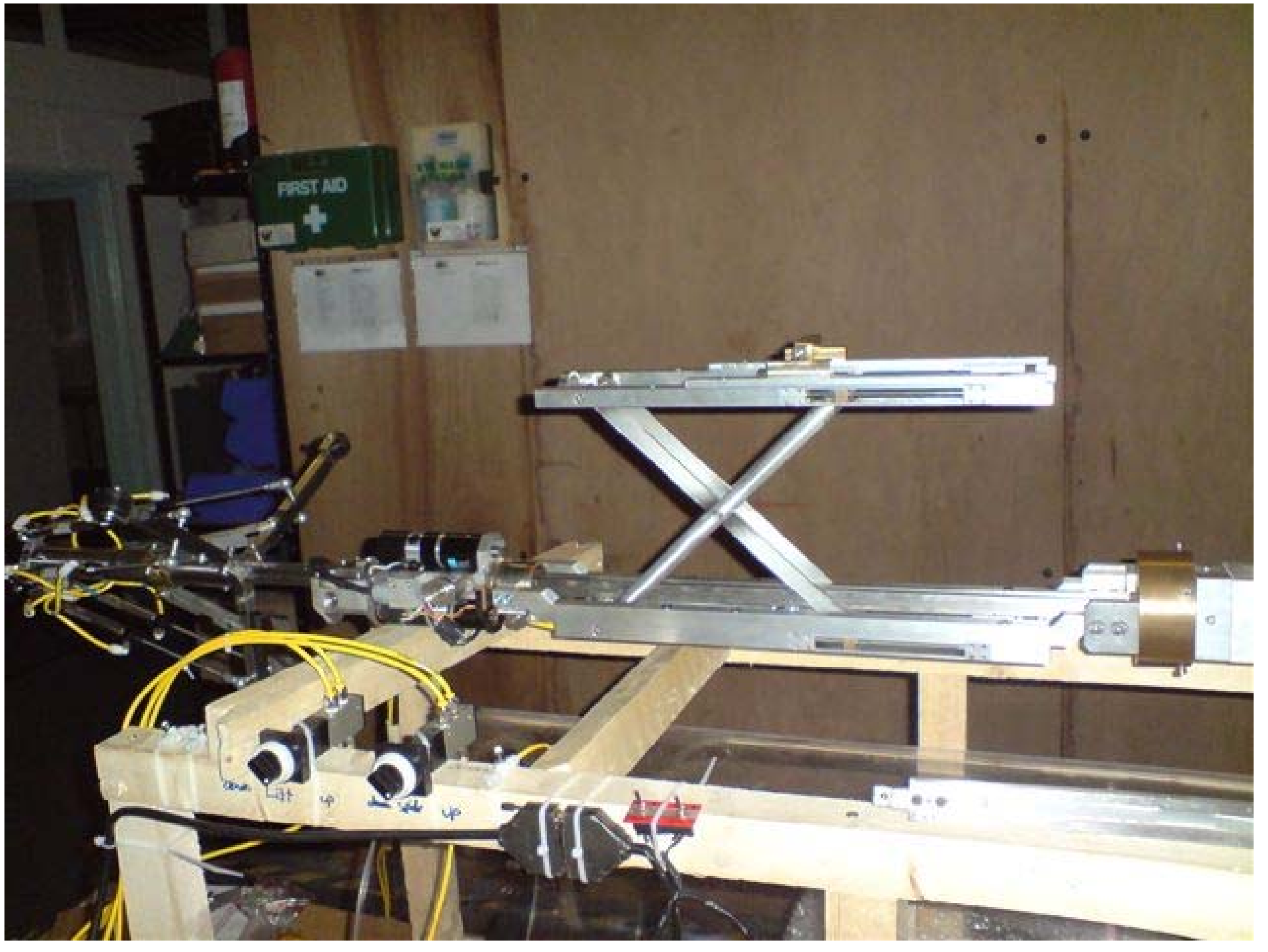
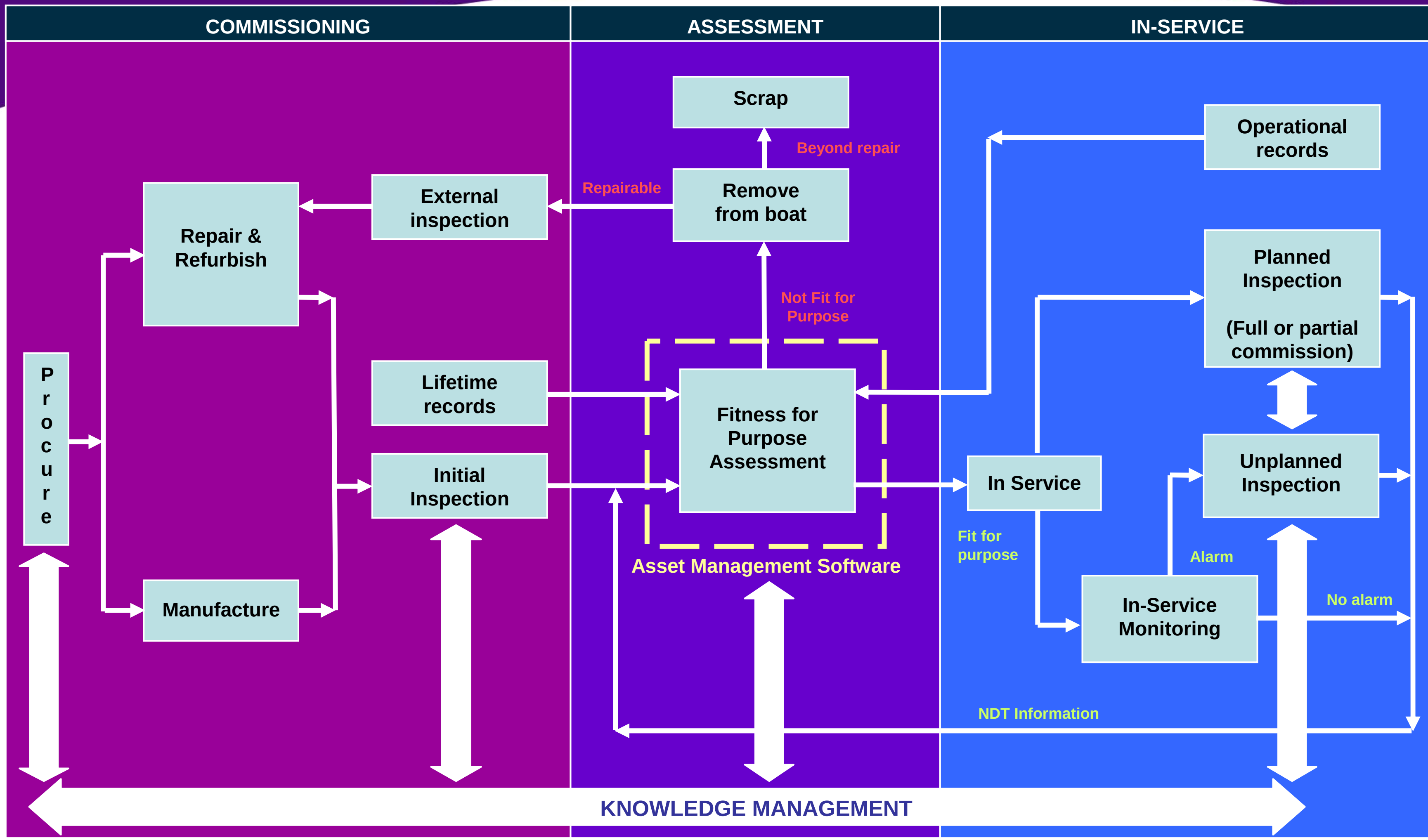
Current status of prototype manipulator



Asset Integrity Management System



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Current Status of Programme

Phase 1 Development of Asset Integrity Management Plan

↓

Phase 2. Development of Integrity Management Requirements

↓

Phase 3. Requirements, Feasibility & Demonstration for NDT

↓

Phase 4. Technology Development for NDT

↓

Phase 5. Qualification for NDT and inspection plan

↓

Phase 6. Delivery and Implementation

Conclusions

- The safety and cost drivers for through-life ownership of tailshafts have been used to specify an Asset Integrity Management Plan

- The System Requirements for an NDT inspection system have been robustly defined using:
  – The outputs of a reliability-based integrity model
  – Stakeholder workshops

- A Technology Development Programme is underway to deliver a qualified NDT inspection capability by the end of 2008

- The knowledge and equipment developed has the potential to influence the through-life support solutions for Successor

Thank you

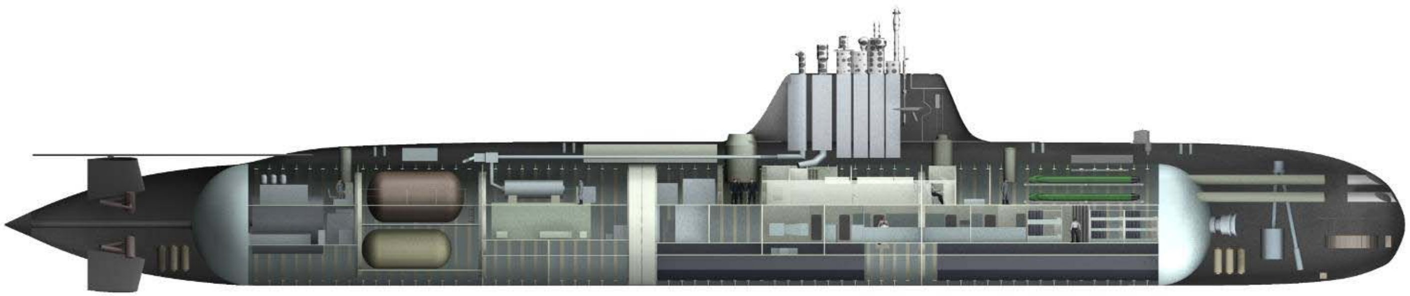
Questions?

CONTENTS

RINA Naval Submarines 2008: Keynote Address

Understanding Whole Submarine Capability and Cost

Howard Mathers, Chief Engineer
UK MoD DG Submarines



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Introduction

- Cold War Submarine Procurement:
  - Complex and high safety requirement
  - Sophisticated Industrial Base with large volume throughput
  - Priority was Capability not Cost

Introduction

- 21st Century Submarine Procurement:
  - Focus on Littoral Operations
  - Flexibility in tasking
  - Adaptable through life
  - Change in Industrial Base
  - Priority shifted to Cost Through Life

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Overview of UK Market Drivers

- Downward pressure on defence budget
- Need to sustain a credible and sustainable Submarine Industrial Base
- Improving standards of safety

Future UK Submarine Procurement

- Industrial Lead rationalisation
- Rainbow Teams – Future Submarine Team
- Change of Contracting from Bi-lateral agreements to Collaboration between MoD and:
  - the Builder(BAES),
  - Maintainer(Babcock Marine)
  - Propulsion System manufacturer(RR)
- from start of pre-concept work

babcock

BAE SYSTEMS

Rolls-Royce

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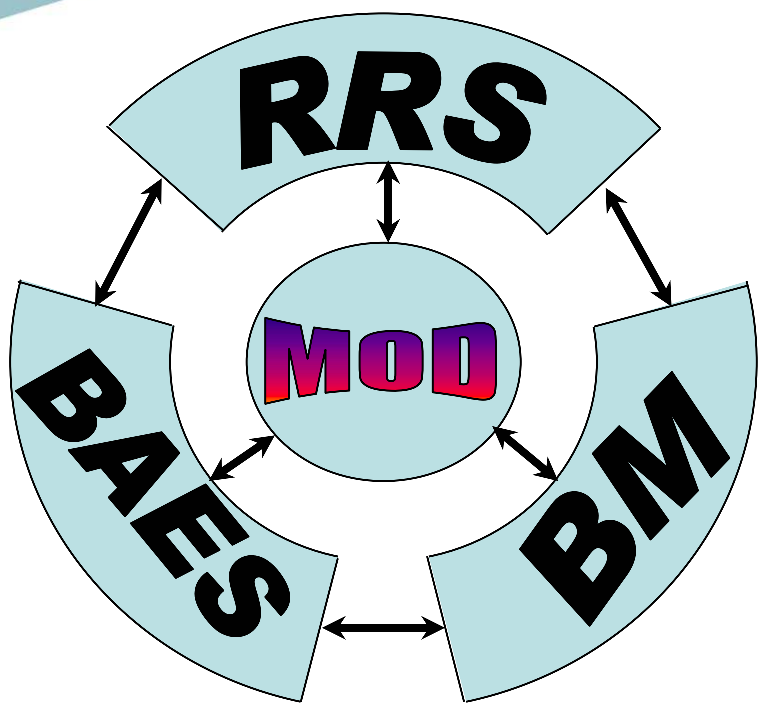
AS IS: BILATERALS



- Bi-lats with each Tier 1
  - T&Cs specific to each contract
  - Risk & Reward designed and managed at sub-enterprise level
  - Output incentivisation fails due to dependence on other parties
- Historically volume driven
- MoD manages Enterprise risk
- Retained and duplicated capability

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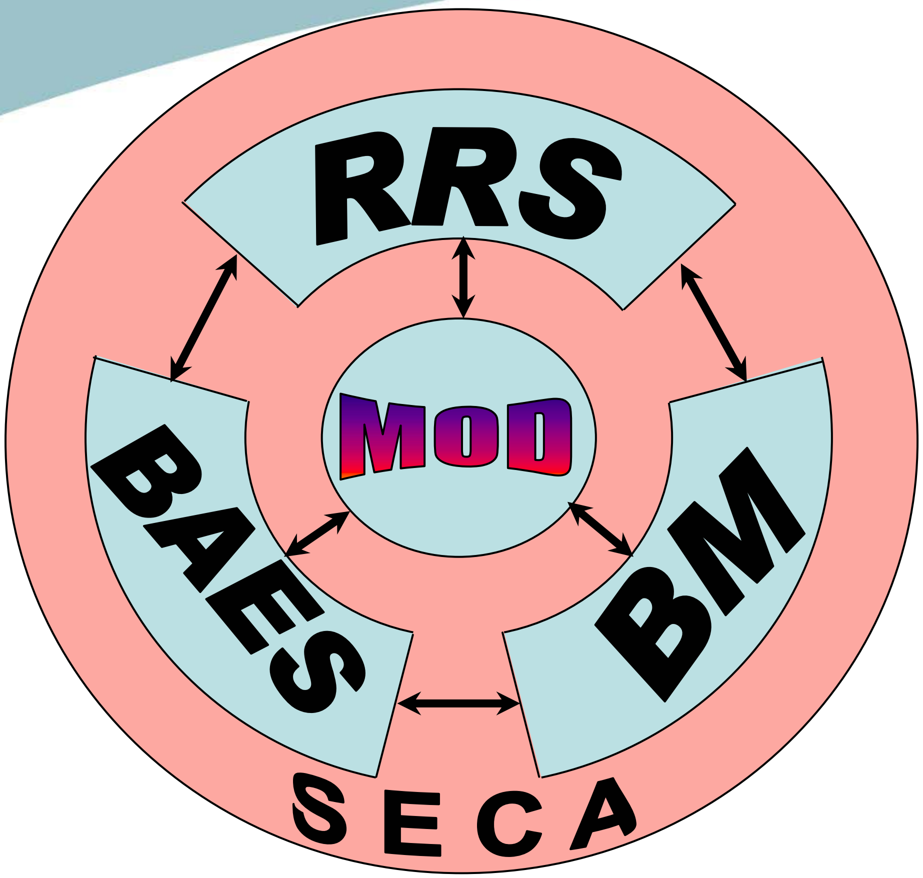
TO BE: COLLABORATION



- SECA enables access to collaborative benefit
- Integrated
  - Collective Risk & Reward linked to Enterprise outputs
  - Benefits share based on individual contributions
- Alignment
  - Between each parties objectives and Enterprise
- Profit linked to performance
- Improved Shareholder value
- Duplication reduced
  - capacity; capability; skills

Future Submarine Procurement

- the complexity of the cost picture
- how design and engineering has a bearing at numerous points
- how this must be developed in conjunction with the supply chain

- All of the above have significance for both nuclear and conventional submarine procurement

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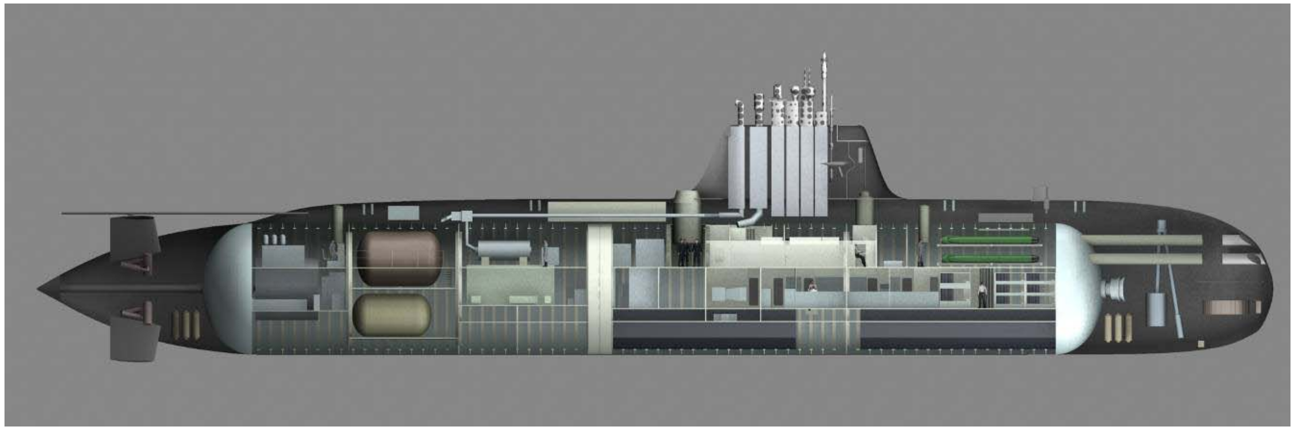
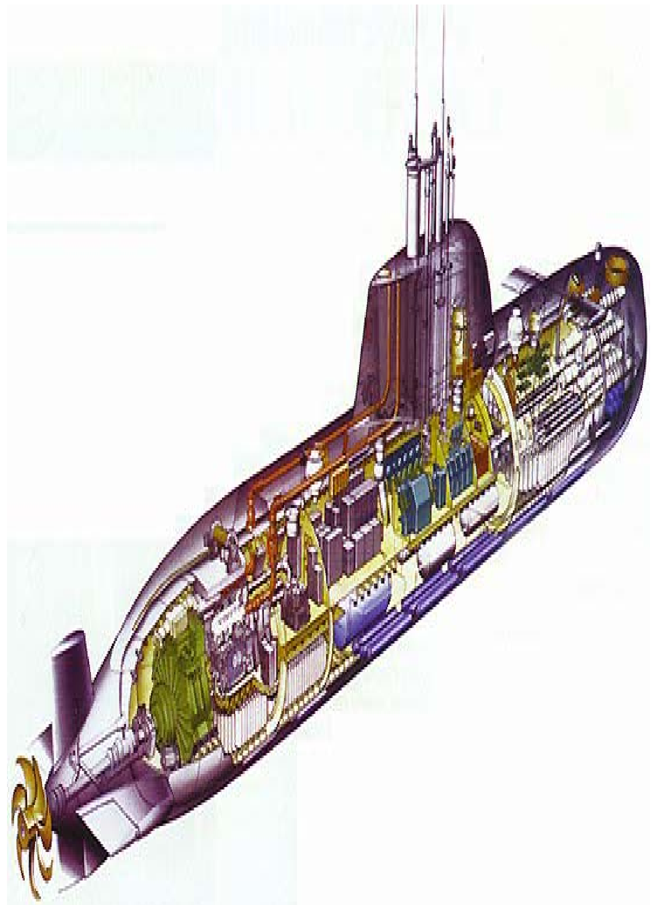
International Market Drivers

- Submarines offer unique defence capabilities
- Governments continue to be willing to consider making the necessary investment to acquire the capability
- This seems to be stimulating even more countries to modernise their submarine fleets
- BUT:



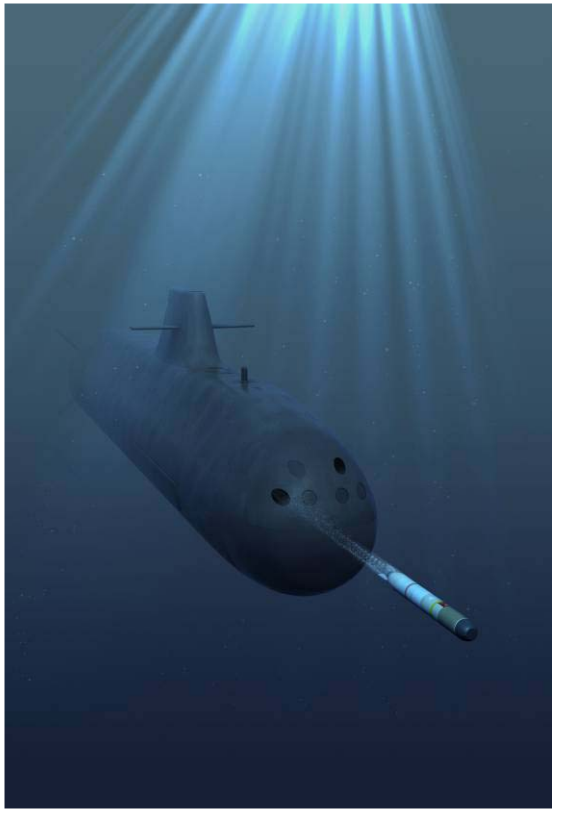
Submarine Market Drivers – Cost versus Capability

- The solution must be cost effective
- The solution must, at least in part, be indigenous
- Both nuclear and conventional submarine designers need to focus on driving out cost
- Flexible through life
- Make use of technologies through life
- Understand the cost drivers of overall capabilities, including:
  - Infrastructure
  - People and training
  - Technical assurance
  - Disposal



Conference Theme

- Many papers will focus on this theme of Capability versus Cost
- A strong emphasis on safety: how can we streamline this important regulatory role?
- Insights and a lot of interesting questions for the presenters
- Co-location with UDT will certainly enhance the event for the attendees
- Opportunity to discuss the insights with a world wide network of submarine designers and their supporting Equipment manufacturers



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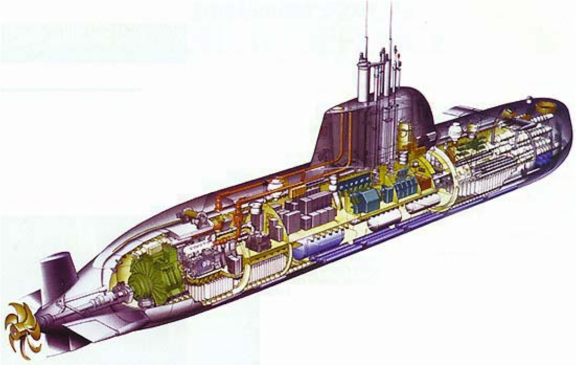

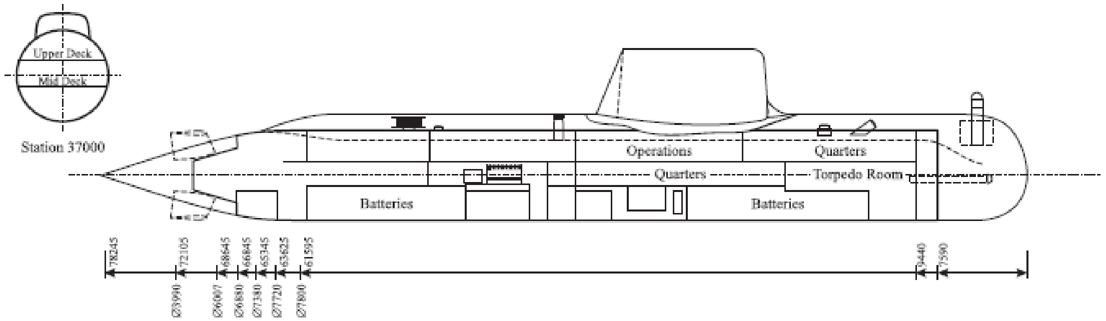

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SUBMARINES, NAVAL ARCHITECTS & SYSTEMS ENGINEERING

G MacDonald, BMT Defence Services, Australia.

SUMMARY

Systems Engineering dates back to Bell Telephone Laboratories in the early 1940s with the US Department of Defense embracing the discipline in the late 1940s in support of the initial development of missiles and missile-defense systems followed by MIT first teaching the subject in 1950. The discipline of Systems Engineering consists of a body of rigourous engineering process which can be applied to the most complex acquisition projects to achieve successful delivery and through life support. It is about the key creative processes that transform concepts into system designs, and the key technological and management processes that enable system development to proceed in an orderly, interdisciplinary fashion - maximising opportunities to meet client's needs while minimising risk. Submarines are arguably the most complex engineering systems produced by man and as such is a key candidate for embracing the methodology and indeed the weapons, communications and combat system element of submarine design already implement the approach. It is time for the Naval Architecture community to embrace, adopt and adapt the disciplines associated with the field of engineering and therby take the lead as the "Maritime Systems Engineer".

1. MILITARY CAPABILITY

Navy's do not operate submarines as an end in itself.

Submarine's provide a military capability that is a vehicle by which a government can achieve it's national and foreign policy objectives. Current practice in modern warfare is to express these objectives in terms of effects. An effect "is the physical, functional, or psychological outcome, event, or consequence that results from specific military action."

Examples of maritime related effects that a government may wish to exert may include:

- Gain military advantage through the covert collection of intelligence;
- Achieve asymetric advantage through concentration of adversary forces on ASW activities tying up or slowing down enemy assets/actions through hunting for sub;
- Exert control/exclusion in a maritime area of operations
- Interdiction of maritime commercial trade
- Blockade foreign ports and restrict ocean transport eg mine laying
- Support special force activities through the covert deployment/extraction of forces in the littoral environment
- Exploit enemy defence vulnerability to land strike from covert platforms;
- Maritime strike of hostile submarines and surface ships;

The ability to achieve a specified military effect is a function of four major components: force structure, modernization, readiness, and sustainability.

- force structure -Numbers, size, and composition of the units that comprise the national defence force and where appropriate interoperable allied forces;
- modernization -Technical sophistication of forces, units, weapon systems, and equipments.
- unit readiness -The ability to provide capabilities required by the combatant commanders to execute their assigned missions derived from the ability of each unit to deliver the outputs for which it was designed.
- sustainability -The ability to maintain the necessary level and duration of operational activity to achieve military objectives.

These in turn draw upon the Fundamental Inputs to Capability (FIC) which integrated together to field this capability ie the capability to achieve the effect. The 8 FIC elements are shown in Figure 1.

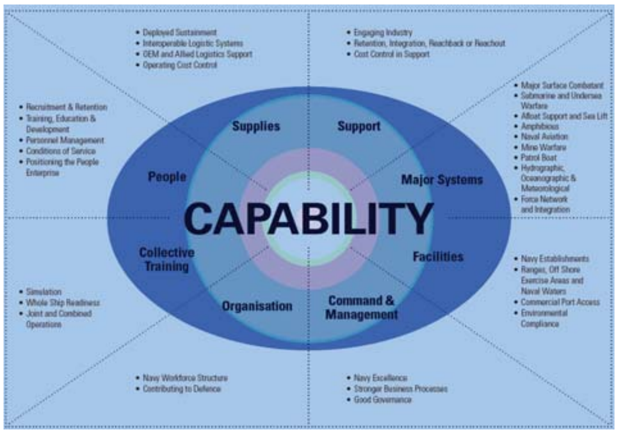

Figure 1 - Fundamental Inputs to Capability

The purpose of the foregoing is to explain the overall complexity of the military system into which new equipments are acquired and must be integrated.

The acquisition of major equipments that do not fully consider the implications of this complex tapestry have the potential to distort the wider system (eg the Navy itself) giving rise to unforseen cost and/or structural issues which may well outbalance any individual platform cost/benefits considered in isolation.

Adding further to this already complex problem is the time frames associated with the life cycle of the platform, specifically delivering superior technical performance at entry into service and a through life upgrade path to avoid technical obsolescence.

2. SUBMARINES

Submarines represent one "major system" FIC element capable of delivering the military effects identified in the previous section.

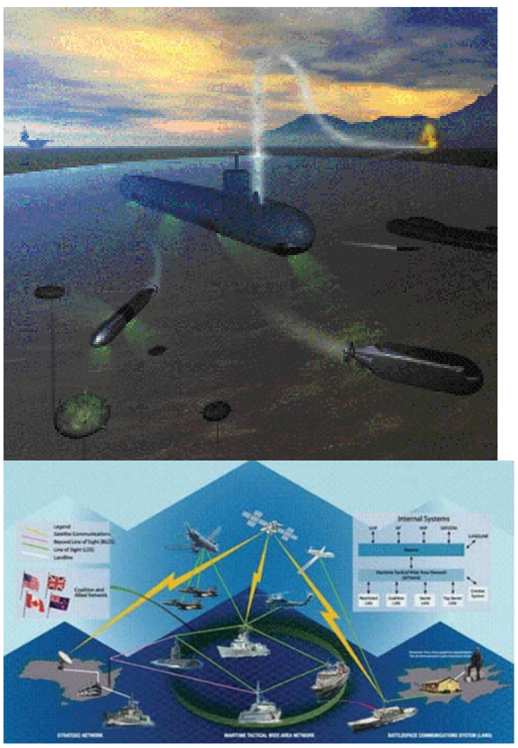

Figure 2 - Submarine Operating Environment

A submarine (nuclear or conventional) is unique in its technological and engineering challenges. The combining of a highly sophisticated sensors and weapons suite (eg an advanced weapons systems that can land a Tomahawk cruise missile on a sixpence from 1,000 miles away), a complex propulsion sytem with a large crew operating underwater within a pressure hull sustaining high external pressures, undetected by others remaining self-supported for months is an unparalleled challenge.

The engineering design, production and through-life capability management of a submarine, especially to achieve an affordable product, which can be sustained economically through its 25-year service life, during which the central technologies will upgrade and the operational requirements will change, requires the application of a wide span of scientific, technological and engineering disciplines with practical domain experience.

These include naval architecture, marine mechanical and electrical engineering, systems engineering, electronics, acoustics, nuclear engineering, metallurgy, atmosphere chemistry and many others.

To quote Murray Easton of BAESystems the design of the Astute Class has been "a more complex engineering project than a space shuttle, the 97m-long Astute is made up of more than one million components and was built with the aid of more than 7,000 design drawings." Engineers have integrated the thousands of sub-systems that require up to 100km of cabling, 23,000 pipes and over five million lines of software code – all whilst managing the supply chain, which consists of more than 30 main suppliers and numerous sub contractors.

With respect to the USN, assuming that the next nuclear powered attack submarine would be similar to that of the *Virginia* class, then the design effort will last 15 years and require approximately 35 million design and engineering man-hours.

In the case of the RAN Collin's class conventional submarine, over 33,000 drawings and 5,000 work orders were produced before the submarine build process even began, and once work commenced, each submarine took 2.5 million hours to assemble.

If this isn't complex enough then consider the interface requirements/drivers that the entry of a new submarine capability into the wider Defence framework has on the other FIC elements (Figure 2).

2.1 PEOPLE

With respect to the anticipated Collin's class replacement it is expected that it will take 17 years to design the submarines, gain government approval for the project and deliver the first boat.

Sea trials for the first new submarine are tentatively scheduled for 2024 so that the boat is ready to replace the first *Collins* class submarine scheduled to be decommissioned in 2025.

The personnel that will form the first crew of that boat have not even been recruited to the Navy and yet the compliment size, composition, experience, skill set, training requirements are all essential inputs and drivers on the design.

Decisions with respect to minimum manning, equipment and system fit have wide reaching impact on this element of the greater system as indeed do issues of habitability and community expectations on the ability to attract and retain the personnel in the first instance.

2.2 ORGANISATION

The impact of integrating the new platform and its associated capabilities into the wider Navy and Defence organisation that forms the overall submarine community must be considered. Backward compatability into the exisiting/developing C4I structure both at the national and allied international level.

2.3 COLLECTIVE TRAINING

The term "Collective Training" typically refers to training that is conducted within a unit and focused on preparing the unit to perform its assigned missions. It drives the requirement for a complex infrastructure of training support materials and strategies that are designed to assist Commanders and Leaders at all levels in planning and conducting such training. With respect to submarines this impacts on how the submarine crew achieve and retain the level of competence required to accomplish the designated missions at the Combined, Joint, Single Service and unit levels.

2.4 SUPPLIES

The specific areas of concern relate to the balance between achieving commonality with exisiting supplies and the introduction of new systems and equipments into the RAN inventory. Areas of concern with submarines would include new wepons and munitions eg long range cruise missiles, air independent propulsion system products etc

2.5 FACILITIES

The requirements to interface the new design with exisiting infrastructure or conversley the need to develop new or to modify exisiting buildings, structures, property, plant equipment and utilities, areas for training and other purposes (eg exercise areas and firing ranges), necessary to support capabilities, both at the home station and at a deployed location.

2.6 SUPPORT

The wider impact/call upon the National Support Base including training/proficiency support, materiel/maintenance services,

Communications /IT support, intelligence, recruiting/retention, research and development activities, administrative support and transportation support.

2.7 COMMAND AND MANAGEMENT

Command and management processes at all levels are required to plan, apply, measure, monitor, and evaluate the functions an agency performs, with due cognisance of risk and subsequent risk management. Command and Management include written guidance such as regulations, instructions, publications, directions, requirements, doctrine, tactical-level procedures, and preparedness documents.

In conclusion, Submarines are complex and are made up of – and interact with - many other systems, decissions have many interfaces and impacts which must be understood or at least appreciated if the system being delivered is to be optimised.

3. MANAGING COMPLEXITY - SYSTEMS ENGINEERING

Complexity is driven by is the number of decisions that have to be made regarding design, the number of people or organizations that have to be involved in those decisions, and the unfortunate fact that they're probably inconsistent.

Complexity is also driven by the advent of new technologies and the ever increasing demand for more capable platforms resulting in an increase in the amount of data, variables, or the number of engineering and production disciplines that are simultaneously involved in the design. Consequently there is an increased requirement for increasingly integrated systems with ever more sophisticated interfaces. These interfaces may be either hardware, software or procedural.

Platforms such as submarines therefore require the adoption of an interdisciplinary approach to engineering systems which in itself is inherently complex, since the behavior of and interaction among system components are not always well defined or understood (at least at the outset). The engineer has to define and characterize such systems and subsystems, and the interactions among them and therby identify any gap that exists between requirements from users and operators and technical realities and constraints that an engineer can specify and implement successfully.

As a consequence of this complexity it is no longer practicable to rely on traditional design approach or design evolution to improve upon a system. It is argued that the existing tools are no longer sufficient to meet the growing demands and consequently new methods have to be developed that addressed the complexity directly. A further consideration in this problem is the reduction of experience available in the Naval community, a consequence of the reduced throughput of acquisition programs and the extended duration of the activity. In the absence of continuity in design experience ther is a need to resort to more rigour in design process. This has been the genisis of Systems Engineering

Systems Engineering (SE) is the discipline of building highly sophisticated systems that work successfully. It is about the key creative processes that transform concepts into system designs, and the key technological and management processes that enable system development to proceed in an orderly, interdisciplinary fashion - maximising opportunities to meet client's needs while minimising risk.

To achieve this outcome Systems Engineering focuses on the identification and development of new methods and modelling techniques, methods that can aid in better comprehension of engineering systems and manage complexity in systems.

Systems Engineering encourages use of tools and methods to better comprehend. Some examples of such tools are: Requirements management, Modeling and Simulation, Optimization, System dynamics, Systems analysis, Statistical analysis, Reliability analysis, and Decision making.

One way to understand the motivation behind systems engineering is to see it as a method, or practice, to identify and improve common rules that exist within a wide variety of systems. The intent is that the principles of Systems Engineering can be applied to any system, complex or otherwise, provided systems thinking is employed at all levels. Analysis by the INCOSE Systems Engineering center of excellence (SECOE) indicates that optimal effort spent on Systems Engineering is about 15-20% of the total project effort essentially leading to reduction in costs among other benefits.

4. THE SYSTEMS ENGINEERING PROCESS

Systems Engineering has embraced a number of standard approaches to development. Almost all of these approaches are consistent with the the "vee diagram" as the representation of the structured development process that proceeds from concept to production to operation and, in some cases, through to termination and disposal. The process flows from the definition of the problem through the Investigation of alternatives, Modeling of the system, identification of the component sub systems, Integration and development of the candidate system solution, Assessment of performance, and acceptance into service. It is important to note however that the systems engineering process is not sequential waterfall or cascade activity, : many tasks are performed concurrently and in an iterative manner.

With respect to a typical acquisition program this can be articulated in project phases as follows.

The standard V-model (Figure 3) can be modified to progress the activities from the development phase into the production phase.

4.1 NEEDS ASSESSMENT, CONCEPT EXPLORATION, AND BENEFITS ANALYSIS

Concept Exploration is used to perform an initial feasibility & benefits analysis and needs assessment for the project. A business case is developed and specific cost benefit analyses presented for alternative project concepts. The output of this stage is a definition of the problem space, key technical metrics, and refinements to the needs, goals and objectives. This stage identifies the highest cost/benefit concept project to move forward into development.

4.2 SYSTEMS ENGINEERING PLANNING

The concept that moves forward for further development as the genisis of a procurement project must be planned with schedules that identifies the key systems engineering milestones and activities throughout the follow on phases.

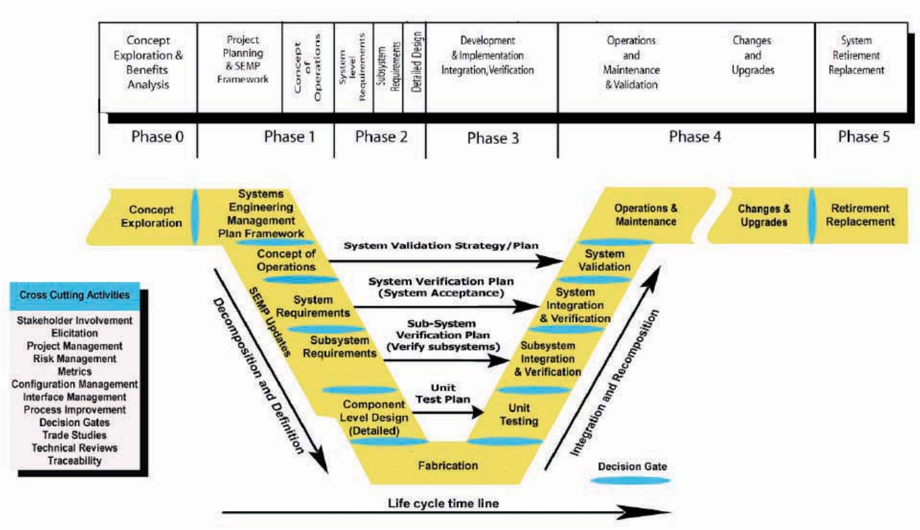

Figure 3 - System Lifecycle

These plans, once approved by the system's owner, become the control documents for completion of the development and implementation of the project.

4.3 CONCEPT OF OPERATIONS

The Concept of Operations is the initial definition of the system. At this stage, the project documents the way the envisioned system is to operate and how the envisioned system will meet the needs and expectations of the stakeholders. The operation is defined from multiple viewpoints consisting of operators, technical specialists and maintainers. The focus is on how the system will be validated (the Test Concept Document) to prove that it satisfies the intended capability. The problem space, definition, needs, goals, expectations, stakeholder lists, and project constraints is captured in the concept of operations document. This document contains the updated, refined summary of work done at the Concept Exploration phase.

4.4 SYSTEM LEVEL REQUIREMENTS

The system level is the highest level of abstraction of the ie the Submarine Capability which incorporates its associated FIC elements. Requirements are developed for the system. At the system level; the definitions of *what* the system is to do, *how well* it is to do it, and under *what conditions* are documented. System requirements are based on the user needs from the Concept of Operations. Requirements do not state *how* the system will be implemented unless it is intended to constrain the development team to a specific solution.

4.5 HIGH LEVEL DESIGN AND SUB-SYSTEM REQUIREMENTS

The High Level Design stage takes the top level system requirements established in the previous phase and translates them into subsystem requirements at the FIC level which will define the functions the capability is to deliver.

These requirements normaly generate a few alternate system configurations/ designs that can deliver the desired capability. Each requirement is periodically examined for validity, consistency, desirability and attainability, through this examination/evaluation process a decision can be made on the preferred system design. With the chosen design a requirements analysis will be performed and a functional design can be made. This functional design is a description of the product in the form of a model: the functional architecture. This model describes what the system does and of which items it consists of (allocation and synthesis). Thereafter, the product can actually be developed, integrated and implemented in the user environment.

The System level requirements are further refined and allocated [assigned] to the sub-systems considering the constituent elements of hardware, software, databases, people etc. Requirements for each sub-system element are documented the same way as the system level requirements. This process is repeated until the system is fully defined and decomposed to component level. Each layer will have its own set of interfaces defined. Each layer will require an integration step that is needed when the sub-system is developed. The control gate that is used for this final review called the Preliminary Design Review [PDR].

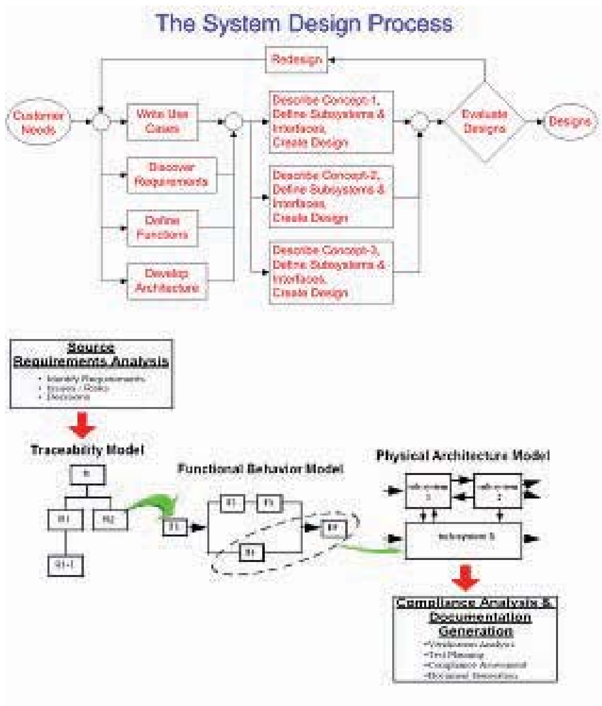

Figure 4 - The System Design Process

4.6 COMPONENT LEVEL DETAILED DESIGN

At the Component Level Detailed Design step the development team defines *how* the system will be built. Each sub-system has been decomposed into components of hardware, software, personnel etc. For these components, Detailed Design specialists in the respective fields create the "build-to" specifications which will be used to build or procure the individual components. A final check is done on the "build–to" specifications before the design moves forward to the actual hardware fabrication which does not commence until a review is completed and approved by the system's owner and stakeholders. The control gate used for this final design review is called the Critical Design Review [CDR].

4.7 FABRICATION

The program then progresses to the procurement of equipment and fabrication phase. This stage is primarily the work of the prime contractor. The system's owner and stakeholders monitor this process with planned periodic reviews, ie. technical review meetings.

Concurrent with this effort, unit test procedures are developed that will be used to demonstrate how the products will meet the detailed design. At the completion of this stage, the developed products are ready for unit test.

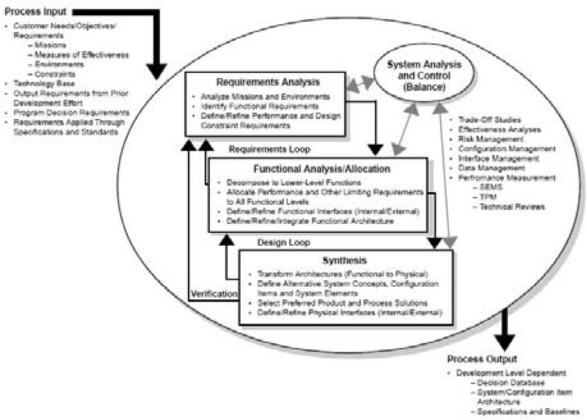

Figure 5 - System Analysis

4.8 UNIT TESTING

The components consisting of the hardware and software are verified in accordance with the unit Verification Plan. The purpose of unit testing is to verify that the delivered components match the documented Component Level Detailed Design. This is done by the prime contractor in preparation for the next level of integration. It is also a good review point for the system's owner and stakeholders.

4.9 SUB-SYSTEM INTEGRATION AND VERIFICATION

At this step, the components are integrated and verified at the lowest level of the sub-systems. The first level of verification is done in accordance with the Verification Plan and is carried out in accordance with the Verification Procedures developed in this stage. Prior to the actual verification, a Test Readiness Review is held to determine the readiness of the sub-systems for verification. When it has been determined that verification can proceed, the sub-systems are then verified. When the integration and verification are completed, the next level of sub-system is integrated and verified in the same manner. This process continues until all sub-systems are integrated and verified.

4.10 SYSTEM VERIFICATION

System verification is done in two parts. The first part is done under a controlled environment ie "factory acceptance test". The second part is done within the environment that the system is intended to operate called "harbour acceptance trials" after initial system deployment. At this stage, the system is verified in accordance with the Verification Plan developed as part of the system level requirements performed early in the development. The system acceptance will continue through the next stage, Initial System Deployment. The final part of system verification is then completed. A control gate is used for this conditional system acceptance.

4.11 INITIAL SYSTEM DEPLOYMENT

At Initial System Deployment, the system is finally integrated into its intended operational environment through thre conduct of sea trials. This step may take several weeks to complete to ensure that the system operates satisfactorily in the long term. This is sometimes called a "shake down". Many system issues surface when the system is operating in the real world environment for an extended period of time. This is due to the complexity of the system and the diversity of operational conditions that may only occur under specific and infrequent conditions. Once the system verification is completed, the system is accepted by the system's owner and stakeholders and then moves into the system validation and operations & maintenance phases.

4.12 SYSTEM VALIDATION

Validating the system is a key activity of the system's owner and stakeholders. It is here that they will assess the system's performance against the intended needs, goals, and expectations documented in the Concept of Operations and the Validation Plan. This represents a series of operational trials known as "System Qualification and Acceptance Trials" conducted by the fleet test specialists which completes with the milestone of "Accepatnce Into Naval Service". It is important that this validation takes place as early as possible [after the acceptance of the system] in order to assess its strengths, weaknesses, and new opportunities. This activity does not check on the work of the system integrator or the component supplier [that is the role of System Verification]. It is performed after the system has been accepted and paid for. As a result of validation, new needs and requirements may be identified. This evaluation sets the stage for the next evolution of the system.

4.13 OPERATIONS & MAINTENANCE

After the initial deployment and system acceptance, the system moves into the Operations & Maintenance phase. In this phase the system will carry out the intended operations for which it was designed. During this phase routine maintenance is performed as well as staff training. This phase is the longest phase, extending through the evolution of the system and ends when the system is retired or replaced. In the case of a submarine this phase will continue for decades. It is important that there are adequate resources to carry out the needed Operations & Maintenance activities; otherwise, the life of the system could be significantly shortened due to neglect.

4.14 CHANGES & UPGRADES

Changes & upgrades should be implemented in accordance with the Vee technical process described previously. Using the Vee process for changes & upgrades will help maintain system integrity including configuration control between the system components and supporting documentation.

4.15 RETIREMENT/REPLACEMENT

Eventually, every system will be retired or replaced for one of the following reasons:

- No longer able to ensure materiel/technical integrity;
- Capability no loger relevant or viable;
- The system may no longer be needed;
- It may not be cost effective to operate; or
- It may no longer be maintainable due to obsolescence of key system elements.

This phase looks at how to monitor, assess needed changes, and make change/upgrade decisions.

5. KEY ACTIVITIES

A number of key system engineering activities are conducted in support of the development of the Systems during one or more of the life-cycle process steps.

5.1 STAKEHOLDER INVOLVEMENT

Stakeholder involvement is regarded as one of the most critical activities within the development and life-cycle of the project and system. Without effective stakeholder involvement, the systems engineering and development team will not gain the insight needed to understand the key issues and needs of the system's owner and stakeholders. This increases the risk of not getting a valid set of requirements to build the system or to obtain buyin on changes & upgrades.

5.2 REQUIREMENTS ELICITATION

Elicitation is an activity that when performed correctly, effectively, and accurately, gathers and documents information needed to develop the system. The typical types of information include needs, goals, objectives, requirements, and stakeholder expectations. Some information may be in a documented form or stated clearly by the stakeholders, but much of the needed information may be implied or assumed. The Elicitation processes help draw out and resolve this information, resolve conflicting information, build consensus, and validate the information.

5.3 PROJECT MANAGEMENT PRACTICES

Various project management practices are needed to support the development of the system. Project management practices provide a supportive environment for the various development activities. It provides the needed resources, then monitors and controls costs and schedules. It also communicates status between and across the development team members, system's owner, and stakeholders.

5.4 RISK MANAGEMENT

There will be many risks identified during the development of a systemincluding technical, operational, commercial etc. Risk Management is a process used to identify, analyze, plan, and monitor risk. Then, it mitigates, avoids, transfers, or accepts those risks.

As the development proceeds down the left hand side of the V-diagram the project risk will reduce as the design matures and uncertainty is reduced. Risk is further reduced as the design progresses up the right hand side of the V-diagram as the test and integration activities are performed that lead to acceptance,

5.5 PROJECT METRICS

Project metrics are measures that are used by both the project manager and systems engineer to track and monitor the project and the expected technical performance of the system development effort. The identification and monitoring of metrics allow the team to determine if the project is "on-track" both programmatically and technically. One key element of the establishing of metrics is the associated activity of Technical performance Management which is the program by which the metrics are monitored and action taken to rectify any divergence.

5.6 CONFIGURATION MANAGEMENT

Managing change to the system is a key process that occurs throughout the life of the system. Configuration management is the process that supports the establishment of system integrity [the documentation matches the functional and physical attributes of the system]. It maintains this integrity throughout the life of the system [managing changes to the system with its documentation]. A lack of change management will shorten the life of the system and may prevent a system from being implemented and deployed.

5.7 DECISION GATES

Decision Gates are formal decision points along the life cycle that are used by the system's owner and stakeholders to determine if the current phase of work has been completed and if the team is ready to move onto the next phase of the life cycle. By setting entrance and exit criteria for each phase of work, the control gates are used to review and accept the work products done for the current phase of work. They also evaluate the readiness for moving to the next phase of the project.

5.8 DECISION SUPPORT/TRADE STUDIES

Technical decisions on alternative solutions are a key enabler for each phase of system development. This starts when alternative concepts are evaluated and continues through the system definition and design phases. This chapter provides a method to perform a trade study.

5.9 TECHNICAL REVIEWS

Technical reviews are used to assess the completeness of a product, identify defects in work, and align team members in a common technical direction. Technical reviews may consist of the following reviews:

- Initial Technical Review (ITR);
- Alternative Systems Review (ASR);
- System Requirements Review (SRR);
- System Functional Review (SFR);
- Preliminary Design Review (PDR);
- Critical Design Review (CDR);
- Test Readiness Review (TRR);
- Production Readiness Review (PRR);
- System Verification Review (SVR); and
- Operational Test Readiness Review (OTRR).

There is little merit in dogmatically applying a standard for project reviews. Instead the review process should be based on an accepted standard or industry practiced and tailored to meet the needs of the individual project or client.

5.10 TRACEABILITY

Traceability is a key cross-cutting process that supports verification & validation of requirements by ensuring that all needs are traced to requirements and that all requirements are implemented, verified, and validated. Traceability supports impact analysis for changes, upgrades and replacement.

6. THE SYSTEMS ENGINEER

System development often requires contribution from diverse technical disciplines. By providing a systems view of the development effort the Systems Engineer helps meld all the technical and operational contributors into a unified team effort and through a rational process:

- Produce systems that satisfy the customers' needs;
- Increase the probability of success;
- Reduce risk; and
- Reduce total-life-cycle cost.

Systems engineers are concerned with the "big picture" of a project in addition to technical aspects and must consider details such as operations, performance, testing, manufacturing, cost and schedule, training and support, and disposal.

The Systems engineering examines a problem using a creates a system of systems approach where by not only the product is considered but all aspects of the process that produces the product:

- Concept and problem definition;
- Requirements definition and management;
- Design Systems;
- Testing systems;
- Production and manufacturing system;
- Operating environment;
- Mmaintenance and upkeep system;
- Performance evaluation system;
- Customer service; and
- Retirement and replacement.

The Systems Engineer approaches the task of developing a system through the following approach and activities:

- Viewing the system from the stakeholder points of view [walk in the shoes of the system's owner and stakeholders]. Key processes include needs assessment, elicitation, Concept of Operations, and stakeholder involvement.
- Start at the finish line defines the output of the system and the way the system is going to operate. Key processes include Concept of Operations and Validation Plan.
- Address risks as early as possible where the cost impacts are lowest. Key processes include risk management, requirements, and stakeholder involvement [spend more time on the left side of the Vee]
- Push technology choices to the last possible moment. Define *what* is to be done before defining *how* it is to be done [form follows function].
- Focus on interfaces of the system during the definition of the system. Defining clear and standard interfaces and managing them through the development will ease the integration of the individual elements of the system.
- Understand the organization of the system's owner, stakeholders, and development team.

Systems engineer must assess the existence of feasible solutions, and rarely will customer inputs arrive at only one.

Some customer requirements will produce no feasible solution. Constraints must be traded to find one or more feasible solutions. The customers' wants become the most valuable input to such a trade and cannot be assumed. Those wants/desires may only be discovered by the customer once the customer finds that he has overconstrained the problem.

Normally however, many feasible solutions can be found, and a sufficient set of constraints must be defined to produce an optimal solution. This situation is at times advantageous because one can present an opportunity to improve the design towards one or many ends, such as cost or schedule. Various modeling methods can be used to solve the problem including constraints and a cost function.

Systems engineering encourages the use of modeling and simulation to establish the feasibility and validate design solutions, assumptions or theories on systems and the interactions within them. Use of methods that allow early detection of possible failures are integrated into the design process.

At the same time, decisions made at the beginning of a project whose consequences are not clearly understood can have enormous implications later in the life of a system, and it is the task of the systems engineer to explore these issues and make critical decisions.

There is no method which guarantees that decisions made today will still be valid when a system goes into service years or decades after it is first conceived but there are techniques to support the process of systems engineering.

Initially, when the primary purpose of a systems engineer is to comprehend a complex problem, graphic representations of a system are used to communicate a system's functional and data requirements. Common graphical representations include:

- Functional Flow Block Diagram (FFBD);
- Data Flow Diagram (DFD);
- N2 (N-Squared) Chart;
- IDEF0 Diagram;
- Quality Functional Deployment;
- Use Case; and
- Sequence Diagram.

A graphical representation relates the various subsystems or parts of a system through functions, data, or interfaces. Any or each of the above methods are used in an industry based on its requirements. For instance, the N2 chart may be used where interfaces between systems is important. Part of the design phase is to create structural and behavioral models of the system.

Once the requirements are understood, it is now the responsibility of a Systems engineer to refine them, and to determine, along with other engineers, the best technology for a job.

At this point starting with a trade study, systems engineering encourages the use of weighted choices to determine the best option. A decision matrix, or Pugh method, is one way (QFD is another) to make this choice while considering all criteria that are important.

The trade study in turn informs the design which again affects the graphic representations of the system (without changing the requirements). In an SE process, this stage represents the iterative step that is carried out until a feasible solution is found.

A decision matrix is often populated using techniques such as statistical analysis, reliability analysis, system dynamics (feedback control), and optimization methods.

Table 1 provides an indication of the full scope of activities within the remit of the systems engineer while Figure 6 indicates the Systems Engineers role as the central integrator in the project.

State the problem	Design the system	Produce documentation
Understand customer needs	Sensitivity analyses	Lead teams
Discover requirements	Assess & manage risk	Assess performance
Validate the system	Reliability analyses	Prescribe tests
Investigate alternatives	Integrate system components	Conduct reviews
Define quantitative measures	Design & manage interfaces	Verify requirements
Model the system	Configuration management	Perform total system test
Functional decomposition	Project management	Re-evaluate & Improve quality

Table 1 - Systems Engineer Activities

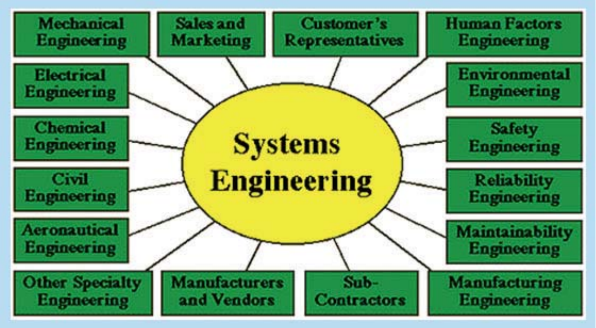

Figure 6 - Systems Engineer Role

7. NAVAL ARCHITECTS

By way of comparison to the forgoing definition of the role of the systems engineer I would like to provide the following a comparison taken from the RINA web site.

A Naval Architect is a professional engineer who is responsible for the design, construction and repair of ships, boats other marine vessels and offshore structures, both civil and military, including:

- Merchant Ships - Oil/Gas Tankers, Cargo Ships, Cruise Liners etc.
- Passenger/Vehicle Ferries
- Warships - Frigates, Destroyers, aircraft Carriers, Amphibious Ships etc
- Submarines and underwater vehicles
- Offshore Drilling Platforms, semi Submersibles, FPSO's
- High Speed Craft - Hovercraft, Multi Hull ships, Hydrofoil Craft etc
- Workboats - Fishing Vessels, Tugs, Pilot Vessels, Rescue Craft etc.
- Yachts, Power Boats and other recreational craft

Some of these are amongst the largest and most complex and highly valued moveable structures produced by mankind.

Modern engineering on this scale is essentially a team activity conducted by professional engineers in their respective fields and disciplines. However, it is the Naval Architects who integrates their activities and takes ultimate responsibility for the overall project.

This demanding leadership role requires managerial qualities and ability to bring together the often-conflicting demands of the various professional engineering disciplines involved to produce a product, which is 'fit for the purpose'.

In addition to this vital managerial role, the Naval Architect has also a specialist function in ensuring that a safe, economic and seaworthy design is produced.

To undertake all these tasks the Naval Architect must have an understanding of many branches of engineering. He or she must be able to utilise effectively the services provided by scientists, lawyers, accountants and business people of many kinds.

A Naval Architect requires a creative, enquiring and logical mind; the ability to communicate clearly in speech and writing with others inside and outside the engineering profession, sound judgement and qualities of leadership. The education and training given to the Naval Architect are designed to develop these skills and to lead him or her to recognised qualifications and professional status.

Depending mainly on the type of qualifications held and personal inclination, Naval Architects may become specialists in one field or develop broad experience in several. Eventually they may find themselves in senior executive positions using their knowledge and experience of general management as well as their professional skills in engineering a project leadership. Indeed, aided by the breadth of their education, training and experience, professional Naval Architects are successful in top management posts in government, industry and commerce quite outside the maritime field.

Referencing back to the definition of the Systems Engineer and Figure x.x the Naval Architect would be considered in the narrow role of “specialists in one field” and as such come under the category of “Other Specialty Engineer”.

The contention of the author is that the Naval Architect has always conducted the role of the Systems Engineer with respect to the maritime industry however there has been a trend over the past 10 years to marginalise our role, particularly with respect to maritime defence projects. The Naval Architect community must claim the mantle of the “Maritime Systems Engineer” as their own in order to stop this errosion and to benefit from participation in this supporting field of process engineering.

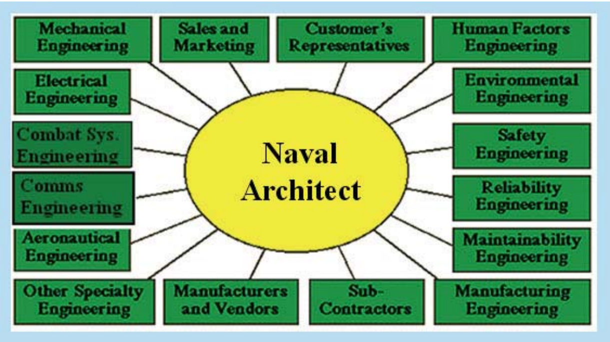

Figure 7 - Naval Architects Role

8. THE CHALLENGE

How does an engineering community maintain its experience base and discipline integrity in the absence of the continuity of appropriate projects to gain and develop the skills of its members.

The limited number of warship projects available for the young engineer to cut their teeth on, the lengthy duration of the modern acquisition project coupled with the aging workforce removing those whom can act as mentors has given rise to concerns over long term knowledge management.

In the absence of this continuity one is forced to turn to process to maintain engineering integrity. This is where the practice of systems engineering can come to the support of the Maritime Engineering community and the Naval Architect.

Systems engineering is a category of engineering without a subject matter, it is the science of developing an operable system capable of meeting requirements within imposed constraints.

It is all about a body of rigourous process to be applied in a holistic, integrative discipline, wherein the contributions of the supporting discipline engineering specialist and other stakeholders are weighted and considered and balanced, one against another, to produce a coherent whole that is not dominated by the view from the perspective of a single discipline. System engineering is about tradeoffs and compromises. This is the role of the Naval Architect in an acquisition project.

BMT Defence Services (Australia) has adopted a structured approach to the application of the systems engineering practices through our Systems Engineering Framework which is based on current best practice.

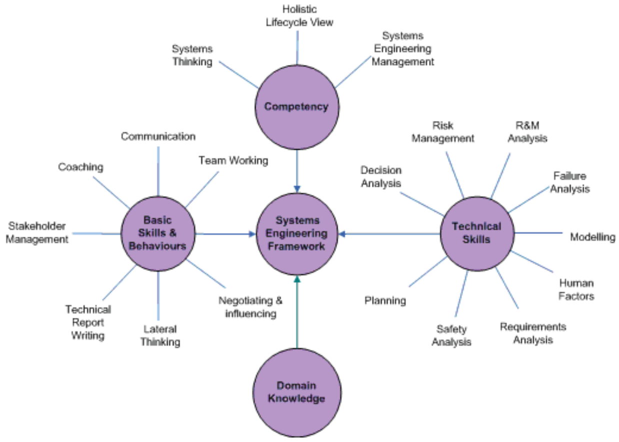

Figure 8 - BMT Systems Engineering Framework

It is the adoption and integration of system engineering competencies together with the domain knowledge that we believe provides the strength to the framework.

The competency area covers the systems thinking along with life cycle, technical and business issues and their management. Our core domain knowledge includes naval architecture and the maritime engineering disciplines and includes a detailed understanding of the maritime defence domain, its stakeholders and their needs.

The challenge is to integrate the discipline of systems engineering into the education and development of the Naval Architect as their carrers progress. The Naval Architect community needs to embrace the body of knowledge and practice that is resident in the Systems Engineering community with a view of being recognised as the "Maritime Systems Engineer".
To this end I am pleased to note that the Australian Maritime College in Tasmania has developed an undergraduate unit for their Degree Course in Naval Architecture on Systems Engineering thereby introducing the subject at the outset of the students career. In this way it is my hope for the future that the Naval Architect will look upon the body of systems engineering practice as an element of their overall armoury of skills.

9. REFERENCES

1. ANSI/EIA 632, Standard, *Process for Engineering a System*, January 1999.

2. Blanchard, B.S. and Fabrycky, W.J., *Systems Engineering and Analysis*, Prentice-Hall, 1998.

3. DSMC, *Systems Engineering Fundamentals*, Defense System Management College, 1999.

4. IEEE 1220 Standard, *Application and Management of the Systems Engineering Process*, IEEE Standards Dept., NY, December 1998.

5. *MIL-STD-499B, Draft Military Standard for Systems Engineering*, AFSC/EN, 1992.

6. Shishko, R. and Chamberlain, R.G., *NASA Systems Engineering Handbook*, SP-6105, 1995.

10. AUTHORS BIOGRAPHY

Gordon MacDonald is the Technical and Operations Director of BMT Defence Services (Australia) Pty Ltd, a specialist Maritime Defence Engineering consultancy. Mr MacDonald has been employed in the maritime industry for over 30 years most recently as the Director of Navy Platform Systems in the Navy Systems Branch of the Navy Systems Command. Mr MacDonald graduated as a Naval Architect from Strathclyde University in the UK in 1985 and has held positions as a sea going marine engineering officer in the merchant marine, classification society trainee surveyor, ship repair manager and warship/submarine design engineer with VSEL. In 1990 he joined the Australian Department of Defence where he has held various positions in the Navy Engineering Organisation.

3D VISUALISATION OF SUBMARINE RESCUE SYSTEMS AND RESCUE MISSION SIMULATION

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J Ramsay, B Sharples, James Fisher Defence, Glasgow UK

SUMMARY

The three-dimensional representation of complex mechanical structures has recently received substantial research attention as it assists significantly during the design review process. Being the epitome of engineering products, submarine designs have an additional need for not only structural visualisation but also for mission rehearsal and analysis of on board procedures. This paper presents the visualisation process of a submarine rescue vehicle (SRV) and the re-enactment of a rescue mission in a 3D virtual environment. This case study was primarily used by the contractors for processes evaluation and potentially for training. Finally the paper discusses the potential benefits of presenting the systems and processes in a real time, direct manipulation, virtual environment.

Keywords: 3D design and construction, 3D mission rehearsal, Inspections techniques.

1. INTRODUCTION

Current CAD programs enable review of the mechanical systems by assessing the 3D models. It possible to animate operation sequences as non-interactive, off-line rendered video using fixed cameras. However, it is a rather challenging, if not impossible, process to assess operational aspects in real time. Our system, developed upon existing VR capabilities, can provide a substantial level of flexibility through the free manipulation of time, moving cameras and cutaway views within an animated sequence (Naef et al, 2006). This is feasible by employing a number of interaction techniques relying on visual, haptic and auditory cues.

Notably our core research does not focus on the technological advances of the aforementioned VR system, but to the Human Computer Interface (HCI) and the VR simulation which was developed explicitly in a user-friendly virtual environment. Hence this study is user-centred, as the main objective is to enhance and accelerate the understanding of complex mechanical systems and operational procedures.

During the development of the VR simulation system, the team of naval architects and engineers highlighted that our type of VR system could provide them with a unique toolkit for three different purposes; aiding the design process, explanatory presentations to the end users and, potentially, to assist with operational planning. These three aspects will be explicitly analysed in the following sections.

The paper is structured as follows: Section 2 offers a brief overview of the initial predetermined simulation with regard to the development process and the original outcomes. Section 3 discusses the rationale behind the development of an agile system which could facilitate the three aforementioned requirements. Section 4 presents the simulation requirements for valid structural representation and operating scenario re-inaction with emphasis on the development of an interface which will follow closely current human-factors norms. The final Section 5 discusses the potential benefits and pitfalls of the proposed system. The paper concludes by outlining the imminent research areas and a tentative plan for future work.

2. PREDETERMINED MODELLING AND SIMULATION

Advances in digital modelling and simulation have fostered the development of complicated structures with minimal design time and implementation costs during the development process (Anderson et al, 2002). This occurred mainly due to the elimination of intermediate levels of physical prototyping which can be exceptionally costly and lengthy processes. Thus the vast majority of structural alterations and design evaluation can be achieved considerably faster in CAD programmes. Additional evaluation of large scale virtual models can be achieved in large virtual environments (Charissis et al, 2007). However, due to the unusual and inherently hazardous nature of submarine rescue, the engineers and end users face a number of additional engineering and operational challenges particularly in the area of human factors. In the case of submarine rescue, the most obvious challenge lies in the difficult task of safely transferring potentially injured and pressurised, submariners (Rescuees) from a distressed submarine back to the surface and into a decompression / medical treatment facility.

James Fisher Defence (JFD) and the Digital Design Studio (DDS) jointly developed a predetermined simulation of the rescue process based on highly detailed 3D models in order to provide the users with a simple and understandable communication method of the procedures involved in a rescue mission. Additionally, the final visual reconstruction was effectively used as a presentation and to provide explanatory material to demonstrate the SRV's capabilities to potential customers. As such the 'Submarine Rescue System' project was divided into two levels of development.

2.1 MODELLING

The scenario under simulation, defined by James Fisher Defence (JFD) engineers, comprised of three main systems: the SRV and rescue equipment provided by JFD, the mother-ship (MOSHIP) carrying the rescue spread, and a damaged or distressed military submarine (DISSUB), randomly selected, which in this case was an SSN Akula Class (BARS Type 971).

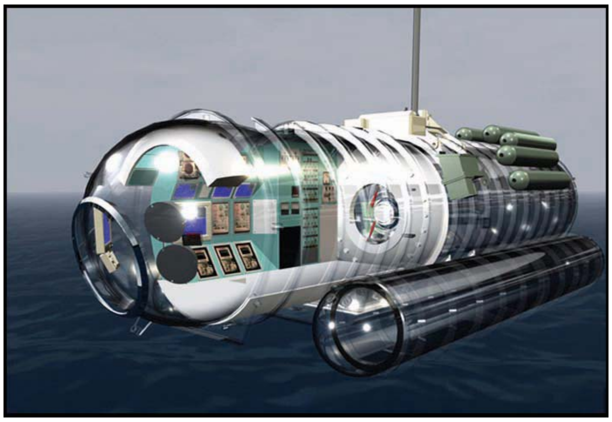

Figure 1. Screenshot of SRV selectively transparent sections.

All three systems were precisely modelled with the use of CAD and advanced 3D visualisation programmes. The SRV and DISSUB's level of detail are illustrated in Figures 1 and Figure 2 respectively. Particular emphasis was placed on the SRV structure and the associated launch and recovery, decompression facility and 'transfer under pressure' systems.

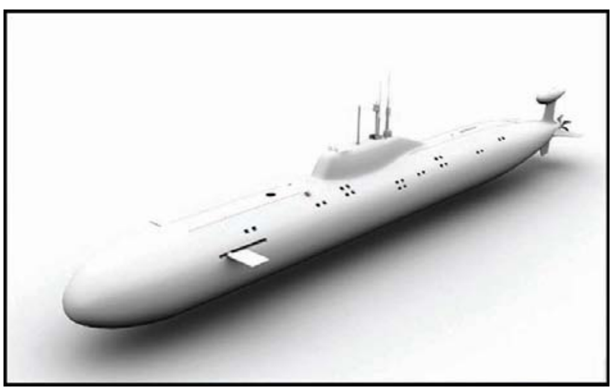

Figure 2. Volumetric rendering of the Akula class submarine

2.2 SIMULATION

The predetermined simulation scenario was developed in order to thoroughly explain the operational procedures involved in a rescue mission. The dive cycle of the Submarine Rescue Vehicle (SRV) from the MOSHIP was comprehensively described.

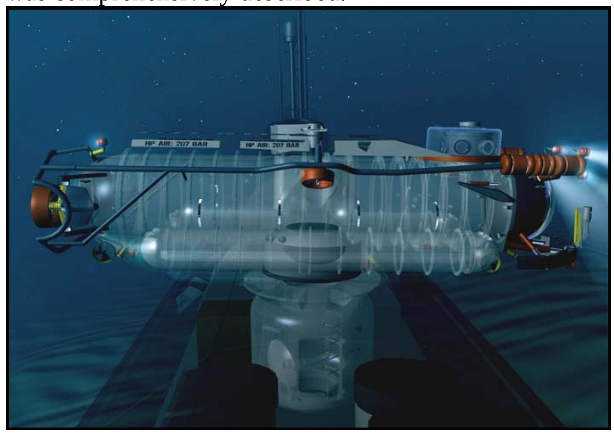

Figure 3. Explanatory shot during the connection of the SRV and the DISSUB

Wherever possible explanatory text was introduced to assist the potential users in the faster assimilation of the information provided. Low underwater visibility and accurate lighting was simulated to demonstrate the actual conditions near the seabed in realistic manner, as typically encountered by the SRV pilots. Precise manoeuvring of the SRV into position on the DISSUB was also replicated in order to mimic all the different aspects of such a mission as precisely as possible. Excerpt from the sequence is depicted above in Figure 3.
The final predetermined simulation was produced as an animation, assisting users in understanding the structural elements of the system, the complex operational procedures and the human interaction. Additionally the proposed HCI system provides the users with the opportunity to revisit the explanatory information either with regard to the structural elements of the vessels or for rehearsing the rescue mission overall. Elaborating in the above objective, the following section describes the rationale behind the development of such a simulation and elaborates further on the real-time simulation scenarios that could be hosted in a virtual environment.

3. RATIONALE

Predetermined visual simulation scenarios that allow the users to maniupulate time, cameras, object transparency and cutaway views could facilitate in numerous ways the development process of complex products (i.e. Submarine Rescue Vehicles) and the overall understanding of the procedures that take place during the operation of such systems as illustrated in Figures 4 and 5. Additionally simulation of human factors and interaction could be extended to the hosting vessels (i.e. MOSHIP) with simulation through computer aided ergonomics based on the different operational scenarios (Karwowski et al 1990).

The benefits of employing such virtual representations, simulation and animation tools can be investigated with regards to both design evaluation, explanatory presentations and operation planning as described below.

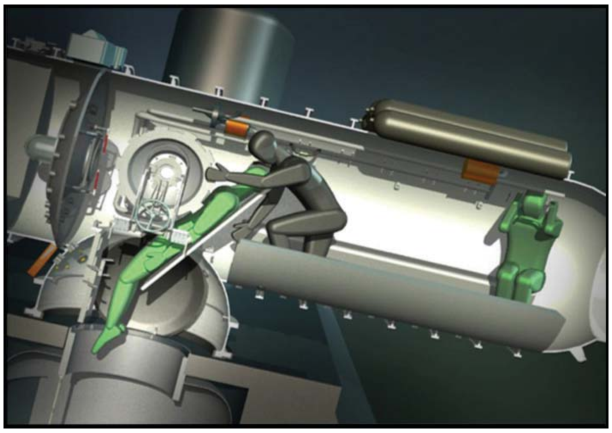

Figure 4. Human modelling and movements simulation: Evacuation of an immobile rescuee.

3.1 DESIGN EVALUATION

3D visualisation and simulation of the structural design can offer naval architects and engineers an early stage appraisal of the complete system. Such insight can significantly minimise the ergonomic errors in the design process. In turn, optimisation of the ergonomics can be achieved through digital prototyping with significantly lower cost than complete physical mock-up models for evaluation (Chaffin, 2001). Evidently the vessel developers can present to the customers a genuine insight into the complex functionalities and design features involved in such a multifaceted system. For example, an ergonomic model demonstrating the transfer of an able bodied or stretcher-bound rescuee from the DISSUB up though the submarine escape hatch, through the SRV transfer skirt and into the SRV pressure hull, was created to demonstrate the suitability of the physical layout of the SRV's hull configuration.. Human modelling and movements simulation can be introduced in order to identify potential hazards and obstructions during the operation and transfer between systems (Raschke, et al 2001).

However, in a typical technical review environment it is often difficult for the designers and engineers to portray design intent in a manner that is fully comprehensible by the evaluation team as the presentation material is typically restricted to static 3D images and 2D drawings.

In the case of the ergonomic model described above, it was only possible to extract 2D images and a fixed camera animation for review purposes. The benefits of agile system are that it would allow designers and engineers to easily demonstrate complex designs by presenting 3D models with moving parts and processes in a virtual environment, whilst allowing the evaluation team to easily extract the relevant information using a number of techniques as described below.

- Allowing processes to be repeated from multiple viewpoints and played back at different speeds
- Including transparency or cutaway views to allow the review of internal mechanisms and processes
- Allowing team members with a non-technical background, typically operators or clients, to control and manipulate the 3D environment

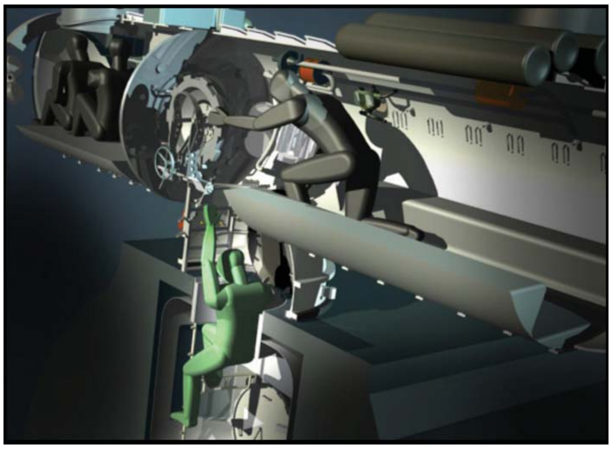

Figure 5. Human modelling and movements' simulation: Hatch opening procedure.

During the development process, the 3D models could be rapidly updated and newly introduced changes can be reviewed individually and within the overall context of the structure

3.2 EXPLANATORY PRESENTATIONS

For the initial study, the SRV was modelled with CAD software with a view to demonstrating the approach procedure with the DISSUB on the seabed, locking onto the DISSUB's rescue seat, depressurisation of the interlock, opening of the hatches and subsequent transfer of the Rescuees. The scenario was visually simulated with a focus on the evacuation of the Rescuees and their transfer from the DISSUB to the SRV and on to the decompression chambers onboard the MOSHIP.

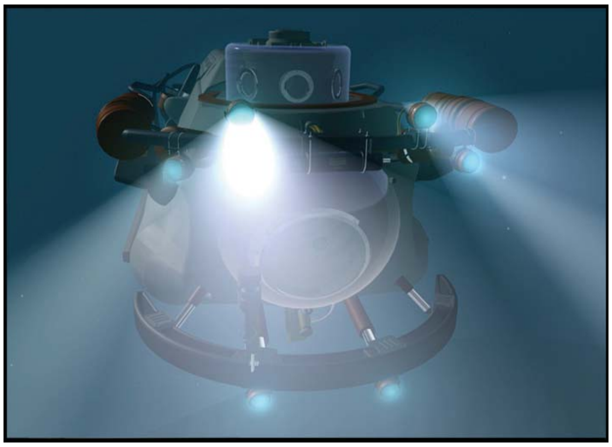

Figure 6. Underwater visibility simulation.

Generating a realistic underwater environment, visibility ranges and lighting were simulated according to the depth and the conditions of the approach as illustrated below in Figure 6.

Rendering of photo-realistic images based on these simulations and 3D representations can demonstrate effectively the relevance of newly introduced hardware to the contemporary equipment. Although such photo-realistic visualisation is a valuable demonstration, it is restricted to pre-determined series of camera paths and perspectives.

Integrating engineering CAD models and animation sequences, that are typically generated for rendered video scenes, into an environment that allows customers & users the ability to explore and control the scene could provide a much deeper understanding of the operational complexities of such a system, whilst allowing design teams and companies to capitalise on the material generated during the engineering and ergonomic development.

3.3 VISUALISATION-ASSISTED OPERATION TRAINING

From a procedural point of view the accurate depiction of the rescue systems onboard the mother-ship can provide the different rescue teams involved during the rescue mission with crucial information regarding the timing of each action and the required procedures of each group.

Furthermore the simulation of on-board procedures would allow the user to assess simultaneous operations to be viewed and repeated from various angles and ranges, maximising the preparation level of the involved groups. For example, there are a number of complex operations involved during recovery of the submersible from the sea to the deck of the ship, some of which are occurring simultaneously and are difficult to portray in a single animation. Notably in such operations the human simulation and animation could significantly benefit the designers to estimate the interactions between the groups and the vessel equipment (Badler et al, 1993).

4. REAL-TIME SIMULATION ENVIRONMENT

The off-line visual simulations described in the previous sections were created and rendered using a combination of Autodesk Inventor to generate the engineering CAD models and Maya create the scenes and perform the rendering, responding to an immediate need of the customer. The availability of the test case and the models, however, provided the opportunity to start an investigation into other, more flexible modes of presentation.

Virtual reality and real-time visualisation systems were associated with often prohibitive hardware and software cost in the past. However, mass market items designed for high-end home entertainment are often perfectly suitable and exceed yesteryear's high-end technology in features and performance while costing a fraction of the amount. The cost of virtual reality applications today is dominated by the man-power required to prepare CAD models and add the interactivity for real-time display.

The following sections describe the environment and tools we use to interactively visualise designs before going into details about the modes of presentation and evaluation.

4.1 HARDWARE

Real-time visualisation in this context is used as a powerful means of communication within a team or to external stakeholders. A reasonably large display environment is critical to enable group discussions and interaction with the 3D model, hence a projector-based environment is considered a necessity.

We use a range of VR display environments for our experiments, including stereoscopic projection (providing a sense of depth) that enables better understanding of the spatial structure, and a high-resolution wide screen (2800 x 1050 pixels on 4.4m x 1.65m) to convey a feeling of the actual size of the SRV. All our display systems are driven by PC workstations with dual Xeon processors and nVidia Quadro FX4400 graphics hardware. While those display systems offer superior quality and performance, the processes described in this paper could also be run successfully on less expensive hardware for the enthusiast gamers in combination with a decent quality presentation projector.

4.2 INTERACTION DEVICES

We have developed a range of interactive design review tools that enable direct interaction with the 3D model in a semi-immersive environment (Naef et al, 2006).

These hands-on interaction paradigms require 3D tracking and a data glove with tactile feedback. The less complex presentation tools only allow manipulation of time, viewer position, layer visibility and cut-away plane manipulation and are therefore served well through a combination of a 3Dconnexion SpacePilot ("3D mouse") for navigation and a joystick to control the cutting planes.

4.3 SOFTWARE

Given that the major cost factor in VR today is in the data and simulation preparation aspects, efficient software tools are crucial for an effective solution. We base our recent real-time activities around the platform offered by Presagis (formerly Multigen-Paradigm) including Vega Prime for the real-time simulation and Creator for model preparation. Although cheaper solutions exist, including open source scene graph and virtual reality toolkits, we found that in our case development time is sufficiently decreased using the commercial solutions to offset the license cost.

4.4 LEVELS OF INTERACTIVITY

Interactivity is the key contribution of our visualisation environments over existing rendering options available in most CAD packages or off-line animation tools such as Maya. While the visual quality does not fully approach that of a Maya rendering, particularly regarding lighting effects such as shadows, real-time rendering can produce a realistic impression of the design. Unlike pre-rendered videos, the real-time system enables spontaneous reaction to requests from the viewers.

On the most basic level, the interactive environment allows free control over time, enabling the team to set the pace of a review or presentation session, whereas the basic transport controls for videos are somewhat awkward to use.

It is the free viewpoint and motion control capability that gets most users excited, as it allows inspecting any part of the design from a range of angles that may not have been foreseen during the planning of a review session. Consequently, most commercial VR add-ons to CAD system provide exactly this type of flexibility enabling real-time walk-through. As long as the CAD model remains within moderate complexity, this feature comes almost “free” as it requires little or no expert involvement for set up. We typically use a SpacePilot device for free navigation and a range of preset viewpoints in our simulations.

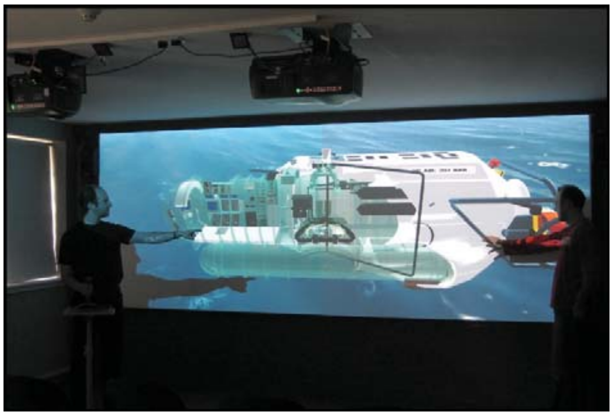

Figure 7. Design review session using the VR system.

When transferring models from a CAD into our custom real-time environment, we generally equip the data with a range of switches to toggle the visibility of key components or layers between visible, semi-transparent or hidden. The transparent stage is particularly interesting when the position of modules must be shown within the context. For example, showing the Rescuees transfer from the DISSUB into the SRV from a camera positioned outboard of both boats.

Interactively placing a cut-away plane enables looking inside the design and complements the layer functionality as shown in Figure 7. We dynamically place the plane using a joystick. Enabling cut-away for selected layers only allows to interactively “strip away” parts of the design to gradually reveal the inside without losing the context information.

4.5 USE OF ANIMATION

The tools and techniques described above enable inspection and review of the static design model. Our main interest, however, lies in the communication of procedures. While switches enable the visualisation of discrete stages, continuous animations are much more powerful to convey a process flow. The tools (Maya) described in the first part are extremely powerful for defining and rendering complex animated sequences. Unfortunately, these sequences are not directly portable into our real-time, interactive environment. Instead, animation sequences are pre-defined in the application code by a programmer. As such predetermined simulation scenarios developed in the original CAD program (Maya) have to be re-introduced in virtual-prototyping and simulation suites (i.e. VEGA). Evidently an initial appraisal of the simulation requirements and client expectations can be achieved in a first level through animation sequence. Typically the animation can be further exploited as explanatory tool presentation

5. DISCUSSION

Submarines have been categorised amidst the most valuable warships ever deployed as their operational results have proved repeatedly through different situations. However their operating environments and tactical operations have created numerous constrains which have been resolved through meticulous structural design and exhaustive experimentations. Such extensive evaluations were considered mandatory in order to maximize performance and ensure human safety. Additionally submarines must be able to respond efficiently to a plethora of manoeuvres (considerably more complicated than a typical ship) such as surface and dive swiftly, operate safely underwater for months, communicate and move quietly to avoid detection. Finally submarines have to provide a habitable space for the crew. Regardless of the type of submarine, the aforementioned tasks are accomplished equally well from each vessel in a similar fashion.

Adhering to the above observations derived from Digital Design Studio’s collaboration with JFD it was made obvious that modern submarine design could use virtual reality and 3D technology in order to circumvent potential design and ergonomics issues well in advance of the completion stage. Our initial approach was through a gentle introduction to the complexity of mechanical structure and operational capabilities. As such we tried to develop a meaningful initial simulation, which provided an explanatory animation of rescue mission. Although beneficial to the design evaluation process, these preliminary studies were clearly limited in their capability to genuinely demonstrate the complex systems and multi-layered processes involved in a Submarine Rescue System / Operation.

As video-recordings of such operations are difficult to reproduce, a manipulatable, real-time simulation of a predetermined series of events depicting meticulously the real-life processes could provide potential users or collaborators an unobstructed multi-view of the operation.

6. CONCLUSIONS

Based on the success of this case study, we intend to expand our future work to the development of the real-time visualisation of the SRV and associated Rescue Equipment. We are particularly keen to enable non-expert users in CAD to explore and interact with the 3D environment in real-time using a virtual-reality-based interface and allowing them to easily inspect, review and analyse the physical and human interactions.

Finally, to prevent or minimise onboard or procedural accidents we envisage developing a series of simulated scenarios which will demonstrate human interaction with the various systems under difficult situations. Utilising the aforementioned information we aim to offer the means for submarine developers to evaluate in real-time and in a controllable and safe environment the structural designs and the human factors involved in their operation.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

1. Anderson, P., Kenny, T. & Ibrahim, S.: The role of emerging visualization technologies in delivering competitive market advantage. In: Proceedings of the 2nd International Conference on Total Vehicle Technology, Institute of Mechanical Engineers, University of Sussex, Brighton, UK, 2002.

2. Badler, N. I., Phillips, C., B., and Webber, B. L., Simulating Humans: Computer Graphics Animation and Control, Oxford University press, New York, 1993.

3. Chaffin, D. B.: Digital Human Modeling for Vehicle and Workplace Design, Society of Automotive Engineers Inc. Warrendale PA, USA, ISBN 0-7680-0687-2, 2001.

4. Charissis, V., Naef, M., Patera, M. Calibration Requirements of an Automotive HUD Interface Using a Virtual Reality Environment: Methodology and Implementation. Proceedings of the IASTED Conference on Graphics and Visualization in Engineering, Florida, USA, 3-5 January, 2007.

5. Gabriel, R. F.: What Engineers and Managers Need to Know About human Factors, Society of Automotive Engineers Inc. Warrendale PA, USA, ISBN 0-7680-0975-8, 2003.

6. Karwowski, W.,Genaidy, A. M., and Asfour, S. S., (Eds), Computer Aided Ergonomics, pp 138-156, Taylor and Francis, London, UK. 1990.

7. Naef, M., Interaction and Ergonomics Issues in Immersive Design Review Environments. Proceedings of COMPIT 2007, , Cortona/Italy, 23-25 April, 2007.

8. Raschke, U., Shutte, L., and Chaffin,D. B., Simulating Humans: Ergonomic Analysis in Digital Environments, in Salvendy, G., (Ed.), Handbook of Industrial Engineering, J. Wiley & Sons, New York, 2001.

9. Sherwood Jones, B., Naef, M., McLundie, M.: Interactive 3D Environments for Ship Design Review and Simulation. 5th International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT). Leiden, The Netherlands, May 8-10, 2006.

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THE DELIVERY OF THE SUCCESSOR DETERRENT SUBMARINE CONCEPT DESIGN - A COLLABORATIVE APPROACH

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Summary

Following the decision by the Government and the subsequent vote in Parliament to continue the UK's Independent Nuclear Deterrent, the Future Submarines IPT was formed to put in place the programme to deliver this vital capability. This will be the largest engineering programme in the UK in recent times, with a budget approximately double that of the Olympic Games. An innovative approach is being taken by both MoD and Industry to deliver the programme, with a truly Integrated Project team being formed utilising the best available resources from both the MoD and Industry. This paper will describe the approach being taken to the collaborative delivery of the Concept Design for the Successor Deterrent Submarine and will reflect on the lessons learned in this area during the first six months of this programme.

1. INTRODUCTION

The Government's reasoning for continuation of the UK Independent Nuclear Deterrent was clearly set out in the 2006 White Paper, "The Future of the United Kingdom's Nuclear Deterrent" [1], and following Parliament's approval in March 2007, the Future Submarines Integrated Project Team (FSMIPT) was established in April 2007. The Team was charged with the renewal or replacement of those elements of infrastructure and the UK submarine fleet necessary to deliver the will of Parliament.

In October 2007, as part of this overall programme of work, the Concept Phase for the UK Successor Deterrent Submarine began. This is a two year programme, designed to deliver the key high-level decisions, design policies and concept design definition necessary if the successor to the in-service Vanguard Class submarine is to enter service in 2024.

The Successor Deterrent is one of the first major defence programmes to adopt the collaborative approach between the MoD and Industry signalled in the Defence Industrial Strategy [2] published in 2006. The Future Submarines Integrated Project Team is staffed by personnel from Defence Equipment and Support (DE&S) and staff from the three primary companies in the 'Submarine Enterprise' – BAE Systems Submarine Solutions, Rolls-Royce Submarines and Babcock Marine.

This paper will discuss, and draw interim conclusions on the following aspects:

- The issues and challenges in setting up a collaborative team from across the submarine enterprise
- The role, structure and method of working of the IPT
- The development and management of the User and System requirement
- The planning and the delivery of a viable Submarine Concept Design
- The delivery of affordable and available submarine platforms

2. THE ISSUES AND CHALLENGES IN SETTING UP A COLLABORATIVE TEAM

The Submarine 'market' in the UK is effectively shrinking. While the United Kingdom's submarines have become more effective over the past two decades, reduced requirements and increasing costs have resulted in the reduction of the submarine flotilla. With the introduction of the Astute Class submarine over the next decade, this will result in a flotilla of up to 11 nuclear submarines – four ballistic missile submarines and seven hunter-killer submarines.

The natural corporate response to a shrinking market is to seek to increase market share at the expense of the other participants in the market. Where a market has reduced to a minimum level, this form of competition tends to dominate the senior management attention in each company as each are focussed on survival, and any success simply transfers activity between virtual monopolies of expertise and can lead to the loss of key expertise to the nation.

This situation was recognised by the Defence Industrial Strategy. This sought to ensure that the UK's strategic capability to design, build and support a submarine flotilla could be sustained while ensuring that the cost of the submarine programme in the UK represented value for money. It recognised that this was only achievable by increased collaboration within the Submarine Enterprise, both between the industry participants and between MoD and Industry.

This transition from competitive to collaborative behaviours represents the first challenge faced in establishing the FSMIPT. The culture of an organisation sets the behaviour of its staff, and such cultures are notoriously difficult to change. This organisational culture is reflected in policies and processes of each company and in the MoD and is also embedded in the behaviour of its staff. The challenge posed by the UK Successor Deterrent Programme is not to change the culture in a single company, but to change it in four organisations – all at the same time.

The challenge is, in itself, multi-facetted, presenting significant issues in terms of policy, process, systems and behaviours.

The very concept of collaboration, rather than competition, to deliver reduced costs lies somewhat uncomfortably against a long-standing position within the MoD that competition was the primary mechanism of ensuring value for money in defence procurement. This 'position' is reflected in a vast array of formal policies and ways of conducting business within the MoD and is also enshrined in law. Equally, within industry, corporate governance requirements generally reflect the need to protect a company's competitive advantage and assume a 'traditional' commercial position where the protection of information is important.

Each partner within the collaborative construct delivering the Concept Phase of the Successor Deterrent Submarine has found that this collaborative approach has 'clashed' in one way or another with established policies. For example, corporate governance policies for the release of a proposal would generally ask the question 'are the customer's requirements clearly and unambiguously defined'. The provision of a response of the form 'No, we have agreed to develop the requirements collaboratively alongside the Concept Design so that we can together trade requirements against whole life cost and agree an outcome that represents the minimum whole life cost' is likely to be unexpected, and potentially might normally be considered to be unacceptable.

In terms of process, the collaborative approach presents both issues and opportunities. Consider a simple concept such as the review of the Concept Design as it emerges. All of the industrial partners have 'design review' processes, and each is, to some extent, different. What may well be missed is that each company has a different definition of the term 'Concept Design' while using identical terminology. Patently, a common understanding of both the subject matter and the conduct of the review is essential, and this is addressed by the development of specific processes supporting the collaborative delivery of the Concept Design. The fact that a number of the participants have extant processes presents the opportunity of 'benchmarking' these to identify good practice, incorporating this into the new process. The approach taken to the development of all processes for the Successor Deterrent Concept Phase ensures that good practice is sought and that the appropriate stakeholders from any of the participants are engaged in the development and approval of the process.

Each of the participants recognises that effective 'business systems' are an essential feature of an efficient organisation. However, each has to date pursued its own strategy for the selection and deployment of these key elements of the organisation's infrastructure. Unsurprisingly this has not resulted in significant commonality across the collaborative landscape, other than in the ubiquitous email and standard PC desktop tools. Even simple tools such as email can initially present issues, with differing firewall and spam detection settings. Significant efforts will be required to provide an effective collaborative environment for the delivery of The Concept Design and enable the development of the detailed submarine design in the future.

Finally, the most difficult challenge is likely to be ensuring that the people who will together deliver the Concept Design (and the larger number who will deliver the detailed design of the submarine) exhibit constructive behaviours. Our behaviours are the unconscious result of experience, and until recently this experience has been competitive.

Each individual responds differently to a new situation – we all know individuals who are 'stuck in their ways' or who 'relish a new challenge'. A key success factor in changing the behaviour of both individuals and a team is to ensure that the basis for the behaviours exhibited is consciously understood. At a high level, this can be achieved by including measures and incentives in contracts to reward the right, collaborative behaviours, thus ensuring that the senior management in each participant is appropriately (and consciously) focussed.

At a team and individual level, the experience of a number of the participants has demonstrated the value of the deployment of structured development programmes that equip staff with a basic understanding of the drivers that result in effective and ineffective behaviours within the team. This provides a conscious understanding at an individual level, and although not a 'quick fix' has been shown to reap rewards in the medium to long term.

3. THE ROLE, STRUCTURE AND METHOD OF WORKING OF THE IPT

The Future Submarines IPT must essentially work, and organise itself, in two levels to deliver the continuation of the UK's independent nuclear deterrent. The delivery of the complete 'deterrent capability' requires the co-ordination of a large and complex set of organisations, each of whom contribute one or more elements of the 'capability. At this level, the Defence Lines of Development - Training, Equipment, Personnel, Information, Concepts and Doctrine, Organisation, Infrastructure and Logistics - must all be delivered in a co-ordinated manner, and the senior stakeholders within the Ministry of Defence and wider Government must be engaged. A Programme Support Office has been established to assist the Senior Responsible Owner, the MoD's Director General of Equipment.

Within this broad co-ordinated programme, significant elements such as the design and delivery of a new class of submarine must also be managed. It is this latter aspect that is the subject of this paper. This is the primary responsibility of the IPT, and - while the capability level is vital - we shall concentrate today on the delivery of the submarine Concept Design.

We have formed a single team comprising staff from each participating organisation and the wider Submarine Enterprise, designed to deliver the submarine Concept Design effectively. The team has elements at three levels.

At the highest level, a MoD/Industry Steering Group provides strategic direction and collaborative governance for the submarine platform programme. Each participant is represented at Director (board) level, with the Terms of Reference for the Steering Group encouraging consideration of the best interests of the programme as a whole and the building of consensus.

The senior 'working' level of the collaborative organisation is the Operations Board. Again, each participant is represented at Director level, but in this instance the representatives are closely engaged in the delivery of the programme. The Operations Board also includes other senior members of the IPT with other managers joining as appropriate.

Finally, the Concept Design is being developed by the organisation shown in Figure 1. The organisation reflects the need to work at both the 'capability delivery and 'submarine delivery' level and to deliver the 'business aspects' of the IPT. The appointment of industry team members is managed collaboratively by all participants to ensure that the best available expertise is deployed without consideration of the individual's employer.

3.1 BUSINESS DELIVERY

The Business Delivery element of the organisation is responsible for the financial and commercial management of the programme. The transition from competitive to collaborative has presented some challenges in this area and the partners have worked together to develop a commercial construct that reflects the collaborative strategy of the programme. The contractual arrangement must also reflect that, within the collaborative framework, there remains a client - provider relationship

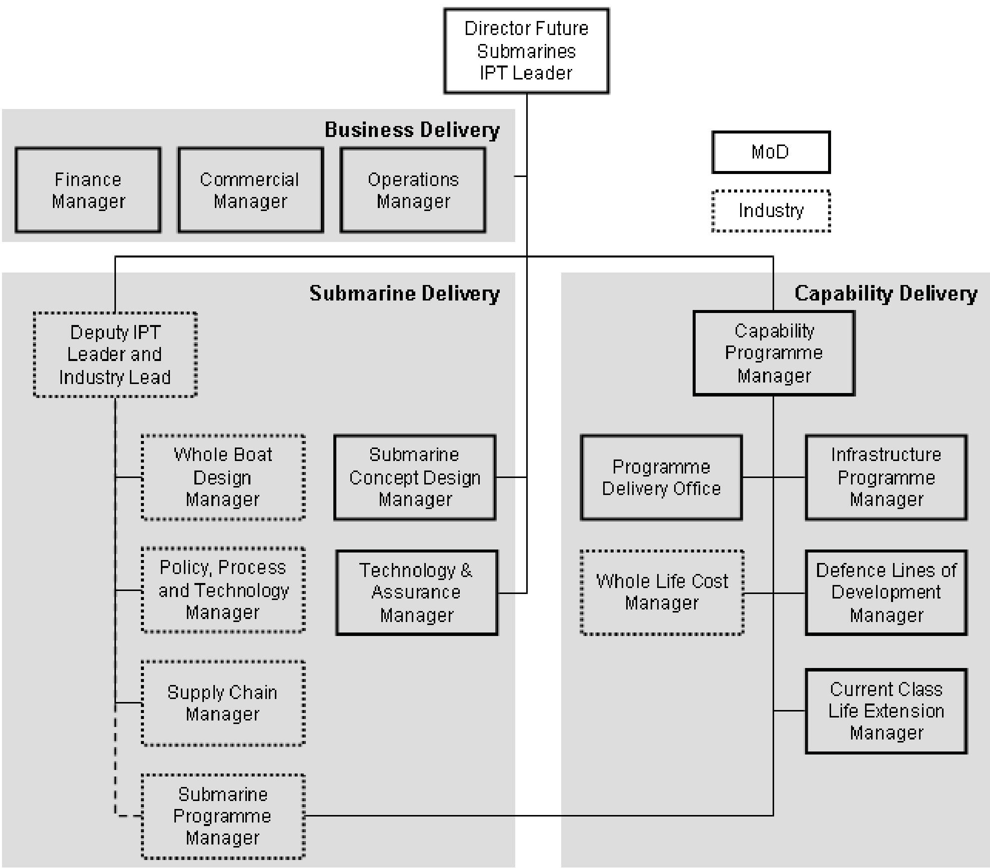

Figure 1: Future Submarines IPT Organisational Structure

The individual contractual arrangements with each of the industrial partners include a collaboration agreement and associated financial incentives that are available to all of the industry partners based on the delivery of evidence of effective collaboration.

This part of the organisation is also responsible for developing and presenting the programme's business case for scrutiny within the MoD "HQ", Defence Equipment and Support, and by wider government.

3.2 CAPABILITY DELIVERY

The Capability Delivery element of the organisation is responsible for ensuring that the necessary actions are taken across all elements of the Defence Lines of Development to ensure the continuation of the UK's independent nuclear deterrent capability. The role is primarily one of co-ordination, ensuring that the overall requirements of the programme are understood by the wide range of organisations involved and that an integrated programme capturing the necessary high-level activities is developed, maintained and delivered.

In addition, this part of the organisation is charged with developing an adequate understanding of the Whole Life Costs of the overall programme to enable the primary cost drivers to be identified and managed. This element is also highly collaborative, with each partner actively involved.

3.3 SUBMARINE DELIVERY

The Submarine Delivery element of the organisation is charged with the delivery of the Submarine Concept Design. At a high level, this comprises a record of the key decisions made during the Concept Phase (together with a capture rationale for the decision and all supporting evidence), a Submarine Concept Design Definition capturing the emergent design and reflecting the decisions made, and a set of Design Policies that set the 'design direction' for the completion of the functional and detailed design of the submarine.

The organisation has been designed to avoid any unnecessary 'man marking' between the MoD and the industry participants. Conscious efforts have been made to foster close working relationships throughout the team. MoD and Industry team members are located together in two main offices in Abbey Wood and Barrow-in-Furness and frequent working level meetings are held. The organisation also ensures that the Submarine Concept Design Manager (who is responsible for the submarine's User and System Requirements) works closely together with the Whole Boat Design Manager, promoting effective and timely decision making and enabling requirement/performance trades.

In a similar way, collaborative teams have been formed to address the adoption of innovative technologies into the submarine design, the development of the commercial arrangements, the development of a co-ordinated Supply Chain strategy, and the development of Whole Life Cost models.

4. THE DEVELOPMENT AND MANAGEMENT OF THE USER AND SYSTEM REQUIREMENT

In general, recent major defence programmes have been 'requirement-based', this is the customer defined the requirement for the system and industry provided a product the demonstrably met these requirements.

While this has some obvious advantages, there a number of significant issues that can arise as the result of this approach. The definition of a complete, consistent and correct requirement for a complex system such as a submarine is notoriously difficult. The process inevitably involved a large number of people each experts in their own field, and is developed as a textual document with the inevitable ambiguities that this entails. The old joke about a camel being a horse that has been designed by a committee rings particularly true here.

In addition, careful commercial management of such as contract and the long design and production timescales associated with such a complex and large product results in the customer receiving precisely the product that he has asked for more than a decade ago, but potentially not the product that the Government needs at the time. The imprecise nature of any such requirement specification coupled with a limited understanding (in both the MoD and Industry) of the capability/cost equation is also a crucial factor contributing to cost overruns in these large, complex programmes.

The Successor Deterrent programme has consciously decided to take a different approach. There are a number of overarching principles that can be summarised as:

- Cost is king in the capability/cost/time equation – there are some crucial aspects to the requirements for a nuclear deterrent submarine (safety, continuous at-sea deterrence, stealth, etc.) but in principle, all requirements can be considered for trading against whole life cost. The Government have asked for a submarine in the water by 2024 at a cost between £11bn and £14bn
- Requirements can, and should, be challenged – a requirement must have a valid rationale – the rational 'because a previous design was like that' is not acceptable. Proposal for slightly reduced performance for significantly reduced cost will be considered, and this is actively happening within the Submarine Delivery team
- The requirement set will reflect the factors that are crucial for the submarine to be able to perform its

defined role. This will include constraints such as the maximum limits of the current supporting shore infrastructure

The intention is that the User Requirement will remain ‘fluid’ during the Concept Phase, enable capability / requirement / cost trades to take place. Towards the end of the Concept Phase the User Requirements will be baselined. At this stage, the System Requirement for the submarine will be drafted, together with a Submarine Design Specification that will capture the high-level design decisions made during the phase.

All requirements are being managed and developed using the DOORS toolset. Functional Analysis is being undertaken using System Architect and the MODAF method. Textual requirement documents will be generated from the DOORS toolsets.

5. THE PLANNING AND THE DELIVERY OF A VIABLE SUBMARINE CONCEPT DESIGN

The development of a submarine Concept Design does not happen very often, and such an opportunity is available perhaps only once or twice in a career. In addition, the circumstances prevalent at the inception of each submarine programme are likely to be different, presenting different design drivers and constraints. Both of these factors mean that there is no reference ‘body of knowledge’ on which to base these early phases.

The value of the collaborative approach is that we have been able to collectively determine the key aspects that need to be undertaken during the Successor Deterrent Concept Phase. At a high level, these are:

- The determination of the key user requirements for the submarine
- The identification of the key decisions that must be made regarding the submarine design
- The development of Design Principles and supporting strategies and policies for significant elements of the submarine design
- The development of a common understanding of Whole Life Cost issues
- The development of the Business Case for the programme and its scrutiny at senior levels within MoD and the Government
- The development of the processes, tools and infrastructure for the future phases of the programme
- The development of a single integrated programme

5.1 KEY USER REQUIREMENTS

The determination of the key user requirements for the submarine is an obvious requirement of the early phase of the programme. It is important, however, that this is undertaken in a way that does not undermine some of the other key principles, particularly the minimisation of Whole Life Costs, and this has been discussed in an earlier section of this paper.

5.2 KEY DECISIONS

The identification of the key decisions that must be made regarding the submarine design in these early phases was not straightforward. While the need for some decisions to be made was relatively obvious, it quickly became clear that very few decisions could be taken in isolation from the others and from the emerging design concept. At a very simple level the maximum speed at which the submarine can proceed through the water is a function of propulsion power and hull diameter (among other things), so any decisions relating to the hull diameter must recognise any constraints imposed by the propulsion plant (and vice versa).

The complex nature of all of these inter-relationships mean that these is no single ideal sequence for the necessary decisions, and many must proceed in parallel with an holistic view of the design being maintained at all times. Some would say that this represents the art of Naval Architecture and perhaps they would be right, but the net of decisions extends significantly outside what might normally be considered as Naval Architecture to the edges of the ‘deterrent capability’

A ‘decision’ is also in itself a complex thing. Such a large, complex and politically sensitive programme has many stakeholders, together with an even greater number of organisations and people that will potentially be affected by any decisions taken. A critical success factor in this area is (borrowing somewhat from ‘Allo Allo’) the ability to make decisions *only once*. This large and complex programme will only be able to proceed to the required programme if key decisions are not re-visited and potentially reversed over time. If this happens, then the level of re-work will be significant, with a consequent impact on both cost and programme.

A ‘decisions process’ has been developed encompassing all of the FSMIPT and the wider stakeholder community to ensure that all decisions made are well founded (that sufficient analysis and evidence supporting the decision made has been captured), that they are well understood (that all stakeholders have been actively engaged in making the decision) and well communicated (that all potentially impacted know that the decision ahs been made and are aware of its impact on them).

5.3 DESIGN PRINCIPLES

The development of a set of overarching Design Principles was a key deliverable of the pre-concept phase of the programme. These Design Principles set out the high-level strategic direction for the design process and cover elements such as design for minimum whole life cost, Safety, the use of commercially available equipment, and similar high-level aspects

Priority has been given in the initial three months of the programme to the development of more detailed design strategies covering significant elements of the submarine design and overarching aspects such as Information Management and Systems Engineering. These Design Strategies will be subject to appropriate scrutiny within the FSMIPT and by appropriate stakeholders and subject matter experts.

As the Concept Phase develops, these Design Strategies will be further refined and will become policies to guide the design process through to release to manufacture. The intention is that, having embodied the high-level Design Principles and validated strategies, they will provide a firm foundation for the achievement of the programme's overall goals.

5.4 COMMON UNDERSTANDING OF WHOLE LIFE COST

By definition, all of the participants in the programme contribute in some way to the Whole Life Costs of the programme, and each holds knowledge information that will be crucial to the management and minimisation of Whole Life Costs. This development then, of a *common understanding* of Whole Life Cost drivers and outcomes is crucial to the overall success of the programme.

The ability of the industrial participants to share detailed cost information is limited by UK and European competition law, and by commercial confidentiality to suppliers and other third parties. The legal aspects are currently being addressed and consultation on the granting of a 'competition waiver' is currently underway at the time of writing.

The latter aspects of commercial confidentiality are being addressed by the formation of a Cost Modelling function within the MoD element of the collaboration, and a Data Collection function within industry. This approach, with appropriate processes, checks and balances to preserve the necessary confidentiality is intended to enable the necessary common understanding to be developed with the aim of influencing the design process to 'design out' or minimise significant cost drivers.

5.5 THE BUSINESS CASE

The development of the Business Case for the programme and its scrutiny at senior levels within MoD and the Government is a vital element of the Concept Phase. The Initial Gate for the programme has been set approximately 18 month into the Concept Phase, with the intention of achieving approval for subsequent phases of the programme prior to the end of the Concept Phase, and thus enabling a smooth transition to the Functional Design phase of the programme

While the Business Case will draw upon documents and evidence produced as a result of the other elements of the Concept Phase, the programme also considers the specific evidence required to support the business case.

Again, the collaborative approach established for the programme has enabled a more 'joined up' approach between MoD and Industry with a single programme being able to utilise the same deliverable more than once – supporting the delivery of the Concept Design and the requirements of the Initial Gate review.

5.6 PROCESS, TOOLS & INFRASTRUCTURE

The development of the processes, tools and infrastructure for the future phases of the programme is also a crucial deliverable from the Concept Phase.

A set of key processes are being developed to support the collaborative development of the Concept Phase. A number of these have been mentioned in passing in this paper – the selection of industry members of the IPT, the decisions process, and the concept review process. The deployment of a single set of processes across four collaborating partners presents some challenges, but also provides an opportunity for benchmarking and the sharing of good practices across these organisations.

The delivery of the future design phases of the programme will require a significant supporting infrastructure and specialist design toolsets available to engineers based at a number of geographic sites. Again, a collaborative approach has been adopted, with all participants being actively engaged in the development of the strategies and more detailed plans to deliver the required facilities.

5.7 THE DEVELOPMENT OF A SINGLE INTEGRATED PROGRAMME

The collaborative approach taken for the delivery of the Successor Deterrent Concept Phase has enabled the development of a single integrated programme of activities to deliver the required outputs. While this might seem an obvious step, this has been difficult to achieve in the past.

It is intended that this approach also be applied to the complete programme with and integrated Master Schedule for the delivery of the deterrent capability being developed. This Master schedule will be linked with more detailed schedules for each major project across the Defence Lines of Development that is needed to deliver the overall programme.

The key measure of success of this approach is the ability to identify and manage the key dependencies within the programme at an appropriate level.

6. THE DELIVERY OF AFFORDABLE AND AVAILABLE SUBMARINE PLATFORMS

This paper has set out the approach being taken in the early stages of the Successor Deterrent programme to ensure that those involved will be able to deliver an affordable and available capability.

The first six months of the Concept Phase programme has presented a number of challenges, some expected and others less so. In these early stages is it evident that a collaborative approach has already paid dividends, with Design Principles being adopted by all concerned and design strategies being developed collaboratively in a very short period to begin the process of embedding these principles into the submarine design.

A single common programme for the delivery of the Concept Phase by all collaborating partners has also been established, with progress meetings being attended by all participants with issues and dependencies within the programme being identified and resolved.

The programme has also been able to populate the team that will deliver the Concept Design from across industry, with all of the collaborating partners being engaged in the selection of the best person for the job. This has resulted in a number of the teams being populated from two or more companies, with consequently a wider set of knowledge and expertise being available within the team. This process has also identified where expertise from other companies can be usefully employed on the programme.

The key processes required to deliver the Concept Phase are now established and have involved all of the collaborating partners. Concentration in this area is now beginning to move to the development of the processes, tools and supporting infrastructure that will be required to deliver future phases of the programme.

You would not expect such a large and complex programme to be without its difficulties, and a number of challenges have been faced. A number of areas have found it difficult to identify and engage engineers with the experience to contribute to the programme. This is particularly the case for Systems Engineering where capable engineers with an in-depth knowledge of submarine design do not routinely attend their local Job Centre seeking work!

Similarly, expertise in the design and development of Strategic Weapon Systems are not needed for every submarine programme. The available expertise in this area (generally with experience gained from the Vanguard programme) tend to be towards the end of their careers, and an active succession management strategy will be needed to ensure that their knowledge and experience is transferred to a younger generation who will complete the work on this programme.

One of the advantages of a collaborative approach is that knowledge and expertise can be sought from other organisations. The first six months of this programme have underlined the fact that the knowledge and resources to deliver this programme successfully can only be deployed collaboratively, since no one company or the MoD has the full range of expertise and resources necessary.

Finally, the delivery of this programme within cost and programme constraints presents a very real challenge. On a personal note, I feel very privileged to be contributing to this programme in these early stages. Working together we can set the programme of 'in the right direction' to achieve a successful outcome.

7. ACKNOWLEDGEMENTS

The author would like to acknowledge the assistance and editorial suggestions received from his colleagues in the Future Submarines Integrated Project Team from industry and the Ministry of Defence.

8. REFERENCES

1. The Future of the United Kingdom's Nuclear Deterrent, *HMSO*, December 2006

2. Defence Industrial Strategy, *HMSO*, December 2005

9. AUTHORS BIOGRAPHY

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HYBRID NUCLEAR/FUEL-CELL SUBMARINE

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SUMMARY

This paper describes the concept design for a hybrid nuclear/fuel-cell power plant for a submarine capable of nuclear powered high speed transits and fuel-cell powered slow speed operations. Additionally, the concept provides a fully air independent auxiliary power source to increase safety in the event of unplanned reactor shutdowns during under-ice operations and high sea states. The PEM fuel-cells provide 477kW, sufficient to power the 3,000 tonne submarine to a maximum sustainable 8 knot dived speed. Sufficient hydrogen and compressed oxygen is carried to provide 7 days fuel-cell operations at an average 6 knots; the fuel-cell system could either be distributed around the hull or inserted as a 5.6m plug. The selection of reversible fuel-cells allows onboard hydrogen and oxygen regeneration whilst in nuclear mode, negating the requirement for separate electrolysers. A full safety analysis failed to identify any risk from hydrogen although using compressed pure oxygen requires further investigation.

NOMENCLATURE

AIP	Air Independent Propulsion
BOP	Balance of Plant
GMP	Gas Management Plant
HCWT	Hydride Cylinder Water Tank
HPA	High Pressure Air
LOX	Liquid Oxygen
PEMFC	Proton Exchange Membrane Fuel-Cell
RFC	Reversible Fuel Cell

1. INTRODUCTION

Increasing environmental concerns and ever-dwindling fossil fuel reserves are demanding cleaner, more efficient power generation. As a result a number of recent ship designs have incorporated fuel-cells into their power plants as either a prime mover or an auxiliary power generator. This paper, based on part of a MSc thesis on the Integration and Safety of Fuel-Cells in Ships [1], describes the concept design for a hybrid nuclear/fuel-cell power plant for a submarine capable of nuclear powered high speed transits and fuel-cell powered slow speed operations. The design is reliant on a number of novel technologies and raises serious safety concerns; these are addressed as well as carrying out basic calculations to provide an indication of weight and volume requirements of the fuel-cell plant and to quantify the safety risk.

2. BACKGROUND

The German U212/4 class has already proven the concept of a fuel-cell equipped conventional submarine (SSK) and therefore the opportunity was taken to investigate the integration of fuel-cells into a nuclear powered attack submarine (SSN). In addition to the reactor, SSNs have standby batteries and diesel generators to provide short and long term backup power during planned or unplanned reactor shutdowns. In order of increasing complexity and innovation the possible options for a fuel-cell equipped SSN are as follows:

- <u>Option 1</u>. Partially replace the battery with a fuel-cell system to provide longer duration/higher available power during a reactor scram (unplanned reactor shut-down for safety purposes) than is possible with existing lead-acid or lithium-ion batteries.

- <u>Option 2</u>. Replace the diesel generators with a fuel-cell system to reduce noise, vibrations, maintenance requirements and air dependence.

- <u>Option 3</u>. Design a hybrid nuclear/fuel-cell plant for a submarine capable of high speed transits and quiet operations. Though of a similar system design the fuel-cell system size would be significantly greater than that in Option 2 which would be sized for emergency power only.

In order to fully explore the concept of a hybrid nuclear/fuel-cell submarine Option 3 was selected for further investigation.

3. REQUIREMENT

Fitting fuel-cells to a submarine results in a significant operational advantage. With both hydrogen and oxygen stored onboard, a fuel-cell equipped SSK can remain submerged for many weeks without the requirement to snorkel and run diesel generators with the attendant signature issues (noise and visual signature of the snort induction and diesel exhaust masts). Whilst a SSN has no requirement to snort and can therefore remain submerged indefinitely (personnel dependent) the noise of continually running pumps and the large quantity of waste heat rejected to the sea significantly increase the submarine's signature. A fuel-cell equipped SSN could shut down the reactor for quieter performance during operational patrols, remain on task following a scram giving ships staff time to rectify the defect and recover to normal reactor operation and maintain a fully air independent auxiliary power source for under-ice operations.

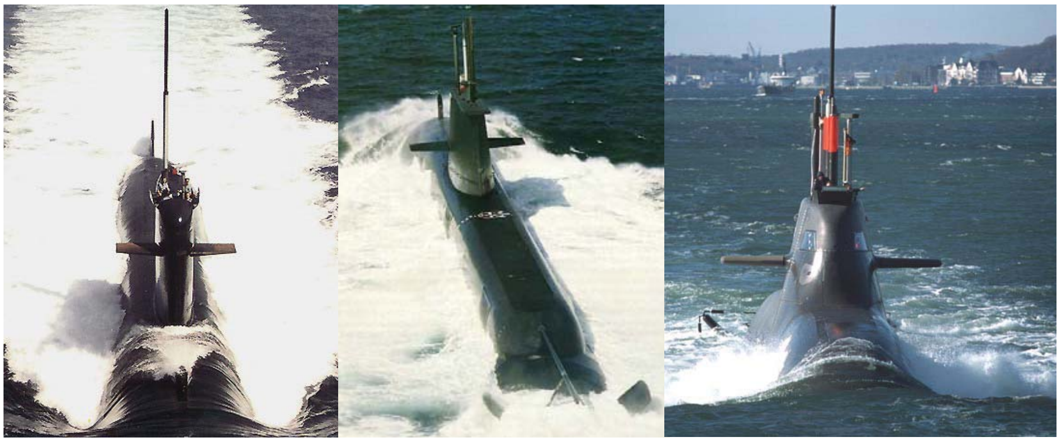

Figure 1: RUBIS, COLLINS and U212 class submarines [2].

3.1 OTHER BENEFITS

- Removal of diesel exhaust mast with associated large pressure hull breach.
- Removal of dangerous (in a fire) hydrocarbon fuel.
- Nil emissions when on auxiliary power source therefore future proof to IMO legislation.
- Easier build and maintenance as the components of the fuel-cell system are small and can be removed through existing hatches. The exception is the metal hydride cylinders depending on whether they are located internally or externally. This is in contrast to diesel engines which require hull cuts for removal.
- During an emergency surface compressed oxygen tanks could contribute to emergency blow air.
- No requirement for oxygen candles in a DISSUB environment thus reducing the potential for a HMS TIRELESS type fire and explosion.
- Fuel-cells can be rapidly "switched on" following a scram thus significantly reducing the required battery size, diesels can only be run once the submarine reaches the surface and the snort mast has been raised.

In general these points give the platform greater flexibility and reduce the risk of mission compromise but the limited energy density of hydrogen and oxygen storage results in a lower fuel-cell range than that available from diesel generators.

4. SUBMARINE CHARACTERISTICS

In the absence of a defined operational requirement a number of assumptions were made as to the SSN's role, size and power requirements. The exact displacement was not required but was assumed to be similar to a small SSN/large SSK (RUBIS/COLLINS class, i.e. 2–3,000 tonnes) making it approximately twice the displacement of the U212/4 class.

The operating profile was assumed to consist of high speed transits under nuclear power to operational patrol areas where the fuel-cells would take over and the reactor shut down into a stand-by state. Despite recent advances critical nuclear reactors almost always require some rotating machinery running and hence can never be totally silent. With an appropriate reactor design (i.e. encompassing natural circulation cooling when shut down) such a submarine could rival the acoustic signature of a SSK.

Therefore, the fuel-cell system has been sized for the typically low speeds used on operations. Though not considered within this investigation the reactor would be of a suitable power to achieve the required maximum transit speed and though reduced, a battery bank would still be required for immediate stand-by power in the event of a reactor scram and sprint speeds whilst running on fuel-cells. It is recognised that this concept of operations is impossible with today's generation of reactors and hence would require a new design. However, next generation naval nuclear power plants are already heading in the direction of low shut down power and increased passive safety, both of which are major requirements for such a stop/start operating concept.

4.1 POWER CALCULATIONS

The following specifications were chosen, roughly equivalent to the COLLINS class SSK:

Effective length	75 m
Diameter	8 m
Surface area	1885 m^2
L/B ratio	9.375
Block coefficient	0.72

Table 1: Submarine specifications.

These figures were used to determine a power speed curve for the submarine as described in Concepts in Submarine Design [3]:

$$P_E = 1/2.\rho.V^3.S_{ref}.C_{TS} \quad (1)$$

Where P_E = effective power, ρ = sea water density, V = submarine speed, S_{ref} = total wetted surface area and:

$$C_{TS} = C_{FS} + C_R + C_A \qquad (2)$$

C_R + C_A are obtained from graphs (ref [3] pp.294) depending on the L/B ratio and block coefficient and:

$$C_{FS} = 0.075/(\log_{10}Re_L - 2)^2 \qquad (3)$$

Using a seawater density of 1025 kg/m^3 and kinematic viscosity of 1x10^{-6} m^2/s the power-speed curve was calculated, the low speed section of which is at Figure 2. Selecting a maximum sustained operational speed of 8 knots (short term sprints can be achieved using the battery although it should be noted that most fuel-cells are capable of considerable short term overload) results in an effective power of 187kW. Assuming the following efficiencies: propeller 75%, motor 95% and power electronics 95% results in an installed propulsive power requirement from the fuel-cells of 277kW. By comparison the U214 class has 240kW of fuel cells installed. It is interesting to note that the air breathing PEMFC developed for automobiles are rated in the range of 30 - 50kW.

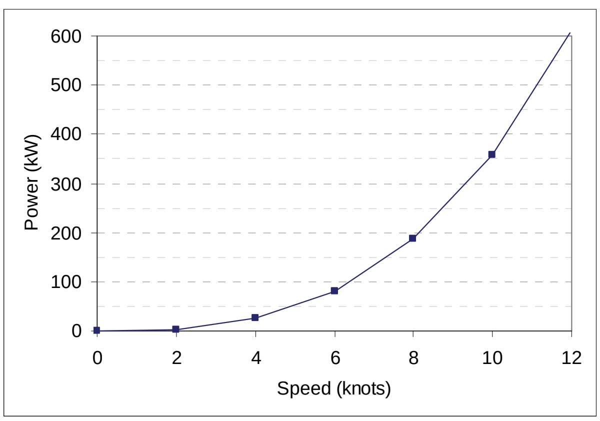

Figure 2: Low speed power-speed curve.

It is assumed that there is a 100kW hotel service load (obtained from similar size UCL Submarine Design Exercise concepts) and in the absence of any data for an appropriately sized nuclear power plant the reactor safety load was estimated as also equalling 100kW; **note this figure is not representative of current class SSNs.** Therefore, the fuel-cells are required to produce a total of 477kW. However, the average speed on operations was assumed to be 6 knots which equates to 81kW effective power and a total average power of 320kW; this figure was used for duration calculations. In the absence of a dedicated mission profile it was assumed that the submarine would be required to conduct fuel-cell operations for a period of up to 7 days.

5. POWER PLANT

An IFEP plant has been selected with a single reactor driving 2 steam turbo-generators feeding onto a DC busbar, also supplied from four 120kW fuel-cell stacks providing a total of 480kW. No diesel generators are required with all auxiliary power coming from the fuel-cells if needed. All propulsion, ship, reactor, weapon and hotel service loads are supplied from the busbar with propulsion being achieved with an appropriate electric motor mounted directly onto the shaft as on contemporary SSKs.

5.1 FUEL-CELL SELECTION

In order to minimise thermal signature, provide adequate start up and response times and reduce onboard cooling requirements, a low temperature fuel-cell would be required. Of these, Proton Exchange Membrane Fuel-Cells (PEMFCs) provide the high power density required by submarines and though a pure oxygen breathing version differs to the air breathing types being developed by the automotive industry they can still benefit from technology transfer. Balance Of Plant (BOP) systems (thermal, gas and water management systems, control circuitry etc.) were assumed to occupy the same volume again as the fuel-cell stacks. Air-breathing PEMFCs have an efficiency range of 45-60% although the higher values are projected only. As part of the MSc thesis [1] a literature survey was undertaken and realistic, representative efficiency values determined for each major fuel-cell type. 49% was settled on for the PEMFC although as pure oxygen increases efficiency by approximately 20% [4] a total system efficiency of 69% was used for calculations.

5.2 FUEL STORAGE SELECTION

The chosen fuel storage system must be volumetrically efficient owing to the restricted space available within a submarine, Table 2 summarises the potential options. The peculiar packing properties of hydrogen are also demonstrated, for example a litre of water contains more hydrogen than a litre of pure liquid hydrogen. Compressed and liquid hydrogen storage are considered unsuitable, the former is volumetrically inefficient and the latter requires a significant plant to achieve 70^{o}K to liquefy the hydrogen whilst both require significant containment vessels. The practical alternatives are either metal hydride or fossil fuel reformation. Fossil fuel reformation produces carbon dioxide that must be disposed of either through absorption or overboard discharge.

	State	Symbol	Atomic mass	Density kgm^{-3}	Volume (litre) and mass (kg) per kg of Hydrogen	
Hydrogen	Gas (STP)	H_2	2.016	0.095	10,500	1.00
Hydrogen	Gas(250bar)	H_2	2.016	23.75	42.00	1.00
Hydrogen	Liquid (70K)	H_2	2.016	71	14.08	1.00
Water	Liquid	H_2O	18.015	1000	8.94	8.94
Methanol	Liquid	CH_3OH	32.042	794	10.01	7.95
Ethanol	Liquid	C_2H_5OH	46.068	798	9.55	7.62
Dodecane (Diesel)*	Liquid	$C_{12}H_{26}$	170.340	748	8.69	6.50
Ammonia	Liquid (300K 10bar)	NH_3	17.032	623	9.04	5.63
Titanium hydride	Solid	$TiFeH_2$	105.763	5470	9.59	52.46

* Dodecane is accepted as a representative average of the many constituents of Diesel.

Table 2: Comparison of hydrogen vectors (excludes containment vessel) [5].

The former requires dedicated storage space and the latter can increase the submarine's signature. Therefore, metal hydride storage was considered the best option; its two biggest disadvantages (cost and weight) are less relevant to a submarine than for other applications. Submarine designs tend to be volume rather than weight driven and often have ballast added to achieve the desired buoyancy and stability conditions. So where the low gravimetric density of metal hydride storage is a big disadvantage for most transport applications it is less so for a submarine. The metal hydride cylinders as used in the U212/4 class are considered appropriate. Solid storage of hydrogen using metal hydrides or carbon nanotubes is an area of technology that is developing rapidly and significant improvements in performance can be expected in the next decade.

Figure 1: U212/4 class metal hydride cylinders [6].

5.3 OXIDANT STORAGE SELECTION

Unlike the majority of fuel-cells which use atmospheric oxygen and accept the consequential loss in efficiency for a "free" fuel source, submarine fuel-cells are designed to use a pure oxygen supply. This can either be stored as liquid oxygen (LOX) or as a compressed gas. LOX has a volumetric compression ratio of 860:1 and compressed oxygen of anywhere between 200:1 and 300:1 according to the selected storage pressure. As a result the obvious choice, and that chosen by the U212/4 designers, is LOX. However, as shall be seen below, a liquifaction plant would need to be carried in addition to the storage tanks and as they are bulky and maintenance intensive compressed oxygen was preferred. Oxygen bottles similar to existing UK SSN high pressure air (HPA) bottles of approximately $3.2m^3$ volume and 500kg mass were used for calculations.

5.4 REACTOR SAFETY

In order to guarantee reactor safety there must be an immediate notice back-up power source in the event of a reactor scram (unplanned shutdown) capable of providing sufficient power until the reactor can be restarted or a suitable port reached. Current SSNs divide this task between a battery and diesel generators. The battery is used for immediate power and lasts long enough for the majority of scram events. In serious cases where longer term power is required the diesel generators are used but these can only be started once the submarine is near the surface and has access to air for the diesels. Broaching the surface may well compromise a mission and not be possible at all under ice.

Were fuel-cells used as the back up power source a small battery would still be required to provide instantaneous power following a scram before the fuel-cell system can be started. This battery would also be used to provide a high speed sprint capability when the reactor is shut down. In addition, sufficient hydrogen and oxygen must be carried to ensure that there is always power available following a scram. If supplies were limited to a single charge of the onboard tanks as per the U212/4 class then reactor safety could be compromised following a series of multiple scrams. Therefore, it is necessary to provide onboard recharging facilities for the oxygen and hydrogen consisting of electrolysers and compressors as required. This has the added advantage of making the submarine independent of shore refuelling.

Without diesel generators the submarine's emergency power comes from the fuel-cells. Therefore, a proportion of the hydrogen and oxygen must be set aside for emergencies in addition to that used on operations. This must be sufficient to provide 137kW for 7 days, i.e. sufficient power to achieve 4 knots (37kW) and maintain an assumed absolute minimum of 50kW each for the reactor and hotel service loads.

5.5 FUEL-CELL SYSTEM

A basic system sizing was carried out. In order to minimise the volume taken up by the fuel-cells and electrolysers a reversible PEMFC/electrolyser system was selected (henceforth referred to as RFC). It is understood that this technology is still immature but can be expected to develop rapidly over the next few years as NASA develops it for space applications. Horizon Fuel-Cell Technologies produce a 0.6W single cell RFC for laboratory demonstration with the following specifications:

Rated net power	0.6 W
Rated net current	1 A
DC voltage range	1.65 V
H_2 production	10 ml/min
O_2 production	5 ml/min
Volume	$1.4x10^{-4}$ m^3

Table 3: Reversible PEMFC and electrolyser specifications.

Figure 2: Horizon Fuel-Cell Technologies 0.6W reversible fuel-cell [7].

Figure 3: Siemens BZM120 PEMFC fuel-cell as fitted to the U214 class, around 1.4m long [6].

The majority of this fuel-cell's depth is taken up by the retaining plate structure, the size of which is largely independent of the number of cells stacked up. Therefore, a linear relationship cannot be used in sizing a larger fuel-cell stack from this example. As a result the (admittedly large) assumption was made that an appropriate device need be no larger than a dedicated PEMFC with each 120kW fuel-cell stack assumed to be the size of a Siemens BZM120 (as fitted to the U214 class), namely 500litres and 900kg each[8].

Any size increase associated with the reversible nature of the fuel-cell is assumed to be offset by continuing improvements in PEMFC power densities. BOP volume is assumed to be equal to the fuel-cell stack.

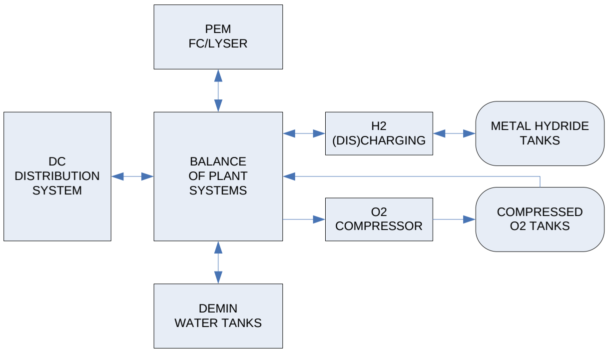

Figure 4: Hybrid SSN/FC submarine fuel-cell system schematic.

In order to release hydrogen from the metal hydride heat must be applied and vice versa; therefore the charging/discharging mechanism requires a heating/cooling system. Both electrolysers and pressurised water reactors require demineralised water and can therefore share the same water tanks. A single reverse osmosis plant such as the Derwent RO4/2 is sufficient to meet the electrolyser water demand. This would have to be fitted in addition to normal water production needs otherwise water for other uses would be limited during the 2 days required to replace the hydrogen and oxygen used during operations. Additional electrolysers would be required to produce oxygen for crew consumption during SSN mode with a proportion of the compressed oxygen used for the same purpose when in fuel-cell mode.

5.6 SYSTEM SIZING

The calculations were split into operational and emergency modes. It was found that oxygen required for crew breathing is negligible compared with that for fuel-cells and has no effect on total numbers of oxygen cylinders required.

Scenario	Metal Hydride Cylinders (H_2)	O_2 Bottles	Water Production (litres/manday)
Operations	42	14	43
Emergencies	18	6	18
Total	60	20	/

Table 4: Metal hydride cylinder and O_2 bottle numbers.

Thus a total of 60 hydride cylinders and 20 oxygen bottles are needed. In order to allow cooling and heating of the metal hydride cylinders (required for charging/discharging) and to swiftly detect any leaks, the cylinders are located in seawater tanks fitted with a sounding tube connected to a detector thus providing an immediate leak indicator. The O_2 bottles are positioned alongside the HPA bottles within the ballast tanks, the volume of which would require a corresponding increase. On operations the RFCs produce 3 tonnes of water a day, equating to 43 litres/man/day for the 70 man crew (minimum required 23 litres/man/day [9]). At emergency power levels the RFCs still produce 18 litres/man/day which is sufficient for drinking and cooking. In electrolyser mode the RFCs produce 477m^3 of hydrogen and 238m^3 of oxygen per hour which, taking into account continued crew oxygen consumption, results in a 3 day recharge.

The total volume of the fuel-cell system (RFCs, H_2 cylinders, O_2 bottles, O_2 compressors, RO plants, BOP and a 100% access envelope) is 285m^3. This could either be distributed around the hull as shown in Figure 7 (preferred owing to the increased survivability and electricity/water generation capabilities of the fuel-cells in survival situations) or inserted as a dedicated 5.6m plug. The mass is 313 tonnes, roughly 10% of the total displacement. Although exact figures are difficult to obtain very approximate calculations show that this is approximately half the volume and three times the mass of the now-redundant diesel generators and diesel tanks.

6. SAFETY ANALYSIS

6.1 HYDROGEN EXPLOSION

There are three areas that hydrogen could be released from: the hydride cylinder water tanks (HCWTs), the RFC compartments and the transfer pipework between the two.

6.1 (a) Hydride Cylinders

The metal hydride cylinders are located low down within the pressure hull. Should a leak develop in a metal hydride cylinder the hydrogen would expand out of the leak site, thus cooling down the surrounding hydride. As the hydrogen release process is endothermic the leak would self-seal. Should a pipework fitting within a HCWT fail hydrogen would displace the water up the sounding tube. The HCWTs temperature ranges from 4^{o}C (lowest realistic sea temperature) to 40^{o}C (heated during discharge) and thus the water expands/contracts by ~1% over an operating cycle. Assuming each HCWT volume is 30% larger than the 30 cylinders inside, each HCWT would hold 10.8m^3 water which would expand by 0.1m^3 during an operating cycle. The hydrogen leak detector would be designed to only alarm if more than this volume of water was displaced and therefore the worst case undetected leak is 0.1m^3, a trivial amount.

Should more hydrogen be released it would be detected and the contents of the containment tank could be flushed overboard using the trim or ballast system. As a result the risk from the metal hydride tanks is considered negligible.

6.1 (b) RFC Compartments

The RFC compartments would normally be sealed with the exception of a ventilation supply and exhaust each of which would be fitted with flame suppressors and atmosphere monitoring equipment. All ignition sources would be properly sealed and rated for gas-dangerous compartments.

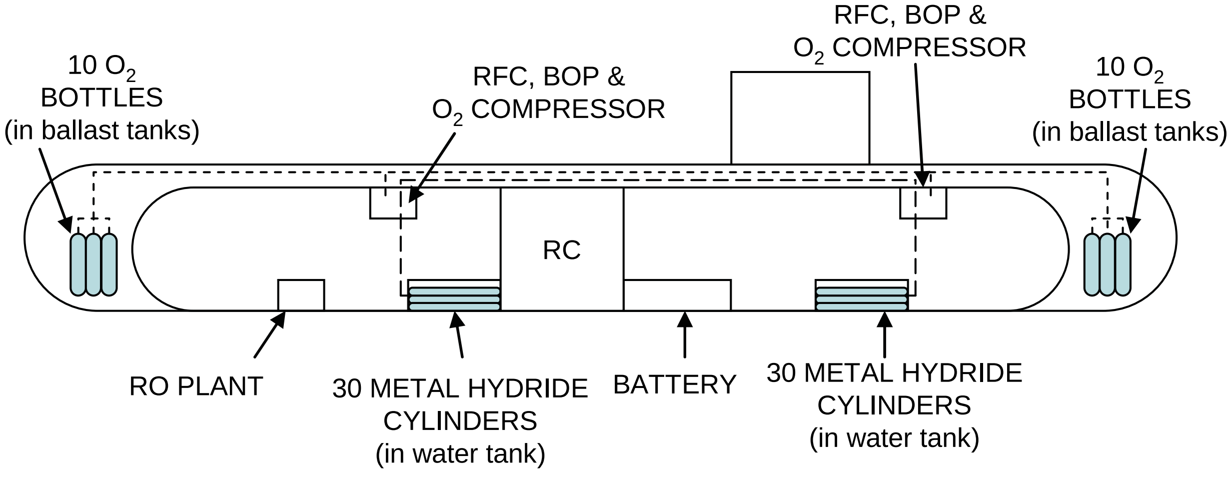

Figure 5: Hybrid SSN/FC submarine layout.

Should hydrogen be detected the RFC would automatically shut down, isolation valves shut and a purge cycle started as with the RN's Gas Management Plants (GMPs). Ventilation would continue in order to diffuse the hydrogen throughout the submarine; each RFC compartment is only 0.3% of the internal volume of the submarine, therefore even if a compartment was 100% full of hydrogen the lower flammability limit submarine wide would not be reached. Existing CO/H_2 burners would be sufficient to remove any residual hydrogen from the atmosphere.

Were the detection system defective a major leak would still be identified by pressure drop or power loss but a small pinhole leak might be missed by the control systems. Assuming a flow meter comparison system has an accuracy of 1% the trip setting would be set at 5% to allow for transient induced system lag. The maximum hydrogen flow rate in each half of the system is 42l/s, therefore a leak up to 2.1l/s might go unnoticed. Each RFC compartment would contain 8.6m^3 free volume and a ventilation flow rate of 72l/s assuming the air is turned over 30 times an hour (the value specified within provisional Lloyd's Register rules for gas fuelled ships [10]). As this is a far higher turnover of air than the leak a dangerous hydrogen build-up would not occur provided the ventilation system has been adequately designed to minimise air pockets, particularly at the top of the pressure hull where the H_2 is likely to collect. Even without the fitted CO/H_2 burners it would take over 11 days to reach the 4% lower flammability limit within the whole submarine.

6.1 (c) Hydrogen Pipework

The transfer pipework would be double walled, isolable in the HCWTs and RFC compartments and with no fittings between the two. Internal pipework has been minimised by positioning the HCWTs underneath the RFC compartments and the fore-aft connection routed outside the pressure hull, under the Casing. As a result the risk from the hydrogen pipework is considered negligible. Because hydrogen gas consists of such small energetic molecules special pipework is required to avoid hydrogen embrittlement and welds and seals must be extremely tight.

6.2 HYDROGEN FIRE

Should a hydrogen fire develop in a RFC compartment (the only credible place it could) the difficulty would most likely come in detection as hydrogen burns with an almost invisible flame. It is worth noting that submariners are experienced with equally hard-to-find steam leaks. Should the 2.1l/s leak calculated above ignite on exit from the leak site (i.e. before it has dispersed) it would produce 23.0kW. Using:

$$\Delta t \quad \frac{P}{\dot{m}C_p} \qquad (4)$$

Results in a 2.2^{o}C temperature rise per second which would be easily detected by the fire detectors already fitted throughout RN submarines. The system would be automatically shutdown and a fixed CO_2 drench system activated. With proper design the chances of other materials combusting (and hence producing smoke) can be minimised, the only other result from such a fire would be the production of a small amount of water vapour (1.7cc/s). It is the heat from a hydrogen fire that is the main danger followed by oxygen consumption, unlike a hydrocarbon fire where the main danger is the production of toxic gases such as carbon monoxide and soot which can rapidly poison the confined volume of a submarine. As a result the risk from a hydrogen fire in the RFC compartment is considered negligible.

6.3 HYDROGEN ASPHYXIATION

The effects of oxygen starvation range from a reduction in coordination (15-19%) to coma and subsequent death within 40 seconds (4-6 percent) [11]. For the purposes of this investigation it is assumed that 16% is the cut-off point below which injury may occur either from cellular oxygen starvation or as a result of reduced coordination and decision making. For the oxygen concentration to fall by 4% to 16% requires 20% of the compartment volume to be displaced by hydrogen, i.e. 5 times the lower flammability limit for hydrogen. As it has already been proven that the lower flammability limit cannot be reached there is no danger of hydrogen asphyxiation occurring in general conditions. Furthermore, as hydrogen is so buoyant the usual reaction to oxygen starvation is to collapse thus probably lowering the head below the hydrogen cloud. The only exception to this could be during a tank entry to the HCWTs for maintenance or inspection; under these circumstances normal confined space entry procedures would mitigate the asphyxiation risk to tolerable levels.

6.4 OXYGEN REACTIVITY

Oxygen is a highly reactive gas and when in a pure form can react extremely violently with flammable materials such as oil and grease. By citing the RFCs adjacent to the oxygen compressors, leading the compressor discharge pipework immediately outside the pressure hull and running the fore and aft connection under the Casing the risk of an internal oxygen leak is minimised as far as possible. However, if a leak should occur the risk of fire would be mitigated by maintaining the RFC compartments as "clean" spaces with no flammable materials allowed within. Oxygen can also be toxic if the partial pressure exceeds about 0.5bar (in standard atmosphere it is 0.2bar). As the tanks are stored external to the pressure hull a significant leak into the submarine is unlikely and even if an entire tank were discharged into the submarine the partial pressure of oxygen would only increase to 0.27bar.

In the authors' opinion the risk posed by compressed oxygen is the greatest risk of the design and a detailed investigation would have to be carried out prior to any further design work.

6.5 INCREASED AIR INDEPENDENT PROPULSION REDUNDANCY

The safety analysis has concentrated on disproving, mitigating or highlighting potential problems; however, their safety advantages must also be considered. These comprise of a number of factors such as greater reliability and reduced temperatures; however, the advantage that stands out the most is the provision of a second Air Independent Propulsion (AIP) system.

Submarines have an extremely low reserve of buoyancy and with a nearly circular cross-section they are liable to roll heavily, causing equipment damage and crew exhaustion, thereby increasing the risk of a potentially fatal incident. In times of rough weather or conflict it is far safer for the submarine to remain deep underwater in the environment for which she is optimised; however, current SSNs are either forced to the surface or periscope depth if they have to run their auxiliary diesels.

An AIP fuel-cell system would not only allow the submarine to remain dived following reactor scrams but would also provide the confidence to engage in unfettered under-ice operations. Whilst SSNs have been operating under the Arctic ice cap since USS NAUTILUS first did so in 1957, there is a caveat. The chance of a reactor scram has meant that such voyages always come with the added degree of risk that a suitable polynia (open area of water within the ice) might not be found within range of the submarine's batteries. The recent interest expressed in the mineral resources believed to be under the Arctic sea bed has led to a correspondingly increased interest in the importance of controlling these waters. A hybrid nuclear/fuel-cell submarine would be able to operate there with a substantially greater margin of safety than contemporary SSNs can achieve.

In an emergency the compressed oxygen could also be used to replenish the air without the need to burn oxygen candles. The recent fatalities onboard HMS TIRELESS, as well as the final cause of death for the KURSK survivors demonstrate the advantages this would bring.

7. CONCLUSION

Fuel-cells offer such substantial economical, political, environmental and operational advantages that they will eventually achieve widespread usage. Whilst the automotive and stationary power generation industries are leading their development the technology is likely to be subsequently transferred to the marine industry. The authors believe this hybrid nuclear/fuel-cell submarine concept to be revolutionary with the possibility of potential dramatic improvements in operational capability and submarine safety. However, a number of design tradeoffs must be fully explored before the exact characteristics of such a submarine could be finalised. As a result it is recommended the following are investigated:

- The design tradeoffs between liquid and compressed oxygen storage, in particular with regard to safety.
- The specific temperature requirements for cooling and heating metal hydrides during charging and discharging, in particular with regard to Worldwide variations in seawater temperatures.
- The size, efficiency and reliability tradeoffs between a reversible fuel-cell system or separate PEMFCs and electrolysers.
- The effect of shock upon fuel-cells and their associated systems (not discussed in this report due to lack of information but of critical importance to submarine designers).
- The reliability and chance of failure of component parts of each fuel-cell system.
- Finally, the balance between fuel-cell and reactor powers would require settling for each design depending upon the operational profile and concept of operations.

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9. REFERENCES

1. GOODENOUGH,R.H., 'The Integration and Safety of Fuel Cells in Ships', University College London, 2007.

2. http://www.naval-technology.com/projects/#Submarines last accessed 1/9/07 at 1435.

3. BURCHER,R., RYDILL,L., 'Concepts in Submarine Design', Cambridge University Press, 1994, pp.291.

4. BÜCHI,F.N., REUM,M., FREUNBERGER,S.A., DELFINO,A., 'On the efficiency of automotive H_2/O_2 PE fuel-cell systems', 3rd European PEFC Forum, July 2005.

5. GREIG,A., 'Fuel-cells and issues for their use in warships', Proc IMarEST 2003, Pt.B, No.B3, pp.9-20.

6. HAMMERSCHMIDT,A.E., 'Fuel-cell propulsion of submarines', Intl. Conf. on Hydrogen and Fuel-Cell Technologies, Munich, 2006.

7. http://www.thehydrogencompany.com/products_54-226.html last accessed 1/9/07 at 1456.

8. BUCKINGHAM,J.,HODGE,C., HARDY,T., 'Submarine Power and Propulsion - Trends and Opportunities', Pacific International Maritime Conference 2008.

9. UCL Ship Design Data Book, 2007.

10. 'Provisional rules for the classification of methane gas fuelled ships', Lloyd's Register, Jan 2007.

11. http://ehs.ucdavis.edu/hs/ConfSpace/index.cfm last accessed 30/8/07 at 1518.

10. BIBLIOGRAPHY

1. LI,X., 'Principles of Fuel-Cells', Taylor and Francis, New York/London, 2006.

2. LARMINIE,J., DICKS,A., 'Fuel-cell systems explained', Wiley, New York, 2003.

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THE VICTORIA CLASS SUPPORT: – A CLASS DESK PERSPECTIVE

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SUMMARY

The paper will address the support program as outlined in the Class Plan. Working with industry is key to enhanced performance metrics, procurement strategy and Extended Docking work periods (EDWP) involvement by the defence industry. The support infrastructure is aligned using the VICTORIA In-Service Support Contract (VISSC) five main pillars: Project management, Records Support Services, Engineering Support Services, Material, Logistics and Maintenance Support Services. The paper will discuss the key features of the Class requirements to sustain the Victoria Class platform. The EDWP framework will also be presented as the format for future third level VICTORIA class project management and technical support.

1. INTRODUCTION

The Canadian Navy currently operates the Victoria Class Submarines (VCS). There are four submarines in the class, HMCS VICTORIA (VIC), WINDSOR(WSR), CHICOUTIMI(CHI) and CORNER BROOK(COR). The VCS are internationally recognised as a maritime core capability able to perform in a variety of roles that support national security and defence objectives. Combining characteristics of stealth, lethality, endurance, and relative invulnerability, submarines are a platform of profound power and flexibility. This can be deduced by the composition of the maritime forces of major powers and smaller nations with regional interests, most of which all contain a submarine element. Nuclear-propelled and armed submarines are incorporated as the pre-eminent capital ships of nations such as USA and UK, charged with missions of strategic deterrence, sea control, and surveillance of the maritime and coastal environment. Smaller nations with appreciable maritime interests, such as Canada, strive to maintain a credible non-nuclear-propelled, or conventional, submarine capability. The VICTORIA class submarine is a complex platform operating in a challenging marine environment and due to the extreme engineering/environmental demands placed on that platform (very similar to the jet fighter quality and safety standards) have resulted in high levels of Quality Assurance and Material Certification. These levels are far greater and complex than when Canada was operating the Oberon Class of submarines that the VICTORIA class replaced.

Figure 1: VICTORIA Class Submarines **[1]**

2. BACKGROUND

The VICTORIA class submarine forms a critical part of the Canadian Navy's international role. The modern diesel electric submarine is capable of being deployed anywhere in the world in support of Canada's foreign policy objectives, whether to participate in an international military exercise with our allies, or as part of Canada's contribution to a multi-national military operation. The rationale for submarines did not end with the Cold War. In fact, despite the end of the Cold War over a decade ago, 45 countries continue to operate over 275 submarines worldwide. The same surveillance and intelligence gathering capabilities that are so vital to Canadian domestic marine security operations can be used with great effectiveness in an international crisis with our allies. Canada’s submarines will be capable of conducting independent or coordinated patrols in foreign waters to monitor or intercept suspicious maritime traffic or protect Canadian and coalition warships in a dangerous environment. [2]

The VICTORIA class submarines give the Canadian Navy a wide range of capabilities in the new Naval aspect of warfare as they are extremely quiet and stealthy and are well suited to work independently or with other maritime forces. Also, a range of critical naval roles including safeguarding our maritime sovereignty as well as supporting Canadian foreign policy overseas given the terrorist activities that confront the nation. The Victoria class Submarines are indispensable because they offer a number of important capabilities:

- Stealth - The Victoria Class submarine is very difficult to detect, and with their on-board senor systems are excellent for conducting surveillance and gathering intelligence for use in a military operation or in a domestic marine security role;
- Special Ops - Their stealth enables them to remain hidden and perform missions that are not possible by any other military unit;
- Coastal - A submarine can maintain covert surveillance of 125,000 square kilometres of ocean and has weapon systems capable of

defending itself or if necessary engage other vessels with great lethality;

- Cost - Submarines are comparatively inexpensive – they can operate for about one-third of the cost of a frigate or destroyer; and
- Endurance - With a crew of 48 sailors, the Victoria Class submarine can remain on patrol for more than 45 days in all extremes of weather without needing to refuel or re-supply. [3]

The ability for a stealthy, strategic deterrent, special ops, anti-surface, anti-submarine warfare, long range vessel makes the VICTORIA class a formidable platform for Canada's requirements. The reality of having our own submarines forces will enhance our presence and afford other nations an opportunity to think twice before operating their submarines in Canadian waters. A brief glimpse of the Control Room in the VCS shows the fighting centre of the submarine, from where the Captain 'fights' the boat with the assistance of the Control Room team. Combat system computers process external data received from sonar's and other sensors. The various sensors provide a stream of constant real-time data that contributes to the development of a coherent tactical picture. This picture allows the combat team to understand what is taking place outside the submarine.[4] The information provided by the sensors and the functionality of the platform make it a formidable forum to launch a weapons in hostile environments and given the crew training and the skill set of the team, the execution of the mission rests well with the submarine team and their efforts while in a combat role.

3. ACCEPTANCE INTO SERVICE

The first submarine to achieve Initial Operational Capability was WINDSOR and was scheduled for as early as 2005 as shown in table I. VICTORIA, now having been transferred to Maritime Forces Pacific, (thereby re-establishing a permanent Pacific submarine presence by Canada for the first time since 1974), conducted essential trials within the limits of her equipment suite. She also established Operational Test and Evaluation requirements for the entire class in 2004. Therefore it is expected that a level of submarine capability equivalent to the one that was in place for the OBERON operation in the late-1990s will be achieved in the 2010-11 timeframe. This will allow the CF to have a submarine available for global deployment in support of any security requirement. Achievement of operational status for the Class by late 2010 is predicated on the assumption that VICTORIA and WINDSOR technical schedules can be achieved. This is also dependent on essential crew training and Operational Test and Evaluation activity. It must also be understood that, should a national contingency scenario arise – measures could be quickly put in place to provide a submarine capable of undertaking a surveillance or deterrence mission in Canadian areas of maritime responsibility off the East and West coasts of North America.

Table I VICTORIA Class Key Dates

Sub	Deliver Date Planned	Actual Delivery	Operationally Ready Planned	Operationally Ready Revised (1)
VIC	April 2000	October 2000	January 2001	Spring 2005
WSR	October 2000	October 2001	July 2001	Fall 2004
COR	April 2001	March 2003	January 2002	Spring 2005
CHI	October 2001	Oct 2005	July 2002	Winter 2005

Note (1) Dates reflect Project Management Office date as of March 2003[5]

4. IN-SERVICE SUPPORT

The VCS were designed with a projected operating lifetime of thirty years, based on the original Royal Navy (RN) operations and maintenance concepts. Following Canada's lease of the submarines and arrival in Canada, the VICTORIA Class were enhanced with additions or upgrades to a number of systems and the equipment was Canadianized from the original RN configuration. In routine operations that are roughly analogous of peacetime operations, the VICTORIA Class submarines will conduct operations within the area of interest of the Formation Commander. Operations conducted by the VICTORIA class submarines in this scenario include Intelligence gathering, Surveillance and Reconnaissance (ISR), Contribution to deterrence, Submarine proficiency training, Operational training of antisubmarine warfare (ASW) forces, Support to civil and military Research and Development (R&D), and oceanographic activity; and Public engagement and Support to other Government departments for counter narcotic, fisheries and immigration. The domestic contingency operations occur at a level in the operational continuum above normal peacetime operations, but below general conflict. Operations undergone by the VICTORIA class submarines in this scenario includes Focused ISR, Anti-Surface Warfare (ASW), Anti surface warfare (ASuW); and Special Operations. These operations are either in the form of 'Limited Operations', conducted by the appropriate Formation Commander in their area of interest or responsibility, or 'Complex Operations' conducted by the assigned task force commander on behalf of the Deputy Chief Defence Staff (DCDS).

As part of the regular life-cycle management, VICTORIA entered an Extended Docking Work Period (EDWP) from July 2005 until sometime realistically in 2009. VICTORIA ceased her operational period on 27 June 2005. VICTORIA is currently situated in the dockyard dry-dock of Fleet Maintenance Facility Cape Breton at CFB Esquimalt.[6] The remaining maintenance support includes both scheduled and unscheduled requirements. Although third line work will be part of VISSC, DND will retain responsibility for the definition of VCS maintenance requirements. For each submarine and for each running cycle, the Contractor shall identify the complete scope of work for the maintenance to be performed by ship's staff and the FMF during the running cycle. The scope of work is to include, but not be limited to, the following: Preventive maintenance, Tests and trials, Deviations, waivers and concessions, Corrective maintenance and approved ECs.

5. CLASS PLAN

The Director Maritime Equipment Program Management (Submarines), DMEPM(SM) has a mission to Coordinate and Manage the Materiel Component of Submarine Capability. The key priorities include: Our people and transition to steady state (include roles and responsibilities), Sustainable material support to submarines and in support of submarine operational requirements, Quality Business Framework within DMEPM(SM) (Quality Management System), Improve Technical Authority effectiveness (between HQ & Coastal authorities), and Meeting the submarine service future needs in support of ops capability. The DMEPM(SM) SM 5-5 section has an overall responsibility for the In-Service Support management of the Victoria Class Submarines. Roles include development and maintenance of the Class Plan, technical advice to DND's asset disposal organization for the OBERON Class Submarines disposal, Project Management of submarine minor engineering changes, implementation of all submarine related engineering changes and Canadian Work Package (CWP) Project Management. Some of the current projects that DMEPM(SM) is involved in are rationalizing of EC Processing, EC Performance Management, Submarine Fault Tree Development, Submarine Defect and Reporting Analysis, Test and Trial Form Framework development, Transition of OBERON disposal, air quality, trials development, battery life, weapons certification, and quality management system. Technical obstacles invariably arise as work progresses and numerous unforeseen technical difficulties occur. For example, a significant delay in the CWP arose due to the need to convert British design specifications to Canadian standards and yet another delay was experienced when some hazardous material was discovered that required special procedures for removal. [7]

The issues, dependencies and/or risks that have been identified as common to many of the top tasks for the VCS Class Plan are common issues identified during early Class workshop sessions and dealt with items that may impact the success of the prioritized tasks. Such issues as personnel postings and turnover relate to the loss of expertise and corporate knowledge may have a negative impact on the accomplishments and the momentum acquired by the Class Desk since its inception. The Design Agent/Authority has the role conducted by the Class Desk. During VISSC, the contractor will conduct the role of the Design Agent for the Canadian submarines. The contractor role will need to be fully scoped during VICTORIA In-Service Support Contract (VISSC).

To be successful, the class plan will need to create/address many of the issues identified above and supported by DMEPM (SM) is a robust process. Like most solutions, the starting point is first to clearly define the problem. The stakeholders in defining the issues and the way forward had considered succession implementation planning to deal with the change of Class Desk personnel, and the potential loss of expertise and momentum. It was important to create of an "Actions and Issues" database so that new personnel can inherit items from existing personnel to maintain momentum. The Design Agent Role was developed from the Class Desk policy document that defines the role of a Design Agent (currently in VISSC Performance Work Statement (PWS)). The Engineering Change Process required a session be held with the sub community to map out the Engineering Change Process step by step, map personnel and responsibilities against that process, and then identify opportunities for increased efficiencies. The identification of resource requirements for Submarines is another very common issue identified was the lack of resources in dealing with the current demands on the sub program. A suggestion has been to thoroughly investigate the current and future personnel demands and determine based on current resource levels the impact to the submarine program. Unfortunately, the impact is challenging and limited in success for personnel replacement due to the experience required to sustain the various positions in the submarine community with possible mitigation strategies being developed (more staff incentives, out source, reduce the workload).

6. COREX

The CORNER BROOK (COR) Submarine Safety Document Register (SSDR) Extension Project (COREX II) made recommendations for all systems requiring approval by their respective Design Authority OPI for continued operation through the proposed extension to June 2011, and an MSG-based platform Aggregate Risk

Assessment was calculated an overall COREX II risk of Acceptable With Review. Acceptable mitigating actions were determined for any materiel issues that would have precluded the recommendation to extend the SSDR to 30 June 2011. A significant number of Preventive Maintenance routines were added to COR's PM load chart in order to mitigate the risk posed by the continued operation of COR and the delayed start of EDWP maintenance. These additional routines include some docking dependent work and total an estimated 47,000 hours (without arisings), to be completed over the course of the extension, primarily in SWPs 7 and 8. Many of these activities are docking dependent and it was not deemed feasible to consolidate all docked work into one SWP. There is also a high probability of arisings resulting from many of the required mitigation work. The majority of mitigation activities can be accomplished within the current scheduled program with a few significant exceptions. The battery replacement will require minimum 13 weeks (without growth or arisings) in a dock and the remaining docking dependent work (e.g. air bottle surveys and DDSTP testing) will necessitate an extended docked SWP, likely in SWP 8. There is potential for impact to the remaining platform programs as a result of COREX requirements, which the Navy are mitigating through project management and resource loading.

The following assumptions were made by the project team: COR will continue to operate under the Submarine Maintenance OpCycle and Rationalization (SubMOAR) Evaluation; SWPs will be executed within normal frequency; All PM will be completed or properly deviated each cycle; Escape inspections will be conducted at normal periodicity; and planned maintenance (including docking dependant requirements) in addition to scheduled 1st and 2nd level cycle PM may be added as required to mitigate the risk of the SSDR extension.

Figure 2: VICTORIA Class in Work Period

7. WORKING WITH INDUSTRY

The support from industry has been in numerous forums as we establish the long-term sustainability for the VCS platform through work with ISI (CHI docking contract, spring 2005), Victoria Shipyard Limited (VIC EDWP work – June 2005), Weir Canada Inc (VIC and WSR EDWP WHDS/SSE contract – Feb 08) and BAE (Engineering and Supply Management (ESM) contract – August 1998). Industry continues to show interest in the In-Service work for the VCS as the current VISSC negotiations continue with the preferred bidder. Interest in the documentation also continues as DND is continually providing an Access to information forum for such questions as 'A-2007-00149 a copy of MCU2007-00764 Victoria In – Service Support contract' [8] where internal DND documentation is provided to the general public upon request. The unfortunate circumstances of loosing a sailor still reverberate through the submarine community since October 2004 when CHICOUTIMI had a fire while on the surface off Scotland. The damage as shown in Fig 3 could have been much worse if it were not for the dedication of the submariners onboard at the time.[9]

Figure 3: CHICOUTIMI Fire (CO Cabin) – October 2004

The follow-on support of other nations such as UK was outstanding and their efforts helped to ease the difficulties that the Canadian Navy experienced after loosing one of their submariners. Industry also aiding in the repair and safety of the platform, as the vessel was sea lifted back to Canada in the spring of 2005 (Fig 4).

Figure 4: CHICOUTIMI Sealift – February 2005

8. VCS SUPPORT STRATEGY

The uses of Non-nuclear submarines like the VICTORIA class are assets of strategic impact in the domestic and expeditionary realms. Under certain circumstances, they have the capacity, alone, to influence the political, diplomatic, and military decision-making of an adversary. This capacity is imparted by characteristics of stealth, endurance, mobility, lethality, and flexibility, combined with the option for selective disclosure and the ability to conduct offensive or defensive operations. There are few, if any, CF capabilities that exert this degree of influence and leverage, either with neighbors, allies, or potential adversaries, in such a consistent and affordable manner. [10]

The ownership of these four VICTORIA class submarines allows Canada to stay in the submarine business and no one ever expected the re-activation of the vessels to be an easy task. Modern submarines have never been mothballed before and there are many technical problems associated with getting them back to sea safely. The approximately five years alongside Barrow, UK did not help the platform and the timeframe for reactivation was extremely challenging. Throughout the VCS program, safety has been a paramount consideration, and if this causes delays, then that is the price required to instil the training ad confidence of our submariners, as it is too important to take shortcuts. The main factor is that submarines are now high technology platforms and not only are they superb and cost- effective surveillance systems able to remain at sea for extended periods, but they are also test-beds for new and emerging underwater and information systems technology. Canada's ownership of modern submarines, gives Canada the opportunity to be a world leader in underwater and many other technologies. The modern submarines serve Canada's interests at home and in coalition operations around the world. The VICTORIA class submarines represent a prudent investment in Canada's future maritime security, even if they take a little while to reach full potential. Notwithstanding the various positions taken by particular interest groups to disparage submarine capability, on every occasion to date that government has examined the requirement the decision has been made to retain the capability. [11]

9. SUBMOAR

The Submarine Maintenance OpCycle Alignment and Rationalization (SubMOAR) project had two key mandates: Firstly, to evaluate the proposed OPCYCLE along with other viable alternatives and recommend a preferred option. Second, once the new OPCYCLE is approved, to deliver the preventive maintenance regime to underpin the OPCYCLE. In the OPCYCLE Working Group, the following key recommendations were made: VICTORIA Class submarines adopt a six-year OPCYCLE comprising a 4.5 year operational period followed by a 1.5 year EDWP; the operational period consist of seven, thirty-four week running cycles, each running cycle comprising a one-week self maintenance period, a twenty-six week operational phase and a notional seven-week short work period and the thirty-four week running cycle be implemented as an evaluation in CORNER BROOK. If the evaluation is successful, each of the remaining submarines adopt the new OPCYCLE on completion of its first EDWP.

10. LIFEX

The Life Expectancy (Lifex) project is a new endeavor by DMEPM(SM) undertaken to investigate the extent to which the VCS can be extended in life given the reality that Canada will not be in a position to procure new submarines for several years. The study has a broad mandate and will consider past experience with the Oberon class and discussions with other submarine Navies.

11. SELEX

The average age of the VICTORIA class submarines is in the vicinity of 13 years. Many of the systems onboard are approaching a state of obsolescence. In order to keep the VICTORIA class submarines relevant and combat capable, the requirements directorate initiated the Submarine Equipment Life Extension (SELEX) scoping exercise to address these issues. The purpose of SELEX was primarily to address equipment obsolescence and secondly to provide for some capability enhancement. It is anticipated that implementation of SELEX changes will commence in 2011 with a duration of 6 years. It is intended to implement the SELEX changes within scheduled EDWPs as outlined in the Class Plan under the In-Service Support (VISSC) construct. A scoping exercise was conducted to prepare SELEX for the Identification (ID) phase. The results of this exercise and DGMEPM had requested to further define its scope in order to achieve this it is necessary to review the work of the scoping exercise and rationalize it through engineering assessment. From a technical point of view, the Life Cycle Material Managers (LCMM's) are best placed to determine whether the inclusion of additional items, or deletions from the scoping exercises.

12. EXTENDED DOCKING WORK PERIOD (EDWP)

The VICTORIA is undergoing a third level maintenance period in FMF CB, Victoria, BC and WINDSOR is also undergoing a similar EDWP period and followed behind VICTORIA eighteen (18) months later. The Docking Work Periods (DWPs) for the VICTORIA Class commenced in June 2005 with HMCS VICTORIA in Victoria, BC and HMCS WINDSOR in January 2007 in Halifax, NS. There has been much discussion on 'scope vs time'; namely can time be gained by reducing the scope of the EDWP? Therein, the key becomes the identification of work elements with potential to shorten not only total of 'work' but more critically, elapsed time. The other obvious question is whether more resources can be applied to the EDWP to increase the existing completion date. Yet before either of these questions can be answered, the over-riding question becomes - 'what is it that we want VIC to be able to do when she comes out of the EDWP, Tiered Readiness Program (TRP) and what operational capability does that intended use require?' This question is influenced by the Canadian Navy's expectations in maintaining the skills and currency of its submariners.

The issue of scope vs time, the critical path (CP) through the project schedule is important in putting this issue into perspective. There are two work groupings that impact on the critical path in the EDWP. They are the Weapon Handling and Discharge System/Submerged Signal Ejector (WHDS/SSE) and the mechanical & hull systems package that need to be complete before the flood-up of the boat. The main mechanical & hull systems work, accounting for about 160K hours, includes refurbishing NAB castings, hull valves, hydraulics, diesels, HP air systems and a general systems surveillance specification that in itself accounts for 32.5K hours of work. The main mechanical & hull systems work has a direct impact on boat safety and structural integrity. No one work package can be eliminated, however, analysis is ongoing to reduce the magnitude of the general systems surveillance specification, which includes non-destructive testing and disassembled inspection of 29 major piping systems, 400+ separate piping and trunk lengths, and over 1100 valves.

Figure 5: WINDSOR in EDWP (Halifax, NS) – March 2008

13. WEAPONS CONTRACT

The intent for the VICTORIA EDWP Weapons Handling and Discharge System and Submerged Signal System (WHDS/SSE) contract is for the VICTORIA WHDS/SSE systems to be refurbished completely with new/overhauled equipment and/or components' provided that this intent meets the requirements of the VICTORIA WHDS/SSE systems EDWP Work program. In-service support contracts for equipment in use and for repairable components are being arranged with performance incentives in the terms of payment. **[12]** FMF is very capable of doing this work and this contract will reduce the risk of material responsibility and allow FMF to gain technical knowledge transfer from the original equipment manufacturers OEM.

Figure 6: VICTORIA in EDWP (Victoria, BC) – April 2008

14. CONCLUSION

VICTORIA Class submarines, as a component of the Navy's balanced, combat capable fleet, and the broader Canadian Forces joint capability; will conduct domestic and deployed operations worldwide in support of national and allied objectives. The class plan performs a significant role in the determination of the expectations of the VCS and is pivotal in relaying the message to the fleet concerning the future of the platform. Many factors have impacted the class plan over the past six years and the multitude of priorities has had a leveling effect on the achievement of steady state for the VCS. Continued efforts by DMEPM(SM) will be required to attain a successful battle rhythm regarding completion of the EDWP packages for VIC and WSR while requiring the involvement of a myriad of outside contractors and OEMs.

Although progress is being made, establishing support contracts has not been as rapid as expected and we remain hopeful that this will be resolved and are reviewing ways to mitigate the impact on future class planning and EDWP schedules. Project management is not an exact science and delays of this magnitude are fairly common occurrence worldwide given the range of work and organizations necessary to complete the execution of the Work. The EDWPs are extremely challenging given the resource, material, engineering, obsolescence and project management issues. The EDWP team continues to remove obstacles/barriers and focus the achievement of a combat capable fully functional VICTORIA Class Submarine.

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16. REFERENCES

1. http://www.naval-technology.com/projects/ssk_victoria/, SSK Victoria Class Long-Range Patrol Submarines, Canada.
2. http://www.forces.gc.ca/site/newsroom/view_news_e.asp?id=1460, VICTORIA Class Submarines: An Indispensable Asset, October 2004.
3. ibid, para 3.
4. http://www.navy.forces.gc.ca/cms_fleet/fleet_e/fleet-home_e.asp?flash=1, VICTORIA Class, Department of National Defence.
5. Halle M. and Hughes D., ‘Supporting the VICTORIA Class SSK: - a naval perspective –‘, WMTC 2006, pp 3, 7 March 2006.
6. Hughes D. and Wilson M., ‘Project managing a VICTORIA class extended docking work period (EDWP): a snapshot naval perspective’, INEC 2008, pp 4, 2 April 2008.
7. http://www.index.forces.gc.ca/Viewer.aspx?query=submarine%20class%20plan&parser=Internet_Advanced_en-CA&k2dockey=http%3a%2f%2fwww.forces.gc.ca%2fcrs%2fpdfs%2fsubaq_e.pdf%40Forces&mimetype=application/pdf&queryParser=Internet_Advanced_en-CA&serverSpec=131.137.250.210:9900, 7050-11-33 CRS Report, pp 2.4, May 2003.
8. http://www.admfincs.forces.gc.ca/daip/new_e.asp?sel=atip#dec, DAIP website for Access to Information, December 2007.
9. HMCS CHICOUTIMI - Board of Inquiry, http://www.forces.gc.ca/site/Focus/chicoutimi/boi_parish_e.asp, 1080-1 (CHI BOI Pres), November 2004.
10. Craven, M., http://www.journal.forces.gc.ca/engraph/Vol7/no4/05-craven_e.asp, A Rational Choice Revisited – Submarine Capability in a Transformational Era,
11. Craven, M., http://naval.review.cfps.dal.ca/forum/view.php?topic=41, Canadian Naval Review, Fall 2007.
12. Chief Review Services, ‘Review of the Submarine Acquisition/Capability Life-Extension Program’, pp B-2/2, 7050-11-33 (CRS), May 2003.

A PARTIAL SAFETY FACTOR FOR PRESSURE HULL COLLAPSE PREDICTION USING FINITE ELEMENT ANALYSIS

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SUMMARY

The traditional design methods for submarine pressure hulls are based on analytical and empirical methods, and use partial safety factors to account for uncertainties in the design method and hull parameters. The Finite Element (FE) method has been used in stress analysis and comparative collapse analyses but is not entirely trusted for collapse pressure prediction because there is no similarly defined partial safety factor. This paper describes the validation of state of the art FE methods against collapse data from a legacy database of model tests, acquired over a period of about fifty years at Rosyth, in an effort to give guidance on such a partial safety factor. Models designed to fail specifically in interframe, overall and interactive modes were considered. FE models as close to the 'as-built' condition as possible were generated and, with certain conditions, a partial safety factor of 1.06 was demonstrated. There are still some outstanding issues to be considered, such as residual stresses caused by welding and details of material behaviour, and some preliminary work to address these issues is also described. Validation of FE techniques is particularly important for the future if novel designs are to be implemented without recourse to comprehensive testing programs as was done in the past.

1. INTRODUCTION

Despite the apparent ubiquity of the finite element (FE) method in many areas of structural analysis and engineering design, its application has not been fully embraced in the design and analysis of submarine pressure hulls. An existing, well proven design methodology, based on analytical and empirical methods, and a lack of validation has undoubtedly led to a lack of take up of FE methods, although efforts are being made to redress this, e.g. [1]. Despite its apparent simplicity – an axisymmetric structure subjected to a uniform static load - the collapse of a pressure hull is a complex process to model, involving as it does: geometric non-linearities, elasto-plastic material behaviour, and loss of stability. The collapse can also be affected by the presence of substantial residual stresses, caused by cold bending of plate and welding, and is sensitive to a variety of shape imperfections such as: overall out-of-circularity (OOC), interframe dishing and frame misalignment. Data from physical models, gathered over a period of about fifty years by the predecessors to QinetiQ at Rosyth, has been used as a baseline to validate current non-linear FE methods [2].

2. SUMMARY OF THE VALIDATION EXERCISE

2.1. TEST MODELS

The mode of collapse of a pressure hull tends towards two extremes: if the stiffeners are sufficiently strong, the collapse will occur in the short sections of cylindrical plating between frames i.e. an interframe collapse; if the stiffeners are inadequate, or the model is long, collapse can occur in an overall mode. Obviously there is also a middle ground where interaction between the modes is possible.

Deliberately short models, typically 10 to 12 frames, were used to isolate the interframe collapse mode in a structure with scantlings representative of a submarine pressure hull. This ensured that the overall collapse pressure of the model was higher than the interframe collapse pressure without artificially increasing the frame dimensions. The results of a large number of tests, carried out over several decades, have been condensed into an empirical curve, which is considered accurate to ±10% provided the magnitude of the OOC is no greater than 0.5% of the radius. Because of this accuracy, design is based on interframe collapse and frames are subsequently sized to avoid overall collapse [3]. Conversely, deliberately long models were tested to isolate the overall modes of failure. As well as the extremes of 'short' and 'long' cylinders there exist many examples of models representative of real submarine compartments.

2.2. FE MODELLING

The shape of any real pressure vessel will inevitably include departures from perfect circularity and these grow steadily as external pressure is increased from zero. In fact, many of the models tested were fabricated deliberately with a dominant overall OOC, normally n=2, 3 or occasionally 4. Welding the frames to the plating also causes an indentation of the plating ('hungry horse' effect) which influences the interframe collapse. Recognizing the importance of shape imperfections, the true shapes of the test models were extensively measured. Because overall collapse behaviour is limited to lower modes, n=2 (ovalisation), 3, 4, or 5, OOC data were typically measured at 15° intervals at frames. Interframe buckling can be driven by higher buckling modes, n=12 to 15, therefore OOC was measured at 5° intervals when recorded at midbay. Frame spacing and misalignment data were usually recorded at 90° intervals, when taken.

Models were generated using PATRAN [4]. The geometry was created by generating points in space at measured locations. Curve and surface fitting techniques were then used to complete the geometry. Previous work has shown that perturbations in the geometry generated by the interpolation involved in these processes are of similar magnitude to those measured in the physical models.

Analysis was carried out using ABAQUS [5], which provides flexibility in terms of elements, material models and non-linear solution strategies. Previous experience with stress and collapse analysis of pressure vessels and associated structure informed modelling decisions such as element selection and mesh density; second order thin shell elements were used with a density of six or eight elements between frames.

The pressure hull plating of a submarine is cold bent, or cold rolled, a process which results in permanent plastic deformation of some of the material, which in turn locks in a pattern of residual stresses in the plate. Obviously this will affect the subsequent response of the structure. In many models the T stiffeners were fabricated, with only the flanges being rolled and therefore subject to similar residual stresses.

A simple analytic solution, based on beam theory, exists for residual stresses in bent rectangular beams and this has been applied to cold-bent plate. However, there are limitations, e.g. it doesn't account for material hardening or Poisson effects in the plate and it was decided to calculate the residual stresses directly using the FE method. A model of a typical section of plate used to form the shell of a model was analysed for each case. Two steps were carried out: plastic bending, or rolling, which was idealised in a single step by applying a rotation at one end of the plate, and primarily elastic springback. An iterative procedure was used to determine the required overbend radius. The results of one such analysis are shown in Figure 1.

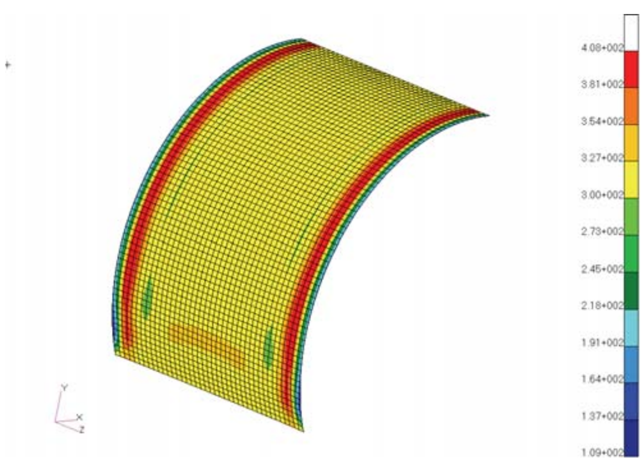


Figure 1 Contour plot of the residual circumferential stress on the inner surface of a typical plate section after cold-bending.

The calculated stresses showed substantial variation close to the edges of the plate. Away from the edges it was found that, although the residual circumferential stresses were high, they were not overly sensitive to modelling details such as exact plate thickness or material hardening behaviour, and agreed closely with the simple analytic solution for the stress s-xx in the bending direction, as shown in Figure 2. However, it was also found that significant residual longitudinal stresses, s-yy, were developed. Unlike the circumferential stresses, these were unbalanced with the resultant moment tending to deform the plate to an anticlastic surface after springback. The variation of the final radius of the plate was small and was ignored on the basis that the unbalanced residual moment would be reacted in the adjoining plate when the structure was welded up.

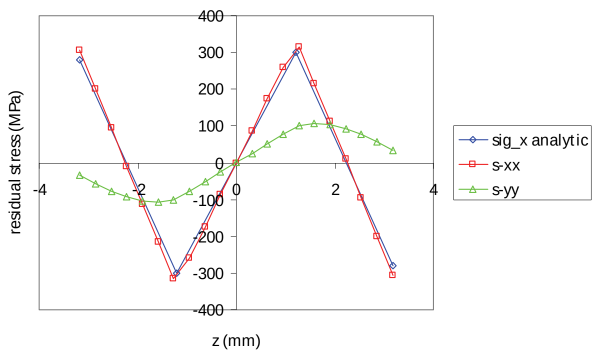


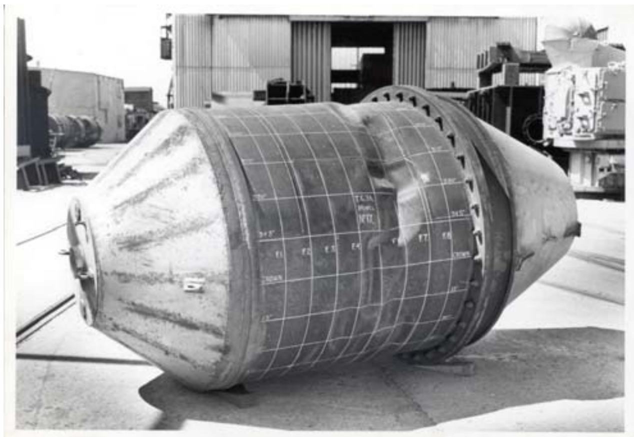
Figure 2 Residual stresses through the thickness of cold rolled plate.

The residual stresses were then simply included as an initial equilibrating condition in the appropriate components of the structural model. By default ABAQUS defines shell behaviour at five section points through the thickness but this was raised to 21 to give adequate resolution of the residual stresses.

A number of models were selected for analysis based on the amount of data recorded during the fabrication and testing of the models. Typically, OOC measurements were recorded at many, if not all, frame locations and for some models, at mid bay locations too. Frame spacing and misalignment were also recorded in many cases. Plate thicknesses were usually limited to minimum, maximum and average values for individual plates, and scantlings were normally recorded for individual frames. Extensive records of material properties were also taken, often as tables of proof stresses, in which case the material was modelled as elastic/perfectly plastic, but in some cases detailed load-displacement curves were available and more complex material models used.

2.3. RESULTS

Figure 3 shows the interframe collapse of a short model (top) with the predicted collapse (bottom) and Figure 4 shows the interframe collapse of a longer, more representative model. In both cases the qualitative agreement is excellent. The results of the analyses of a series of short models is summarised in Table 1. In some cases excellent agreement between the calculated and observed collapse pressures was achieved but in a few cases the calculated pressure was significantly overestimated. Inspection of the raw data for these models revealed large variations in thickness across individual plates and further analyses were undertaken with minimum values. These results are shown in parentheses and all results agree to within 6% of the observed collapse pressures.



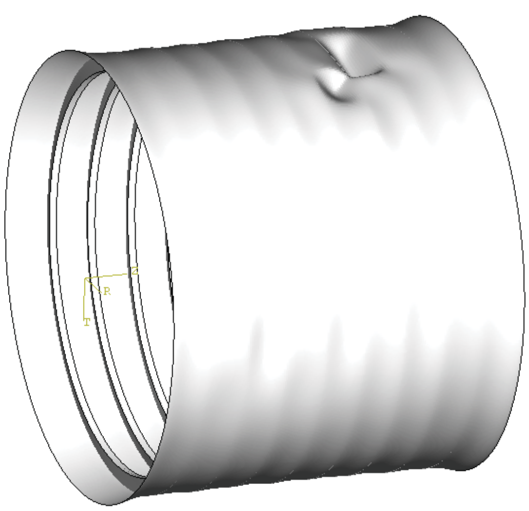


Figure 3 Interframe collapse in a short cylinder.

Figure 4 Interframe collapse in a model representative of a submarine compartment

Model	Mode	PFE/Pexpt
11	buckle	1.14 (1.006)
13	buckle	1.002
15	yield	1.098 (1.059)
17	buckle	1.062 (1.019)
18	yield	1.074 (1.054)
19	yield	0.963 (0.920)
20	overall	0.999

Table 1 Failure mode and predicted collapse/experimental collapse pressures of short models.

Figure 5 shows an overall collapse mode and Table 2 summarises the results of the analyses of longer models. Only two of the models considered actually failed in an overall mode. The first (the 36 frame model), and two other cases which are not reported here, were predicted to within +6% but the 40 frame model was initially overpredicted by 8.7%. Further investigation into the source data appeared to show that the Young's modulus of the plating used in the central section, and for some of the frame tables, was significantly lower than the assumed 207 GPa. When rerun with the measured value of 177 GPa, the collapse pressure was predicted to 4.2%.

This issue of variable modulus is also touched upon in the next section.

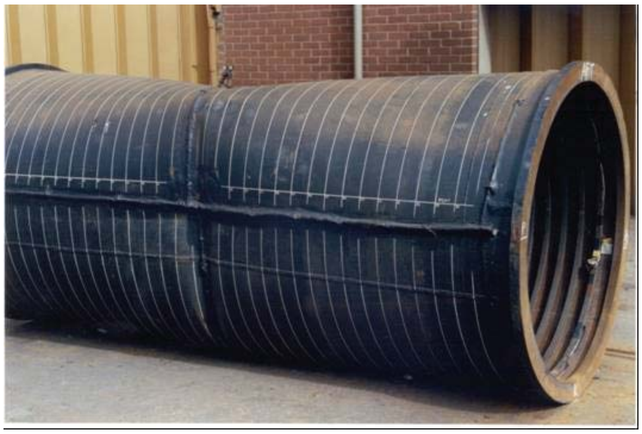


Figure 5 Overall collapse.

The conclusion of the validation exercise was that if sufficient detail of shape, scantlings, residual stress and material properties are included in a finite element model then the collapse pressure of a submarine pressure vessel can usually be predicted to within +6%, providing the mode of collapse is identified and, if interframe, the analysis is repeated with the minimum measured plate thickness.

The major sources of error are likely to be inadequate knowledge of the structure and effects omitted from the model. Examples of the former include insufficient measurements of plate thickness and values of yield stress without stress-strain curves. Examples of the latter include residual stresses due to welding and anisotropic non-linear material behaviour. It was suggested that non-linear and anisotropic behaviour could be a result of production processes, e.g. a preferred rolling direction during the production of flat plate. Analysis of the production process has been carried out to inform plant design [6] but the output of such analysis may be useful in defining the initial condition of the material in the further development of the collapse analyses described here.

Model	Mode	PFE/Pexpt
25 frame	IF	1.017
28 frame	IF	1.015
36 frame	OA n=3	1.051
40 frame	OA n=2	1.087 (1.042)

Table 2 Failure mode and predicted collapse/experimental collapse pressures of long models.

3. ADDITIONAL 29 FRAME MODEL

After the validation exercise was completed, an additional 29-frame model was analysed. Somewhat uniquely, the thickness over whole plates had been surveyed and this detail was included in the model. A plot of the thickness is shown in Figure 6. Using the same techniques and procedure as the validation exercise, the predicted collapse pressure was just over 5% greater than the experimental value. The mode of collapse also appeared to be reasonably well predicted, see Figure 7. However, closer inspection revealed that the location of the interframe pleat was incorrect; in fact it was on the wrong side of the model.

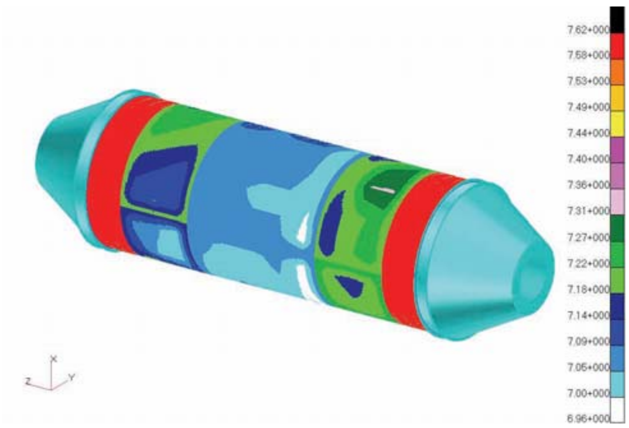


Figure 6 Plating thickness of additional 29-frame model.

Comparing Figure 6 and the second part of Figure 7 shows that, although the plate was generally thinner on this side of the model, it was relatively thickest at the predicted collapse location. Inspection of the OOC data showed that this was greatest at frame 20, close to the predicted collapse location, which possibly helped initiate the predicted collapse.

It is possible that the relative coarseness of the plate thickness measurement has missed a localised area of thinning, which has precipitated the interframe collapse at the observed location, at a slightly lower pressure than predicted. However there are other factors that should be considered.

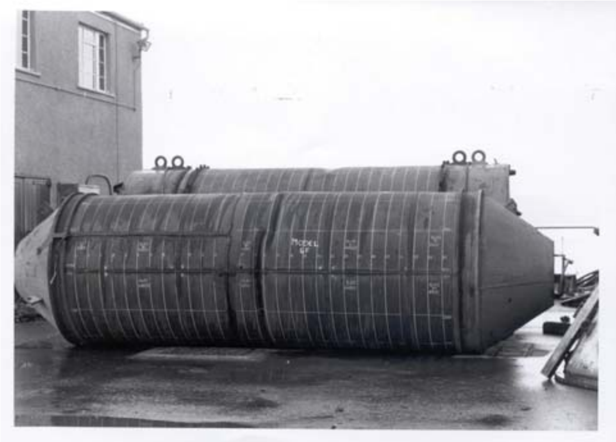


Figure 7 Predicted and observed collapse mode of 29 frame model

During testing a collapse run was aborted at the relatively high pressure of 84% of the final collapse pressure because of a pump failure and strain gauge data indicated that some frames may have yielded. It was suspected that this would have altered the OOC of the model but it was not re-measured. Obviously, if the OOC was more greatly affected at the centre, then this could explain the location of the observed collapse.

The analysis was carried out in stages to replicate this load history and selected strain outputs were compared with measured data. Figure 8 shows the circumferential strains at frame 13 from the collapse test. The measured and calculated strains were set to zero at the start of the collapse run and agreement is reasonably good. It is clear that the overall n=2 OOC is growing rapidly and that overall collapse was close when the cylinder failed in an interframe mode.

Figure 9 shows the raw strain data for the collapse test. The FE model has developed some plastic strain but this appears to be much less than that in the test model.

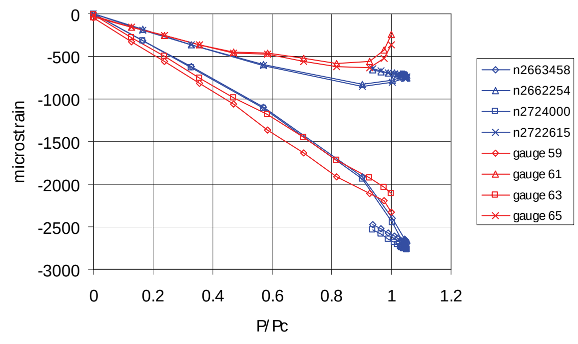


Figure 8 Experimental and predicted strains at frame 13 on collapse run (initially zeroed).

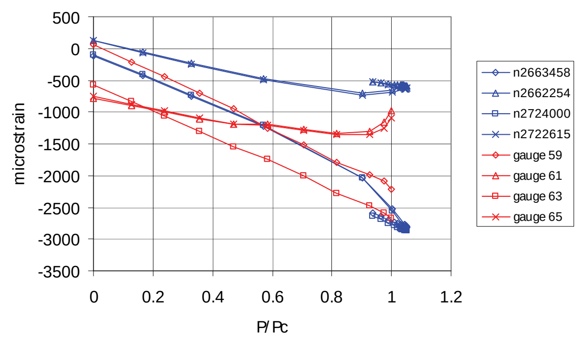


Figure 9 Experimental and predicted strains at frame 13 on collapse run.

Further inspection of the raw data uncovered load/displacement data for the plating which showed that the materials used in the plating and frames exhibited significant non-linearity prior to the 0.2% proof stress value. Stress against extension is plotted for plates 6489 and 6490, which made up the central shell of the model, in Figure 10. It is normally thought that the elastic modulus is relatively invariant [7] but the slopes of the initial linear response suggested Young's moduli of 209995 MPa and 259503 MPa respectively. It was suspected that this variability may have been a result of hardening from previous operations but for modelling purposes appropriate E values were used to define the initial slope.

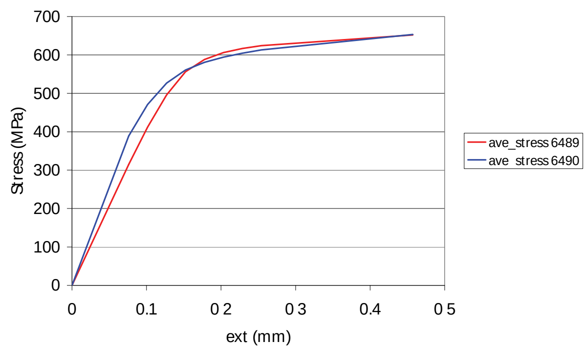


Figure 10 Stress against extension curves for plates 6489 and 6490, which form the shell of the 29 frame model.

The material properties shown in Figure 10 were used in further analyses, using updated material models available in the most recent version of ABAQUS, version 6.7 (2007). Different techniques for modelling the plastic behaviour including isotropic hardening, kinematic hardening and a combined model were investigated, as were various initial conditions of residual stress, plastic strain and hardening as calculated for the cold bending of shell plating and frames. None of these were found to make a significant impact on the plastic strains developed during the aborted collapse loading cycle.

The predicted collapse pressure from what was considered to be the most complete analysis was 8.5% greater than the observed value. The guidelines developed by the validation exercise acknowledged that the assumption of elastic/perfectly plastic material behaviour could be conservative, but the initial evidence was that this effect would be small. In spite of this conservatism, the trend was for overprediction of the collapse pressure, albeit to within +6%. More detailed modelling of the material behaviour has increased the discrepancy, suggesting that something is missing from the models.

4. WELDING RESIDUAL STRESSES

It is known that welding the frames to the shell plating also introduces significant residual stresses. On an internally stiffened cylinder these tend to draw the plating in between frames, creating a 'hungry horse' effect. This was included to an extent in the validation exercise since the exact geometric shape, including these deformations, was modelled. However, this did not include the residual stresses explicitly.

Attempting to calculate these stresses accurately is a far from trivial exercise. They depend on many factors including: existing residual stresses, from previous manufacture and fabrication operations; material properties of the weld and parent materials, including composition, microstructure, thermal properties and mechanical properties; geometry of the parts being joined; and restraints applied to these parts [8]. Such detailed analysis was outwith the scope of the present work but a short 'numerical experiment' was carried out in an attempt to gain at least a qualitative feel for their likely effects on the structural response.

The approach adopted was to apply a cooling through the thickness of the shell, at the nodes to which frames were attached. This was limited to a linear distribution, as shown in Figure 11, because of the formulation of the shell elements used. Because temperature dependency was not included in the material properties, a trial and error approach was used to determine values of temperature drop which developed believable residual stresses. The overall effect was achieved, as shown in Figure 12. The residual stresses at the frame are equal to the yield stress.

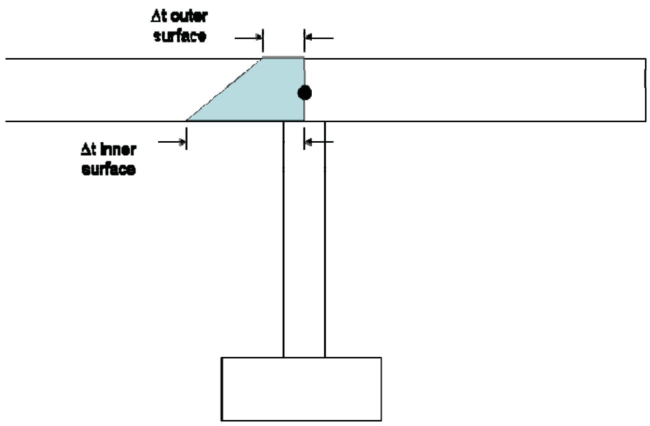


Figure 11 Temperature distribution applied to shell, at node, to simulate frame welding residual stresses.

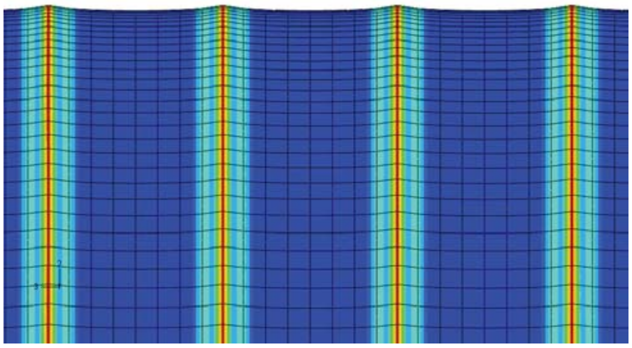


Figure 12 Detail of the von-Mises stresses, on inner surface, and interframe deformation (×100) developed by thermal cooling.

Generic overall and interframe shape imperfections were introduced to a model to seed an interframe collapse and three analyses carried out: a reference case, with no thermal residual stresses; a case with the thermal residual stresses; and a case with an additional interframe imperfection, equal in magnitude to that induced by the thermal cooling, but without the thermal stresses, in order to isolate the effect of the welding residual stresses. The results are shown in Table 3.

Previous work has shown that introducing a small interframe imperfection is critical to seeding an interframe mode of collapse, and can significantly reduce the collapse pressure, however, once introduced, changes in the magnitude of the imperfection have a lesser effect on the magnitude of the collapse pressure [2]. This perhaps explains why the additional imperfection on its own has little effect. The results suggest that the welding residual stresses have a much more significant effect. However, although this appears to be relatively small, about 1%, this cannot be quantified with any great confidence, given the simplifying assumptions. It was felt that this simple approach would give higher, more widespread residual stresses, and hence gives a conservative estimate; however this cannot really be justified without more detailed analysis or physical measurement.

Case	Relative Pc	Relative decrease
Reference	1.0	-
With welding residual stresses	0.989	-1.15%
With equivalent interframe imperfection	0.999	~ -0.1%

Table 3 Relative interframe collapse pressures with welding residual stresses and equivalent interframe shape imperfection.

5. CONCLUSIONS

This paper has summarised a validation exercise comparing collapse predictions using FE analysis with a series of large scale physical models. It was found that, if certain procedures were observed, then a partial safety factor (PSF) of 1.06 could be assumed.

A subsequent exercise on an additional model confirmed the PSF when the same procedure was followed. However, when more detailed material modelling, including a better description of non-linearities and hardening, was used; the predicted collapse pressure overpredicted the experimental value by 8.5%, i.e. a PSF of 1.085.

A 'numerical experiment' showed that the effect of residual stresses caused by welding the frames to the hull plating could be significant but was likely to be relatively small, resulting in a 1% drop in the predicted collapse pressure.

Further work is required in the following areas: the fundamental modelling of material behaviour, to take advantage of the rapid development of commercially available codes; and modelling of manufacturing and fabrication effects, which are crucial to the structural response of the as-built structure.

It should be remembered that the ultimate aim is not necessarily to produce an FE model which is absolutely accurate for its own sake, but, if FE is to be seriously used in the design and assessment of existing and novel structures, it is essential to understand, and quantify, all sources of error and variability.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

1. MacKay, J. R., Smith, M. J. and Pegg, N. G. Design of pressure hulls using nonlinear finite element analysis. Proceedings of OMAE2006.

2. Graham, D. Predicting the collapse of externally pressurised ring-stiffened cylinders using finite element analysis. Marine Structures 20 202-217 (2007).

3. Kendrick. Externally Pressurised Vessels. In The Stress Analysis of Pressure Vessels and Pressure vessel Components, ed Gill, S. S., 405-511 (Pergammon Press, 1970).

4. MSC PATRAN 2005(b) MSC Software Corporation 2003.

5. ABAQUS Version 6.4 User's Manual. ABAQUS Inc. Pawtucket USA, 2003.

6. Wright, S. J. FE modelling of roll design – cost savings and application to capital project planning. Twentieth ABAQUS UK User Group Conference, November 2006.

7. Dieter, G. E. Mechanical Metallurgy. McGraw-Hill. 1988.

8. Leggatt, R. H. Residual stresses in welded structures. Pressure Vessels and Piping 85 144-151 (2008).

8. AUTHORS BIOGRAPHY

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FINITE ELEMENT MODELING OF COLLAPSE EXPERIMENTS OF RING STIFFENED CYLINDERS WITH SIMULATED CORROSION DAMAGE

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T N Bosman, Delft University of Technology, Netherlands

SUMMARY

Defence Research & Development Canada (DRDC) and the Netherlands Ministry of Defence (MoD) are conducting collapse tests on externally pressurized aluminium ring-stiffened cylinders to validate numerical modelling methods, and to better understand the effects of corrosion on pressure hull strength and serviceability. A variety of short and long cylinder specimens exhibiting interframe and overall collapse modes are being fabricated and tested. Corrosion effects are introduced artificially in the specimens by machining away material according to pre-defined patterns. Nonlinear finite element analysis (FEA) is being used to simulate elasto-plastic collapse of the cylinder specimens, and the present paper gives results for thirteen specimens that have already been tested and analyzed. Good qualitative agreement between experimental and predicted collapse shapes was obtained for all cylinders. Comparison of experimental strain measurements with FE model predictions are given for several specimens and show good agreement in elastic and inelastic response regimes, for intact and corroded specimens. Overall, FEA collapse pressure predictions for the thirteen specimens are within ±7% of measured values. This represents a significant improvement over traditional empirical design methods, which underestimate the experimental collapse pressures in this study by, on average, 23%.

NOMENCLATURE

a	mean shell radius (mm)
FEA	finite element analysis
n	circumferential wave number
OOC	out-of-circularity
P_c	collapse pressure (MPa)

1. INTRODUCTION

Pressure hulls are the main load-bearing structures in naval submarines, commercial and research submersibles, autonomous underwater vehicles, and many off-shore marine structures. Pressure hulls typically operate in a salt-water environment, and are therefore susceptible to corrosion damage due to, for example, ingress of seawater at pressure hull penetrations and at poorly bonded acoustic tiles in submarines.

Corroded pressure hull material, once detected, is ground away; if the damage is severe, corrective action, such as clad welding or replacement of the shell plating, is undertaken. Otherwise, the pressure hull must operate with reduced plating thickness in the unrepaired region, which could affect structural performance.

A previous numerical investigation [1] indicated that the initiation of structural failure due to local pressure hull thinning needs to be better understood. A series of cylinder collapse tests was initiated by the Netherlands MoD and DRDC to gain understanding of these effects on pressure hull strength, stability and serviceability. This testing program is also aimed at building a database of experimental results for validating predictive methods, especially nonlinear finite element analysis (FEA).

The experimental program consists of approximately 50 small-scale ring-stiffened cylinders that are being tested in the 2005-09 time frame. The test specimens are machined from aluminium tubing and vary with respect to design geometry, geometric imperfections and corrosion damage. At the time of writing, collapse experiments have been performed on twenty-two specimens, of which the results of the first thirteen are reported here [2, 3].

This paper is concerned with the numerical simulation of these tests, especially as this pertains to the identification and validation of appropriate nonlinear FE modeling and analysis methods for corroded and undamaged pressure hull structures. A description of the test specimens and the experimental procedures are presented in Sections 2 and 3, respectively. The finite element (FE) modelling and analysis methods used in this study are discussed in Section 4. Numerical results for selected cylinders are presented and compared with the experimental data in Section 5. Finally, some concluding remarks are given in Section 6.

2. EXPERIMENTAL SPECIMENS

A summary of the cylinder specimens considered in this paper is presented in Table 1. All the specimens were machined from extruded aluminium pipe on a CNC lathe. During testing, the ends of the specimens are sealed with heavy steel end-caps.

Table 1: Summary of cylinder specimens

Specimen	Collapse Mode	Ring-Stiffeners	Specified Corrosion
L300-No1	Interframe	External T-Sections	None
L300-No2	Interframe	External T-Sections	None
L300-No3	Interframe	External T-Sections	25% shell thinning
L300-No4	Interframe	External T-Sections	25% shell thinning
L510-No1	Overall	External T-Sections	None
L510-No2	Overall	External T-Sections	Flange
L510-No3	Overall	External T-Sections	Flange
L510-No5	Overall	Internal T-Sections	None
L510-No7	Overall	Internal T-Sections	20% shell thinning
L510-No9	Overall	Internal T-Sections	13% shell thinning
L510-No11	Overall	Internal T-Sections	13% shell thinning
L510-Test	Overall	None	None
L500-Pen	Overall	External Rectangular	None

The nominal dimensions of a typical short cylinder are shown in Figure 1. This layout is common to all test specimens. The L300 series of specimens are short cylinders designed to fail inelastically in an interframe mode (collapse of shell plating between frames). The L510 series are longer cylinders designed to fail inelastically in an overall mode (combined collapse of rings and shell). Figure 2 shows some typical cylinders after collapse testing.

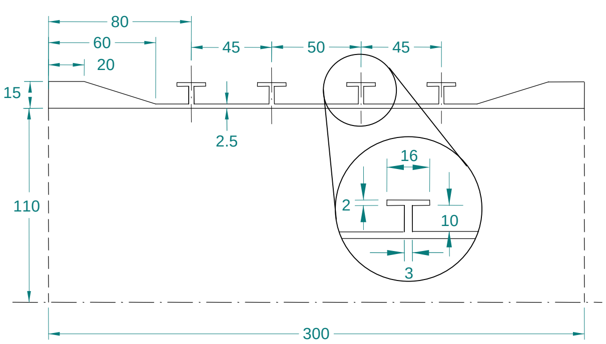

Figure 1: Geometry of specimen L300-No1 (mm)

Corrosion damage was introduced in seven of the specimens by machining away material in a specific manner. In most cases the corrosion damage consisted of uniformly thinned rectangular patches on the outside of the shell. For instance, a simulated square corrosion patch, spanning 70% of the width of the central bay and nominally reducing the shell thickness by 25%, was applied to the central bay of specimens L300-No3 and -No4. For the externally stiffened cylinders designed for overall collapse, L510-No2 and -No3, corrosion was applied in the form of flange width reductions on the two central stiffeners. Shell corrosion was applied to internally stiffened cylinders over increasing areas of the shell (i.e. spanning one, two and four frame bays for specimens L510-No7, -No9 and -No11, respectively).

Figure 2: Typical undamaged and corroded cylinders

A cylinder with no stiffeners, L510-Test, was designed to fail in elastic buckling. Cylinder L500-Pen was fitted with two reinforced penetrations on opposite sides of the cylinder.

3. EXPERIMENTAL PROCEDURE

In earlier experiments [2], specimens were loaded to collapse in the DRDC Atlantic pressure testing facility by applying external hydrostatic pressure to sealed and air-filled specimens (Figure 3). At failure, the surrounding fluid suddenly rushes into the ruptured specimen, releasing a large amount of stored energy, and causing much additional deformation and rupture of the specimen. With this approach it was difficult to determine the failure mode from post-test inspection (e.g. see specimen L300-No4 in Figure 2).

A revised experimental procedure was used for subsequent tests, with the goal of preventing catastrophic failures [3]. The revised procedure consists of the following steps, with reference to the schematic diagram shown in Figure 3:

- The specimen is filled with testing fluid (mineral oil), connected to a hydraulic line, and immersed in the pressure tank .

- With the fluid-release valve closed and the cross-over valve opened, the system is pre-pressurized to a pressure higher than the anticipated collapse value. This results in a pressure differential of zero between the inside and outside of the specimen.
- The cross-over valve is then closed and the fluid-release valve is used to slowly release the fluid from the cylinder while monitoring the pressure differential and strains. The flow, and therefore the applied load, can be reduced or stopped altogether when approaching collapse, as indicated by the pressure-strain behaviour.

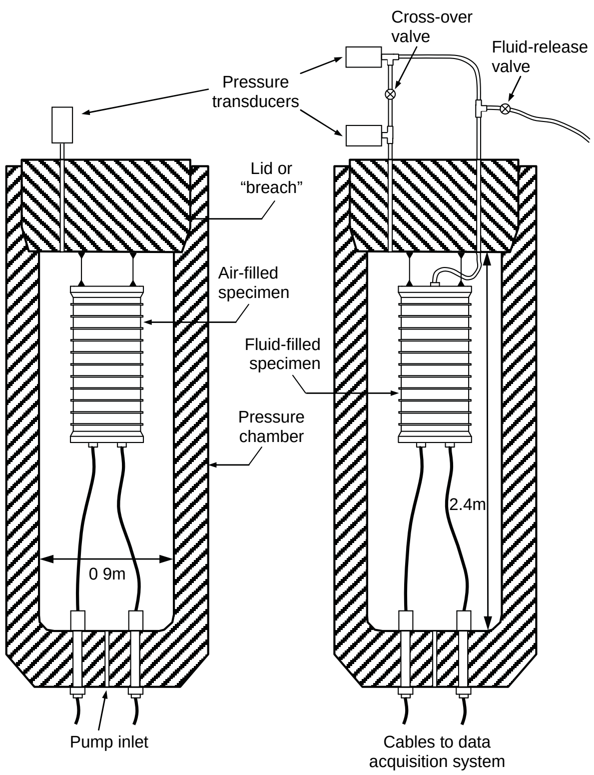

Figure 3: Original (left) and improved (right) pressure testing apparatus used in collapse experiments

The results of the most recent cylinder tests [3] indicate that the improved pressure testing apparatus and procedure has been successful at eliminating the excessive post-collapse deformations and rupture (e.g. see specimens L510-No11, L300-No1 and L510-No3 in Figure 2).

In addition to the measurement of the collapse pressure, the entire pressure-strain histories were measured using a large number of strain gauges attached to the test cylinders. These test data help to understand the failure modes of the cylinders in the vicinity of the peak load, and are also valuable for verification of the FE solutions. The accuracy of experimental collapse pressures (±0.09 MPa) is associated with the accuracy of the pressure transducers.

4. FINITE ELEMENT MODELLING

4.1 MESHES

FE models of the test cylinders were initially generated using SubSAS, a software program that has been developed to aid in the generation of finite element models of submarine structures, including stiffened pressure hulls and internal structure such as decks and bulkheads. Certain features, such as corrosion patches and tapered end sections, were later added to the FE models using customized FORTRAN codes.

All finite element models in the present study were constructed using a 4-node quadrilateral shell element, described in the next section. Ring-stiffeners were explicitly modelled using these shell elements. The tapered end sections were modelled with shells with variable nodal thicknesses. Nodes were located at the mid-plane of the shell elements, except in the corrosion patches (see Section 4.7).

4.2 NUMERICAL PROCEDURES

The nonlinear calculations presented in this paper were performed using the VAST finite element code [4]. In the present work, a four-node quadrilateral shell element was employed for all FE models. This shell element was developed using the technique of mixed interpolation of tensorial strain components (MITC) and is free from shear locking. The geometrical nonlinearity was dealt with through an element-independent consistent co-rotational formulation, which is applicable for arbitrarily large displacements and rotations [5].

The elasto-plastic deformation was characterized by a rate-independent plasticity material model based on the J_2-flow theory [6]. In order to ensure optimal convergence properties, an implicit numerical integration scheme with a consistent tangent modulus matrix was adopted.

The orthogonal trajectory solution procedure was used in all nonlinear analyses in the present study in order to obtain the structural responses of the cylinders in the post-collapse region. This solution method involves a constraint equation similar to the one used in the constant arc-length method, but is more robust because it eliminates the requirement for solving quadratic algebraic equations. For all analyses, a load increment of 0.5 MPa was used to start the solution process. No numerical difficulties were encountered in any of the nonlinear analyses.

4.3 MEASURED GEOMETRY

The extrusion of the aluminium tubing and subsequent machining of the specimens left a small amount of out-of-circularity (OOC) imperfection [2,3]. Measurement of the specimen surface geometries using a coordinate-measuring machine revealed that the OOC shapes were primarily n=2 with an amplitude of approximately 0.001a. Measurements were taken on the outer surface of the specimens at evenly spaced points in the circumferential direction, and along the length of the cylinder at stiffener and mid-bay locations. A continuous mapping was then constructed by fitting to the discrete radial measurements using a combination of Fourier series along the circumference and spline curves in the axial direction. This mapping was applied to the nodal positions of the FE model.

A discretized shell thickness mapping was also constructed for each cylinder specimen by comparing inner and outer radial measurements at evenly spaced circumferential positions in the central bay. The thicknesses measured at each circumferential position were then uniformly applied to the corresponding axial strip of shell plating in the FE model. Model thickness variations in the circumferential direction were defined in a piecewise constant manner. Radial measurements at the inside of the shell were available in all bays for the internally stiffened cylinders, and so a thickness map was applied to each bay of the FE model as described above.

4.4 MATERIAL PROPERTIES

The nonlinear material properties for the cylinders were determined from tensile coupon tests. The material test data indicated that the yield strength of the aluminium in the axial direction was approximately 10% greater than in the circumferential direction. This anisotropy was not explicitly accounted for in the numerical models, as the quadrilateral shell element used here only supports isotropic material models. Instead, an isotropic material model, based on measured material properties in the weaker circumferential direction, was used. This has been found to give a better fit with the experimental results compared to using the axial material properties.

The experimental specimens discussed in this paper were fabricated from two separate batches of aluminium tubing. Characteristic stress-strain curves were determined by taking the average of all of the experimental curves for each batch. These curves were further discretized into a simplified multi-linear stress-strain curve consisting of a set of fourteen data points. This was handled in the FE analysis using an overlay material model, which has proven to accurately represent the behavior of metals under cyclic loading [7].

4.5 BOUNDARY CONDITIONS

The steel endcaps were not explicitly modeled, but were instead included indirectly via boundary conditions applied at the cylinder ends. A separate study exploring the influence of various boundary conditions options on the FE results considered a fully clamped, a simply-supported and an intermediate end condition. This indicated that the location of failure was more greatly influenced by the choice of boundary conditions than the actual collapse pressure.

The most appropriate scheme was found to be fully constrained conditions applied to all nodes at one end of the model, with nodes at the other end fully constrained against translations and rotations, except for translation along the axial direction. This convention, which was employed in all analyses reported in this paper, allows out-of-plane warping at one end of the cylinder. An FE model with these boundary conditions was compared to a similar model with warping prevented at the axially loaded end using constraint equations. Nonlinear analyses showed that allowing end-warping did not have a significant effect on the pre-collapse behaviour or collapse pressure.

4.6 APPLIED LOADS

External pressure was applied to the cylinder shell of each FE model. The effects of live loading (i.e. the follower force) have not been considered due to the relatively small pre-collapse displacements. Concentrated axial forces were applied to the end of the model where axial translation was permitted. These forces are associated with the pressure loads acting on the end-caps and were computed based on the mid-surface geometry of the shell elements at the cylinder ends. No loads were applied to the flange and web of external stiffeners since both sides of these components were exposed to the same external pressure, thereby producing a net load of zero.

4.7 SIMULATED CORROSION

As indicated in Table 1, seven of the thirteen cylinders included some form of simulated corrosion. Regions of one-sided shell thinning were modeled using the shell thickness offset feature in VAST [4], which allows the nodes of a quadrilateral shell element to be offset from the mid-surface in the thickness direction. Flange corrosion was modeled by adjusting the coordinates of the flange nodes so as to reduce the width of the flange locally, thus forming the “dog-bone” pattern used in the experimental specimens.

5. RESULTS AND DISCUSSION

Before nonlinear analyses were carried out for each of the thirteen cylinder specimens, a parametric study was undertaken to investigate the effects of various modeling parameters on the numerical results. This included the external load definition, boundary conditions, material models, cylinder self-weight, modeling details at the shell-stiffener intersections and convergence studies to determine suitable mesh densities for various geometries, especially around regions of corrosion. These preliminary numerical studies, some of which were described in the previous section, served as a guide for subsequent nonlinear analyses.

The FE-predicted collapse pressures, failure modes and pressure-strain histories at all strain gauges locations were compared with the measured data for all thirteen cylinders. Results for a few typical cases are given here in detail, followed by a summary of the complete set of analysis and test results. A brief overview of the experimental results is presented first.

5.1 SUMMARY OF EXPERIMENTAL RESULTS

The experimental results indicated that the cylinders collapsed in the design failure modes; that is, interframe collapse triggered by shell yielding for short cylinders and overall collapse, precipitated by yielding of the stiffeners and/or adjacent shell, for long cylinders. The collapse strength of cylinders with simulated shell corrosion was found to be less than similar undamaged specimens in all cases.

Stiffener corrosion was found to have, on average, a relatively smaller strength-reducing effect on collapse pressure, and in one case the corroded cylinder was actually stronger than its companion undamaged specimen. This latter discrepancy may be related to the testing procedure for the undamaged cylinder L510-No1, which was pressurized to failure after it had been loaded past its yield limit in a previous test that was aborted due to equipment malfunction [2]. This may have negatively impacted its collapse strength and is a possible explanation for the greater strength of the corroded specimen L510-No3.

In general, loss of strength due to corrosion was associated with the early onset of yielding in the region of material loss. Some additional conclusions of the experimental program regarding the effect of shell corrosion on pressure hull strength are:

- the reduction in collapse strength is in percentage terms proportional to the amount of shell thinning;
- yield strength is more sensitive to shell thinning, by a factor of approximately two, than collapse strength;
- the eccentricity due to one-sided shell thinning appears to have a strength-reducing effect in addition to the thinning itself; and
- the magnitude of thinning is more significant for strength considerations than the total volume of material lost to corrosion.

5.2 SHORT CYLINDERS

Figure 4 shows a typical FE mesh for a short, externally stiffened cylinder. A local mesh refinement was utilized in order to accurately represent the behaviour in the vicinity of the corrosion patch in the central bay. The predicted nonlinear load-displacement curves for typical intact (L300-No1) and corroded (L300-No3) short cylinders are given in Figure 5. For L300-No3, the maximum radial displacement occurred at the centre of the corrosion patch.

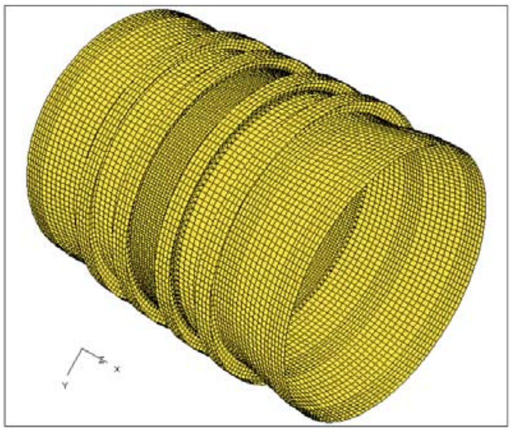

Figure 4: Typical FE mesh for short, externally stiffened cylinders

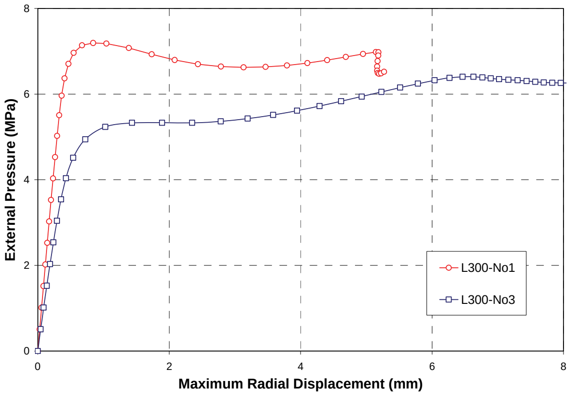

Figure 5: Pressure-displacement curves predicted by FE for undamaged (L300-No1) and corroded (L300-No3) cylinders

The results shown in Figure 5 indicate that the nonlinear behaviour of the intact and corroded cylinders is very different. The undamaged cylinder L300-No1 collapsed with an initial failure mode showing a single dimple in the shell. After this initial failure, the cylinder showed significant residual strength, mainly due to a reserve of stiffness in the frames. Mode-jumping occurred at the first post-collapse peak, with the FE model predicting the appearance of additional buckling waves, as shown in Figure 6. These features are consistent with the expected interframe collapse mode and the structural response observed in the experimental specimen [3], as shown in Figure 2.

The FE model of the corroded cylinder L300-No3 predicted the initial instability to occur at a pressure 26% lower than that for the intact model. This compared with a 23% reduction observed in the experiment. This initial failure occurred in the corrosion patch and was associated with significant prior yielding in that region.

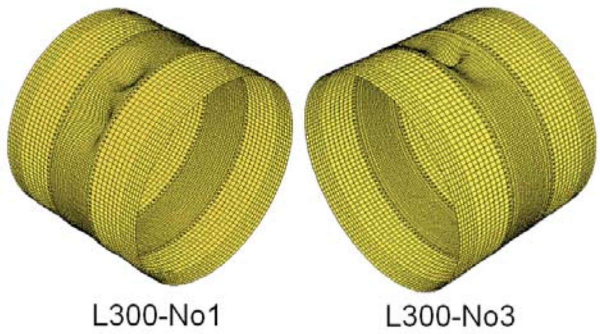

Figure 6: Final deformed configuration of the FE models for cylinders L300-No1 and L300-No3 (external stiffeners not shown)

After the initial failure of the corroded area, the cylinder continued to take on additional load, largely due to the residual strength of the intact cylinder wall and the surrounding stiffeners. The experiments showed that the ultimate collapse strength of the corroded cylinder was reduced by approximately 11% compared to the undamaged cylinder. The FE models predicted a lesser strength reduction of about 5% due to the corrosion damage.

The ultimate strength of the corroded cylinder was reached with significant yielding and collapse in the region of non-corroded shell close to the corrosion. While this agrees with the experimental results, even the most refined FE model could not reproduce the exact experimental buckling mode. The final configuration of the FE model shown in Figure 6 predicts a half sine wave deformation pattern over the corrosion patch. The experimental model showed a local buckling mode in the corrosion patch after testing, consisting of approximately 1.5-2 sine waves in the circumferential direction [2]. This cylinder was tested with the original test setup, and with insufficient strain gauges to track the short-wavelength buckling mode, so it is uncertain at what point in the loading history the final post-testing configuration in the corroded region appeared.

5.3 LONG CYLINDERS

Figure 7 shows an FE mesh for a typical long, internally stiffened cylinder. In this case, cylinder L510-No11, which has a large patch of simulated shell corrosion, is considered. The mesh was locally refined around the corrosion patch in order to adequately capture the high stress gradients in that region.

Figure 7 also shows the final deformed configuration of the shell of cylinder L510-No11, with a map of the shell thicknesses superimposed on the mesh, clearly indicating the shell thinning in the corroded region. The FE model predicted the collapse failure to occur at the interior edges of the corrosion patch with significant deformation of both shell and stiffeners; this qualitatively agrees with the experimental results, as shown in Figure 2 [3].

The FE results shown in Figure 7 indicate inward local buckling of the shell and stiffeners on either side of the central bay, whereas the experimental cylinder buckled in the centre bay and one adjacent bay. This discrepancy may be due to the fact that the shell thickness in the corroded region was uniform in the FE model but varied somewhat in the real model.

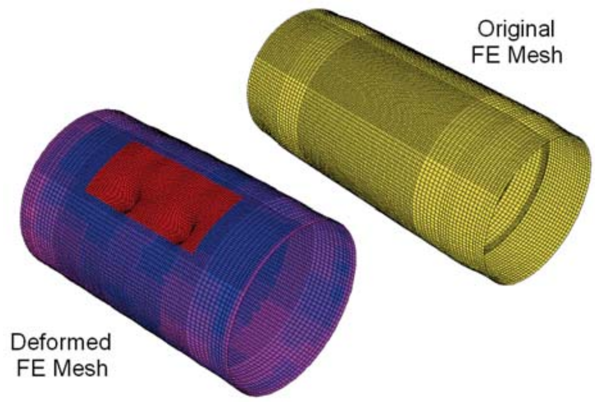

Figure 7: Original and deformed FE mesh for internally stiffened cylinder L510-No9

Figure 8 shows the experimental and predicted distributions of circumferential strains in the shell on the outside of the central bay. This figure shows that the experimental strains, including increases in magnitude due to the one-sided corrosion thinning and associated bending moments at the edges (±15°), have been accurately predicted by the FE model over the entire loading history.

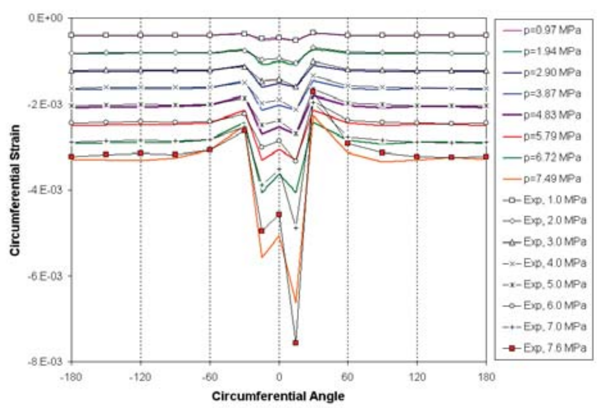

Figure 8: Measured (solid lines) and predicted (lines with symbols) circumferential strains at the central bay of cylinder L510-No11 for increasing pressures

Quantitatively, the FE models for cylinders L510-No5 and L510-No11 indicate that the shell corrosion resulted in a decrease in strength of 16.5% compared to the experimental value of 15.1%. These results indicate that the experimental and numerical results are in good agreement.

5.4 CYLINDER WITH PENETRATIONS

Results for a cylinder with external rectangular section stiffeners and two reinforced hull penetrations, L500-Pen, are shown in Figures 9 and 10.

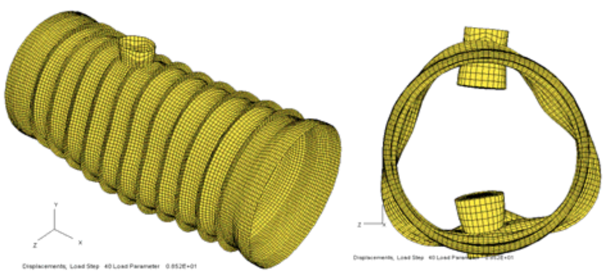

Figure 9: Deformation at failure for FE model of the test cylinder with penetrations

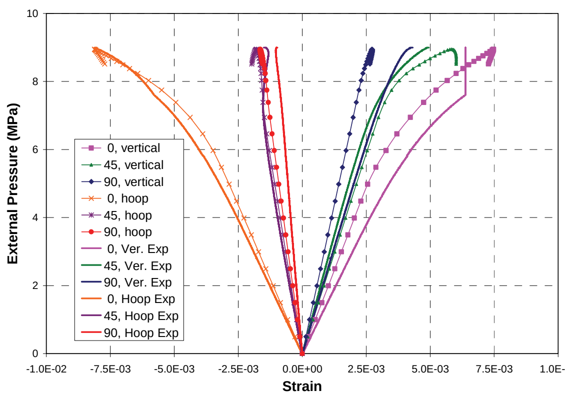

Figure 10: Measured and predicted strain histories at a reinforced penetration in cylinder L500-Pen

Figure 9 shows the final deformed configuration predicted for this test cylinder viewed from different angles. The deformed shape suggested an overall failure in mode *n*=3, which is consistent with experimental results [2]. The measured and predicted pressure-strain histories for strains on the inside wall of one of the reinforced penetrations are compared in Figure 10. Close agreement between numerical and experimental models is observed, even in these secondary structures.

5.5 OVERVIEW OF FINITE ELEMENT RESULTS

Experimental collapse pressures for all of the cylinder specimens are plotted against the corresponding FE strength predictions in Figure 11. These results show that the predicted collapse pressures are uniformly scattered around the line of perfect correlation, and that all but two of the FE results were within 5% of the experimental values.

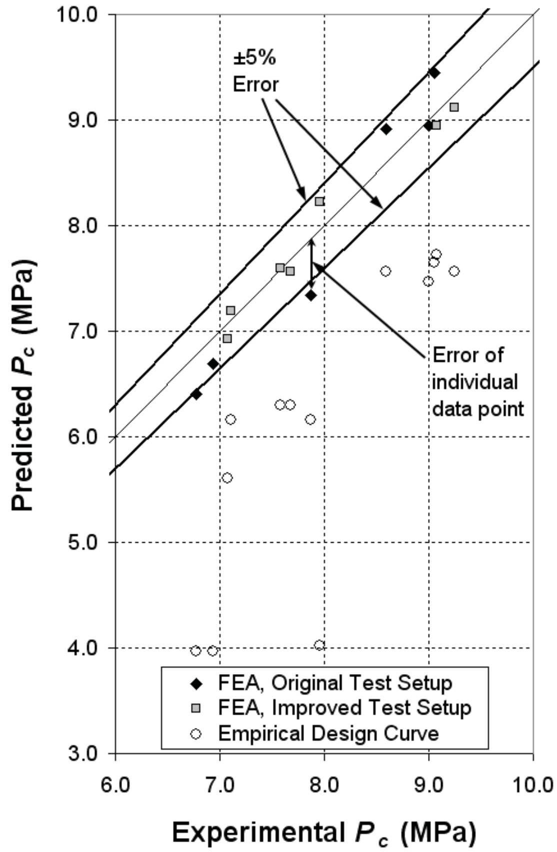

Figure 11: Comparison of measured and predicted collapse pressures (MPa) for all test specimens

Figure 11 indicates whether the experiment was performed using the original (black diamonds) or the improved (grey squares) experimental procedures, as outlined earlier in this paper. The improved experimental technique provided better control of the applied pressure, especially near the collapse load, compared to the original method. Thus, experimental collapse pressures determined using the improved method should be more reliable than those measured using the original test method. Also, measured shell thickness distributions for the externally stiffened cylinders, most of which were tested using the original method, were only available in the central bay.

Since all of the nonlinear analyses were performed using the same FE code and using consistent modeling and analysis methods, the aforementioned factors may explain the better agreement with predictions for those cylinders tested using the improved experimental procedure .

Figure 11 also shows strength predictions for the experimental cylinders based on the empirical design curve used in many contemporary design standards for externally pressurized shells. Collapse pressures indicated in Figure 11 by hollow circles are based on the mean design curve from Ref. [8]. The design curve under-predicts the strength of these cylinders by, on average, approximately 23%. The empirical curve was built up from experimental data for cylinders with up to 0.5% OOC and residual stresses due to fabrication. Corrosion damage was incorporated by using the minimum shell thickness or flange width with the design curve. These factors lead to pessimistic empirical strength predictions for these cylinders, which have small magnitudes of OOC and residual stresses, and a finite region of corrosion.

6. CONCLUSIONS

The main objectives of the current study were to identify and validate FE modeling and analysis methods for predicting the strength of intact and corroded pressure hulls. The ultimate goal of this and ongoing FE and experimental work is to incorporate three dimensional FEA in the pressure hull design methodology [1]. One approach is to establish partial safety factors applicable to FEA predictions by comparing of a large body of experimental and numerical results. An important step towards this goal is to define FE modeling and analysis guidelines for pressure hull structures.

Among the factors considered here, accurately representing thickness variations in the cylinder shell, including localized corrosion, was the most important for predicting the correct failure mode. The material modeling parameters had the most significant influence on the computed pressure-displacement response. As expected, geometric imperfections were also found to have a significant influence on the collapse behavior of the cylinder, especially when the pattern of the imperfection coincided with a buckling mode shape.

The FE modeling and analysis methods chosen for this study – e.g. quadrilateral shell elements with mid-plane offsets for corrosion patches, orthogonal trajectory path-following scheme, nonlinear mapping of measured geometric imperfections, overlay material models, etc. – have been shown to predict the experimental collapse pressures and failure modes of pressure hull structures having a variety of configurations, imperfections, corrosion damage and even reinforced penetrations, to within ±7%. Similar numerical methods have been applied to cold formed and welded ring-stiffened cylinders under external pressure, resulting in a similar level of accuracy for strength predictions, if the most pessimistic geometries are assumed [9].

With regards to future work, it is suggested that the analyses summarized in this paper should be repeated using a material model that explicitly accounts for the anisotropic nature of the extruded aluminium to determine if the strength predictions can be improved further. This may also be relevant to real pressure hull structures, which have anisotropies due to hot-rolling of the base plate, extrusion of ring-stiffeners, and cold forming of these hull components into circular form. These analyses should also be repeated while accounting for the effect of live loads, which were neglected in the current study.

The results of the current and a similar study [9] suggest that nonlinear numerical methods, which are available in most commercial FE packages, are able to predict the strength of ring-stiffened cylinders under external pressure within ±6 or 7%. This represents a significant improvement over contemporary empirical design methods, which significantly underestimate the strength of the experimental models considered for this study.

Notwithstanding the encouraging numerical results, it is suggested the small sample size currently available for comparison – a total of 26 cylinders between the current study and that of Ref. [9] – is not sufficient for assessing a partial safety factor. For comparison, the partial safety factor for interframe collapse prediction in the traditional pressure hull design methodology is based on approximately 700 experimental results [10].

Compared with previous efforts, modern high-frequency digital data acquisition systems that can simultaneously monitor large numbers of strain gauges allow for much more detailed measurement of pressure hull response. Furthermore, high-precision measurements of specimen geometry coupled with advances in computer technology have made possible the nonlinear analysis of highly detailed numerical models. Given these improvements, it might be supposed that correlation of experimental and numerical results can be accomplished with a smaller body of experimental results. To a large extent this is true, but there is a great danger in using too few test specimens, however accurately measured and modelled, as the normal statistical scatter found in real-world structures will not be fully represented. The present work marks an important initial step toward a comprehensive correlation between experiment and the best predictive tools currently available.

7. ACKNOWLEDGMENTS

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8. REFERENCES

1. MACKAY, J.R., SMITH, M.J. and PEGG, N.G., 'Design of Pressure Hulls using Nonlinear Finite Element Analysis', *Proceedings of the 25th International Conference on Offshore Mechanics and Arctic Engineering*, Hamburg, Germany, June 4-9, 2006.

2. MACKAY, J.R., 'Experimental Investigation of the Strength of Damaged Pressure Hulls – Phase 1', *DRDC Atlantic TM 2006-304*, 2006.

3. MACKAY, J.R., 'Experimental Investigation of the Strength of Damaged Pressure Hulls – Phase 2', *DRDC Atlantic TM 2007-013*, 2007.

4. 'VAST User's Manual, Version 8.8', Martec Limited, Halifax, Canada, 2007.

5. NOUR-OMID, B. and RANKIN, C.C., 'Finite Rotation Analysis and Consistent Linearization Using Projectors', *Computer Methods in Applied Mechanics and Engineering*, 1991.

6. SIMO, J.C. and TAYLOR, R.L., 'A Return Mapping Algorithm for Plane Stress Elasto-Plasticity', *International Journal for Numerical Methods in Engineering*, 1986.

7. ZIENKIEWICZ, O.C., NAYAK, G.C. and OWEN, D.R.J., 'Composite and Overlay Models I Numerical Analysis of Elastic-Plastic Continua', *Int. Symp. on Foundations of Plasticity*, Warsaw, September, 1972.

8. 'SSP74: Design of Submarine Structures', Defence Procurement Agency, United Kingdom, 2001.

9. GRAHAM, D., 'Predicting the collapse of externally pressurized ring-stiffened cylinders using finite element analysis', *Marine Structures*, 2007.

10. KENDRICK, S.., 'Externally Pressurized Vessels', in S.S. Gill, (Ed.), *The Stress Analysis of Pressure Vessels and Pressure Vessel Components*, 1970.

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ADVANCES IN EXPERIMENTAL TECHNIQUES FOR UNDERSTANDING THE MANOEUVRING PERFORMANCE OF SUBMARINES

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SUMMARY

As the complexity of modern submarine design increases, it is sometimes necessary to develop or modify the mathematical models which describe the manoeuvring characteristics. Submarine manoeuvring simulations have been developed from quite simple models that can predict basic manoeuvres accurately into more complex models that aim to improve the quality of the prediction when the submarine is undergoing more extreme manoeuvres. These complex, coefficient based, models demand a more extensive experimental test programme in order to derive the terms in the mathematical model; a change to the mathematical model that increases the number of independent variables can dramatically increase the number, and hence the overall duration and cost, of model tests. This paper describes some of the shortcomings in the mathematical models and how new experimental techniques can be developed to help understand these deficiencies and address them.

NOMENCLATURE

CFD	Computational Fluid Dynamics
DNS	Direct Navier-Stokes
DVL	Doppler Velocity Log
LES	Large-scale Eddy Simulations
MLD	Manoeuvring Limitation Diagram
RANS	Reynolds-Averaged Navier-Stokes
RLG	Ring Laser Gyro
RN	Royal Navy
RPM	Revolutions Per Minute
SRM	Submarine Research Model
UK	United Kingdom
B	buoyancy force (N)
m	mass (kg)
Δm	excess mass (kg)
g	acceleration due to gravity (m/s^2)
x_G	longitudinal location of centre of gravity (m)
y_G	lateral location of centre of gravity (m)
z_G	vertical location of centre of gravity (m)
x_B	longitudinal location of centre of buoyancy (m)
y_B	lateral location of centre of buoyancy (m)
z_B	vertical location of centre of buoyancy (m)
Z_{turn}	force acting on hull during turn (N)
M_{turn}	moment acting on hull during turn (Nm)
u	forward velocity (m/s)
v	sideslip velocity (m/s)
w	vertical velocity (m/s)
υ	cross-flow velocity (m/s) = $\sqrt{(v^2+w^2)}$
p	roll rate (rad/s)
q	pitch rate (rad/s)
r	yaw rate (rad/s)
ϕ	roll angle (rad)
θ	pitch angle (rad)
X_{uu} etc.	hydrodynamic axial force coefficient
Y_{uv} etc.	hydrodynamic side force coefficient
Z_{vv} etc.	hydrodynamic lift force coefficient
K_{ur} etc.	hydrodynamic roll moment coefficient
M_{vv} etc.	hydrodynamic pitch moment coefficient
N_{uv} etc.	hydrodynamic yaw moment coefficient
δb, δs	bow/stern hydroplane angle (rad)
δr	rudder angle (rad)

1. INTRODUCTION

Numerical submarine manoeuvring simulation models have been developed by QinetiQ Haslar over many years for use by the UK Ministry of Defence to set safety and operational constraints for the RN fleet. The developments in technology and the requirements of modern submarines have meant that the simulation tools are being used in areas beyond their validated limits. Experience with full-scale trials and experiments has shown that the quality of the prediction of the manoeuvring envelope of a submarine degrades as the manoeuvre becomes more extreme. Such manoeuvres are typical of situations where the submarine has experienced an emergency due to flooding or a plane jam incident.

Submarine manoeuvring simulation codes have developed from quite simple models that can predict moderate manoeuvres with some accuracy into more complex models that aim to improve the fidelity of simulations of more extreme manoeuvres.

It appears that there are some features of the depth and pitch response of a turning submarine that are not modelled sufficiently accurately. The authors attribute this to the cross-coupling terms in the coefficient based model that are derived from captive model tests. Furthermore, the algorithms used in the simulation tools to estimate the forces on the submarine are essentially not for extreme angles of attack or extremes of propulsor state.

As a result of these shortfalls in the prediction capability, potentially excessive safety factors are applied to Manoeuvring Limitation Diagrams which in turn apply conservative operational limitations on the submarine [1]. In extreme emergency manoeuvres there are complex hydrodynamic flows that may not be amenable to numerical simulation using the existing coefficient based approach. Clearly, it would be advantageous to be able to improve the fidelity of the numerical simulation capability, to reduce the safety factors and potentially relax the operational constraints.

The fidelity of the numerical methods needs to be improved to better understand the forces and moments acting on a manoeuvring submarine. Providing data for these more complex models will potentially require a more extensive experimental test programme; a change to the mathematical model that increases the number of independent variables can dramatically increase the number, and hence the overall duration and cost, of model tests. Thus, new techniques that can reduce the duration of experiments without compromising the quality of the data would be beneficial.

2. THE FORCES AND MOMENTS ON A SUBMARINE

2.1 COEFFICIENT BASED MODELS

The essence of submarine manoeuvring codes is that, for each time step, the state variables associated with the rigid body are equated to the external hydrodynamic forces and moments X, Y, Z, K, M and N. Based on the submarine's mass properties, the forces and moments are converted to accelerations, which are integrated to provide velocities and displacements. The mathematical approach to determining the quasi steady state forces and moments on a manoeuvring submarine are described by Gertler and Hagen [2]. For completeness the equations describing the hydrodynamic forces and moments are presented here.

Axial force

$$\begin{aligned} X' \quad & \left(X_{uu}{}' + X_{vv}{}'v'^2 + X_{ww}{}'w'^2\right) \\ & + \left(X_{\dot{u}}{}'\dot{u}' + X_{vr}{}'v'r' + X_{wq}{}'w'q'\right) \\ & + \left(X_{qq}{}'q'^2 + X_{rr}{}'r'^2 + X_{rp}{}'r'p'\right) \\ & + \left(X_{uu\delta r\delta r}{}'(\delta r)^2 + X_{uu\delta b\delta b}{}'(\delta b)^2 + X_{uu\delta s\delta s}{}'(\delta s)^2\right) \\ & + (B' \quad m'g')\sin\theta \\ & + X_n{}' + X_{wave}{}' \end{aligned}$$

Side force

$$\begin{aligned} Y' \quad & \left(Y_{uu}{}' + Y_{uv}{}'v' + Y_{vw}{}'v'w' + Y_{v\upsilon}{}'v'\upsilon' + Y_{uu\delta r}{}'\delta r\right) \\ & + \left(Y_{\dot{v}}{}'\dot{v}' + Y_{up}{}'p' + Y_{ur}{}'r' + Y_{vq}{}'v'q' + Y_{wp}{}'w'p' + Y_{wr}{}'w'r'\right) \\ & + \left(Y_{v\upsilon|r/v|}{}'v'\upsilon'|r'/v'| + Y_{u|r|\delta r}{}'|r'|\delta r\right) \\ & + \left(Y_{\dot{p}}{}'\dot{p}' + Y_{\dot{r}}{}'\dot{r}' + Y_{p|p|}{}'p'|p'| + Y_{pq}{}'p'q' + Y_{qr}{}'q'r'\right) \\ & + (m'g' \quad B')\sin\phi\cos\theta \\ & + Y_{wave}{}' \end{aligned}$$

Heave force

$$\begin{aligned} Z' \quad & \left(Z_{uu}{}' + Z_{uw}{}'w' + Z_{vv}{}'v'^2 + Z_{uu\delta b}{}'\delta b + Z_{uu\delta s}{}'\delta s\right) \\ & + \left(Z_{w\upsilon}{}'w'\upsilon' + Z_{u|w|}{}'|w'| + Z_{|wv|}{}'|w'v'|\right) \\ & + \left(Z_{\dot{w}}{}'\dot{w}' + Z_{uq}{}'q' + Z_{vp}{}'v'p' + Z_{vr}{}'v'r'\right) \\ & + \left(Z_{w\upsilon|q/w|}{}'w'\upsilon'|q'/w'| + Z_{u|q|\delta s}{}'|q'|\delta s\right) \\ & + \left(Z_{\dot{q}}{}'\dot{q}' + Z_{pp}{}'p'^2 + Z_{rr}{}'r'^2 + Z_{rp}{}'r'p'\right) \\ & + (m'g' \quad B')\cos\phi\cos\theta + Z_{wave}{}' \end{aligned}$$

Roll moment

$$\begin{aligned} K' \quad & \left(K_{uu}{}' + K_{uv}{}'v' + K_{vw}{}'v'w' + K_{v\upsilon}{}'v'\upsilon' + K_{uu\delta r}{}'\delta r\right) \\ & + \left(K_{\dot{v}}{}'\dot{v}' + K_{up}{}'p' + K_{ur}{}'r' + K_{vq}{}'v'q' + K_{wp}{}'w'p' + K_{wr}{}'w'r'\right) \\ & + \left(K_{\dot{p}}{}'\dot{p}' + K_{\dot{r}}{}'\dot{r}' + K_{p|p|}{}'p'|p'| + K_{pq}{}'p'q' + K_{qr}{}'q'r'\right) \\ & + \left(m'g'y_G{}' \quad B'y_B{}'\right)\cos\phi\cos\theta \quad \left(m'g'z_G{}' \quad B'z_B{}'\right)\sin\phi\cos\theta \\ & + K_{wave}{}' + K_n{}' \end{aligned}$$

Pitch moment

$$\begin{aligned} M' = & \left(M_{uu}{}' + M_{uw}{}'w' + M_{vw}{}'v'^2 + M_{uu\delta b}{}'\delta b + M_{uu\delta s}{}'\delta s\right) \\ & + \left(M_{w\upsilon}{}'w'\upsilon' + M_{u|w|}{}'|w'| + M_{|w\upsilon|}{}'|w'\upsilon'|\right) \\ & + \left(M_{\dot{w}}{}'\dot{w}' + M_{uq}{}'q' + M_{vp}{}'v'p' + M_{vr}{}'v'r'\right) \\ & + \left(M_{q\upsilon}{}'q'\upsilon' + M_{u|q|\delta s}{}'|q'|\delta s\right) \\ & + \left(M_{\dot{q}}{}'\dot{q}' + M_{pp}{}'p'^2 + M_{rr}{}'r'^2 + M_{rp}{}'r'p' + M_{q|q|}{}'q'|q'|\right) \\ & \left(m'g'x_G{}' \quad B'x_B{}'\right)\cos\phi\cos\theta \quad \left(m'g'z_G{}' \quad B'z_B{}'\right)\sin\theta \\ & + M_{wave}{}' \end{aligned}$$

Yaw moment

$$\begin{aligned} N' \quad & \left(N_{uu}{}' + N_{uv}{}'v' + N_{vw}{}'v'w' + N_{v\upsilon}{}'v'\upsilon' + N_{uu\delta r}{}'\delta r\right) \\ & + \left(N_{\dot{v}}{}'\dot{v}' + N_{up}{}'p' + N_{ur}{}'r' + N_{vq}{}'v'q' + N_{wp}{}'w'p' + N_{wr}{}'w'r'\right) \\ & + \left(N_{r\upsilon}{}'r'\upsilon' + N_{u|r|\delta r}{}'|r'|\delta r\right) \\ & + \left(N_{\dot{p}}{}'\dot{p}' + N_{\dot{r}}{}'\dot{r}' + N_{p|p|}{}'p'|p'| + N_{pq}{}'p'q' + N_{qr}{}'q'r'\right) \\ & + \left(m'g'x_G{}' \quad B'x_B{}'\right)\sin\phi\cos\theta + \left(m'g'y_G{}' \quad B'y_B{}'\right)\sin\theta \\ & + N_{wave}{}' \end{aligned}$$

Current methods of determining this coefficient set include physical captive model tests, numerical methods or a combination of both. In each case the model or geometry is constrained at a fixed angle of attack with or without the control surfaces at a fixed angle of attack; the resultant forces and moments are then measured or predicted.

2.2 REVIEW OF NUMERICAL METHODS

There are various levels of sophistication associated with the numerical techniques that are available for deriving the quasi steady state forces and moments, ranging from methods involving solutions of the fundamental Navier-Stokes equations to those involving highly idealised methods. The range of techniques can be represented as the schematic in Figure 1. As would be expected, the more sophisticated methods provide the highest level of fidelity but are incredibly complex techniques requiring high levels of computing power.

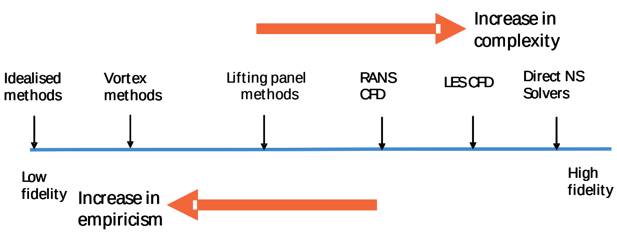


Figure 1: Schematic of numerical techniques

Direct Navier Stokes solvers (DNS) are presently only used by experts within academia, see [3] for example; usually applied to a solution domain that is orders of magnitude smaller than those required for a submarine. A relatively less complex, albeit still computationally intensive, approach is Large-scale Eddy Simulations (LES), see [4] for example. This methodology revolves around the use of large-scale eddies that are associated with the geometry of the submarine. The benefit of this approach is the ability to describe the evolution of vortices and how they impact downstream on the submarine hull or appendages.

The Reynolds-Averaged Navier Stokes solvers (RANS) approach attempts to time-average the Navier Stokes equation by defining the instantaneous velocity components and pressure to be the sum of a mean component and a fluctuating component, see [5]. One issue associated with these CFD techniques is that a significant amount of effort is still required to create a satisfactory grid for the fully appended submarine.

A level of fidelity down from full Navier Stokes type techniques are inviscid methods, [6] for example, which assumes the viscosity is set to zero and so the Navier Stokes equations can be simplified significantly. These types of methods can be generally successful for hulls at modest angles of attack, but break down for any significant manoeuvre. In these instances, the increase in force with angle of attack becomes strongly non-linear due to the centre of pressure moving aft as a result of the flow separation. Thus, the non-linearities present in the moment have different characteristics to the underlying force.

This inability to identify accurately the position of flow separation can influence greatly the resulting prediction of forces and moments. Indeed, much of the data relating to separation points are derived from experiments and thus contain, to a certain extent, embedded empiricism.

Mathematical models with even greater simplification than lifting panel methods are vortex methods and purely idealised methods utilising classical theories. These methods are heavily dependent upon empirical data with the forces and moments on the hull determined using empirical expressions derived from experiments on a standard series such as bodies of revolution with varying fineness ratios and prismatic coefficients.

The obvious limitation of such methods is that any predictions of forces and moments on a submarine based on the empirical expressions must be evaluated in the context of how similar the hull form is to those used in that empiricism.

So, at the present time, physical model experiments remain a necessity for generating the majority of the coefficients which populate the mathematical model.

2.3 CONSTRAINED MODEL EXPERIMENTS

The concept of a constrained model experiment is simple and well-established. Internal instrumentation consists of a strain-gauge balance capable of measuring the forces and moments acting on the body in all six degrees of freedom.

The model is towed in a Ship Tank at a range of body incidences in both the horizontal and vertical plane. This provides the relationship between the forces, moments and velocities. Then, with the model straight and level, the various control surfaces are exercised over their working range to measure forces and moments generated. Typically, the model is then transferred to a Rotating Arm where the forces and moments due to rotational velocities are established.

The data from the two sets of experiments are combined and a least-squares regression is performed to provide the coefficients for the mathematical model.

The choice of range and combinations of rates and angles is generally determined by the form of the mathematical model. Some combinations cannot be physically achieved by a towed model. For example, despite there being an N_{vw}' coefficient in the numerical model, it is not easily possible to generate simultaneous vertical and horizontal velocities. This is where the numerical techniques have been used to provide an insight into the significance of such terms.

2.4 FREE MANOEUVRING MODEL EXPERIMENTS

The conduct of free-manoeuvring model experiments can fulfil several purposes, including:

- confirmation of basic manoeuvring parameters such as turning circles and zig-zag overshoots
- a measure of performance in waves
- confirmation of autopilot performance in a real-time, non-linear environment [7]
- providing manoeuvring data for simulation validation

The QinetiQ Submarine Research Model (SRM) is capable of all the above, but is chiefly used for exploring the extremes of the manoeuvring envelope [1]. Since that reference, the SRM has undergone a significant upgrade to its systems, improving functionality and operability.

Accurate motion measurements (angles and angular rates) continue to be provided by a Ring Laser Gyro (RLG). For the most recent experiment programme, the RLG was augmented with a Doppler Velocity Log (DVL) which provides accurate 3-dimensional velocity measurements. Integration of these velocities provides a reconstruction of the model's track, as demonstrated in Figure 2, which shows the model returning to within 1 m of the launch position, following a run in excess of 1400 m.

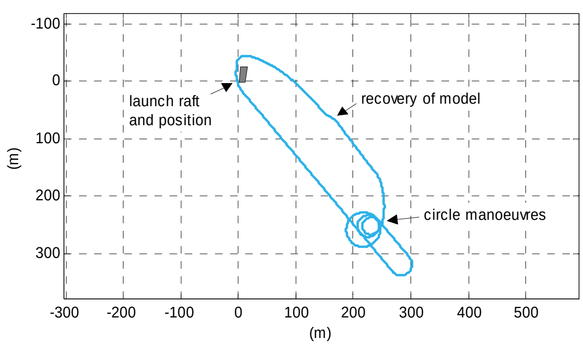


Figure 2: Reconstructed track using DVL output

Free-manoeuvring experiments are not routinely used for direct measurement of the forces and moments acting on the body. However, with accurate trajectory information, techniques are being developed which allow the reconstruction of the forces and moments acting on the body at each instant in time.

3. MODELLING CROSS-COUPLING BEHAVIOUR

The term cross-coupling refers to the vertical force and moment acting on the body during a horizontal plane turn, sometimes referred to as the out-of-plane force and moment.

3.1 CURRENT MATHEMATICAL MODEL

In the model of Gertler and Hagen [2], the force and moment are assumed to be the following functions of side-slip velocity, *v*, and yaw rate, *r*:

$$Z_{turn} = Z_{vv}v^2 + Z_{vr}vr + Z_{rr}r^2$$
$$M_{turn} = M_{vv}v^2 + M_{vr}vr + M_{rr}r^2 \quad (1)$$

The form of these equations dictates the particular constrained experiments to be conducted in order to determine the coefficients. This case requires a range of pure side-slip velocities (or drift angles) on a Ship Tank carriage, a range of pure yaw rates on a Rotating Arm, and combinations of drift angles and yaw rates, also on the Rotating Arm. A regression on the full set of measurements then yields the coefficients. An example is plotted in Figure 3, showing the measurements and curve fits from a typical experiment.

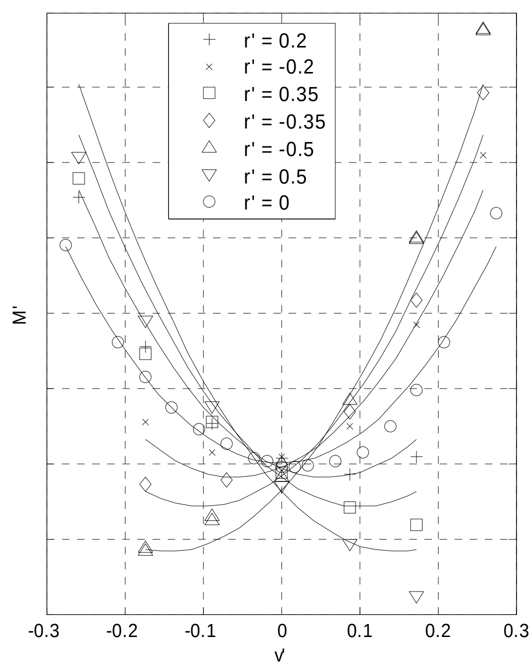


Figure 3: Example measurement of M' as a function of v' and r'

3.2 INITIAL OBSERVATION

A routine test programme consists of constrained model experiments to determine the coefficients which populate the mathematical model. This is followed by free-running model experiments to explore the manoeuvring performance, such as turning circles, autopilot response and depth-keeping under waves. This data is also used for simulation validation.

During one such programme the free-running model experiment included some free-turns. These are open-loop manoeuvres which apply a fixed rudder angle without any depth control during the turn. Following the natural excursions, the hydroplanes are re-activated and the turn continues under depth control.

Simulations of these manoeuvres using the coefficients derived from the constrained model experiments predicted far greater pitch and depth excursions than those demonstrated by the free-running model. There was historical evidence that previous data sets had required modifications to the cross-coupling coefficients, but for this programme, a rigorous method and justification were required.

The first assessment of the cross-coupling coefficient model was to explore a range of variations around the nominal values and observe their effect on the prediction of the pitch and depth response in the free turns.

It was observed for several runs that the coefficients which gave the best prediction of pitch and depth in the open-loop part of the turn did not predict the correct hydroplane angles required to subsequently maintain depth. Conversely, coefficients could be found which predicted the hydroplane angles in the controlled part of the turn, but did not exhibit the open-loop excursions.

Figure 4 plots an example of the experiment data and simulations with the two different modifications to the cross-coupling coefficients.

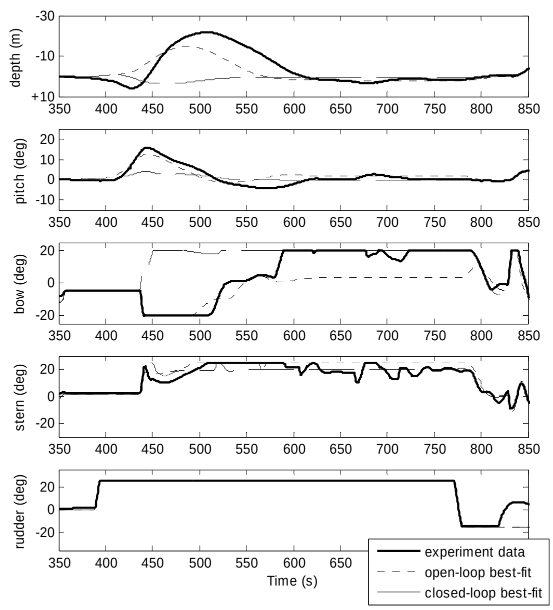


Figure 4: Effect of revised coefficients on open-loop and closed-loop predictions

On the assumption that the open-loop modification is correct (there are no other terms in the mathematical model which affect depth and pitch in a turn), the conclusion was that the sternplane effectiveness on the free-running model must have been greater than that predicted by the simulation. However, for straight-line running and depth changing, simulations agreed very well with the experiment data, including the hydroplane angles required to achieve those trajectories. Any enhanced sternplane effectiveness must therefore only occur in a turn.

There is no coefficient in the mathematical model to account for this, nor were any constrained model tests conducted on a Rotating Arm to explore sternplane effectiveness during a turn. However, it is considered that due to the magnitude of the drift angle during a turn, the aft end of the submarine has a higher local velocity through the water than the centre, and therefore there is a greater flow over the stern hydroplanes.

3.3 REVISED FORMULATION

The current mathematical model assumes that the sternplane lift is proportional to forward velocity (*u*) squared, and is calculated using

$$Z = Z_{uu\delta s} u^2 \delta s \qquad (2)$$

Taking into account the local velocity, an alternative calculation is

$$Z = Z_{uu\delta s}\left(\sqrt{u^2 + v^2} - |r| x_{\delta s}\right)^2 \delta s \qquad (3)$$

where v is the sideslip velocity, r is the yaw-rate and $x_{\delta s}$ is the effective longitudinal location of the stern hydroplanes.

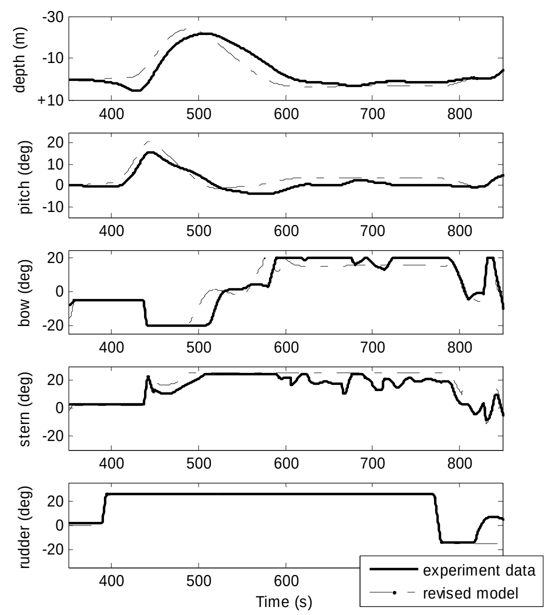


Figure 5 : Effect of revised stern hydroplane model

By making these changes to both the lift and moment calculations for the stern hydroplanes, and re-running the simulation with the original cross-coupling coefficients, the results for the example are plotted in Figure 5.

There is still a little over-prediction of the depth and pitch excursions, but there is now far better agreement for both the open-loop and closed-loop phases of the run.

4. IDENTIFICATION OF CROSS-COUPLING FORCE AND MOMENT FROM FREE-RUNNING MODEL DATA

The closed-loop depth-controlled turns, if run for a sufficiently long period to obtain steady state conditions, provide enough information to calculate the cross-coupling force and moment acting on the hull. In part, this is due to the control algorithm in use, which guarantees that the ordered depth is maintained at zero pitch angle. In this condition, the following equations hold (incorporating equation (3)):

$$\begin{aligned} -Z_{turn} &= Z_{uu}u^2 + Z_{uw}uw + Z_{uu\delta b}u^2\delta b \\ &+ Z_{uu\delta s}\left(\sqrt{u^2+v^2} - |r|x_{\delta s}\right)^2 \delta s \\ &+ \left(Z_{uq} + m + \Delta m\right)uq + \Delta mg\cos\phi\cos\theta \\ -M_{turn} &= M_{uu}u^2 + M_{uw}uw + M_{uu\delta b}u^2\delta b \\ &+ M_{uu\delta s}\left(\sqrt{u^2+v^2} - |r|x_{\delta s}\right)^2 \delta s \\ &+ M_{uq}uq - x_g\left(m + \Delta m\right)g \end{aligned} \tag{4}$$

where Z_{turn} and M_{turn} are the unknown force and moment acting on the hull as a result of turning.

Note that in a steady turn, although the depth and pitch are constant, there are non-zero values of w and q in body axes due to the steady roll angle (ϕ).

$$\begin{aligned} w &= -v\tan\phi \\ q &= \quad r\tan\phi \end{aligned} \tag{5}$$

In order to provide data points for equation (4), the SRM was programmed to conduct turning circles at three different speeds, using three different rudder angles to both port and starboard.

The steady state values of all the contributing parameters were extracted for each turn, and the right-hand side of equation (4) tabulated for each combination of speed and rudder angle.

4.1 FITTING A MODEL TO THE DATA

The standard cross-coupling model of equation (1) calculates the force and moment as functions of sideslip velocity, v, and yaw rate, r. Manoeuvring measurements show that there is such a strong correlation between v and r that it is not possible to separate out the effects of these two variables independently (as can be done with a constrained model). Therefore, this analysis considers the force and moment as a function of a single parameter, v.

The measured force data points are plotted in Figure 6, with the moment data points in Figure 7.

The equations of the best fit lines are given by:

$$\begin{aligned} Z_{turn}' &= Z_{vv}' v' v' + Z_{u|v|}' u' |v'| \\ M_{turn}' &= M_{vv}' v' v' + M_{u|v|}' u' |v'| \end{aligned} \tag{6}$$

This formulation provides a reasonable fit to each of the data sets analysed.

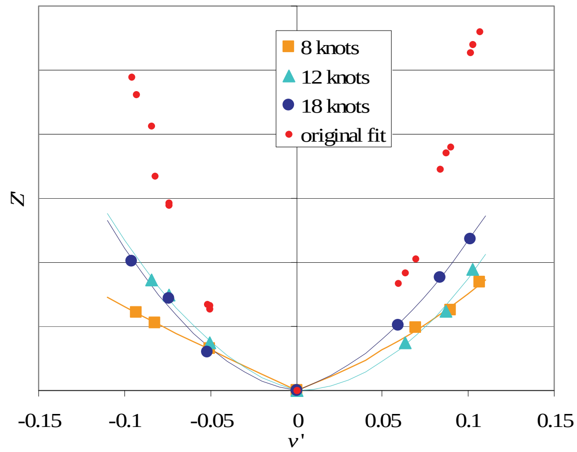


Figure 6 : Z' as a function of v'

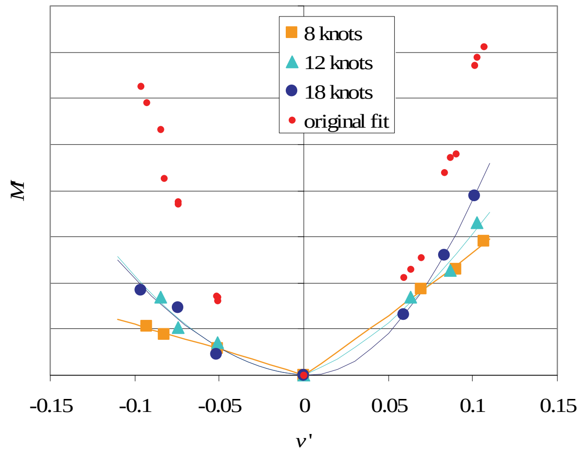


Figure 7 : M' as a function of v'

The results confirm that the current mathematical model, with the coefficients derived from the constrained model experiments, does over-predict the force and moment when turning. The low speed (8 knot) runs show different characteristic curve-fits compared with the 12 and 18 knots results. There is also a noticeable port/starboard asymmetry.

The results do suggest that at the higher speed, the forces and moments are approaching the captive model measurements. The constrained model runs were carried out at around 3 m/s, significantly faster than the free-manoeuvring runs. The assumption that the cross-coupling coefficients are independent of forward speed may therefore not be valid, although there are scaling issues to be addressed.

The comparison of model-scale and full-scale trajectories over a wide range of manoeuvres remains an area of active research. As an experiment technique, this method of deriving a mathematical model of the cross-coupling behaviour has proved successful, with simulations of turning performance greatly improved.

5. RAMP TESTS

The approach described in section 2.1 is based upon the assumption that the external fluid forces can be modelled using the hydrodynamic coefficients described and these coefficients can be conveniently non-dimensionalised with respect to density, submarine length and speed.

When a submarine undergoes braking, the submarine itself may still have forward speed but the propulsor will be going astern.

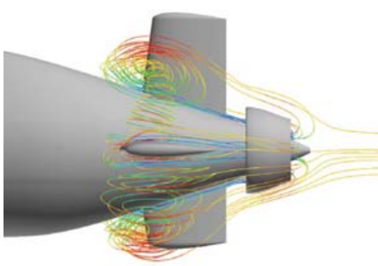


Figure 8: Velocity streamlines during astern RPM

Figure 8 illustrates the effect of increasing astern RPM. It is clear that the flow due to the propulsor running astern creates a complex vortex structure which moves further forward as the RPM gets more negative. This astern RPM modifies the flow of water through the propulsor but moreover over the stern area which in term changes the forces and moments induced by the flow. Thus, some of the coefficients are also dependent upon the state of the propulsor or n' defined as:

$$n' = \frac{Instantaneous\ rpm}{rpm\ for\ self\ \ propulsion\ at\ instantaneous\ speed}$$

So, under braking, n' will be negative becoming more negative as the submarine slows down. The approach used by [2] to modelling this n' dependency is by introducing further coefficients as follows:

Axial force

$$X_{vv}' = X_{vv0}' + (n' \quad 1)X_{vvn}'$$

$$X_{ww}' = X_{ww0}' + (n' \quad 1)X_{wwn}'$$

$$X_{uu\delta u\delta r}' = X_{uu\delta r\delta r0}' + (n' \quad 1)X_{uu\delta r\delta rn}'$$

Sway force

$$Y_{uv}' = Y_{uv0}' + (n' \quad 1)Y_{uvn}'$$

$$Y_{ur}' = Y_{ur0}' + (n' \quad 1)Y_{urn}'$$

$$Y_{vv}' = Y_{vv0}' + (n' \quad 1)Y_{vvn}'$$

$$Y_{uu\delta r}' = Y_{uu\delta r0}' + (n' \quad 1)Y_{uu\delta rn}'$$

Heave force

$$Z_{uw}' = Z_{uw0}' + (n' - 1)Z_{uwn}'$$

$$Z_{uq}' = Z_{uq0}' + (n' - 1)Z_{uqn}'$$

$$Z_{wv}' = Z_{wv0}' + (n' - 1)Z_{wvn}'$$

$$Z_{uu\delta s}' = Z_{uu\delta s0}' + (n' - 1)Z_{uu\delta sn}'$$

Roll moment

$$K_{uu}' \quad K_{uu0}' + (n' \quad 1)K_{uun}'$$

Pitch Moment

$$M_{uw}' \quad M_{uw0}' + (n' \quad 1)M_{uwn}'$$

$$M_{uq}' \quad M_{uq0}' + (n' \quad 1)M_{uqn}'$$

$$M_{wv}' \quad M_{wv0}' + (n' \quad 1)M_{wvn}'$$

$$M_{uu\delta s}' \quad M_{uu\delta s0}' + (n' \quad 1)M_{uu\delta sn}'$$

Yaw moment

$$N_{uv}' = N_{uv0}' + (n' \quad 1)N_{uvn}'$$

$$N_{ur}' = N_{ur0}' + (n' \quad 1)N_{urn}'$$

$$N_{vv}' = N_{vv0}' + (n' \quad 1)N_{vvn}'$$

$$N_{uu\delta r}' = N_{uu\delta r0}' + (n' \quad 1)N_{uu\delta rn}'$$

The above equations are valid for $1 \geq n' \geq -1$. Beyond these limits the coefficients become effectively saturated at the values of $n' = -1$ or 1 as appropriate.

However, in order to understand the variation of the coefficients that have n' dependency, a series of experiments or predictions are required to be undertaken over a range of *n*' values. Described here are the results of a set of experiments undertaken whereby the range of the fixed *n*' was varied between -5 and +2 for a range of constrained model conditions. Furthermore, additional runs were undertaken where the propulsor state was varied over the course of a single tank run as shown in Figure 9.

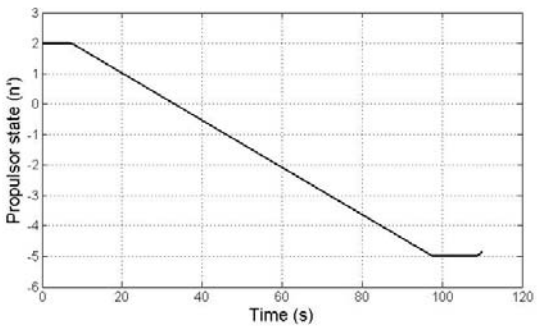
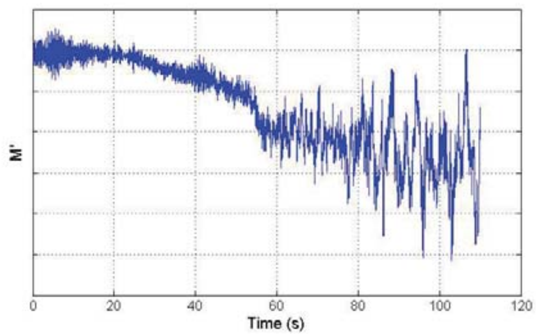
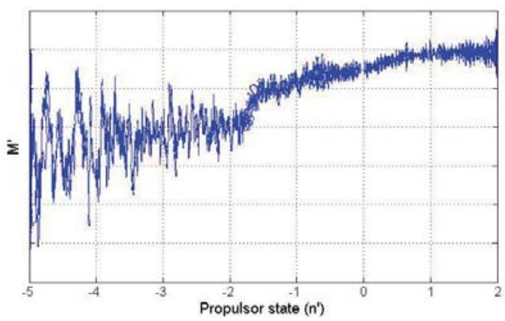


Figure 9: Example of *n'* profile for ramp tests

In general, a ramp test consisted of a steady start of 10 seconds at *n*'=2 followed by a steady reduction in RPM of over a 90 second period to *n*'=-5 for a 10 second steady end to the run. A number of these ramp tests were conducted to investigate the extent to which they replicate the more traditional steady state tests. The exact approach to analysing these kinds of ramp test data is unclear but this section describes a potential methodology.



(a) *M'* plotted against time



(b) *M'* plotted against propulsor state

Figure 10: Variation of *M'* during a ramp test

Figure 10 shows the non-dimensional pitch moment measured for the case where the aft appendages are creating a pitch moment. In Figure 10(a) the variation in *M'* is plotted against time, but in fact the propulsor state is becoming more negative as time increases. Thus, *M'* is re-plotted in Figure 10(b) as a function of *n*'.

Both graphs in the figure show that as *n'* becomes more negative the variation in the measured pitch moment becomes greater. This is no surprise since the flow regime is becoming much more unsteady in nature as the propulsor is running with greater astern RPM.

The first stage in the analysis process was to filter, quite aggressively, the measured time history. This was done using a 2nd order low pass Butterworth filter with a cut-off frequency of 0.5 Hz. This filter design was chosen through trial and error, in an attempt to remove the higher frequency mechanical noise yet maintain the mid-range frequencies that are probably due to hydrodynamic noise as a result of the unsteady nature of the flow. Figure 11 shows an example of unfiltered measured *M'* compared with the filtered data using the above filter design. The higher frequency noise components have been removed but the variations at lower values of *n*' still remain.

The obvious question is how do these filtered results from the ramp tests compare with the mean values taken from the traditional steady state tests?

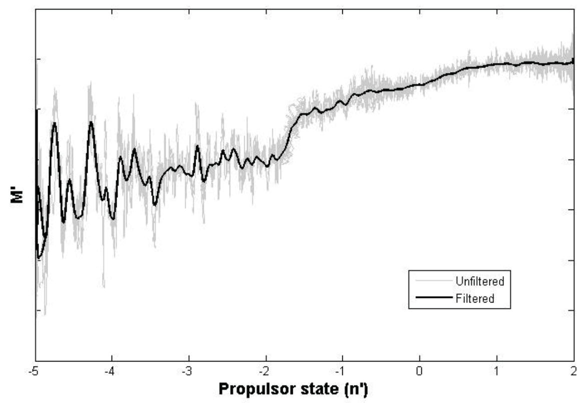


Figure 11: Example of filtered and unfiltered *M'*

Figure 12 shows the results of each of the filtered forces and moments taken from the same ramp test compared with the appropriate steady state tests. It is very encouraging to see how closely the ramp tests agree with the steady state tests. The comparisons are even favourable for quite extreme values of negative *n*'. This example was by no means unique; similar results were reflected across the whole range of ramp tests undertaken.

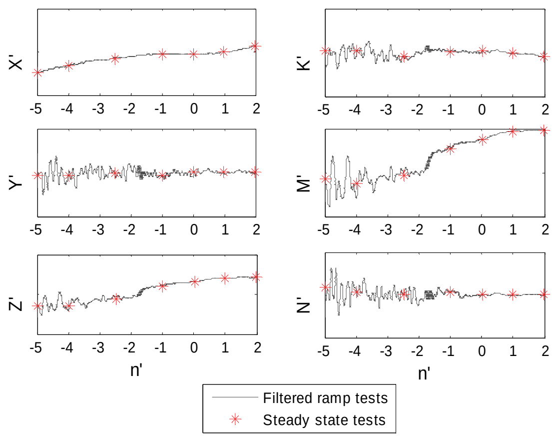


Figure 12: Ramp and steady state tests

Thus, it appears very encouraging that ramp tests can reliably replicate the results from steady state tests. The logical conclusion to this work is that in principle one ramp test could be used to replace up to 7 steady state astern RPM tests.

If this is the case, the next issue is how this data can be used to determine the standard hydrodynamic coefficients that are traditionally obtained from steady state tests. Again, there is no pre-defined mechanism for doing this so the method developed here was to extract a mean value from the ramp test results for a series of *n'* values. This was done by extracting, for a pre-defined value of *n'*, the 10 nearest points in the ramp test time history and taking a mean. This process was repeated for a range of *n'* values from 2.0 to -5.0 in steps of 0.5.

This gave a series of discrete force and moment measurements that were then analysed using the same regression techniques as those which derive the standard set of coefficients. Figure 13 shows the results of this exercise for the after hydroplane coefficients for heave force and pitch moment. The figure shows the traditional hydrodynamic coefficients derived from the steady state tests using the standard regression techniques compared with the same coefficients derived from the ramp test data.

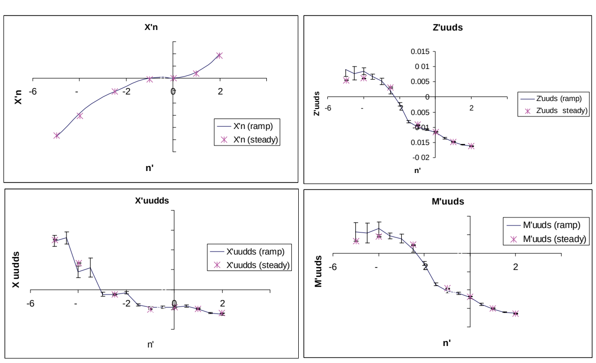


Figure 13: Sternplane coefficients derived from ramp tests

The agreement is very good; 7 ramp tests were used to derive these results compared with the 49 steady state tests conducted. Indeed, the ramp tests give far more information since, because of the extraction process described above, the number of discrete cases of *n*' is higher than the steady state tests. Thus, more information is gained especially over the key area where the astern RPM causes the reverse flow to move across the after hydroplanes.

Figure 14 shows the same results for the tests using the rudder to create a side force and yaw moment. Again the comparisons between the results derived from ramp tests and steady state tests are very good across the whole range of *n*' values. Even at the most extreme values of negative *n*' the comparisons are favourable.

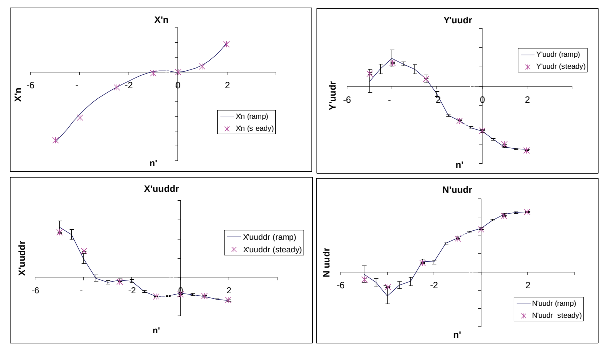


Figure 14: Rudder coefficients derived from steady state and ramp tests

8. CONCLUSIONS

This paper has described the recent development of two different experiment techniques, each with the aim of improving the understanding of submarine manoeuvring characteristics in regimes where simulation codes are known to predict behaviour poorly.

Comparisons between constrained model measurements and free-manoeuvring model behaviour indicate that, for depth and pitch responses in a turn, the former does not predict the latter. The reason for this is not understood. Predictions are improved if the effectiveness of the stern hydroplanes is assumed to increase in a turn. The technique described here allows a cross-coupling model to be determined from free-manoeuvring model experiments. Results obtained by this method show a distinct port/starboard asymmetry and a dependence on forward speed, neither of which is captured by the existing standard coefficient model.

As mathematical models are developed to capture the behaviour of increasingly extreme manoeuvres, the increase in the number of independent parameters can lead to a prohibitively long constrained model experiment programme. The use of ramp tests, where the RPM is varied throughout a run has been shown to replace several individual runs, at fixed RPM settings, with a high degree of accuracy.

The constrained model and free-manoeuvring model experiments have been backed up in recent years by comprehensive full-scale trials to "close the loop", providing correlation between model-scale and full-scale behaviour, and creating a wealth of data for simulation validation and mathematical model development.

The overall aim of improving simulation codes is to maintain fidelity in the prediction of submarine manoeuvres, particularly in emergency scenarios such as a flood or hydroplane jam. By having confidence in the mathematical model, the safe operational limits become better defined. This should lead to a reduction in any conservative safety margins and an opening up of the operational envelope.

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Any views expressed are those of the authors and do not necessarily represent those of QinetiQ ltd.

10. REFERENCES

1. HAYNES D., BAYLISS J., HARDON P., 'Use of the Submarine Research Model to Explore the Manoeuvring Envelope', *RINA Warship 2002, Naval Submarines 7*, June 2002.

2. GERTLER, M., HAGEN, G., 'Standard Equations of Motion for Submarine Simulation'. *NSRDC Report No. 2510*, June 1967.

3. SHAN, H., JIANG, L., LIU, C., 'Direct numerical simulation of flow separation around a NACA 0012 airfoil', *Computers & Fluids 34 (2005) 1096–1114.*

4. KIM, H. J.,LEE S., FUJISAWA N., 'Computation of unsteady flow and aerodynamic noise of NACA0018 airfoil using large-eddy simulation', *International Journal of Heat and Fluid Flow 27 (2006) 229–242.*

5. HABASHI, W., 'Solution Techniques for Large-Scale CFD Problems', *Wiley and Sons, Chichester*, 1994.

6. HESS, J.L. AND SMITH, A.M.O., 'Calculation of Non-Lifting Potential Flow about Arbitrary Three-Dimensional Bodies', *Journal of Ship Research, Vol. 8, No 3, pp22-24*, 1964.

7. KIMBER N., 'The Role of Submarine Model Testing in Controller Design', *RINA Warship 2002, Naval Submarines 7*, June 2002.

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MANOEUVRABILITY OPTIMISATION FOR THE NAVANTIA S-80 SUBMARINE PROGRAMME

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SUMMARY

The object of this paper is to describe the manoeuvrability optimisation process for the new S-80 Submarine programme awarded by the Spanish Ministry of Defence to Navantia. The S-80 Submarines will have performances, in ocean-going force projection and "blue water" warfare scenarios, only available in current nuclear-powered attack submarine (SSN), including a three-weeks anaerobic ranging and the ability to fire submerged land-attack cruise missiles. This new concept in conventional Submarine has been addressed to have an excellent compromise in manoeuvrability requirements, specially the stealthy and littoral water performance, including bottoming.

In this way, Navantia commissioned SSPA to carry out a complete set of manoeuvring tests to firstly obtain the hydrodynamic coefficients and then to investigate the vessel controllability, course keeping and depth capability. Later, external analyses showed as correct and consolidate the preliminary design decisions. For the preliminary studies, Navantia has developed a six-degree of freedom manoeuvring Simulation Code, named "SIMUSUB", sufficient to test the estimated hydrodynamic coefficients in a large set of tactical scenarios and rudder, "X" and "cross", configurations. The Navantia "SIMUSUB" Code presents a classical linear quadratic optimal control theory as the kernel of the simulated autopilot.

Navantia is currently developing, with the collaboration of the UPCt University (Cartagena, Spain), an innovative autopilot model based in the nonlinear controllability theory. This autopilot will be able to adjust the exact minimum energetic (acoustic) cost for any tactical manoeuvring decision.

1. INTRODUCTION

The main missions of the S80 submarine can be summarized in:

Ocean going and littoral operations:

- Surface ships warfare, sub to surface missiles
- Antisubmarine warfare, torpedo strike
- Land attack, tactical missiles
- Intelligence gathering
- Special forces insertion
- Civil personnel rescue

An analysis of the mission scenario in relation with the manoeuvrability shows the necessity of stealthiness respect to the operation in littoral waters, that imply to try to reduce as much as possible the acoustic signature.In relation with the manoeuvrability, one of the designers work shall be to design the control surfaces in such manner that minimum rudders and planes motions occurs for course keeping and depth keeping, in this case the inherent stability in both horizontal and vertical planes of motion are needed.

In second term excellent controllability properties are desirable in the sense of obtaining the wider possible Safety Operating Envelope especially, as mentioned, in shallow water littoral operations, in such way that the tactical motion possibilities increases.

Also for reaching successful tactical missile launching both course keeping and depth keeping abilities are expected for the platform, by this way the launching window will be less performance demanding for the launching equipment, and so shorter noisy periods during launching are foreseen, together with a saving of space inside the torpedoes room.

But what are the common figures in terms of the parameters governing stability and controllability for a typical SSK?.

First of all let's clarify the concepts used regarding stability and controllability parameters.

2. STABILITY AND CONTROLLABILITY. LINEAR MODEL

The mathematical model of the submarine can be established following the Newton 2nd law and the kinetic moment theorem:

$$\sum \overline{F}_{ext} = M.\overline{a}_G,$$

$$\frac{d\,\overline{H}_G}{dt} = \overline{N}_{Fext},$$

Assuming a three axis orthogonal reference system moving along with the submarine where the origin is arbitrarily taken, the expression for the absolute acceleration of a point of the submarine taken as rigid solid, for instance the centre of gravity is as follows:

$$\bar{a}_G \quad \bar{a}_O + \bar{\Omega} \wedge \bar{V}_O + \bar{\alpha} \wedge \bar{r}_{OG} + \bar{\Omega} \wedge \left(\bar{\Omega} \wedge \bar{r}_{OG}\right)$$

Where:

$\bar{\Omega}(p, q, r)$, is the instantaneous angular speed.

$\bar{\alpha}(\dot{p}, \dot{q}, \dot{r})$, is the instantaneous angular acceleration.

$\bar{a}_O(\dot{u}, \dot{v}, \dot{w})$, is the drag acceleration

$\bar{V}_O(u, v, w)$, is the drag speed

In the Linear approximation the expression can be reduced to:

$$\bar{a}_G = \bar{a}_O + \bar{\Omega} \wedge \bar{V}_O$$

The expression for the Kinetic moment is:

$$\bar{H}_G = \{I\}\{\bar{\Omega}\}$$

Where $\{I\}$ is the inertia matrix and

$\{\bar{\Omega}\}$ is the instantaneous angular speed vector

Finally using the simplified equation for the absolute acceleration, deriving the before written expression and avoiding second order inertia products the equations can be written as follows:

$$m\,\dot{u} = \sum X \qquad (1)$$

$$m\left(\dot{v} + ru\right) = \sum Y \qquad (2)$$

$$m\left(\dot{w} - qu\right) = \sum Z \qquad (3)$$

$$I_{xx}\,\dot{p} = \sum K \qquad (4)$$

$$I_{yy}\,\dot{q} = \sum M \qquad (5)$$

$$I_{zz}\,\dot{r} = \sum N \qquad (6)$$

This system of equations is the submarine linear equations of motion in movable axes.

The right term of the equations are the resultant of the total forces and torques applied on the submarine in all the three components of the reference axes, including:

Hydrodynamic forces and torques.
Propulsion Forces, (first equation).
Forces and torques due to control actions.

The horizontal plane equations are (2) and (6), and that for the vertical plane (3) and (5).

To analyze the equations it is necessary to properly describe the forces and moments in the second term. The most frequent approximation is based on the dimensional analysis where the inertia forces appear as proportional to the square of a characteristic speed (lift forces, drags, etc). The known approach used in the cases where the forces are basically defined as orthogonal to the characteristic speed, (the advance speed) is called that of the hydrodynamic derivatives.

Writing the equations in non-dimensional form and deleting the control terms, (terms with "δ"), because the aim is to analyse the submarine natural (non-forced) response for the stability study, the result is:

Horizontal Motion:

- $\left(m' - Y'_v\right)\dot{v}' - Y'_v\,v' + \left(m' - Y'_r\right)r' = 0$ (7)
- $\left(I'_{zz} - N'_r\right)\dot{r}' - N'_v\,v' - N'_r\,r' = 0$ (8)

Vertical Motion:

- $\left(m' - Z'_w\right) - Z'_w\,w' - \left(m' + Z'_q\right)q' = 0$ (9)
- $\left(I'_{yy} - M'_q\right)\dot{q}' - M'_w\,w' - M'_q\,q' + \dfrac{\overline{GB}\,\theta\,g}{u^2} = 0$ (10)

Where:

Z'_i, Y'_i, M'_i, N'_i, etc. are the hydrodynamic derivatives of vertical and transverse forces, and the torques around transverse and vertical axes and in non dimensional form.

Solving both systems for instance, by using the method of D operator, the linear differential equations in constant coefficients are obtained:

<u>Horizontal</u>

$a\ddot{v} + b\dot{v} + cv = 0$

Characteristic equation:

$a\sigma^2 + b\sigma + c = 0$

Where:

- $a = \left(I'_{zz} - N'_r\right)\left(m' - Y'_v\right)$
- $b = \left(I'_{zz} - N'_r\right)Y'_v - N'_r\left(m' - Y'_v\right)$
- $c = N'_r\,Y'_v + \left(m' - Y'_r\right)N'_v$

Vertical

$$A\dddot{q} + B\ddot{q} + C\dot{q} + D = 0$$

Characteristic equation:

$$A\sigma^3 + B\sigma^2 + C\sigma + D = 0$$

Where:

- $A = (m' - Z'_w)(I'_{yy} - M'_q)$
- $B = [Z'_w (I'_y - M'_q) + M'_q (m' - Z'_w)]$
- $C = \left[Z'_w \ M'_q - M'_w \ (m' + Z'_q) + (m' - Z'_w) \frac{m'}{u^2} \overline{GB}\, g \right]$
- $D = -Z'_w \ m' \frac{\overline{GB}\, g}{u^2}$

As can be easily deduced the solution of the characteristic equation in the vertical plane depends of the submarine speed, due to the hydrostatic torque term.

2.1 STABILITY CRITERIA

Horizontal plane

To obtain an inherently stable submarine in the horizontal plane, the solutions of the characteristic equation must be real and negative, for that the Routh-Hurwitz criteria (ref. [2]) establish:

$c > 0$

Vertical Plane

In this case the Routh-Hurwitz criteria are as follows:

$B > 0$

$C > 0$

$BC > AD$

Where A, B, C and D have been previously defined.

The characteristic roots are of two types:

Real negative at high speed.

Complex roots with negative real part at low speed.

At low speed the complex coefficient roots implies oscillatory motions with dampened amplitude, so a new coefficient is defined, the damping. Whose typical values are between 0.7- 1 or 0.6-0.8 depending on the authors.

2.2 STABILITY AND CONTROLLABILITY INDEXES

Apart from the mathematical stability study, the best way to analyse the design decisions using the linear equations of motion is through the use of a set stability and controllability indices, a set of these are for instance those in the table 1 coming from ref (2).

The controllability indices compares the control forces and torques with the corresponding hydrodynamic forces and torques, so they are directly related to the response accelerations.

Also in the table are indicated the main influence of the controllability parameters, useful for addressing the design decisions.

2.3 DESIGN DECISSIONS

The early design decisions when sizing and arranging the submarine control surfaces of a submarine are of vital importance especially for saving time and cost especially during the validation study which starts necessarily with the corresponding towing tank manoeuvrability test and simulations.

In the case of the S80 the decisions were:

-Rudders and aft planes in cross configuration

-Fwd planes in the fin

-Sufficient inherent stability which could guarantee successful depth keeping and course keeping with minimum actuation of planes, and so less noise generated, but in such way that the submarine responses will not be too stiff.

-Critical speed enough below the patrol speed

-Robust Horizontal control movements

-Moderate vertical control movements, especially to avoid high depth excursions in case of an aft planes jam.

In table 1 the typical values for a conventional submarine and the design decisions related to them for the S80 are shown.

Denominat ion	Definition	Typical SSK figures	S-80 Design Decisio ns	Commen t *[Ref (2)]*
Horizontal Index	$G_H \quad 1 + \frac{(m' - Y'_r) N'_v}{Y'_v N'_r}$	< 0,1	> 0,3	Near to upper limit
Vertical Index	$G_V \quad 1 - \frac{M'_w (m' + Z'_q)}{M'_q Z'_w}$	< 0,3	> 0,3	Above upper limit
Heave coefficient	$\frac{Z'_{\delta s}}{\frac{L}{10^3}(Z'_w - m')}$	~ 2,5	> 3	Nearer upper limit
Pitch coefficient	$\frac{M'_{\delta s}}{\frac{L}{10^3}(M'_q - I'_{yy})}$	~ 0,3	> 0,4	Above upper limit
Heave coefficient	$\frac{Z'_{\delta b}}{\frac{L}{10^3}(Z'_w - m')}$	~ 3	> 3	Typical increme nt
Pitch Coefficient	$\frac{M'_{\delta b}}{\frac{L}{10^3}(M'_q - I'_{yy})}$	> - 0,2	> - 0,2	Intermed iate
Sway coefficient	$\frac{Y'_{\delta r}}{\frac{L}{10^3}(m' - Y'_v)}$	~ 4	> 4	Near to upper limit
Yaw coefficient	$\frac{N'_{\delta r}}{\frac{L}{10^3}(N'_r - I'_{zz})}$	~ 0,5	> 0,5	Nearer upper limit

Table 1. Comments for S80 figures from [Ref (2)].

X rudders configuration was not selected due the fact that to this configuration is based on symmetry, but the final arrangement on the ship normally can not be completely symmetrical so added complexity in control to a more difficult arrangement of the submarine stern are expected, on the other hand it is considered the cross configuration as more intuitive from the point of view of the control surfaces movement and design.

Regarding the forward planes in the fin, the arrangement of the submarine and the inherent disadvantages of the forward planes located in the forward body, firstly gear and hydrodynamic noise which could produce interferences with the sonar, and vortices generation which could disturb the efficiency of the aft planes, or if shifted up or down from the horizontal centre waterline, the hydrodynamic radiated noise increases.

2.4 VALIDATION PROCESS

It is clear that for a successful strategy for the control surfaces design it is necessary the utilization of a linear and not linear mathematical model of the submarine motion. In such way the design decisions are checked against the corresponding manoeuvres simulations in real time.
For that purpose Navantia developed the "SIMUSUB" code for the dynamics of the submarine, the code can work in either real time or in calculation time for speeding up the analysis. The code is briefly described in later on in this paper.

The linear approach to the motion equations is used for stability analysis and simulations with the automatic pilot model, and the non linear approach for more complex simulations like aft planes jam or flood recovery trajectories.

The "SIMUSUB" code was previously validated by using the results obtained in SSPA Towing Tank for test and simulations carried out for a Navantia submarine design called P650.

Finally the studies and submarine trajectory simulations carried out by QinetiQ on the Safety Operating Envelope (SOE) complete the validation process followed.

Figure 1 shows an example of Pitch Limited SOE S-80 diagrams (>20 degree Stern Hydroplane Angle Jam).

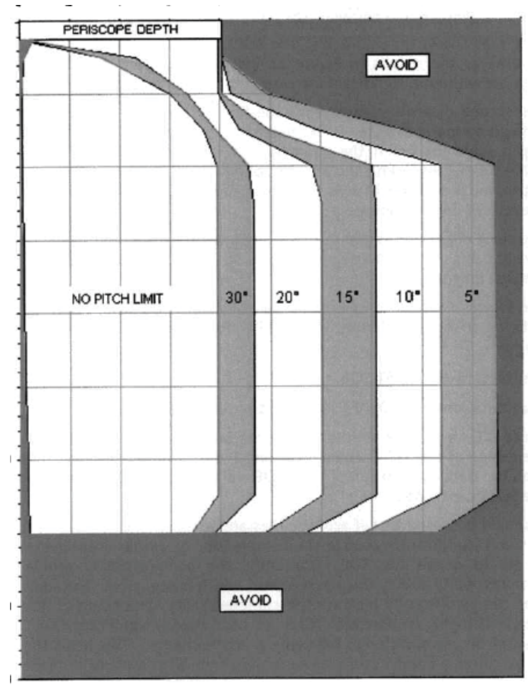

Figure 1

2.5 SIMULATED MANOEUVRES

The manoeuvrability qualities of main interest for submarine operations are:

- Course keeping and depth keeping with minimum rudders and planes work.
- Turning ability.
- Fast Course and depth changes capability.
- Depth keeping ability with minimum diving planes work

These qualities can be studied after the dimensioning process by means of the simulation of a series of standard manoeuvres representative of the manoeuvrability qualities, this simulation study made possible by the use of the "SIMUSUB" code has demonstrated to be a powerful tool to check the planes design against the requirements.

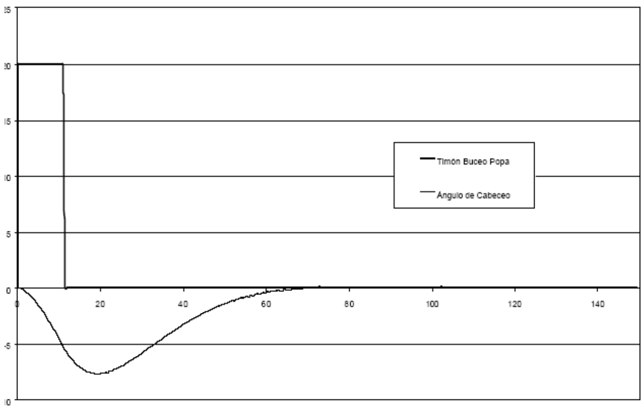

Figure 2: Vertical Meander, 10 knots.

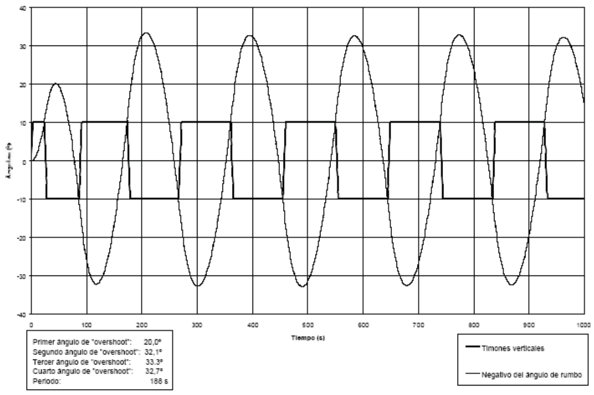

Figure 3: Horizontal to 10º/10º zig-zag, 10 knots

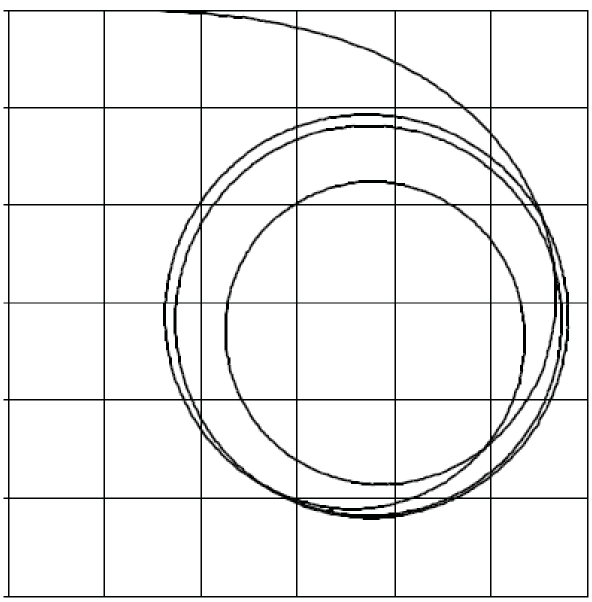

Figure 4: Turning circle. 15 knots (plant view)

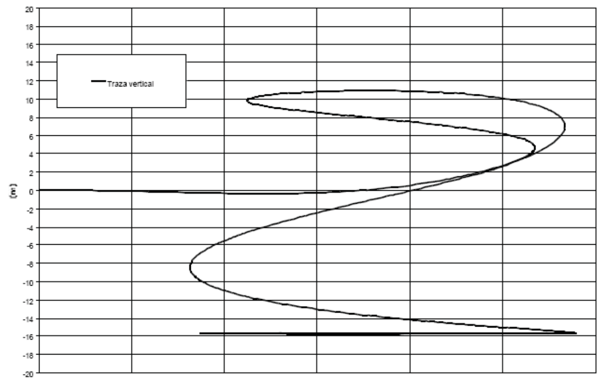

Figure 5: Turning circle. 15 knots (front view)

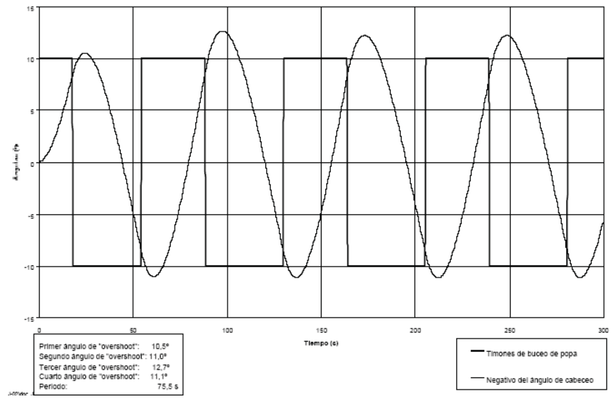

Figure 6: Vertical 10º/10º zig-zag, 15 knots

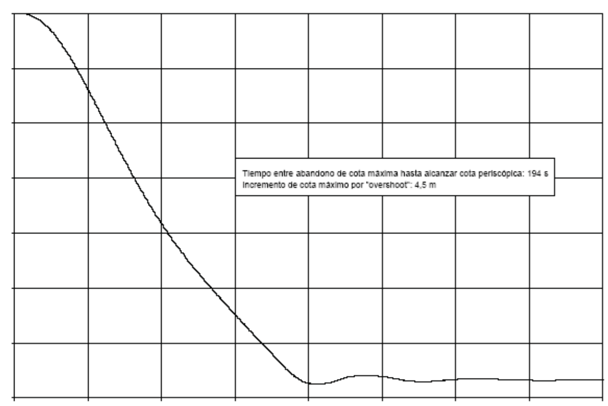

Figure 7: Depth change. 15 knots

3. "SIMUSUB" CODE

The "SIMUSUB" code was designed in order to analyse qualities of primary interest for operation submarines in the coupled horizontal and vertical planes:

- The ability to hold a straight course with minimum amount of rudder activity
- The ability to turn tightly
- The ability to initiate and change course or change depth quickly

So, in order to answer these questions, the simulator must have the possibility to analyse in a programmed way different standard manoeuvres in the horizontal and vertical plane such as zig-zag tests, turning circles, meander tests, stopping tests depth and heading changes, overweight's reaction, etc… In a second phase of development of the code, and taking into account the importance of the emergency reaction against rudder jamming or uncontrolled flooding, the code was implemented to simulate the auto-pilot reaction including the normal and emergency blowing of its ballast tanks.

The general non-linear DTNSRDC equations of motion were implemented as the mathematical representation of the six degrees of freedom for the physical S-80 Class behaviour. In the final part of the article, figures related with the structure and presentations of this code are shown.

Figure 10 shows the algorithm block diagram to integrate the named non linear equation.

Figure 11 shows the Autopilot control algorithm block diagram, and some details about the main block are given in the subsequent paragraphs.

Figure 13 shows the algorithm block diagram for blowing and some detail about physical assumption for the non-linear-related integration.

Figure 14 shows a view of the interface running in a PC-station of the current "SIMUSUB" code.

4. IMPROVING "SIMUSUB" CODE

In the development of a naval architecture tool for the guidance and autopilot of a submarine is important to choose both an appropriate mathematical model for the equations of motion and a suitable control strategy. Navantia is involved in this moment in the implementation of an innovative autopilot model based in the nonlinear controllability theory as more energy efficient compared to other classical control kernels for this work. In the next paragraphs, we analyse two different mathematical strategies for solving the problem which consists in controlling depth change manoeuvrability for a specific type of submarine. Precisely, we will apply both controllability theory and the more classical linear quadratic optimal control theory as it is currently applied in "SIMUSUB" code to a simplified linear model obtained from the general nonlinear DTNSRDC equations of motion, the linear model sufficient to autopilot control. Finally, numerical results will be contrasted to show the advantages and handicaps of the proposed models. It is also important to emphasize that the results presented in this work are only a first step towards a better understanding of the different problems (software, hardware, mechanical & hydraulics control) associated.

4.1 DESCRIPTION OF THE SUBMARINE MODEL

Concerning the underwater vehicle, in this work we will present results mainly interested in a SSK submarine (named the UPCt Class) with main dimensions are: *L* Length: 60m, *B* Beam: 6.4m, *He* Height: 7.4m, *Disp* Form Displacement: 2000m^3, *Xap* Distance from centre of buoyancy to AP: 33.0 m, *Swet* Total wetted area including appendages and flank arrays: 1100 m^2, Sail *Xsl* Distance from CB to the fin mean trailing edge: 7.0 m, *Lsl* Mean chord: 10.0 m, *Hsl* Height (to tip chord): 4.5 m, *V* Velocity: 2 - 22 knots (20 - 180 rpm).

This UPCt Class SSK submarine is used in this paper as a substitute for the S-80 Class Submarine, in order to declassify sufficient inputs and results to show in depth way the "SIMUSUB" Code developments. Forward planes are located in the fin and aft planes are designed in a "cross" configuration as in S-80 Class. The non dimensional linear hydrodynamic coefficients were selected for UPCt Class Submarine to be equivalent to the S-80 Class in terms of their "static" manoeuvrability figures of merit. The non dimensional linear hydrodynamic is shown in the next paragraph as a complete set of "hydrodynamic derivatives" to describe the manoeuvrability performance of a preliminary submarine model. This set is used for linearized equations of motion primarily in analysis of inherent stability and at design studies of automatic depth keeping and programming course keeping control systems. This last interest, the autopilot system design, is our principal motivation because a simplified mathematical model is sufficient to assist the helmsman activity in operational scenarios.

The “hydrodynamic derivatives” were calculated using dedicated software by the Navantia Cartagena Preliminary Ship Design Dept. as:

m`: 1,71*10-2, kx: 0.030, ky: 1.047, kz: 0.849, k`y: 0,732, k`z: 0,932, I`y: 8,70*10-4, I`z: 8,73*10-4, X`u`: -5.15*10-4, Y`v`: -1.80*10-2, Z`w`: -1.46*10-2, M`q`: -6.37*10-4, N`r`: -8.14*10-4, M`w`: -1.40*10-3, N`v`: 6.80*10-4, Y`r`: -8.30*10-4, Z`q`: -7.00*10-5, Z`w:-2.46*10-2, M`w: 6.26*10-3, Z`q: -7,60*10-3, M`q: -3,46*10-3, Y`v: -5,79*10-2, N`v: -2,30*10-2, m`-Y`v: 1,70*10-2, N’r: -7.44*10-3, Z`δb: -3,19*10-3, M`δb: 6,38*10-4, Z`δs: -6,25*10-3, M`δs: -2,45*10-3, Y`δr: 9,03*10-3, N`δr: -4,06*10-3 where the linear terms Z'w, Z`q, M'q, Y'v, Y'r, N'r are assumed as zero.

Coefficients are only representative of the SSK forward speed manoeuvres when avoiding detachment phenomena under high rudders angles.

4.2 MATHEMATICAL MODEL

Taking as a starting point the general nonlinear DTNSRCDC submarine equations of motion (see [1,3]) and making the basic assumptions: (a) constant surge velocity, (b) small variations in pitch and yaw Euler angles, and (c) some particular geometrical hypotheses on the submarine, we obtain a mathematical linear model in the form

$$(1) \qquad x'(t) \quad Ax(t) + Bu(t)$$

where t is the time variable, A is a 7x7 matrix and B is a 7x3 matrix. The coefficients of these matrices include hydrodynamics derivatives for the SSK model and depend on surge velocity and the properties of the underwater vehicle.

Precisely, $A \quad a^{1}b, \quad B \quad a^{1}c$, where

$$a = \begin{pmatrix} m' \;\; Y'_{\dot v} & Y'_{\dot r}\,\frac{L\pi}{180} & 0 & 0 & 0 & 0 & 0 \\ N'_{\dot v} & m'\left(k_{zz}^2 \;\; N'_{\dot r}\right)\frac{L\pi}{180} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & m' \;\; Z'_{\dot w} & Z'_{\dot q}\; L & 0 & 0 \\ 0 & 0 & 0 & M'_{\dot w} & m'\left(k_{yy}^2 \;\; M'_{\dot q}\right)\frac{L\pi}{180} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$b \quad \begin{pmatrix} Y'_v\,\frac{u_0}{L} & \left(Y'_r - m'\right)\frac{u_0\pi}{180} & 0 & 0 & 0 & 0 & 0 \\ N'_v\,\frac{u_0}{L} & N'_v\,\frac{u_0\pi}{180} & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & Z'_w\,\frac{u_0}{L} & \left(Z'_q + m'\right)\frac{u_0\pi}{180} & 0 & 0 \\ 0 & 0 & 0 & M'_w\,\frac{u_0}{L} & M'_q\,\frac{u_0\pi}{180} & \frac{-2}{\rho L^4}\left(Z_G W - Z_B B\right)\frac{\pi}{180} & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -\frac{u_0\pi}{180} & 0 \end{pmatrix}$$

and

$$c = \begin{pmatrix} Y'_\delta\,\frac{u_0^2\pi}{L180} & 0 & 0 \\ N'_\delta\,\frac{u_0^2\pi}{L180} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & Z'_{\delta_s}\,\frac{u_0^2\pi}{L180} & Z'_{\delta_b}\,\frac{u_0^2\pi}{L180} \\ 0 & M'_{\delta_s}\,\frac{u_0^2\pi}{L180} & M'_{\delta_b}\,\frac{u_0^2\pi}{L180} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

For a detailed description of the constants appearing in these matrices we refer to [1]. The state variable is

$$x \quad x(t) \quad (v, r, \psi, w, q, \theta, z)$$

where v = sway velocity, r = yaw rate, ψ= yaw Euler angle, w = component of velocity in z-direction, q = pitch rate, θ = pitch angle, and z = depth. The control variable is

$$u = u(t) = (\delta_r, \delta_s, \delta_b)$$

with δ_r = deflection of rudder, δ_s = deflection of aft plane, and δ_b = deflection of the forward plane.

The controllability problem we address in this work follows. For a fixed final time T and given an initial state $x_0 \in \Re^7$ and a final state $x_T \in \Re^7$, we wonder if there exists a control variable u = u(t) ,0 ≤ t ≤ T, such that the solution of (1) is driven from x_0 to x_T at time T, i.e., x(0) = x_0 and x(T) = x_T.

By using controllability theory one deduces that this problem has a positive answer. Then, the question of numerically computing the control u(t) is in order. Since the linear model (1) is mainly designed to simulate changes of depth, we will focus only on the control of this manoeuvrability. In the next section, we prove that the control term u can be easily computed from the Gramiam matrix that comes from the controllability theory. Then, we show a numerical experiment to compare these results with the more classical approach based on a Linear Quadratic Regulator (LQR).

5. CONTROLLABILITY VERSUS LQR

As is well-known (see [5, p. 737]), the linear system (1) is exactly controllable at time T if and only if the controllability matrix

$$Q_C = [B \; AB \; A^2B \; \ldots \; A^6B]$$

has maximal range. In our situation, this is so. Moreover, the control u(t) is explicitly given by

$$u(t) \quad B^* e^{A^*(T-t)}\left[P(T)\right]^{-1}\left(x_T \quad e^{AT}x_0\right),$$

where A^*, B^* are the transpose of A and B, respectively, e^{AT} is the exponential matrix, and $[P(T)]^{-1}$ is the inverse of the Gramiam matrix

$$P(T) = \int_0^T e^{AT} BB^* e^{A^*T} dt.$$

Once the control u is determined, the state x(t) is obtained in the closed form

$$x(t) = e^{At} x_0 + \int_0^t e^{A(t-s)} Bu(s)ds.$$

On the other hand, a LQ controller is designed by solving the optimal control problem

Minimize in u:

$$J(u) = \int_0^T \left[\overline{x}^*(t) QS \overline{x}(t) + u^*(t) QCu(t) \right] dt$$

subject to the state equation (1). Here QS > 0 and QC ≥ 0 are two weighting matrices and $\overline{x}(t) = x(t) - x_T$. The optimal feedback control u (t) has the form

$$u(t) = -L(x(t) - x_T),\ 0 \le t \le T$$

for an appropriate 3x7 diagonal matrix L and being $x_T = (0,0,0,0,0,0,z_f)$ the final state.

Next, we show some numerical results obtained by implementing both approaches in 'Matlab' for a depth change of 10m in a time T=200s.

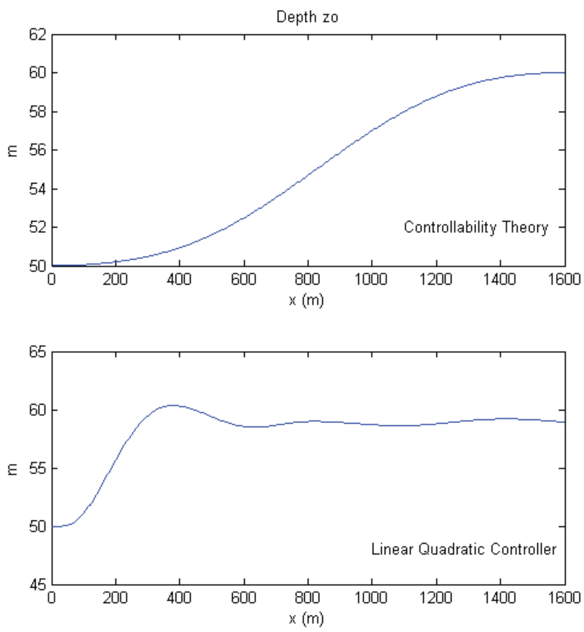

Figure 8: Depth change.

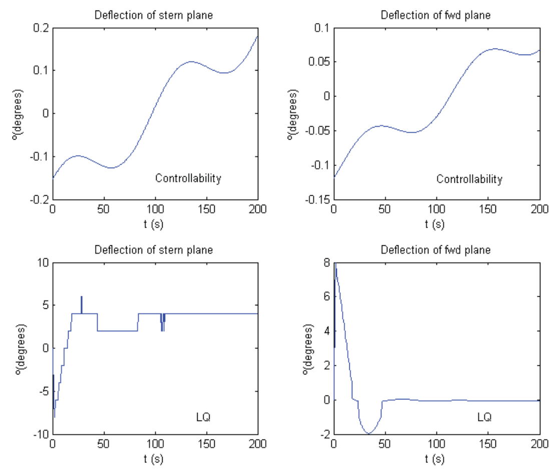

Figure 9: Controls.

6. CONCLUSIONS

With respect to the first part of the paper the main conclusions which can be underlined are:

(1) A first analysis of the mission scenario is a useful guidance to obtain a successful set of control planes for a submarine.

(2) The design decisions shall be quantified initially by using a set of appropriated coefficients related to the manoeuvrability characteristics.

(3) The utilization of a tool like 'SIMUSUB' code, simulating the submarine motions in real time, including the recovery manoeuvres and a control system is essential for assessing the design prior to the validation process.

Regarding the second part the conclusions are:

In addition to the classical LQ control strategy, a new approach based on controllability theory has been implemented for the automatic simulation of a depth change manoeuvrability for an SSK submarine. The main differences between both methodologies are as follows:

(4) The controls obtained from the LQ controller appear in a feedback form. So, from a practical point of view it is necessary to complete the control system with a suitable Kalman filter to correct the data of the state provided by the sensors of the submarine. On the contrary, the controls obtained from the controllability theory do not require the use of those because they are found in an explicit form.

(5) No constraints on the controls are imposed in the controllability strategy. This may lead in some cases, for instance for short times, to some unrealistic results with sharp changes of controls and states. With the LQ controller, these sharp changes may be corrected by

using appropriate weights in the associated cost. This, however, requires a post-processing work. A similar strategy could be applied to the controllability approach. For instance, a minimum time interval for which controllability is physically admissible may be easily calculated.

a) Concerning the accuracy of reaching the final state, it is evident that the best strategy is controllability theory (see Figure 8). Nevertheless, the LQ controller can be also designed to improve this property by choosing an appropriate cost functional.
b) As for the optimality of controls, we notice that the controls obtained from the controllability theory are optimal in the $L^2(0,T;\mathfrak{R}^3)$ norm (see Figure 9). This norm can be considered as a measure of the manoeuvrability energy usage. In this sense, controllability provides the optimal energy usage strategy, so, the minimum energy cost in hydraulics and most reduced acoustic impact if directly linked.
c) Finally, it is important to emphasize that the results in this work easily extend to the case of yawing manoeuvrabilities.
d) As indicated in the abstract, the present work is only a preliminary study on this topic. Many interesting open questions have emerged and scheduled to be analysed.

7. ACKNOWLEDGMENTS

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8. REFERENCES

1. FELMAN, J., "Revised standard submarine equations of motion". *Report DTNSRDC/SPD-0393-09, David W. Taylor Naval Ship Research and Development Center, Washington D.C.,* 1979.

2. UCL, "Submarine Design Procedure. Manoeuvrability Lecture", University Collage London, Revised 2002.

3. FERNÁNDEZ-CARA, E. and ZUAZUA E., "Control theory: History, mathematical achievements and perspectives", *Bol. Soc. Esp. Mat. Apl. 2),* pp. 79-140, 2003.

4. FOSSEN, T. I., "Guidance and control of ocean vehicles", *John Wiley and sons,* 1994.
5. OGATA, K., "Ingeniería de control moderna", Prentice Hall, 1998.

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Figure 11 Integrating Non Linear Equation

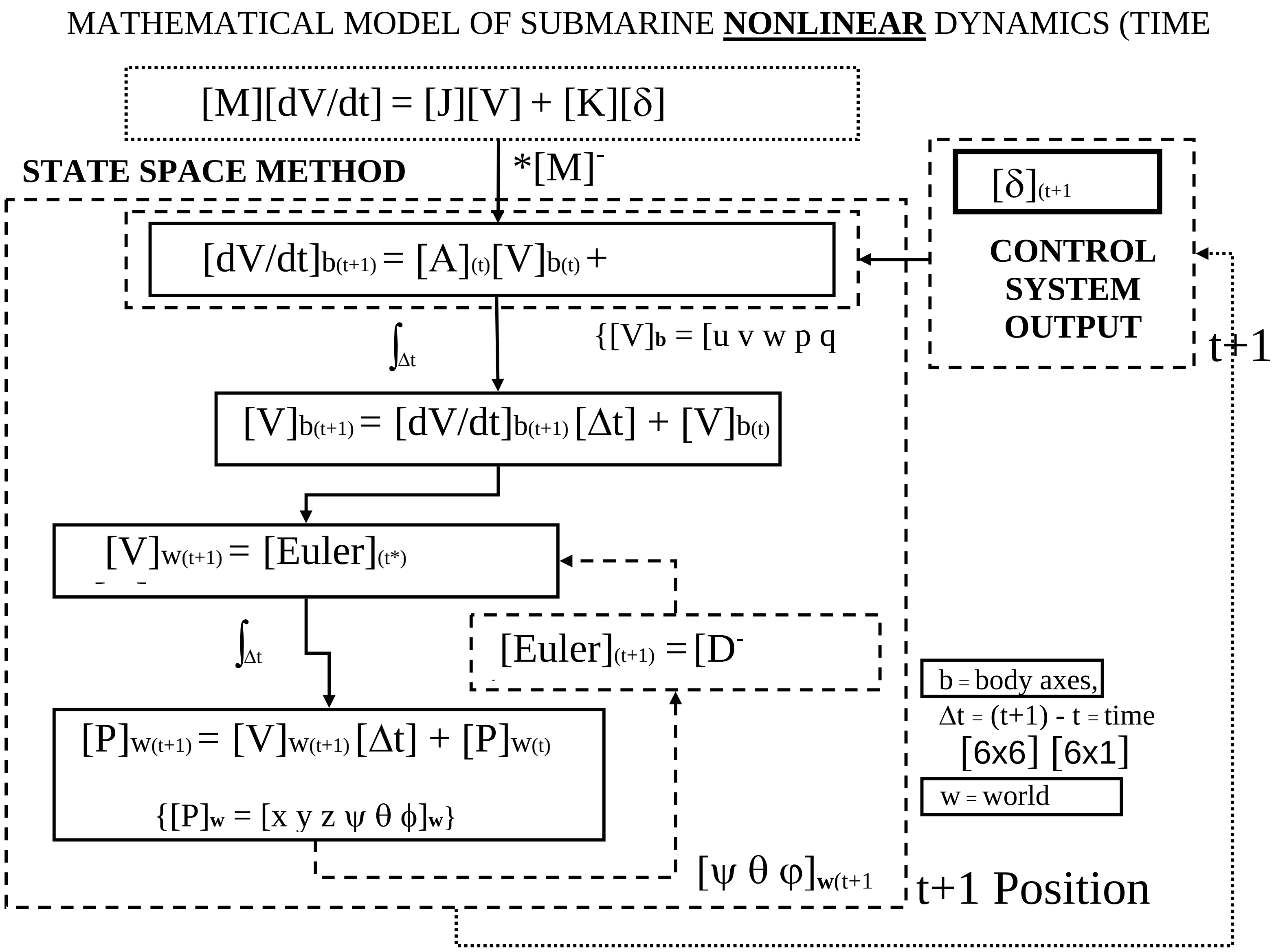


Figure 12 Integrating Autopilot Equation

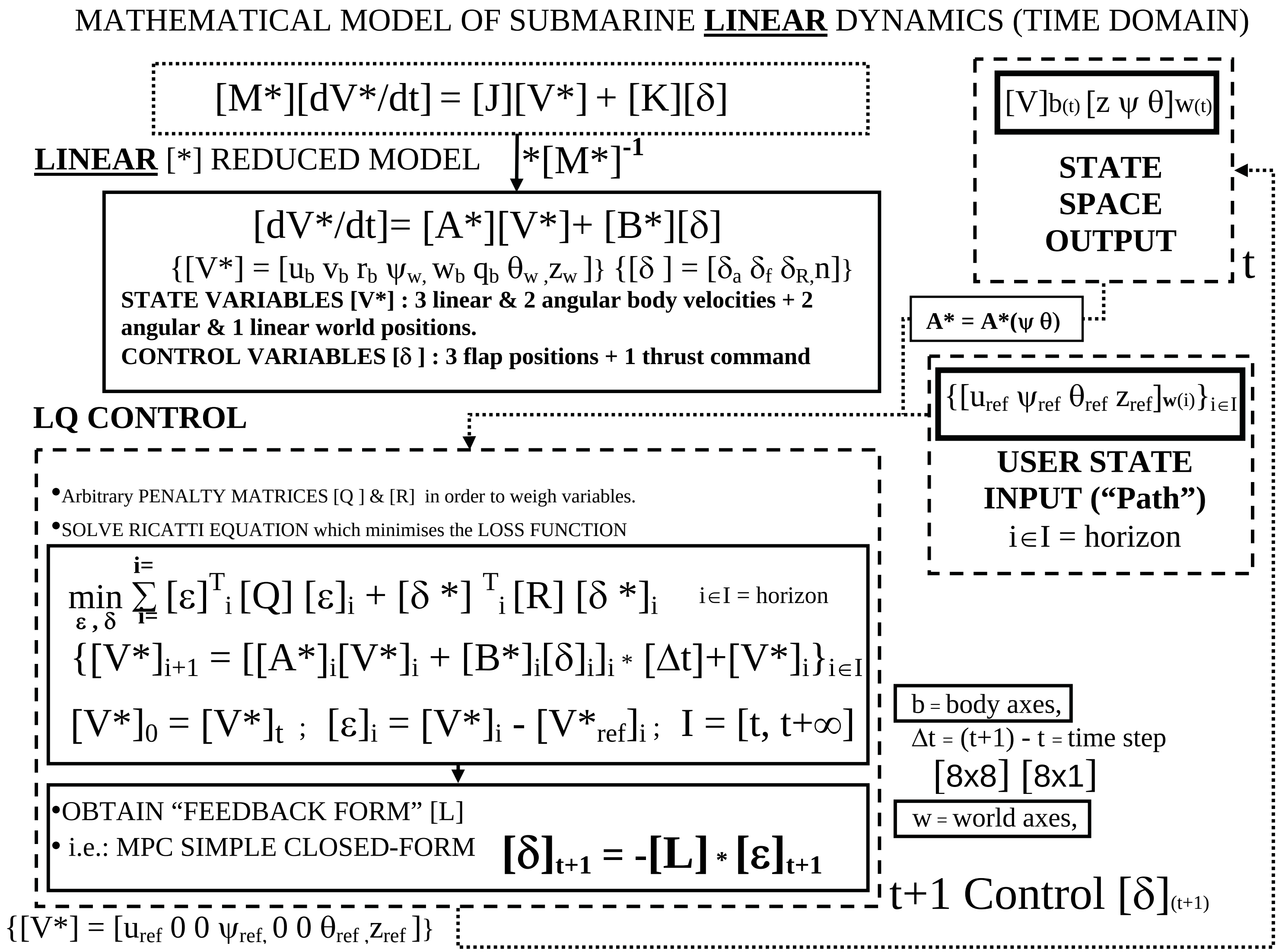


Figure 13: Blowing

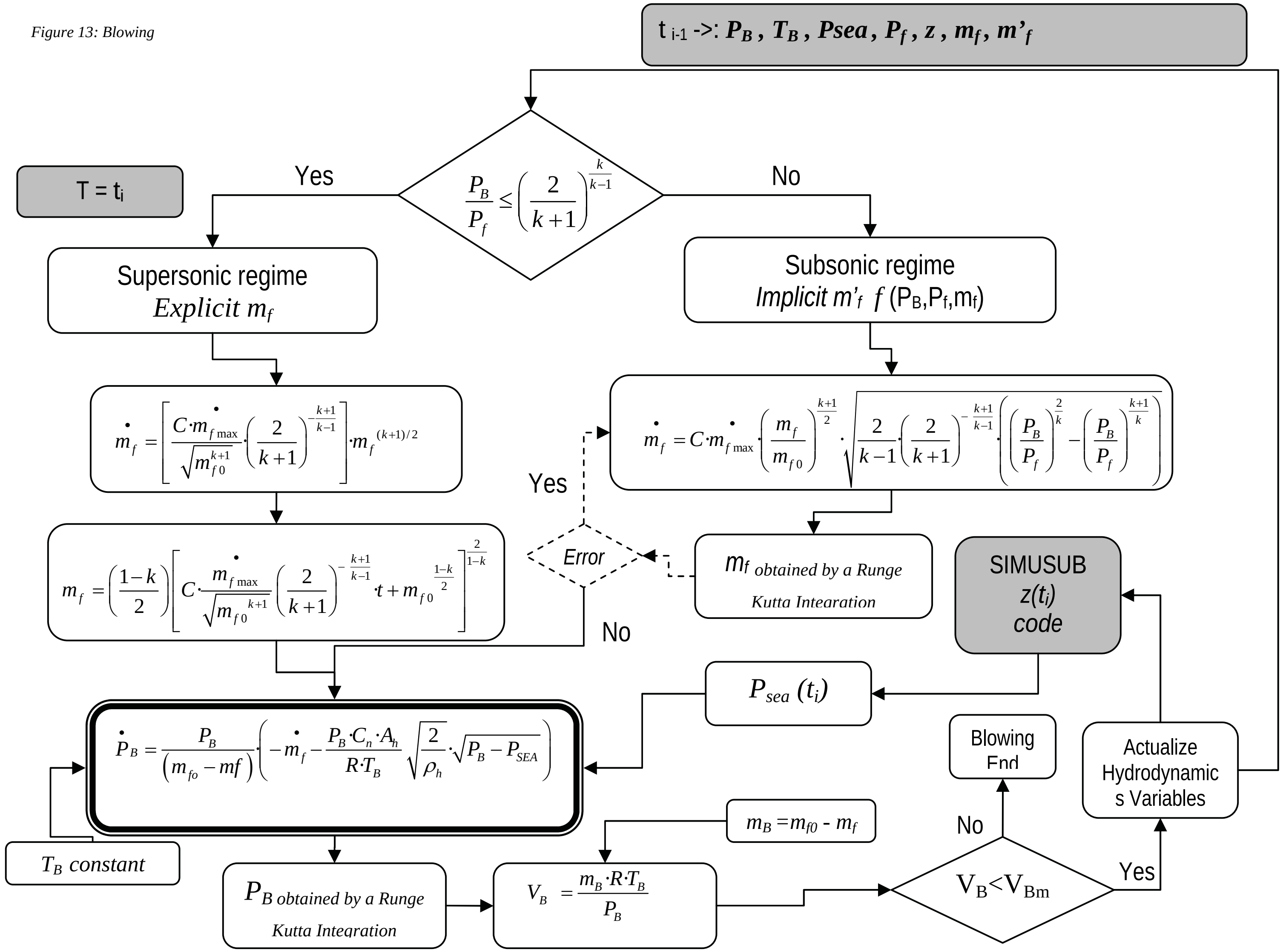
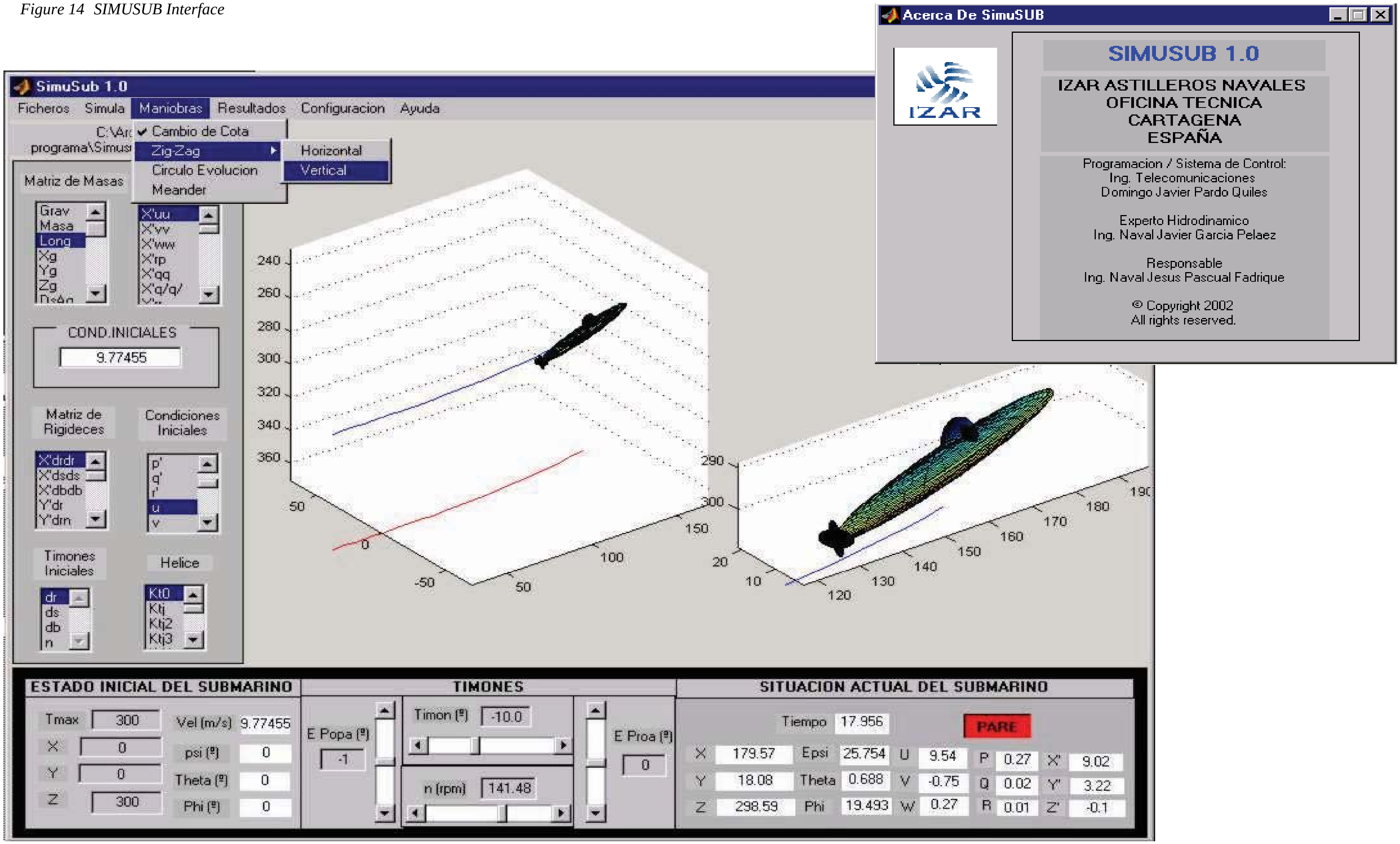


Figure 14 SIMUSUB Interface



MEETING THE CURRENT CHALLENGE OF DESIGNING HIGH CAPABILITY SSKS

Simon D Binns, BMT Defence Services, UK

SUMMARY

This paper describes the current challenges and requirements a designer must meet in designing high capability conventional submarines whilst also striving for affordability. The range of current roles and resulting platform characteristics are discussed highlighting the need for flexibility and adaptability. An overview of the impact of a sample of performance and payload requirements on whole platform design on a number of concept configurations is presented illustrating the difficulty of maintaining inherent SSKs advantages such as low cost and littoral compatibility whilst accommodating new demands from communication and offboard vehicle deployment systems, and increased special operations capabilities. An indicative submarine design, the Vidar-36 is proposed to meet these challenges, offering balanced performance through the incorporation of proven technologies, modularity and open architectures resulting in a submarine that is available, adaptable and affordable but also highly capable.

ABBREVIATIONS

ASDS	Advanced SEAL Delivery System
ASW	Anti-Submarine Warfare
AIO/FC	Active Information Organisation/Fire Control
AIP	Air Independent Propulsion
ASDV	Advanced Swimmer Delivery Vehicle
ASuW	Anti-Surface Warfare
CMH	Casing Mounted Hangar
COTS	Commercial Off The Shelf
D/E	Diesel Electric
DDD	Deep Diving Depth
DDH	Dry Deck Hangar
EMF	Embarked Military Force
ISR	Intelligence, Surveillance and Reconnaissance
LOX	Liquid Oxygen
MCM	Mine Counter Measures
MESMA	Module d'Energie Sous-marine Autonome
PEM FC	Proton Exchange Membrane Fuel Cell
PH	Pressure Hull
ROO	Radius Of Operation
ROB	Reserve Of Bouyancy
RTOF	Recoverable Towed Optical Fibre
SF	Special Forces
SDV	Swimmer Delivery Vehicle
SSK	Diesel-electric submarine
SSN	Attack submarine, nuclear powered
TLC	Through Life Cost
UAV	Unmanned Air Vehicle
UPC	Unit Procurement Cost
USV	Unmanned Surface Vehicle
UUV	Unmanned Underwater Vehicle
UXV	Generic term for unmanned vehicles
VSEL	Vickers Shipbuilding and Engineering Ltd
VLS	Vertical Launch System
WSC	Weapon Stowage Compartment

1. INTRODUCTION

The period since the end of the Cold War and the transition into an era of global terrorism has confirmed that we are now in what may be considered to be relatively unstable times [1]. With the re-emergence of powers such as Russia, India and China, this instability is also highlighted in the Pacific rim where there is expected to be a large increase in 'high-end' defence spending and in particular the proliferation of both nuclear and conventional submarine procurement and operations. This can be attributed to, in part, economic growth and navies desire to project power beyond their boundaries [2]. In addition the opening up of the North-West Passage in North America and the claims being made over these territories is also likely to lead to an increase in the number of submarines operating in the Arctic [3].

Submarines are procured for a range of purposes but it is generally to undertake any role that takes advantage of the submarine's inherent clandestine and persistent nature. Drives for operational efficiency in every navy mean that roles are now wide and varied and may include:

- Traditional sea-denial, or Anti Submarine Warfare (ASW) and Anti-Surface Warfare (ASuW);
- Force protection in support of a task force;
- Land attack/strike;
- Special forces insertion and recovery;
- Intelligence, Surveillance and Reconnaissance (ISR);

Some navies additionally use their submarine in a coastguard role as part of anti-smuggling and anti piracy duties. The ability to operate submarines is also a clear statement of the maturity of a navy. For each of these roles there is an ideal set of performance, platform characteristics and payload. This paper describes the current challenges associated with designing a 'high capability' non-nuclear submarine platform to meet these varied and wide-ranging requirements.

2. CHALLENGES & REQUIREMENTS

2.1 ENDURANCE AND RANGE

One of the major attributes of ‘high capability’ is range and endurance allowing sustained presence in distant areas of operation. The range capability was responsible in part for the relatively high displacement of the Australian Collins Class.

For the near to medium future, nuclear propulsion would appear to continue to remain the ultimate Air Independent Propulsion (AIP) system facilitating sustained submerged transit speeds but also supporting internal power demands. However for many nations the cost, infrastructure and political consequences of moving to nuclear propulsion outweigh the strategic benefits and hence make the non-nuclear or SSK the preferred technology [4].

Current conventional diesel electric systems are typically complemented with a non-nuclear AIP system that provide low speed underwater endurance, however it is not quite as simple as placing a SSN type combat fit in a SSK design; VSEL’s Type 2400 was unable to fully accommodate the then Trafalgar Class SSN AIO/FC and Sonar equipment which was considered too large and too demanding in ship’s services and manpower [5]. Now with further advances in submarines such as the US Virginia and UK Astute SSNs the bar has been raised further and as will be shown later in this paper, it is not a trivial exercise to accommodate these systems and capabilities within an SSK and retain inherent SSK advantages such as affordability and stealth.

2.2 COMMUNICATIONS

In many navies submarines are now required to operate within a network of assets, placing considerable importance on maintaining communications with other platforms and the transfer of real time data at high rates, for example providing targeting information or coordinating a land strike by directing weapons from a platform further offshore.

High data rates are generally achieved at high frequencies which for a submarine mean inevitably raising a mast resulting in an indiscretion. Extending a mast above the water surface has been common practice for submarines since their inception. Now reelable buoy systems such as RTOF [6] that enable UHF satellite communications whilst the submarine is manoeuvring at depth are being developed. Whilst these systems still break the surface, efforts to reduce visual signatures and radar cross section can be made by ensuring the buoy is stationary. As will be discussed later, the incorporation of a large buoy and handling system in the external structure of a single hull SSK under 80m in length is a significant task due to competition for valuable ‘real-estate’ with a range of other systems.

2.3 BROWN AND BLUE WATER OPERATIONS

It is now very commonly highlighted that the focus of current operations has moved from the blue water environment to the littoral. The environment decreases sensor effectiveness and places constraints on manoeuvrability. In addition a platform will face increased threats from mines, aircraft, risk of grounding and or broaching, visual detection and collision with other vessels [7].

Due to independence from support platforms and reduced detection ranges, this environment may call for measures to reduce platform vulnerability such as double hulls and increased Reserve Of Buoyancy (ROB). Operation of unmanned offboard vehicles and sensors on the other hand may permit removal of the submarine itself from the area of danger and features such as hover tanks, increased trim and compensation capacity and the ability to operate in lower density waters may be considered to aid depth control within a reduced column of water.

The SSK’s small size, in particular overall diameter, and ability sit on the sea bed are key advantages over the SSN in this environment; therefore efforts should be made to protect these advantages. However despite the incorporation of features to enable operation in the littoral, the submarine must still be compatible with blue water operations in order to make what is potentially a long transit into theatre. With the growing numbers of navies predicted to be operating submarines and their increasing capabilities there is a risk that the emphasis may return to the blue water operations.

2.4 OFFBOARD SYSTEMS

In addition to standard submarine offboard systems such as torpedoes and missiles, there is growing emphasis on the deployment of offboard static sensors and vehicles from maritime platforms. The interest in the surface warship world is stimulated by the ability to distance the operators from potential threats and extend the platform’s sphere of operation [8]. The same benefits apply to the underwater environment where Unmanned Underwater Vehicles (UUVs) and Unmanned Air Vehicles (UAVs) have been deployed from submarines in the US. As yet there is not a requirement to deploy Unmanned Surface Vehicle (USV) from an underwater platform, however a vehicle capable of operating across all three environments may provide some benefit.

The major challenge in the operation of these systems is simple and effective recovery. The vehicle may be considered disposable which then negates the need to recover it, but this inevitably increases the space required for storage, in addition currently most of these systems are relatively costly assets. Even if the submarine could be positioned completely stationary in the water then a 21” recovery hole is a relatively small target. If complex handling systems such as those recently trialled in the US

[9] with forward facing 21" tubes, are to be avoided then the solution would seem to be some kind of aft facing target that the vehicle can drive itself into allowing it to be recovered whilst the submarine has way on and maintaining depth. Examples of these systems that are being investigated are shown in Figure 1.

Figure 1: UUV deployment concepts [10]

2.5 CREW HABITABILITY

SSKs are renowned for their cramped conditions, 'atmosphere' and the now almost historical phenomenon of 'hot bunking'. However navies now must consider the issue of habitability to retain and ensure the development of their valuable personnel. There is thus a general need to increase habitability standards on board submarines. This may be facilitated by simple provision of deck area, but also by more effective air conditioning such as the biofilter blanket [11] trialled in Australia to remove the 'submarine smell' and facilities such as access to the internet, more regular communications with family and flexible recreation areas. On the other hand, if is possible to trade increased accommodation standard for capability, the question would be whether it is possible to persuade the submariner to sleep happily in his/her hot-bunk safe in the knowledge that he has a more capable submarine than his adversary? For the designer matters may be further complicated if the platform must also accommodate mixed-sex crews.

2.6 EMBARKED MILITARY FORCES (EMF)

Since the First World War, submarines have been used for special operations such as the covert insertion and removal of special teams. In the current climate of the global war on terrorism there has been an increase in the importance of these types of operations. This is highlighted by the conversion by the US of four Ohio Class SSBNs, to amongst other roles, deploy 75 special forces and two Swimmer Delivery Vehicles (SDVs) [12].

In a submarine design the Special Forces (SF) teams can be accommodated by the provision of bunks that may be temporary and collapsible allowing the area to serve alternative roles such as additional recreational areas for the crew. In addition SF teams will inevitably carry with them munitions and explosives requiring suitable storage facilities and consideration of their routes taken during transportation through the boat. The teams will also require a route in and out of the submarine whilst submerged. The torpedo tube has been commonly used, however diver chambers are a more efficient method for teams to enter and leave the submarine. The US Virginia Class submarine incorporates a nine man chamber [13] which again highlights the importance of the role of the submarine in special maritime operations.

Other SF payloads include inflatables and outboards which will also join the competition for space in the submarine's external structure, often under the casing.

However the biggest challenge for the submarine designer in terms of SF equipment is the SDV. These can range in size and capability including personnel vehicles that will fit in a 21" tube, the Mk 8 Mod 1 [14] and the Advanced SEAL Delivery System (ASDS) [14]. The Mk 8 is not resistant to submarine deep diving depths and therefore requires some kind of pressure resistance vessel or storage in the submarine Pressure Hull (PH) itself. In addition to the problems of achieving balance of weight and buoyancy in all envisaged operating conditions, a Dry Deck Hanger (DDH) system that houses a SDV also places increased demands on most of the platform's systems such as high pressure air, power and hydraulics as well as diver quality breathing air.

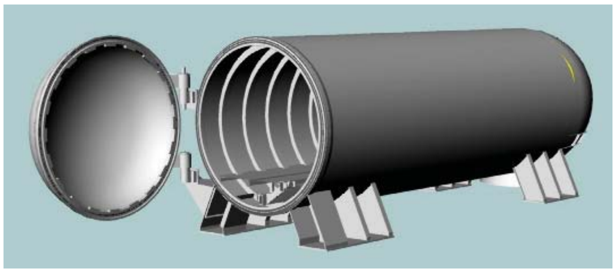


Figure 2: Casing mounted hanger for a UUV

2.7 UNDER ICE OPERATIONS

The requirement for an SSK to operate in the vicinity or actually under the ice places an emphasis on the safety and reliability of key systems due to the difficulty of rescue from this remote environment. These risks may be mitigated by increased redundancy. High endurance AIP systems may allow the submarine to penetrate deeper into ice coverage with more confidence than conventional battery systems would allow. Also offboard systems may allow the platform to remain in relatively safety. However if the submarine is required to operate under ice then strengthened fin and casing structure may be required possibly preventing the incorporation of GRP as a weight saving measure. Another requirement is that any fin mounted hydroplanes must rotate to a vertical position to penetrate substantial ice and added to these issues are the difficulties of maintaining communications and escape and evacuation.

2.8 HIGH CAPABILITY REQUIREMENTS SPACE

A summary of the upper and lower bounds of what are considered to be main naval architectural design drivers in the high capability submarine trade space are shown in Table 1. The top end of the solution space would be a conventional submarine approaching SSN type capability. Weapons rounds are assumed to be either heavy weight torpedoes, anti-ship missiles or land attack missile canisters launched from horizontal 21" torpedo tubes. Missile systems may also be stored in a Vertical Launch System (VLS).

Characteristic	Minimum	Maximum
Transit range	2000nm ROO	3500nm ROO
Range	8000nm	15000nm
Endurance	40 days	80 days
AIP Endurance	14 days	28 days
Transit speed	8 knots	18 knots
Sprint speed	20 knots	30 knots
Weapons rounds	12	36 plus 12 VLS
DDD	200m	400m
Sonar fit	(Thales S-Cube system) Bow array, Flank array, Intercept array, Clip on TA.	Plus enhanced flank array, fully reelable TA.
Communications	2x mast systems	Plus RTOF or equivalent Bouyant Wire Aerial
SF Payloads	Team 4, Inflatables & Outboards	Team 10, Inflatables & Outboards, SDV (Mk8 Mod1)
UXVs*	21" tube UUV, 'micro' UAVs	Oversized UUVs, 'large' UAVs

UXV*: Generic term for unmanned offboard vehicles

Table 1: High capability SSK solution space upper and lower bounds

So far a demanding set of requirements have been discussed, now the challenge for the designer is to attempt to meet them all whilst developing a design that is available in terms of technology readiness but also and probably most important of all, affordable for his intended customer.

3.0 SUBMARINE DESIGN OPTIONS AND DRIVERS

The range of configurations and arrangements available to the designer are described in a narrative by both Fuller [15] and Burcher et al [16]. To the uneducated most non-nuclear submarines would appear to look the same and to a certain extent the internal arrangement does not vary a great deal as illustrated by Prins [4] (although the introduction of AIP systems does create some new challenges). To the designer, interest lies in why designs have evolved to this almost standard arrangement which is due in part to the many trades and compromises that must be made to achieve a balanced submarine design.

However within this arrangement there are still many subtleties, options and design drivers that can have a significant impact on the configuration selected, its performance and ultimately cost. These have been investigated using BMT in-house tools and six concept configurations:

1. Baseline Capability Single Hull
2. Advanced Capability Single Hull
3. Traded Capability Single Hull
4. Baseline Double hull
5. Advanced Capability Double Hull
6. Traded Capability Double Hull

Some of these configurations and arrangements are illustrated below and detailed characteristics are shown in Appendix A.

Figure 3: Concept 1-Baseline capability single hull design

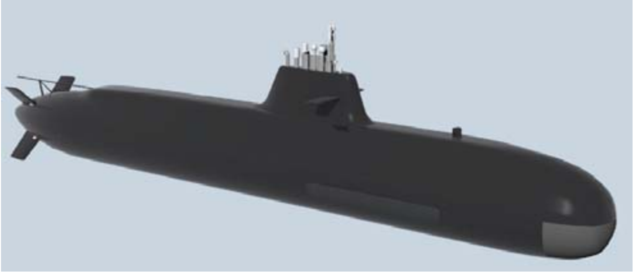


Figure 4: Concept 2-Traded capability single hull design

Figure 5: Concept 3-Advanced capability single hull design

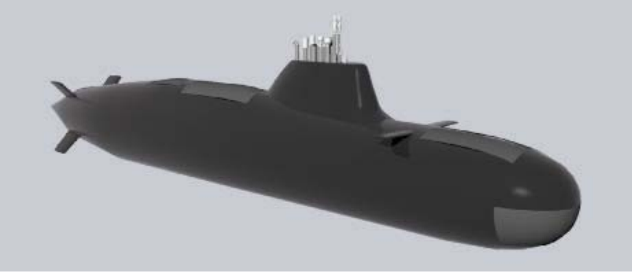


Figure 6: Concept 6-Advanced capability double hull design

3.1 COMBAT FIT

The range of combat system options considered in this study is shown in Appendix B. A selection of some of the challenges these payloads present are now discussed.

3.1.1 Weapons Rounds

The number of rounds an SSK carries generally ranges between 8 and 22, departures from these numbers, as illustrated by Concept 2 where 36 rounds have been incorporated, result in a dramatic increase in the size of the vessel mainly due to the self satisfying nature of submarine design. Other challenges of increased numbers include internal arrangement and weapons handling and compensation. General compensation is further complicated by the range of sea water densities that may be encountered in the littoral and blue water operations.

The choice between 12 and 16 rack capacity for a two deck submarine is driven by the location of the Weapon Stowage Compartment (WSC). Locating the WSC on the upper deck restricts the weapon numbers due to the curvature of the PH but can be traded against ease of weapon embarkation and increased usable volume on the deck below.

3.1.2 Sonar Systems

The bow and flank arrays present their own challenges in terms of weight, space and arrangement, however it is the fully reelable towed array that is the most difficult to integrate whilst striving to minimise size. A fully reelable array decreases the risk of damage due to grounding and fouling, it also circumvents safety issues associated with 'clip on'/partially reelable array systems at the surface. However current arrays and handling systems are relatively heavy and bulky therefore an increase in length is required to fit in an aft ballast tank. Alternative locations include the casing, resulting in a distinct hump, or in a streamlined fairing atop the rudder as incorporated by many Russian submarines.

Further issues include the difficulty of streaming passed fully moveable X-plane stern planes resulting in the requirement for some kind of guide to prevent fouling with the propeller.

3.1.3 Mast Systems

The range and number of mast systems required to be encompassed in the bridge fin due to communication and sensor requirements has increased. Non-hull penetrating masts are now almost standard, and modular mast systems are being developed [17]. This results in considerable competition for space and weight budgets in a structure that has a substantial detrimental impact on hydrodynamic characteristics and which there are drives to remove from submarines altogether. The increase in weight presents a strong argument for the departure from a minimum PH diameter of approximately 7.6m for a two deck submarine in order to increase stability and allow compatibility with modular build strategies.

3.1.4 DDH

Some of the challenges associated with a DDH such as compensation and auxiliary systems have already been discussed; however stability issues in scenarios such an emergency surface also contribute to the argument for an increase in PH diameter.

3.1.5 External Systems

The casing of a single hull SSK is busy and cramped. The standard equipment competing for space include; access to the PH, weapons embarkation hatches, countermeasures, snort induction and exhaust, rescue submarine seats and mooring arrangement. To these are now added offboard launch and recovery systems for UUVs and SDVs, special forces equipment, increased fin length, offboard communication systems, and potentially the towed array. The result is that these requirements can ultimately drive the length of a single hull submarine in a similar way to upper deck requirements driving surface warship length.

3.2 HULL CONFIGURATION

The majority of submarine designs start with the classic question of one hull or two, or whether to consider combination arrangements. This is a very well trodden and sometimes heated debate [18]. As already discussed, there is potentially a current need to increase the survivability of platforms which the double hull may facilitate by reducing signatures and providing a stand-off of between weapon effects and the PH. The full double hull does also facilitate external framing, and provide a large volume that can be used for the storage of oil fuel, countermeasures, boundary layer control systems, external weapons and other offboard vehicles.

The disadvantages would seem to be difficulty of maintenance, and therefore increased through life costs coupled with an increase in beam, draft and displacement which can be constrained by infrastructure such as berths and ships lifts.

A comparison of the baseline and advanced capability single and double hull concept designs is presented in Appendix A. The full double hull configuration requires an increase in PH material yield stress in order to achieve comparable Deep Diving Depth (DDD). However if such a steel is available and affordable, external weapon stowage is sufficiently developed and there is a requirement for the deployment of a large number of offboard systems concurrently then the double hull becomes attractive. Until then the single hull appears the most efficient in terms of reducing overall size, UPC and through life costs.

3.3 DEEP DIVING DEPTH (DDD)

Comparison of submarine maximum diving depths is often difficult due to the characteristic's military sensitivity. However given that the majority of the world's oceans are deeper than 200m and the majority of operations are envisaged to be in the littoral then the requirement for a DDD over approximately 250m can be questioned given the associated weight and cost penalties. Figure 6 shows the impact on submerged displacement for a baseline single hull with HY80 steel in comparison with a double hull design. For depths above 260m, space is created that may be used for increased accommodation standard or other comparatively low density items such as fuel cells thereby increasing AIP speeds. Given the above arguments and the distinct knuckle at 260m, the sensible DDD for a submarine designed to operate in the littoral and blue water environments would be seem to be 240-260m

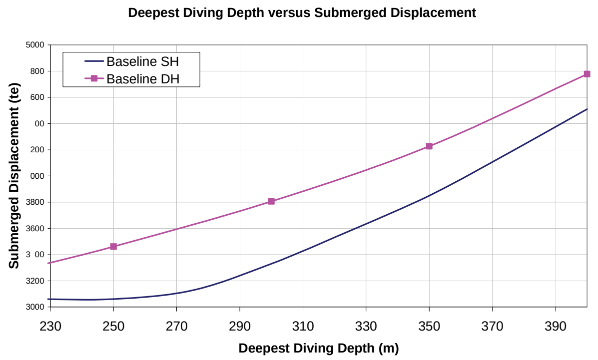


Figure 7: Deepest Diving Depth versus submerged displacement for single and double hull designs

3.4 PROPULSION SYSTEMS

3.4.1 Power Generation

Diesel Generators offer an affordable, reliable and proven method of energy generation in submarines and therefore have been incorporated by the UK Royal Navy for a 100 years since the D1 completed in 1908 [19]. Buckingham [20], as a future option proposes Solid-oxide fuel cells as an alternative air breathing power source, taking advantage of the systems high efficiency, reduced maintenance requirements and stealth compared to a standard diesel. This may become a feasible option once the technology is sufficiently developed for a submarine application.

Other non-nuclear AIP system options suitable for the generation of power to support low speeds and hotel loads include:

- Proton Exchange Membrane (PEM) Fuel Cells
- Closed Cycle Diesel
- Stirling engine
- MESMA (Module d'Energie Sous-marine Autonome)

A full discussion of the advantages and disadvantages of each of these systems is beyond the scope of this paper, however selection is also dependent on customer preference, infrastructure and experience.

3.4.2 Energy Storage

The traditional submarine lead-acid battery has not been challenged until recently with the emergence of alternative technologies such as Rolls-Royce's Zebra batteries or alternatively the Lithium ion battery. Buckingham [20] again gives a description of each battery's pros and cons, however for the Naval Architect at the concept stage primarily interested in weight and space the impact can be summarised using a baseline submarine design of 3,600te as shown in Table 2.

Battery type	Hrs @20knots	Hrs @10knots	Weight	Vol'
Lead acid	1.80	18.80	1.00	1.00
Zebra	3.35	48.70	0.72	1.00
Lithium Ion	4.93	51.26	1.00	0.91

Table 2: Comparison of battery type impact

Ultimately, choice may be driven by cost and technology readiness resulting in continued reliance on the standard submarine lead-acid battery although departure from the lead-acid battery may eventually be forced by economic considerations such as the recent increase in the cost of lead as shown in Figure 8.

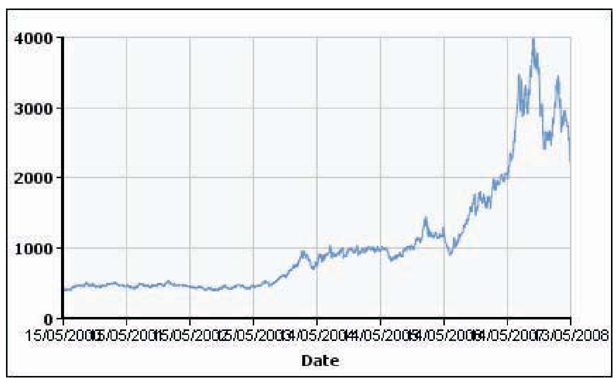


Figure 8: Lead prices 2000-2008 [21]

3.4.3 Fuel Storage

Oil fuel may be stored either internally or externally, if seawater compensation is prohibited due to environmental legislation then this will create significant problems for the Naval Architect where large range requirements mean high volumes of oil fuel, and will undoubtedly result in an increase in overall size to achieve compensation or the introduction of bagged fuel.

AIP consumables include LOX and Hydrogen. There is now a relatively large amount of experience with the storage of LOX onboard submarines being in operation with HDW's T212 and T214 [13] and other small to medium sized SSKs. The T212 stores hydrogen externally in metal hydride canisters that require a partial double hull. Work continues on the development of reformers so that hydrogen can be stored as a hydrocarbon, providing advantages in respect of safety, ease of fuel handling and storage, and energy density. As a result development of a reformer for application in a submarine continues to be watched closely by many submarine designers and operators. When reformer technology is sufficiently mature then methanol may be stored inboard resulting in a shift away from the requirement for a double hull and external hydrogen storage.

3.5 RANGE AND ENDURANCE

Current conventional submarine configurations with diesel-electric (D/E) propulsion supplemented by an AIP system are assumed to use their D/E system 'snorting' during a transit into the theatre of operations, then switch to the AIP system that would then provide all the energy required to remain on station. Figure 8 illustrates the impact of transit range and speed requirements on submerged displacement for a baseline single hull configuration. Transit speed is a complex requirement dependent on envisaged areas of operation, fleet number and maintenance cycles. The figure illustrates that a few knots can have a significant impact on the size of the platform for long transits.

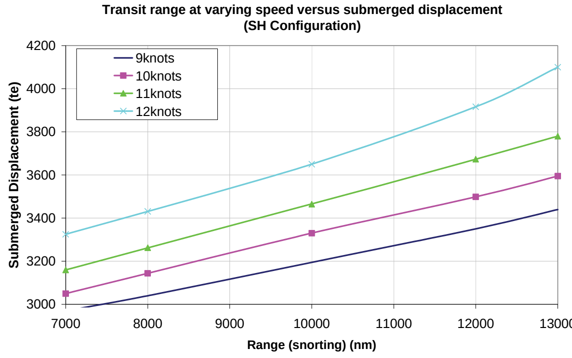


Figure 8: Range versus submerged displacement for varying speeds (TBA)

AIP endurance is limited by the provision of LOX and hydrogen, however a large amount of space is also required to compensate for the change in weight due to their consumption which in turn limits the volume available for fuel storage and drives overall size.

Assuming a baseline AIP fit comprising PEM fuel cells fuelled by LOX and reformed Methanol, the impact of AIP endurance on submerged displacement is shown in Figure 9. With propulsion loads at speeds of four to five knots being in the region of 70 to 90 kW it is the Hotel Load that dominates power requirements and ultimately limits submerged endurance. Therefore a fairly significant increase in displacement is required to facilitate a target thirty days on AIP with high hotel loading.

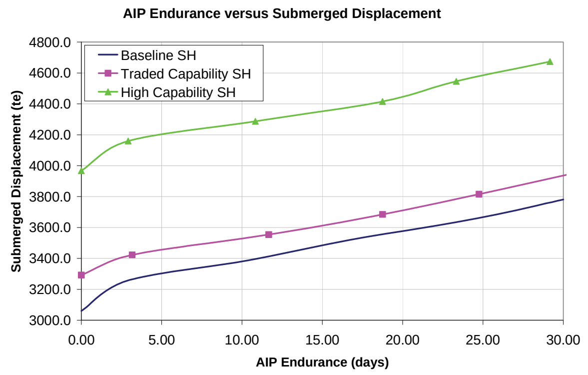


Figure 9: AIP endurance versus submerged displacement for varying combat fit

3.6 COMPLEMENT

Crew size impacts overall size and therefore UPC but also largely drives Through Life Costs (TLC). Crew numbers are driven by watch station, damage control and the requirement to sustain skills. In addition long patrols and maintenance requirements may have an influence. These drivers must be balanced against potential areas of reduction including the sharing of certain skills, such as electronic warfare and sonar operation whilst either surfaced or submerged, reductions facilitated by integrated combat systems and obviously increased automation. However crew numbers and breakdowns will be decided by particular operator requirements and preference, but it is illustrated in Figure 10 where complement has been plotted against relative UPC and TLC that significant savings can be made if efforts are made to reduce numbers. Reduced complement combined with modular build, open architectures and use of Commercial Off The Shelf (COTS) equipment will also facilitate further reduction in costs.

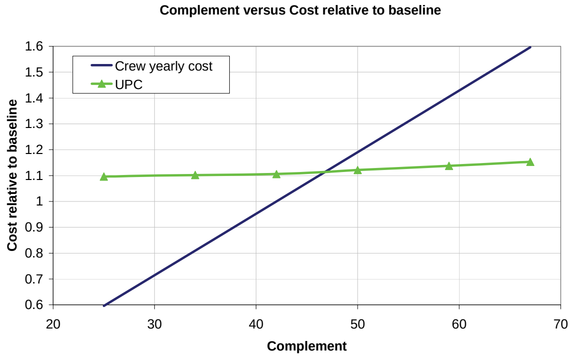


Figure 10: Complement versus cost relative to baseline for UPC and TLC

4.0 CONCEPT DOWN-SELECTION

One concept was selected from the six options for further development using a weighted scoring system. Key discriminators included scores within the table 1 trade space upper and lower bounds, littoral compatibility and cost. The assumed weighting system highlighted the need for range, and communications and SF capability. Concept scores within the trade space are shown in Figure 11. Whilst the high capability options scored well in terms of performance and payload capacity, they scored poorly due to increased cost and size. The double hull options offered extended range and offboard systems options, but were also penalised for increases in overall size and cost

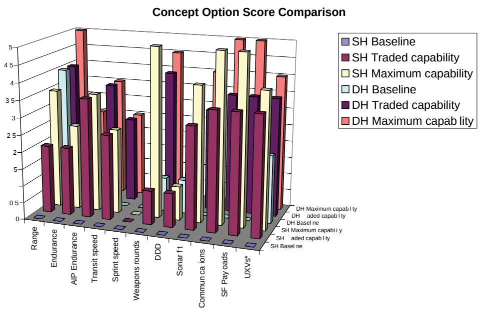


Figure 11: Concept option characteristics comparison

5.0 INDICATIVE DESIGN SOLUTION - VIDAR-36

5.1 GENERAL DESCRIPTION

The Vidar-36 submarine design is an indicative design considered to provide high capability and performance whilst remaining affordable and available in terms of technology readiness. The design has been developed from the extensive solution space analysis and concept selection process that has been briefly described in this paper. Principal characteristics of the submarine are presented in Table 3.

Submerged displ’	3600 tonnes
Surface displ’	3237 tonnes
Length overall	79m
Maximum beam	8.4m
Deepest Diving Depth	over 200m
Range (snorting)	9,000nm @10 knots with extended range option
AIP endurance	21 days
Sprint endurance	1.8 hrs
Torpedo tubes (21”)	6
Weapons rounds	18 (36 mines)
Baseline sonar system	Thales S-Cube system Inc partially reelable TA (Plus enhanced flank array)
Diver chamber	5 &10 man
Countermeasures	6 x externally stored canisters
Propulsion	Diesel Electric with AIP options
Battery	Lead-acid (8800 Ah)
Offboard systems	Modular payload options
Complement	42 plus 10 EMF/trainees

Table 3: Vidar-36 principal particulars

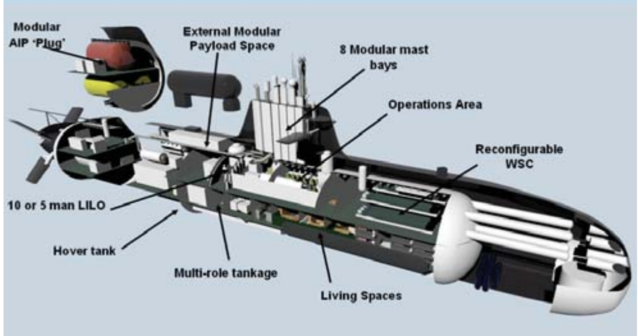


Figure 12: Vidar-36 arrangement

The design takes advantage of the reliability and proven nature of the D/E propulsion arrangement but also incorporates an AIP plug that can be tailored to meet customer requirements. The baseline configuration range is 9,000nm at 10 knots with an extended range configuration allowing ranges in excess of 10,000nm at 10 knots.

The platform is compatible with the launch and recovery of offboard vehicle systems and features a hover tank to aid control during these evolutions and whilst manoeuvring in constrained environments such as the littoral.

From the outset the design has been developed to be adaptable both in design but also during its operational life in order to allow it to undertake a range of roles but also prevent equipment obsolescence. It therefore features a large degree of modularity and the incorporation of open architectures. A summary of modular fit combinations for ASW, Mine Counter Measures (MCM), special operations and land strike roles is shown in Appendix C. Some of these modular and reconfigurable spaces are now described in more detail:

5.2 AIP PLUG

AIP technologies are expected to evolve rapidly and are also dependent on customer experience or preference. Therefore a ‘plug’ has been retained as opposed to integrated systems that are being developed elsewhere. The PH has been designed in this area with the use of heavy stiffeners so that plug length may be varied in design or even during the operational life of the vessel with minimal impact on the rest of the vessel, and the plug can be removed if required with minimal impact on the balance of the submarine.

The baseline plug is seven metres long, a PEM FC and reformed methanol configuration permits 14-21 days at four knots depending on domestic and combat system loading.

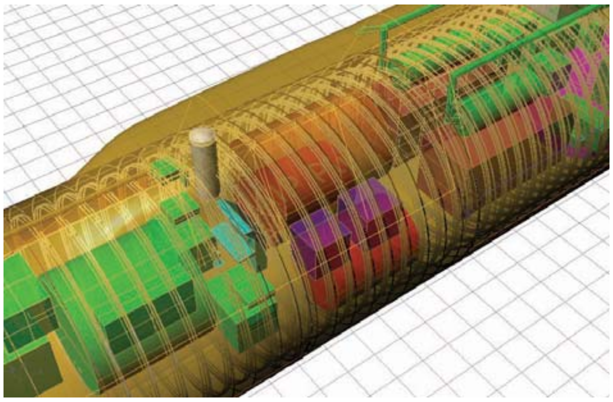


Figure 13: Baseline AIP plug concept

5.3 EXTERNAL PAYLOAD SPACE

A modular external payload space has been incorporated aft of the bridge fin close to the centre of gravity in order to allow the platform to carry a series of payloads whilst permitting a reduction in submerged displacement of 20% in comparison with Concept 2.

Modules are proposed with standard physical, power, air, hydraulics interfaces. The bay itself can receive payloads up to:

- Length: 7.5m
- Width: 2.7m
- Height (to casing): 1.3m
- Maximum weight: 20te

Module options include:

- Dry Deck Hangar Mission Module, designed to withstand parent platform DDD.
- External reelable communications systems such as RTOF.
- SF mission module including inflatables and outboards
- Reelable towed array, replaces baseline partially reelable array.
- UUV launch and recovery systems, that may or may not be resistant to platform DDD.

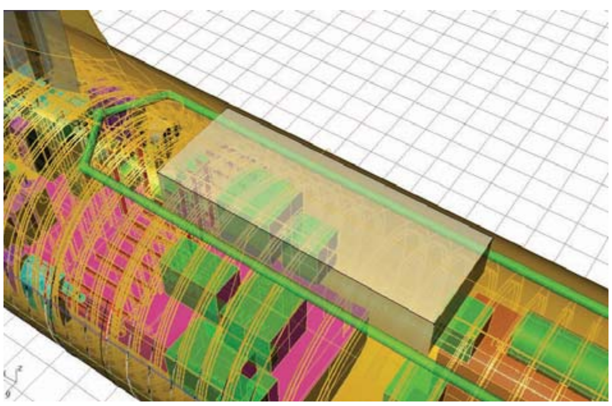


Figure 14: External payload bay

5.4 RECONFIGURABLE WSC

The proposed WSC can accommodate standard payloads such as heavy weight torpedoes, anti-ship missiles and land attack missiles, but is now considered to be more of a flexible garage or magazine space for the storage of other systems such as UUVs, UAVs and special forces equipment. As a result racks are designed to be re-configurable to create additional usable space as illustrated in Figure 15.

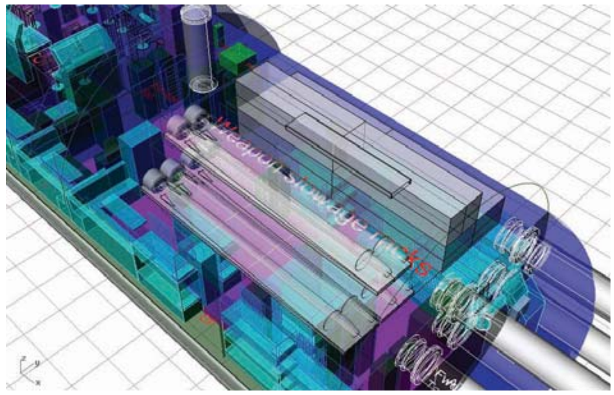


Figure 15: Re-configurable WSC

5.5 RE-CONFIGURABLE ACCOMMODATION SPACES

Provision has been made for the accommodation of ten EMF or trainees. When not embarked this space can be reconfigured allowing it to be used as a flexible recreational space in addition to an increased accommodation standard compared with previous large SSK designs, thereby improving living conditions during long patrols.

5.6 MODULAR MAST BAYS

The design is capable of receiving up to eight modular mast systems. The baseline configuration features a growth bay with margin for alternative systems including surface to air missiles or other self protection systems that may be used to defend against asymmetric threats whilst surfaced.

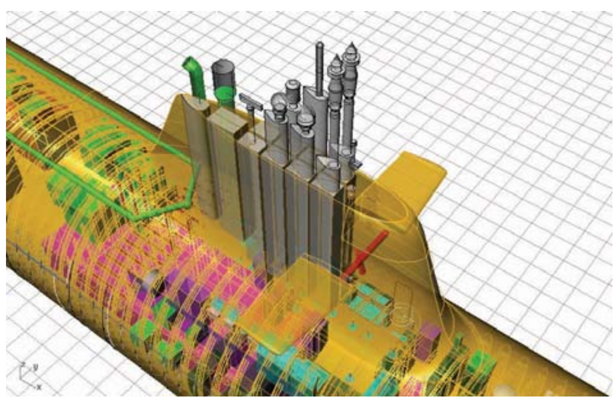


Figure 16: Fin modular masts

5.7 MULTI-ROLE TANKAGE

The features described above create a series of hydrostatic challenges, the novel solution that has been proposed is the incorporation of 'multi-role' tankage that will compensate for each of the payload modules when required. It is located directly beneath the 10 man diver chamber and adjacent to the payload bay and therefore able to compensate for changes in weight with minimal impact on the submarine's overall centre of gravity. A tertiary role of this space is for the storage of bagged oil fuel, therefore creating the extended range option capable of transiting at 10 knots for 11,500nm.

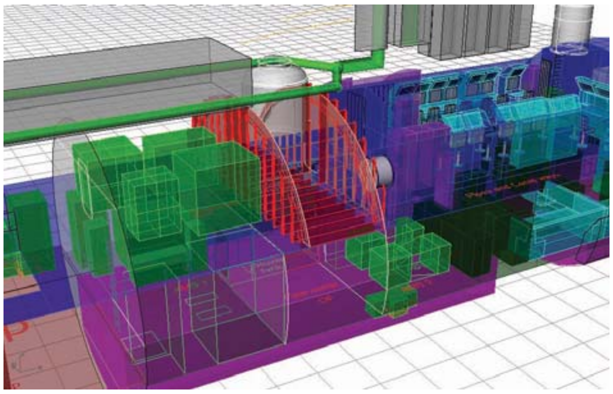


Figure 17: 10 man diver chamber and multi-role tankage

6. CONCLUSIONS

This paper has described the current challenges and requirements a designer must meet in designing a high capability conventional submarine design whilst also striving for affordability. The range of roles and resulting platform characteristics has been discussed highlighting the importance of flexibility and adaptability.

An overview of the impact of a sample of performance and payload requirements on whole platform design of a number of concept configurations has illustrated the difficulty of maintaining inherent SSKs advantages such as low cost and littoral compatibility whilst accommodating new demands such as communication and offboard vehicle deployment systems, and increased special forces operations capabilities.

It is possible to meet a balanced solution to these conflicting requirements. The concept designer must be prepared to generate multiple options for comparison and to determine the available trading space for solutions that meet a particular customer's requirements. This demands time, creativity, innovation and a reliable set of repeatable processes and calculations.

7. AKNOWLEDGEMENTS

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8. REFERENCES

[1] T. Clancy, 'Submarine'. Harper Collins Publishers, 1993. ISBN: 0 00 637947 8

[2] A. Davies, 'The Enemy Below: Anti-Submarine Warfare in the ADF'. Australian Strategic Policy Institute. February 2007 – Issue 2

[3] Cdr. M. Craven, 'A Rational Choice Revisited – Submarine Capability in a transformational Era'. Canadian Military Journal, Winter 2006-2007.

[4] C. Prins & B. Everard, 'Approaches to Submarine Design in a Changing Environment'. INEC 96. 10-12 April 1996

[5] P. Wrobel, 'Design of the Type 2400 Patrol Class Submarine'. Royal Institution of Naval Architects, Spring Meeting 1984

[6] Ultra Electronics, 'Recoverable Tethered Optical Fibre (RTOF) Submarine Communications', White Paper http://www.ultra-scs.com/resources/whitepapers/rtof.pdf

[7] STG-SM1b, 'Submarine Design for Littoral Operations'. UCL Submarine Design Course.

[8] C. Broadbent & S. Binns, 'A Vision for a UXV Enabled Versatile Surface Combatant'. RINA Future Warship 06 London.

[9] Marine Technology Reporter, 'First Submerged UUV Recovery by a Submarine' 26/11/07. http://www.seadiscovery.com/mt/

[10] M. Macdonald et al, 'Effective, integrated UUV launch and recovery from conventional submarines'. Undersea Defence Technology Conference and Exhibition. 5-7 June 2007, La Mostra d'Oltremare, Naples, Italy.

[11] A. S. Gubler, 'Networking & Powering the Underwater Domain'. Capability Brief, Project Sea, 1439/N

[12] Capt J. Patton USN, 'The SSGN-Not your father's oldsmobile submarine'. US Focus, Naval Forces 1/2008

[13] Military.com, SSN774 Virginia-class Fast Attack Submarine. http://www military.com/

[14] Jane's Fighting ships 2007-2008. Cambridge University Press, ISBN-13 978-0-7106-2799-5

[15] G. H. Fuller, 'The Kits of Parts – An Abundance of Choice'. RINA Warship 99 Conference

[16] R. Burcher & L Rydill, 'Concepts in Submarine Design', Cambridge University Press. 1995. ISBN: 0-521-41681-7

[17] Kollmorgen Electro-Optical, http://www.eo kollmorgen.com/

[18] S. Zimmerman, 'Submarine Technology for the 21st Century', Trafford. ISBN: 1-55212-330-8

[19] Cdr. F. Lipscombe, 'The British Submarine', Conway Maritime Press, Greenwich. ISBN 85177 086 X

[20] J. Buckingham et al, 'Submarine Power and Propulsion – Application of Technology to Deliver Customer Benefit'. UDT Europe 2008: 12A.2 Glasgow

[21] London Metal Exchange. http://www.lme.co.uk/

9. GENERAL REFERENCES

N. Polmar & K. Moore, 'Cold War Submarines'. Potomac Books. ISBN: 1-57488-530-8

S. D. Binns, 'A Design Study for a Submarine with a Hybrid Diesel/Electric/Fuel Cell Propulsion System'. University of Southampton 2001/2002

Y. Kormilitsin & O. Khalizev, 'Theory of Submarine Design'.

Dr. I. Prins & Cdr. H. Ort, 'Small Navies, Big Boats'. Submarine Review July 2003, Naval Submarine League

Capt H. Jackson, 'Fundamentals of Submarine Concept Design'. SNAME Transactions, Vol. 100 1992, pp. 419-448

C. Gjm van der Nat, 'Conceptual Submarine Design: How to achieve an efficient and flexible design system'. Journal of Marine Design and Operations No. B8 2005

Capt E. Arentzen & P Mandel, 'Naval Architectural Aspects of Submarine Design'. Trans SNAME 68 1960 622-692

A. Kuteinikov et al, 'Emerging Technology and Submarines of the 21st Century'. RINA Warship 1996.

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11. DISCLAIMER

The opinions expressed in this paper are those of the author and not those of BMT Defence Services or other companies, the UK MoD or any of its agencies.

APPENDICES

APPENDIX A: CONCEPT CONFIGURATION CHARACTERISTICS

	SINGLE HULL CONFIGURATIONS		
	BASELINE	TRADED	ADVANCED
Submerged Displacement (te)	3060.9	3600.4	4415.5
PH Diameter (m)	8.1	8.4	8.4
Length overall (m)	70.5	79.0	94.0
ROB	0.14	0.14	0.11
Performance			
Mission Profile	2.0	2.0	2.0
Transit speed (kts)	10.0	10.0	10.0
Range (nm)	8000.0	9000.0	10000.0
Patrol speed (kts)	5.0	5.0	5.0
AIP speed (kts)	NA	5.0	5.0
AIP range (nm)	0.0	2250.0	2250.0
AIP Endurance (days)	0.0	18.8	18.8

Combat Fit	XXX Cylindrical bow array XXX Flank array XXX HF intercept array XXX Active sonar XXX Underwater telephone XXX Mine & Obstacle avoidance sonar XXX Navigational echo sounders XXX Self noise monitoring system XXX 2x Optronic mast XXX Radar XXX ESM XXX SatComms XXX Integrated comms XXX EHF/SHF XXX 6x 21" tubes XXX 18x 21" rounds XXX 5 man LILO XXX Buoyant Wire Aerial	XXX Cylindrical bow array XXX Flank array (enhanced) XXX HF intercept array XXX Active sonar XXX Underwater telephone XXX Partially reelable towed array XXX Mine & Obstacle avoidance sonar XXX Navigational echo sounders XXX Self noise monitoring system XXX 2x Optronic mast XXX Radar XXX ESM XXX SatComms XXX Integrated comms XXX EHF/SHF XXX Mast growth bay XXX UAV (micro) XXX 6x 21" tubes XXX 18x 21" rounds XXX 5 man LILO XXX 10 man LILO XXX Buoyant Wire Aerial XXX 2x Countermeasures (x3 standard) XXX External Payload XXX 2x 4 man team	XXX Conformal bow array XXX Flank array (enhanced) XXX HF intercept array XXX Active sonar XXX Underwater telephone XXX Fully reelable towed array (thin) XXX Mine & Obstacle avoidance sonar XXX Navigational echo sounders XXX Self noise monitoring system XXX 2x Optronic mast XXX Radar XXX ESM XXX SatComms XXX Integrated comms XXX EHF/SHF XXX Mast growth bay XXX UAV (micro) XXX 6x 21" tubes XXX 36x 21" rounds XXX 5 man LILO XXX 10 man LILO XXX Buoyant Wire Aerial XXX Countermeasures (x3 standard) XXX Countermeasures (x3 enhanced) XXX SF mission package XXX SDV (inc DDH) XXX Reelable buoy comms system XXX 2x 4 man team

	DOUBLE HULL CONFIGURATIONS		
	BASELINE	TRADED (Partial DH)	ADVANCED
Submerged Displacement (te)	3218.2	3692.5	4808.4
PH Diameter (m)	varies	varies	varies
Length overall (m)	68.0	83.0	85.0
ROB	0.30	0.15	0.30
Performance			
Mission Profile	2.0	2.0	2.0
Transit speed (kts)	10.0	10.0	10.0
Range (nm)	11000.0	10000.0	14000.0
Patrol speed (kts)	5.0	5.0	5.0
AIP speed (kts)	5.0	5.0	10.0
AIP range (nm)	0.0	2250.0	2250.0
AIP Endurance (days)	0.0	18.8	18.8
Combat Fit	XXX Cylindrical bow array	XXX Cylindrical bow array	XXX Conformal bow array
	XXX Flank array	XXX Flank array (enhanced)	XXX Flank array (enhanced)
	XXX HF intercept array	XXX HF intercept array	XXX HF intercept array
	XXX Active sonar	XXX Active sonar	XXX Active sonar
	XXX Underwater telephone	XXX Underwater telephone	XXX Underwater telephone
	XXX Mine & Obstacle avoidance sonar	XXX Partially reelable towed array	XXX Fully reelable towed array (thin)
	XXX Navigational echo sounders	XXX Mine & Obstacle avoidance sonar	XXX Mine & Obstacle avoidance sonar
	XXX Self noise monitoring system	XXX Navigational echo sounders	XXX Navigational echo sounders
	XXX 2x Optronic mast	XXX Self noise monitoring system	XXX Self noise monitoring system
	XXX Radar	XXX 2x Optronic mast	XXX 2x Optronic mast
	XXX ESM	XXX Radar	XXX Radar

	XXX SatComms	XXX ESM	XXX ESM
	XXX Integrated comms	XXX SatComms	XXX SatComms
	XXX EHF/SHF	XXX Integrated comms	XXX Integrated comms
	XXX 6x 21" tubes	XXX EHF/SHF	XXX EHF/SHF
	XXX 18x 21" rounds	XXX Mast growth bay	XXX Mast growth bay
	XXX 5 man LILO	XXX UAV (micro)	XXX UAV (micro)
	XXX Buoyant Wire Aerial	XXX 18x 21" rounds	XXX 36x 21" rounds
	XXX 4 man team	XXX 2x External weapon stowage (x2)	XXX 2x External weapon stowage (x2)
		XXX 5 man LILO	XXX 5 man LILO
		XXX 10 man LILO	XXX 10 man LILO
		XXX Buoyant Wire Aerial	XXX Buoyant Wire Aerial
		XXX 2x Countermeasures (x3 standard)	XXX Countermeasures (x3 standard)
		XXX External Payload	XXX Countermeasures (x3 enhanced)
		XXX 2x 4 man team	XXX SF mission package
			XXX SDV (inc DDH)
			XXX Reelable buoy comms system
			XXX 2x 4 man team

APPENDIX B: COMBAT SYSTEM OPTIONS

COMBAT SYSTEM OPTIONS	ID	NAME
SONAR SYSTEMS	1	XXX Spherical bow array
	2	XXX Conformal bow array
	3	XXX Cylindrical bow array
	4	XXX Flank array
	5	XXX Flank array (enhanced)
	6	XXX HF intercept array
	7	XXX Active sonar
	8	XXX Underwater telephone
	9	XXX Partially reelable towed array
	10	XXX Fully reelable towed array (thick)
	11	XXX Fully reelable towed array (thin)
	12	XXX Mine & Obstacle avoidance sonar
	13	XXX Navigational echo sounders
	14	XXX Self noise monitoring system
FIN SYSTEMS		XXX Optronic mast
		XXX Radar
		XXX ESM
		XXX SatComms
		XXX Integrated comms
		XXX EHF/SHF
		XXX SAM system
		XXX Surface self defence system
		XXX Mast growth bay
		XXX UAV (micro)
		XXX Snort induction
		XXX Snort exhaust
WSC SYSTEMS		XXX Heavy weight torpedo
		XXX Anti-ship missile
		XXX Land attack missile
		XXX UUV (micro)
		XXX UUV (21")
		XXX UAV (21" canister)
		XXX SF mission package
EXTERNAL		XXX External weapon stowage

SYSTEMS		(x2)
		XXX Countermeasures (x3 standard)
		XXX Countermeasures (x3 enhanced)
		XXX SF mission package
		XXX SDV (inc DDH)
		XXX Reelable buoy comms system
		XXX Fully reelable TA
		XXX ASDV
		XXX Large UUV (inc CMH)
		XXX UAV (inc L&R system)
		XXX Buoyant Wire Aerial
DIVER CHAMBER		XXX 5 man LILO
		XXX 10 man LILO
SPECIAL FORCES		XXX 4 man team
VLS		XXX Land attack 6 cell module

Table 4: Combat fit options

APPENDIX B: VIDAR-36 MODULAR FIT OPTIONS

ROLE	**MODULAR INTERFACE**				
	Payload Bay	**Multi-Role Tankage**	**Masts**	**Accomm Space**	**WSC**
ASW	XXX Fully reelable TA	OF	Baseline Fit	Rec. space	12x XXX Heavy weight torpedo 3x XXX Anti-ship missile 3x XXX Land attack missile
SF (a)	XXX SF mission package (2x outboard & MIB)	10 man LILO Comp	ISR (a)	2x XXX 4 man SF team	4x XXX Heavy weight torpedo 2x XXX Anti-ship missile 3x XXX Land attack missile 1x XXX SF mission package
SF (b)	XXX SDV (inc DDH)	DDH Comp	ISR (b)	1x XXX 4 man SF team	4x XXX Heavy weight torpedo 2x XXX Anti-ship missile 3x XXX Land attack missile 1x XXX SF mission package
ISR	XXX Reelable buoy comms system	OF	ISR (b) + SAM	2x Technician	8x XXX Heavy weight torpedo 2x XXX Anti-ship missile 3x XXX Land attack missile 5x XXX UUV (21")
Land Strike	XXX Reelable buoy comms system	OF	ISR (b)	Rec. space	6x XXX Heavy weight torpedo 2x XXX Anti-ship missile 10x XXX Land attack missile
MCM	XXX Large UUV (inc CMH)	CMH Comp	Baseline Fit	2x Technician 2x Diver	6x XXX Heavy weight torpedo 2x XXX Anti-ship missile 3x XXX Land attack missile 7x XXX UUV (21")

Table 5: Modular fit options

APPENDIX D: DESIGN TRADE ANALYSIS (ADDITIONAL GRAPHS)

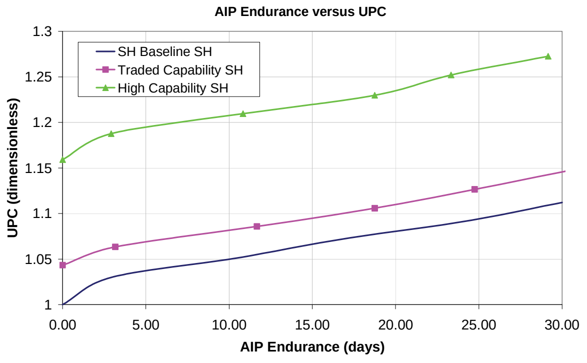

Figure 18: AIP versus UPC

END-OF-LIFE PREPARATION FOR SUBMARINES

Dr T Perry and **C Chia,** Frazer-Nash Consultancy, UK

SUMMARY

This paper examines the implications posed by the forthcoming IMO Convention for the Safe and Environmentally Sound Recycling of Ships paying particular attention to the challenges faced by submarines.

The issues and drivers surrounding current ship recycling and disposal practices as well as the latest development in the IMO Environmental Protection Committee are outlined. These include the proposed mandatory application of certain elements of the IMO Guidelines on Ship Recycling and the development of a reporting system and approval process for ships which involves the preparation of a 'single list' of the on-board and operationally generated potentially hazardous materials.

The UK Government's proposed compliance approach is outlined. The paper then examines how this might translate in to MOD policies and the potential implications for submarines. Additionally, the interfaces with other MOD policy requirements (e.g. POEMS) are also explored.

It should be noted that issues surrounding nuclear decommissioning fall outside the scope of this paper. These are more appropriately addressed in UK MOD specific project known as Interim Storage of Laid Up Submarines (ISOLUS).

1. INTRODUCTION

''On a six-mile stretch of beach at a place called Alang, in India, some 200 ships stand side by side in progressive stages of dissection, spilling their black innards onto the tidal flats. Here is where half the world's ships come to die – ripped apart by hand into scrap metal. Alang is a foul, desperate, and dangerous place, and a wonder of the world.''

- W Langewiesche, The Atlantic Monthly August 2000

While it is highly unlikely that end-of-life submarines would end up on such beaches, the issues surrounding shipbreaking that drives the development of the proposed IMO Convention on the Safe & Environmentally Sound Recycling of Ship will have implications for submarines.

2. KEY ISSUES & DRIVERS

It is acknowledged that ship recycling makes a significant positive contribution towards sustainable development through providing a boost to the local economies and sustaining considerable local employment where the recycling facilities are located. Additionally the re-use/recycling of significant quantities of scrap materials as well as the timely removal of outdated vessels from international waters have obvious environmental benefits.

However, shipbreaking activities are acknowledged to be inherently dangerous due to the presence of considerable quantities of various hazardous wastes such as asbestos, polychlorinated biphenyls (PCBs), tributyltin (TBT), refrigerants and heavy metals likely to be encountered. Such activities are drawn to a number of developing countries, particularly those in South Asia, due to the lower labour costs and operating overheads associated with safety, health and environmental compliance standards.

The health risks and high mortality/morbidity rates of workers at in these countries and the resultant environmental damage caused by poor working practices has led to international concern and heightened scrutiny.

As a result, it is clear that the benefits of ship recycling and its longer term sustainability should, and can only be attained through proactive measures designed to minimise associated environmental, safety & occupational health risks.

3. NEW IMO REQUIREMENTS

3.1 AIMS & OBJECTIVES

The negative perception and intense international scrutiny of the ship recycling industry led to the development of the proposed Convention on the Safe & Environmentally Sound Recycling of Ships. The convention, which is planned for adoption in 2008/9, aims to ensure the safe and environmentally sound withdrawal and disposal of ships that have reached the end of their operating lives.

The development of the Convention has been underpinned by a set of guiding principles. These include:

- the design, construction, operation and preparation of ships so as to facilitate safe and environmentally

sound recycling, without compromising the safety and operational efficiency of ships;
- the operation of ship recycling facilities in a safe and environmentally sound manner; and
- establishing an appropriate enforcement mechanism for ship recycling incorporating certification and reporting requirements.

In addition to design, construction and end-of-life issues, the new Convention also requires the minimisation of operationally generated wastes as well as detailed environmental contingency planning for in-service vessels.

An International Ship Recycling Trust Fund (ISRTF) will also be established as a dedicated source of financial support for international technical co-operation activities on ship recycling.

3.2 GUIDELINES

Many of the guidelines surrounding ship recycling are not new. Rather the proposed Convention builds on existing *recommended* IMO Guidelines on Ship Recycling [8] as well as other relevant guidelines and standards, and seeks to make them legally binding and internationally applicable.

A Joint IMO/ International Labour Organisation (ILO) and Basel Convention Working Group on Ship Scrapping has been formed with the task of developing and formalising the regulations and guidelines proposed for mandatory application.

These proposed guidelines will consider current standards including those derived from:

- the ILO, an international agency forming part of the United Nations (UN) system governing standards on occupational safety & health standards including those relevant guidelines such as ‘Safety & Health in Shipbreaking’ [1]; and
- the Basel Convention (Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal) administered by the United Nations Environment Programme (UNEP) regulating the trans-boundary movement of hazardous and other wastes listed in Annexes I and II of that Convention.

By virtue of governing disposal issues, the Basel Convention also informs the proposed IMO Convention through its relevance to the design and operation of vessels as well as minimum standards required at ship recycling facilities. Other appropriate Basel Convention technical guidelines for ship recycling processes and facilities [2] will also inform guidelines issued under the proposed Convention.

At the time of writing, the provisional list of nine guidelines for the proposed Convention includes:-

General Guidelines
- Guidelines for communication of information;

Guidelines for Ships
- Guidelines for the development of Inventory of Hazardous Materials;
- Guidelines for the submission of a proposal to control hazardous materials;
- Guidelines for surveys and certification;
- Guidelines for the inspection of ships;
- Guidelines for the establishing gas-free-for-hot-work conditions.

Guidelines for Ship Recycling Yards
- Guidelines for the authorization of ship recycling yards;
- Guidelines for safe and environmentally sound ship recycling; and
- Guidelines for the development of Ship Recycling Plan.

3.3 ENFORCEMENT MECHANISMS & KEY REQUIREMENTS

In order to effectively regulate the demands of the Convention, regulatory mechanisms are anticipated to include those described in Table 1.

Regulatory Mechanism	**Description**
Inventory of Hazardous Materials (with an associated issue of International Certificate for Ship Inventory of Hazardous Materials)	Requirement to establish a mandatory vessel-specific inventory of hazardous and potentially hazardous materials, specific to each vessel.
List of Prohibited and Restricted Materials	Requirement to eliminate prohibited materials and minimise use of restricted materials in the construction of vessels.
Surveys	Establishment of a surveying regime encompassing: • an initial survey prior to new vessels entering service or to verify the inventory of hazardous materials for in-service vessels; • periodic 5 yearly surveys to ensure continuing applicability of the Inventory; • surveys following

	significant modifications to vessel structure, machinery or equipment; and • a final survey prior to vessel recycling.
Ship Recycling Plan	Developed by the Ship Recycling Facility in consultation with the Vessel Owner to detail the appropriate manner that the ship would be dismantled and recycled.
International Ready for Recycling Certificate	Issued to Vessel Owner following pre-cleaning and final survey (prior to recycling) and verifying relevant ship-related aspects in the Ship Recycling Plan.
Authorisation of Ship Recycling Facilities	Signatory States are required to authorise and regulate ship recycling facilities located within their jurisdiction.
Statement of Completion of Ship Recycling	Vessel-specific document issued by the Ship Recycling Facility reporting on the completion of recycling activities of the specified vessel and submitted to both the recycling State authorities and to the flag administration.

Table 1 – Proposed IMO Convention Enforcement Mechanism

4. UK INTERPRETATION

Department of Environment, Food & Rural Affairs (DEFRA) mandates the application of its Ship Recycling Strategy [3] on all vessels (including submarines) above 500 gross tonnes, including those owned by the UK Government and its Agencies as follows:

4.1 VESSELS INTENDED FOR FURTHER USE

With UK Government-owned vessels intended for resale, the vessel owner has a responsibility to ensure inclusions in the Terms of Sale placing obligations on the new vessel owner to:-

- ensure that the vessel's Inventory of Hazardous Materials is kept updated throughout the vessel's remaining in-service life;
- obtain advanced written consent of the UK Government prior to disposal;
- demonstrate that the vessel will be recycled in accordance with relevant IMO Guidelines and the Basel Convention Guidelines; and
- take appropriate measures to ensure that the recycling facility adheres to applicable environmental, health & safety standards.

However, it remains unclear what recourse the UK government or the MOD will have in the event the new vessel owner breaches the contractual obligations.

4.2 VESSELS DESTINED FOR RECYCLING AND DISPOSAL

Where end-of-life UK Government-owned vessels are destined for recycling, the obligation is placed on the vessel owner to ensure that:-

- the contract will only be tendered to recycling facilities in OECD countries (in accordance with the Basel Convention);
- minimum environmental, health & safety standards are specified clearly in the tender documentation and in the tender evaluation criteria [Annex I of 3];
- the chosen recycling facility demonstrates adherence to IMO/ILO/Basel Convention Guidelines (representing industry best practice) at all stages of recycling;
- a contract, sales agreement and a Ship Recycling Plan (issued by the recycling facility) is received prior to dispatch of end-of-life vessels to the recycling facility;
- the recycling facility is presented with an updated Inventory of Hazardous Materials; and
- provisions are made for site visits and audits at the recycling facilities to verify standards of working practice.

5. MINISTRY OF DEFENCE IMPLEMENTATION

5.1 APPLICABILITY

The applicability of the Convention requirements to the Ministry of Defence (MOD) vessels is currently yet to be determined.

Whilst draft Article 3 of the proposed Convention provides an exemption for government owned ships including any warships, the same article requires the adoption of appropriate measures (not impairing operations or operational capabilities of such vessels) to be taken to ensure that such vessels act in a manner consistent, so far as is reasonable and practice, with the proposed Convention.

Notwithstanding this, DEFRA's UK Ship Recycling Strategy and the MOD Environmental Policy Statement and Guiding Principles [4] commit the MOD to comply with all legislation which extends to the UK (including legislation giving effect to the UK's international obligations).

For submarines, this commitment is further reinforced by the Navy Management Plan [5] which states that the Navy Board intends that positive actions will be taken to ensure the continued improvement of current practices and adherence to both national and international legislation. Legislative compliance is to be verified through routine inspections and audits.

5.2 POLICY, PRACTICE & INTERFACES

It is anticipated that the proposed IMO Convention and UK Government Strategy would be implemented within the MOD through a number of existing policy commitments as detailed below:

5.2(a) Joint Service Publications (JSPs)

The relevant JSPs providing the authoritative set of high level policies or guidelines with pan-MOD application are:

- JSP 815 (Defence Environment & Safety) - describing in high level corporate system for the management of environmental protection and safety [9];
- JSP 418 (Sustainable Development and Environment Manual) - providing a framework for the protection of the environment in the MOD, having regard for globally accepted general principles of environmental protection and sustainable development [10];
- JSP 430 (Ship Safety Management) – Provision of high level guidance primarily in ship safety issues [11].

These high level policies mandate the application of Project Oriented Environmental Management System (POEMS) as described below.

5.2(b) Project Oriented Environmental Management System (POEMS)

POEMS [6] is an Environmental Management System (EMS) mandated on, and designed to assist, the MOD's Defence Equipment & Support (DE&S) organisation (as well as their contractors, suppliers and advisers) in the through life management of environmental performance and environmental liabilities of equipment, platforms and services.

It provides a useful framework and structure upon which a systematic, documented and auditable system for discharging and managing the proposed IMO requirements can be developed. Figure 1 (Appendix I) provides a suggested outline of how such a system may be established to simultaneously meet both proposed IMO and POEMS requirements.

5.2(c) Sustainability Appraisal

Sustainability Appraisal (SA) [7] is a process to ensure that sustainable development considerations and policy requirements are integrated into all plans, programmes and policies that have the potential to affect the environment, society and/or the economy particularly on, over or around areas owned, occupied or used by the MOD, its agencies or partners.

Applied in this context, SA can assist in the identification of other statutory assessments and enable appropriate environmental, social and economic mitigation to be identified and managed through the MOD or site-based (recycling facility) EMS.

5.2(d) Sustainable Procurement

Sustainable Procurement is a process through which the MOD aims to acquire goods, services, works and utilities in a sustainable manner through the consideration of the through-life social, environmental and economic costs.

The MOD is currently in the process of developing its Sustainable Procurement Strategy and its interface with end-of-life vessel recycling is yet to be clarified.

5.3 SUBMARINES & IMPLICATIONS

The key high level requirements for new, in-service and end-of-life submarines are considered in Figure 2.

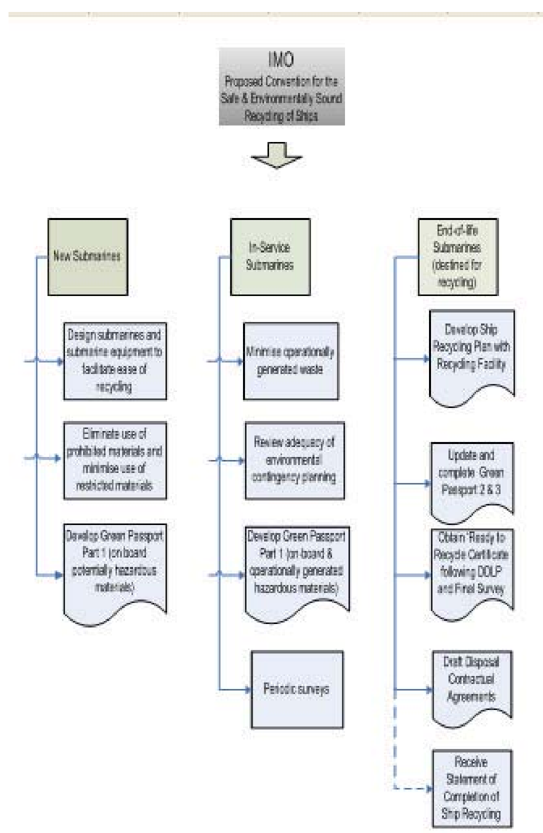

Figure 2 – Key Requirements for Submarines

Other potential implications for submarines of the proposed Convention are discussed below.

5.3(a) Recycling Facilities and Options

Given the security sensitivity surrounding submarines, it is sound to assume that all end-of-life nuclear powered submarines will be recycled and disposed in the UK. Assuming that no vessel components are to be exported for recycling and disposal, the requirements embodied in the Basel Convention and the implementing Waste Shipment Regulations are unlikely to apply.

However, given the lack of recycling facilities in the UK, disposal (and laid-up storage) options and available sites are limited. It should be noted that it is not the intention of this paper to include issues relating to the decommissioning of the Reactor Compartment (RC). These are currently being addressed by a specific MOD project (ISOLUS).

5.3(b) Design for the Environment

Despite its apparent focus on the disposal activities, the new IMO Convention is also intended to drive changes in the design and construction of future vessels through the adoption some of the heuristic Design for Environment principles (outlined in Table 2 in order to minimise environmental impacts during in-service operation and to facilitate the ease of reuse, recycling and material recovery of end-of-life vessels.

With the over-riding priority placed on design and construction to ensure crew safety and operational integrity, the bulk of the submarine will continue to be constructed with robustness of build and maintenance as a design criteria rather than ease of dismantling and recycling.

Nevertheless, other Design for Environment principles are being proactively adopted. For instance, the elimination/ substitution of prohibited hazardous materials and the minimisation of restricted materials are not new requirements in the construction or refit of submarines but rather, they are ongoing processes (e.g. BR1326 process by which new materials are introduced into submarines require an assessment by the Institute of Naval Medicine) driven primarily by the need to reduce the occupational exposure risk of crew to potentially hazardous materials.

Design for Environment Heuristic Rules	
Waste & Energy Reduction	• Design of energy and water efficient equipment; • Reduction of waste by-products in manufacturing, use, and maintenance; • Elimination of unnecessary manufacturing steps; • Incorporation of TQM and JIT philosophies.
Material Selection & Management	**Design for Recycling** • Keep design simple; • Aim for dematerialisation; • Keep different types of materials to a minimum; • Use of materials that are compatible with each other; • Use of recycled materials as starting compounds; • Label parts; • Pay close attention to recyclability; • Re-use/recycle packaging and other peripheral requirements; • Examine components that may be used upon failure/disassembly; • Consider ease of decontamination. **Design for disassembly** • Avoid mixing materials that would be difficult to separate; • Use modular design; • Use moulded-in instructions to illustrate disassembly points; • Design for ease of assembly, separation, handling and cleaning; • Apply tight tolerance principles to reduce need for fasteners (and thereby avoiding the need for special disassembly tools); • Look into the possibility of applying reversible disassembly methods. **Management of Hazardous Materials** • Where possible, avoid secondary finishes, hazardous materials and heavy metals; • Introduce non-hazardous solvents and cleaning materials.
Product Enhancement	• Incorporation of as many functions as possible into any single part; • Design secondary/ multiple uses for a product/equipment; • Design for long operational life; • Keep design simple and timeless.

Table 2 – Design for Environment: Heuristic Rules

Additionally, the use of numerous Commercial-Off-The-Shelf (COTS) equipment on board submarines is beneficial in that new/replacement COTS components would have already largely been manufactured to eliminate/reduce such substances in compliance with the EU Directives and Regulations such as the EU Restriction of the use of certain Hazardous Substances (ROHS) in Electrical Electronic Equipment. Such COTS equipment would have benefited from Design for Environment principles inherent in their manufacture.

5.3(c) Waste Minimisation of Operationally-Generated Waste

Given obvious space constraints, submarines benefit from a distinct advantage in that waste minimisation is a design consideration from the outset. Waste minimisation initiatives include the reduction of packaging and increasing automation (reducing reliance on manpower), thereby reducing waste generation during operations.

5.3(d) Environmental Contingency Planning

Contingency measures and systems focussing on the safety of the crew are already well established. There may be a need to review contingency planning to assess the adequacy of current measures and systems in mitigating environmental damage.

5.3(e) End-of-Life Preparatory Works

In accordance with new IMO Guidelines, such preparatory works include pre-cleaning, decontamination, gas removal, decommissioning of systems required for obtaining the IMO's 'International Ready to Recycle Certificate'. It is anticipated that current decommissioning and Defuel, De-Equip & Lay Up Preparation (DDLP) processes (and corresponding assurance systems) encompassing the following phases depicted in Figure 3, are likely to be sufficiently comprehensive (although this needs to be further verified). Consequently, the new IMO requirements are likely to largely represent the formalisation and translating of current provisions and assurance processes in an IMO acceptable format.

Other implications on submarines may be raised by the Maritime Environmental Working Group (MEWG), a sub-group of the Ship Safety Board, formed with the aim of looking into maritime environmental compliance challenges.

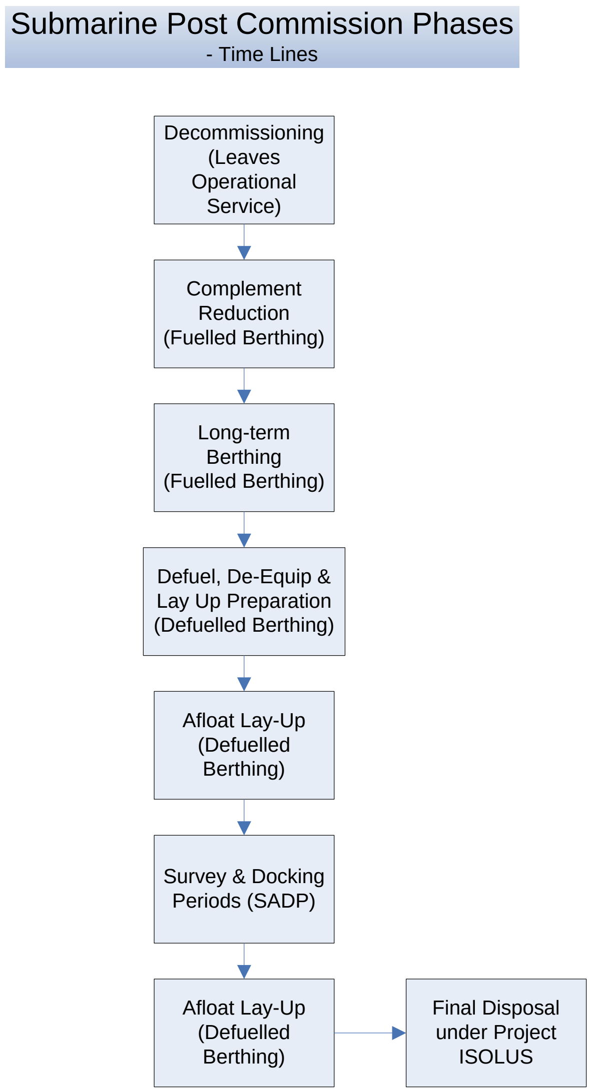

Figure 3 – Time Lines for Submarine Post Commission Phases

6. CONCLUSIONS

The requirements of the proposed IMO Convention on the Safe & Environmentally Sound Recycling of Ships are likely to apply to and affect all new, in-service and end-of-life submarines.

However, the nature of submarines/submarine operations are such that design and operational constraints already take into account many pertinent issues such as reduction of potentially hazardous substances, exercise of extensive controls over decommissioning etc. Consequently, the (new) requirements are likely to largely entail the formalisation of existing arrangements, processes, and assurance & approval systems within an IMO-approved framework.

Notwithstanding this, the MOD has a significant ability to further contribute towards sustainable development goals through, for instance, driving design enhancement and in exercising influence over through-life procurement decisions.

7. ADDITIONAL INFORMATION

The opinions expressed are those of the authors and intended to facilitate ongoing discussions on the implementation approach of the proposed IMO Safe & Environmentally Sound Recycling on Ships for submarines owned by the UK MOD. The opinions should not be taken as reflecting in any way the policies or views of the IMO, DEFRA or the MOD.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

1. ‘Safety & Health in Shipbreaking: Guidelines for Asian countries and Turkey’, United Nations International Labour Organisation, approved March 2004.

2. ‘Technical Guidelines for the Environmentally Sound Management of the Full and Partial Dismantling of Ships’, United Nations Environment Programme (Basel Convention), adopted December 2002.

3. ‘UK Ship Recycling Strategy’, Department of Environment, Food & Rural Affairs, published February 2007

4. ‘Safety, Health, Environmental Protection & Sustainable Development in the MOD’ – A Policy statement by the Secretary of State for Defence, signed March 2008.

5. ‘Navy Management Plan’, MOD, issued 1996.

6. ‘Project Oriented Environmental Management System (POEMS)’, MOD Defence Equipment & Support, Acquisition & Environmental Management System (ASEMS), Release Version 2.1e, May 2005.

7. ‘MOD Sustainability & Environmental Appraisal Tools Handbook’, MOD Defence Estates, Estates Strategy & Policy, Release Version 4.0, December 2006.

8. ‘IMO Guidelines on Ship Recycling’, IMO Resolution A.962(23), adopted December 2003.

9. ‘Joint Service Publication 815 – Defence Environment & Safety’, MOD Directorate of Safety & Claims, October 2006.

10. ‘Joint Service Publication 418 – Sustainable Development & Environment Manual’ MOD Directorate of Safety & Claims, April 2005.

11. ‘Joint Service Publication 430 – MOD Ship Safety Management’ MOD Ship Safety Management Office, Issue 3, March 2005.

10. AUTHORS BIOGRAPHY

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APPENDIX 1

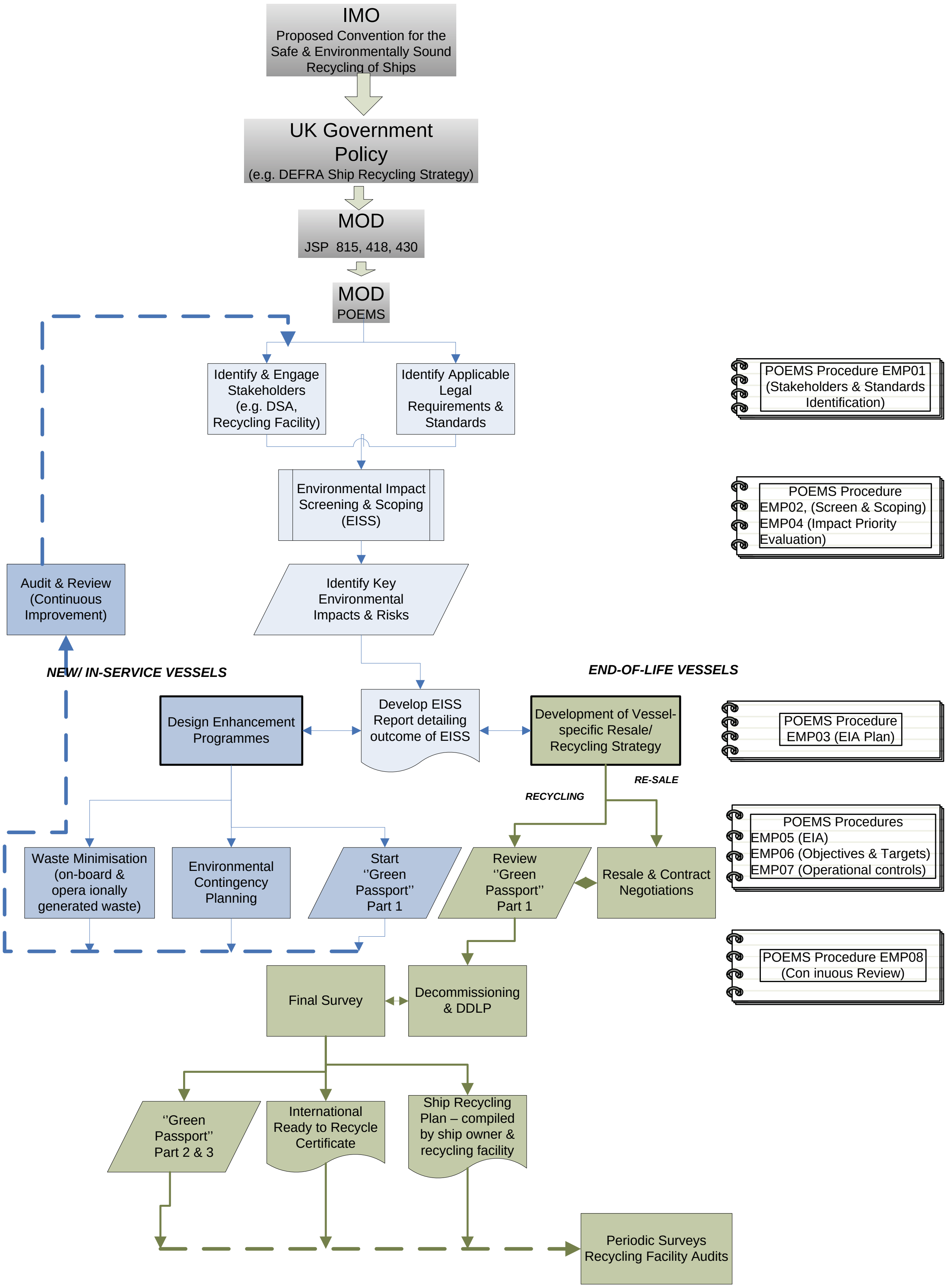

Figure 1 – Discharge and management of the proposed IMO requirements within the POEMS frame

ASSURANCE OF SUBMARINE SAFETY IN A CHANGING ENVIRONMENT

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SUMMARY

The major programme of change in the defence acquisition sector presents real and urgent challenges for navies procuring and maintaining submarines whilst seeking affordable safe capability. The paper focuses on the contribution to the assurance of submarine safety that can be made through continued development of classification rules to specifically address the unique characteristics of submarines and the opportunities offered to navies and suppliers by a different approach to standards and specifications and the verification of compliance, without constraining innovation. The paper presents an approach to the definition and implementation of an appropriate standards policy throughout the submarine lifecycle, with the benefit of using established practices for demonstrating conformance with requirements and thereby providing an effective contribution to reducing project risks, mitigating hazards and assurance of achieving the required level of submarine safety.

1. INTRODUCTION

At present there is a major programme of change across the defence sector in response to challenges posed by the new and evolving world order and the ever present and increasing pressure on naval procurement and support budgets. The consequential action, in relation to procurement and support practices for submarines is to seek transformational change in pursuit of maintaining the required flexible capability at an affordable cost. For navies which continue to seek to play a leading role in underwater operations there is a concentration on the acquisition of assets which are versatile but also exhibit excellent capability. This creates additional challenges as the rate at which new submarines are procured is reduced and their numbers are reduced, affecting the ability of navies to retain the required domain skills and resources to support their existing and future submarine enterprise.

In this changing environment navies are looking outwards to seek examples of best practice in other parts of industry which could be applied, either wholly or in part or offer learning, which can contribute to the pursuit of a sustainable and affordable capability. As is already evident this has lead to increasing collaboration with industry partners and an examination of how these other sectors manage their business. The result is that the traditional submarine procurement and support practices are being challenged and, in many cases modified in an effort to reduce the overall cost of acquisition and ownership. However, the requirement for a robust safety management system, clearly demonstrating through life assurance of submarine safety, remains undiminished.

One aspect that has been transferred to the naval sector is the concept of classification with the basic philosophy adapted to suit the demands of the naval customer base. This brings to the naval sector an established commercial sector safety management model which can provide a convenient benchmark standard. It also affords benefits in terms of valuable support to the management of risks which are faced in procurement and upkeep projects through the application of the classification process to the supply chain. The opportunity offered to navies and suppliers is through a different approach to the selection of standards and specifications and the verification of compliance, without constraining innovation.

The role of classification societies in the merchant shipping sector is complex and central to the development of standards for design, construction, maintenance and verification of compliance with those standards at all stages of the project lifecycle. Whilst it is evident that understanding has increased over the years many naval and defence sector staff remain unfamiliar with the concept of classification, its potential and indeed its inherent limitations. As with any change there will be some unfamiliarity and some associated risks and it is an aim of this paper to provide a background resource for submarine project staff to enable them to realise maximum benefit through intelligent application of the classification process.

The paper therefore presents an approach to the definition and implementation of an appropriate standards policy throughout the submarine lifecycle, with the benefit of using established practices for demonstrating conformance with requirements and thereby providing an effective contribution to assurance of submarine safety and reducing project risk.

2. CLASSIFICATION PRINCIPLES

Although classification has its origins in the coffee houses of London in the eighteenth century when surveyors assigned classes to ships, so that underwriters and charterers could assess their risk exposure, the current position is quite different. The modern classification society is a highly competent technical organisation which operates a system of classification, supported by other certification and verification activities, which in turn provides different parts of industry with an independent assurance of quality and safety.

Classification depends on a published set of Rules which define the requirements and referenced standards set that must be satisfied for the issue of a Certificate of Classification. Rules have been developed by classification societies with the active participation of a wide cross section of industry through their Technical Committees. In the merchant ship sector the Rules are also influenced by agreed Unified Requirements that are adopted by the International Association of Classification Societies, IACS, and implemented by all member societies subject to the approval of each member's Technical Committee. The merchant ship safety regulatory regime depends also on national maritime legislation, of the respective flag administration for the ship, which enacts the requirements of the International Conventions which have been adopted by the International Maritime Organisation, IMO. Requirements set down in the International Conventions and the classification Rules form a coherent set of standards for maritime safety. In many cases the flag administration will authorise the classification society to act, as a Recognised Organisation, on its behalf to issue the statutory certification in addition to the Certificates of Classification.

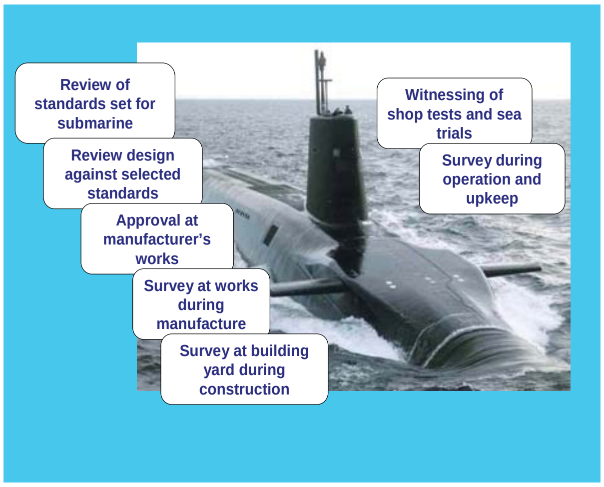

Fig 1 Key elements of the classification process

Classification is founded on the development and publication of a set of standards, the Rules, which define the essential minimum safety requirements for design and construction and the uniform implementation of those standards through a regime of survey and independent examinations throughout the project life cycle. The certification of compliance with the requirements of International Conventions and any additional requirements imposed by the National Administration follows a similar process and may also be carried out by the classification society acting on behalf of the National Administration. The process, illustrated in fig 1, involves the following key elements:

- Review of the standards set selected
- Review of the design, as indicated on the designer's drawings, to ensure that the submarine satisfies the Rule requirements applicable to design
- Review and approval of key manufacturing works for the manufacture of materials and components
- Survey of key materials, equipment and components during manufacture
- Survey during construction and the installation of machinery and equipment
- The witnessing of testing at manufacturers' works and of the dock and harbour trials of the completed submarine
- Survey during operation and upkeep

Survey activities during the design and construction phase are defined in scope and manner in the Rules and Regulations and on delivery the Certificate of Classification is issued to indicate that the platform complies with the requirements set out in the Rules, noting exceptions where appropriate. It is not a form of guarantee but it does give independent assurance that the requirements have been satisfied, thus providing confidence in the design and build phase, which then gives confidence that the asset fulfils its materiel function. Once in service classification is maintained, in the same manner as other forms of certification, through a continuous survey regime that is defined in the Regulations.

This process of independent review and assurance is fully transferable to any business sector as has been demonstrated by the adoption of similar schemes in the offshore oil and gas industry and, more recently, the rail industry. The essential message is that classification is not just about the provision of a set of Rules. The Rules are an essential part but classification is a process and adopting this process can produce significant benefits to safety assurance, procurement and reduced through life cost of ownership of submarines.

3. EVOLUTION OF NAVAL CLASSIFICATION

During the Second World War the Royal Navy procured a large number of warships, and auxiliary vessels that were constructed in shipyards that usually built merchant ships. It was natural, given the urgent need for these vessels, that they were designed and built to standards that were familiar to the shipyards and Lloyd's Register of Shipping played a key supporting role to the Admiralty constructors [1, 2]. The ships built were described as following merchant ship practices, some being based on commercial ship designs and although not intended for a long life many of these ships remained in service for the early post-war period with one of the last ships going to the breakers in 1972 after steaming more than 342 000 miles. The evidence, therefore, is that design and construction in accordance with merchant ship practices does not necessarily preclude a long service life in naval use or imply inferior capability.

Over the last three decades Lloyd's Register has supported naval underwater operations through classification of submersibles used in submarine rescue operations. These rescue vehicles, manufactured in glass reinforced plastic [3] and steel have been maintained in class with satisfactory service using classification rules developed for use in the offshore industry [4]. The latest submersible constructed under class is the NATO submarine rescue system which has recently entered service.

Over the last decade, there has been a renewed interest in the application of the classification process to naval ships. This follows the involvement of Lloyd's Register over the last six decades, in the procurement and upkeep of naval support ships, such as oilers and auxiliaries. The impetus for Lloyd's Register to develop a classification regime aimed specifically at naval ships was the recognition that when the merchant ship classification regime was applied to the procurement and upkeep of increasingly warlike ships there were shortcomings. Difficulties arose not least due to the absence of the equivalent to the merchant ship International Convention requirements. Lack of specific rule requirements relating to key features or hazards which were commonly found on naval ships, of which there is no direct merchant ship equivalent, reduced the value of classification to navies.

The development of the *Rules and Regulations for the Classification of Naval Ships* [5] has provided a comprehensive, yet flexible, set of standards which dealt with these shortcomings and thereby removed a barrier to the adoption of classification for naval ships.

Supplementary guidance for designers and project managers has been extracted from the deliberations of expert focus groups, acting through Lloyd's Register's Naval Ship Technical Committee, to capture useful information that supplements the Rules. Although this does not form part of the standards against which a ship would be assessed it is, nevertheless, valuable and it is intended to develop this into a usable format and, if appropriate, to publish this as a supplement.

Lloyd's Register is further developing the Rules to take account of the experience gained in application to new construction projects and feedback from operations in service. The Rules will also be developed to take account of new and emerging technologies as soon as these have reached sufficient maturity to permit the development of standards. Wherever possible the *Rules and Regulations for the Classification of Naval Ships* will replicate the requirements used for merchant ships where these are consistent with the military application, so that the naval community can benefit from the use of standard materials and equipment without attracting a defence premium. To realise the potential benefit the navy must understand the full implications of selecting a particular standard and be certain that the specific naval use is considered.

Following publication of the Rules in 1999 several navies around the world have procured or are in the process of procuring combatant ships to Lloyd's Register classification.

It is against this background that the *Rules and Regulations for the Classification of Naval Ships* are being developed to include submarines. This development will pull through appropriate standards from existing Rule sets to ensure consistency and to maximise the benefits of proven marine technology. These standards will be supplemented, where required, with submarine specific standards to produce a comprehensive set of standards which will provide an equivalent level of safety to that contained in bespoke naval standards, where these exist, whilst allowing use of commercial or military off the shelf (COTS/MOTS) equipment where this is appropriate.

4. SAFETY REGULATION AND VALUE

Safety regulation is sometimes treated, particularly when it is being introduced, as an additional burden on the "enterprise" and experience with a number of navies which are developing their safety management systems suggests that there is considerable resistance. Conversely, there is very little resistance to the adoption of risk management into projects and operations. The evidence from a wide range of industries is that the management of risk is considered to be a business imperative but regulation imposes an external control which is a constraint, and this constraint becomes more invasive if the Regulator considers the management to be weak or ineffective. Evidence of this is very clear when the financial services sector is studied.

The maritime industries have managed to retain a high level of self-regulation and the classification society is a reflection of this state. Safety regulation can, however, take a number of forms and it is easy to identify the impact of accidents in determining the regulatory response. There is still a culture of compliance, which works on the basis that the prescriptive requirements have been met and that this is enough, The challenge to the safety regulator is to provide an effective regulatory regime which recognises active risk management, provides prescriptive requirements and verification where this is an effective strategy and delivers benefits such as safety and flexibility to the operational managers.

The principles of good safety regulation mean that any requirements must be applicable even to the smallest companies, since the maritime industry depends for many critical components on very small suppliers often located in interesting places. The benefits of the requirements must justify the total costs of implementation. Prescription can be a constraint on innovation and encourage an unquestioning compliance culture, neither of which is desirable, and so performance standards are often an appropriate solution for the regulator.

The challenge to the safety regulator is to demonstrate that by following the safety management regime there are benefits to the project, over its life cycle, which outweigh the costs. The detractor argues that safety regulation adds visible costs, in terms of the charges made by the verifiers such as classification societies, and bureaucracy. The latter may result in inevitable delays and loss of control by the project managers. From the perspective of the professional individual, responsibilities and competences are challenged. However, the good safety regulator is able to demonstrate that there are real benefits to the project as the discipline within the verification processes provides an effective approach to active management of the project's technical risks. The safety regulatory regime will also support the through life safety management and provide a benchmark, in the case of classification, with a civil sector standard. In the remainder of the paper this argument will be developed.

5. PROCESS AND PROJECT RISK MANAGEMENT

The desire to provide best value in both procurement and upkeep of submarines brings with it an increased focus on the identification and management of project and programme risks. Of course, there are well-established techniques for project management and this paper will not deal with these, or with the management of the schedule and commercial risks. However, for submarines as complex naval platforms there are sources of risk where it is argued that the application of a well-chosen and clearly identified set of standards and the classification process can be cost-beneficial in managing the project risk profile. This is principally associated with the management of the technical risks which tend to manifest themselves during the concept, design and construction phases and the safety risks, associated with design assumptions, which become more apparent during the operational phases.

The choice of the contractual route will influence the project risks, including those related primarily to technical issues and safety. The wider use of private sector contractors to undertake tasks previously kept under the direct management and fiscal control of the navy offers both opportunities and threats. Changes in the initial procurement process for submarines include the concept of contracting against a capability requirement, allowing a greater possibility for innovation in the response by the contractor. In many cases this is accompanied by the transfer of greater responsibility to the industrial partner. Once in service there is a move towards establishing long-term contracts with support contractors, who may be the platform supplier but more often are not, to provide full logistic support throughout the operational life. The changes affect not only the commercial contracting practices but also the important working practices and partnering relationships, all of which change the project risk profile.

In this and the following sections of this paper the potential benefits that can accrue from the adoption of a classification approach in terms of reducing the level of risk exposure are described.

Seeking best value is often synonymous with competition for contracts. This may be against well-defined platform specifications but in many cases involves competition between similar concepts that meet most of the capability requirements. Comparison of competing offers is not straightforward unless there is some common baseline. The use of a suite of standards that underpin design and construction can provide a rational baseline for determining that all competitors do meet an acceptable minimum standard. In this regard the application of *Classification Rules and Regulations as* the baseline requirement and any critical specific owners' requirements that must be satisfied could provide a suitable approach to creating a standard which would ensure equality of proposals. The adoption of a standards policy and the selection of an appropriate set of standards for a submarine is a complex task. Lloyd's Register advocates an approach based on workshops to develop the requirements and to define the scope of classification at a very early stage in the project. It is unlikely that the greatest benefits will be achieved if selection of the standards is not sufficiently thorough and rigorous.

A major technical risk is associated with the introduction of new technologies which are not familiar to the navy. The distinction in technical terms between naval and merchant vessels, at least as far as marine equipment and key systems are concerned, is becoming less distinct. There are, of course, distinctly different requirements on system design and integration for military reasons, such as the shock resistance, weapons fit, duality of systems and the ability to reconfigure and reduce the impact of damage. It is, perhaps, the system that is "military" whereas a lot of the individual equipments can be very similar to those used in the commercial sector. In order to reduce programme risk there is a lot of interest in taking proven technology into the next generation of submarines, which means that more reliance will be placed on marine equipment intended for the larger commercial sector. Successful adoption of COTS equipment, of course, implies a thorough assessment of any critical deltas in the anticipated operational profiles.

Lloyd's Register has gained considerable experience from the developments in the merchant ship market and the practice is to develop appropriate Rules at an early stage to set out the essential requirements for safe operation. The Rules are developed based on available information and with the active involvement of industry through the Naval Ship Technical Committee (NSTC). The Rules and Regulations for the naval sector are also developed to take account of the changes made to equivalent Rules in other sectors and so the benefits of the experience of new technologies are transferred through the Rules to the naval sector. A significant number of the members of Lloyd's Registers' current NSTC are either ex-submariners or possess specific submarine technical expertise.

Further changes at the project level, where use of the classification processes can provide real benefits, are related to the changing marketplace for equipment, components and systems. Traditional suppliers are changing, new suppliers are entering the market and it is becoming increasingly difficult and expensive to procure spares for longstanding or bespoke equipment as a result. Supply chains are lengthening, in many cases to the extent of being global, and often for critical components. The classification process, as operated by Lloyd's Register, makes considerable use of approval schemes which involve a critical review of manufacturing facilities and the manufacturer's quality control arrangements. Construction under survey remains a key aspect for the most important components. However, use of the Type Approval scheme for supply of components such as electric motors and the Quality Scheme for Machinery for supply of machinery such as diesel generating sets offer flexible cost effective ways of verifying compliance during procurement. Generally, the schemes cover materials, and principal components and equipment, and the operation of these schemes and the general survey at manufacturers' works, necessary for classification, gives Lloyd's Register a good insight into the capabilities of suppliers.

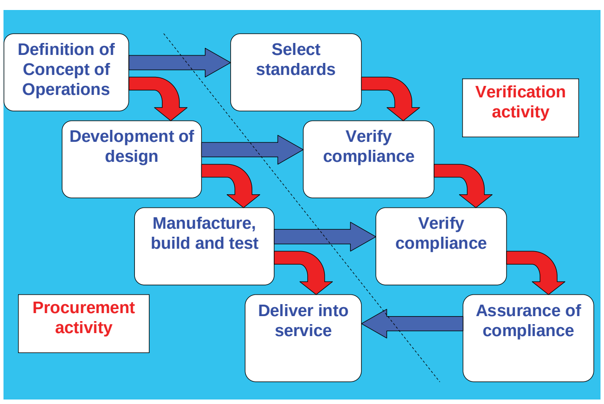

Fig 2 Relationship between procurement and verification

As procurement moves through its various stages it is important that the activities associated with verifying compliance with the specified requirements progress in step. By progressively compiling the records of verification, as indicated in fig 2, the risks are contained and the assurance of compliance on delivery can be expected with greater confidence.

The transformational changes in procurement and upkeep contracting involve changes in relationships, technology and aspirations but the anticipated gains will only be achieved if the project and process risks are successfully managed. The classification processes are well established and offer a number of risk mitigating features founded on the published standards for design, construction and maintenance, the Rules, and independent assurance resulting from intervention by professionally qualified and experienced people.

The next two sections amplify the issues of standards and the through-life continuum of the classification process.

6. STANDARDS AND COMPLIANCE

There is a widely held view that standards constrain the designer and inhibit innovation, but standards are also an essential part of the communication between the buyer and the seller. However, as noted above, the selection of the set of standards that is applied does demand careful consideration to ensure that those specified are directly relevant and appropriate to the particular case. Some standards can be justified for reasons of interoperability or safety or to reflect operating profiles but others can only be justified by the preference of the owner, which may also reflect "the way we do things". Whatever the underlying reason, standards have a central role in defining the relationships within any project and provide the cornerstone against which contractual performance can be determined.

The naval classification rules and regulations offer a coherent set of standards which provide the minimum requirements for the management of risk. The rules also allow the use of alternative perhaps national or defence standards where these can be shown to be equivalent in terms of safety provision. This flexibility enables navies to tailor their selection of standards to reflect their preferences, and which will contribute to the specific operational profiles associated with their own strategic purpose.

The selection of the total standards set has to be agreed by an appropriate "person" on behalf of the navy. Lloyd's Register has to date adopted, in the rules, the concept of a Naval Authority as being the "person" who takes overall responsibility for defining and accepting the definition of the standards set. This role may be the same as the naval safety authority, if there is a clear safety management system in place, such as in the Royal Navy [6] and the Royal Australian Navy [7], but is more likely to have a wider remit for the entire platform capability. The selection of standards must be entirely consistent with the platform capability requirements and any constraints, such as requirements for interoperability and safety. The standards must also be entirely consistent with the intended operation of the platform so that, for instance, the fire safety arrangements in terms of any fire detection and containment arrangements and the provision of fixed and portable fire fighting systems are compatible with crew training in fire fighting and the specific inventory of hazards that is anticipated such as smoke containment and atmosphere control.

The rules allow, wherever possible, the use of commercially-available marine equipment. Additional military requirements, such as shock qualification or short-term sprint ratings, can be added to the specification where these are specifically necessary to meet the capability requirements. The stepwise addition of a military premium is, therefore, possible so that cost-capability trade-offs can be made during the standards selection process and before any contracting is in place.

The classification process model is consistent with taking the specified requirements, as defined by the appropriate class notations and taking cognisance of any agreed alternative standards, and providing assurance through life of compliance with these baseline assumptions. The effort and cost expended in the selection of standards is recovered by reduced project and programme risk downstream through the increased clarity and transparency of a clear standards policy, which is reinforced by the evaluation of the cost implications of those policy decisions at the earliest practical stage of the project. Without a clear standards policy or where use is made of inappropriate standards, the project and programme risks become increased as the supply chain fails to understand the expectations of the navy [8]. This inevitably can compromise achievement of the required levels of safety and effective management of the key hazards associated with operating a submarine. Without doubt, the experience of Lloyd’s Register suggests that this early stage of the project is best undertaken with the classification society working closely with the project team, generally through a series of workshop sessions to develop the right set of standards to be applied.

The application of a robust process to assure compliance with standards provides a cost-effective route to substantiating the safety case, where such an approach is adopted to support a safety management system. In constructing the safety case, a large number of hazards, such as fire, structural strength, water tight integrity, propulsion and manoeuvring and atmosphere control, will be identified and the associated risks determined. Risk control measures will be assigned which may involve training or engineering solutions but in many cases, the risk will be minimised to a level that is acceptable, as low as reasonably practicable, through the application of accepted industry standards. The safety case is a through-life living document that is revisited and updated as necessary with changes in operational requirements and alterations to the platform or its maintenance regime. This necessitates a robust system for managing the through-life standards compliance, which is provided by the classification process with full documentary traceability. The link between standards and verification of compliance may at first sight appear somewhat incongruous. The safety case regime is often taken to be a route which frees the designer from adherence to a prescriptive, and by inference constricting, system. Experience in other industries, notably the offshore industry, has shown that where risks can be shown to be mitigated, meeting the as low as reasonably practicable criterion, in many cases it is sufficient to show that equipment has been designed and constructed to a recognised code or standard. The value of the safety case lies in the inclusion of operational issues and the living nature of the documented safety case.

7. THROUGH LIFE

In this section the application of the through-life classification process as a major risk mitigation measure is discussed, based on the approach to classification of naval platforms that has been developed and demonstrated by Lloyd’s Register.

Key decisions are being made during the earliest phases of any prospective naval project. It has also been the practice that when a classification society is engaged it is often at the time that the procurement contracts are being tendered, by which time the framework has been defined, not necessarily in the most beneficial manner. During the concept study phase, whilst the outcome is very uncertain, considerable advantage can be gained from discussions of the standards that might be applied and the cost-capability implications. The Rules, unlike many sets of standards, represent a consistent and coherent package but with options that must be selected by the Owner.

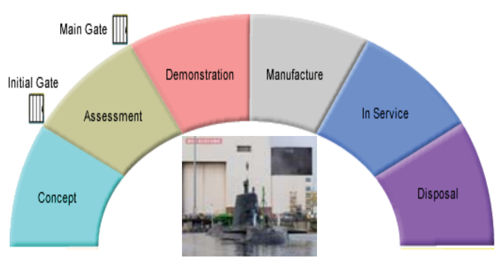

Fig 3 Project phases through life

Throughout the project phases indicated by the example shown in fig 3, the classification society essentially works as an independent third party on behalf of the navy, irrespective of the contractual arrangement for engagement of the classification society. The navy is the only direct beneficiary of the services provided by the classification society, although the designer and builder may find added value. Working on recent naval projects, Lloyd’s Register has found it imperative to be engaged early so that the selection of standards can be properly informed.

As the project advances, the design is developed against the agreed standards and the capability requirement. The classification process offers opportunities for de-risking through progressive assessment of the design to establish compliance with the Rules and agreed alternative and additional standards. This can often be achieved by placing classification society design review staff alongside the designer so that advice can be provided with minimum delay. The classification process is based on the premise that the design must be demonstrated to satisfy the Rules prior to the commencement of construction so that a clear baseline is established. Whilst changes may occur during the later project phases, these can be assessed against the known baseline to give assurance that the original intent is not compromised. It may be prudent to carry out the design reviews and grant "approval in principle" at key decision stages throughout the design development so that any lack of compliance is found at the earliest opportunity and either corrective action taken or appropriate mitigating measures put in place to manage the risks associated with the non-compliance. Multiple reviews obviously incur costs but may yield benefits in terms of overall project risk management. The process is valuable to the ultimate benefactor but it is also helpful to the various levels of contractors, who may hold a level of design authority and the associated risk, since the likelihood of future identification of non-compliances and correspondingly expensive remediation is reduced.

The most obvious involvement of the classification society is during the manufacture, construction and testing phase of the project, simply by the engagement of surveyors to attend at various locations to carry out the classification processes. Classification surveys are not intended to replace either the quality control procedures of the manufacturers and constructors or the supervision of the navy. The owner's supervision, which will involve a large number of matters that are not covered by standards and compliance therewith, is aimed at ensuring that the ship, when delivered, meets the expectations of the navy in all details and that contractual requirements are met.

The classification process will give an assurance that the requirements for materials, components, equipment, construction, installation and testing are met through a programme of survey. Since this process is progressive throughout the production and construction phase, any technical issues can be detected as early as possible and risks to the programme can be minimised, providing that appropriate corrective actions are taken at the right time. The use of suppliers with previously approved facilities and of equipment that has been previously Type Approved, against the relevant test specifications, will also reduce the risk exposure. The certification of materials and components throughout the supply chain provides clear traceability.

Where a critical piece of equipment, such as a pressure hull valve is procured for inventory and may subsequently rest in a spares pack or on a warehouse shelf for a number of years, how can the owner and indeed the crew of the submarine have an appropriate level of confidence in the provenance and efficacy of the part? Provided the equipment has been procured to appropriate standards, verified as continuing to meet those requirements through traceable certification and an acceptable material state condition is confirmed at the point at which it is required then an acceptable level of safety assurance has been demonstrated to have been achieved. The classification processes in this respect can meet the expectation and deliver cost-effective independent assurance.

Once the platform is completed and the commissioning activities begin, classification provides an objective and independent oversight of the test and trials programme. The Rules define certain key survey requirements and additional oversight tasking may be added by the navy. Within the test and trials programme there will be requirements that relate to demonstrating that the design assumptions identified with risk identification processes, such as Failure Modes and Effects Analysis, and the risk mitigation measures incorporated as a result of the analysis are correct and complete.

At final delivery, the classification process results in the completion of surveys and design reviews that confirm the requirements of the Rules and any agreed additional requirements have been complied with and that the appropriate statements, in the form of Certificates of Classification, are issued. A traceable route will be available through design appraisal documentation and other certificates to support the overall Certificate of Classification, noting that this certificate may cover the elements that in the merchant sector would be covered by statutory certification issued by or on behalf of the flag administration. At delivery a complete record of the submarine, as built, will have been assembled that provides the baseline for any future changes or reassessments.

The building of naval ships under a classification regime has found some measure of acceptance, as the assurance given by independent design review and survey during construction is seen to give clear benefits, which are of greater relevance with the introduction of the *Rules and Regulations for the Classification of Naval Ships*. Lloyd's Register is currently or has recently been involved in the building of a wide range of naval ships to class, including aircraft carriers, destroyers, corvettes, landing platforms, patrol boats and auxiliaries.

However, the adoption of the "maintenance in class" regime, illustrated in fig 4, by navies has been less enthusiastic, although it is considered by Lloyd's Register that equally valuable benefits in terms of reduced cost of ownership can be obtained with reduced risk through application of the classification process, ensuring that original standards are maintained, during the in-service phase, especially in upkeep and refit periods. The principal risk mitigation benefit of continuing through-life involvement is the assurance given that any repairs, alterations and additions do not compromise the original baseline standards, so that proposed changes are reviewed for compliance with the agreed standards and all work is surveyed to give an assurance that appropriate standards are satisfied. The regular periodic surveys, carried out by professional surveyors to determine condition and advise on necessary and suitable repairs, also provide key risk mitigation. The benefits appear to be greatest where the platform is being maintained under a contracted support arrangement e.g. contractor logistic support (CLS), where an independent review against clearly defined standards provides clarity and objectivity, and ensures that any remedial work for maintenance of the submarine is both necessary and appropriate. The survey records provide a documented and traceable history in terms of condition, modifications, repairs and maintenance. The classification process, therefore, can assist the navy in managing the technical and safety risks for submarines in service by application of well-proven independent and impartial survey services.

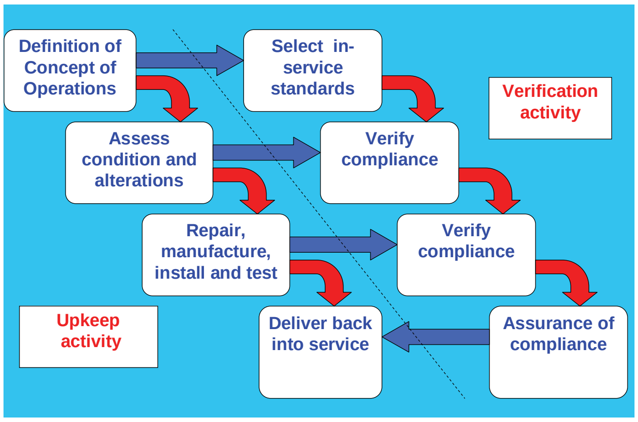

Fig 4 Relationship between upkeep activity and maintenance of verification

The disposal of submarines in an environmentally acceptable manner is becoming an issue of concern. The through-life services provided by classification societies now encompass the provision of records of materials so that appropriate decisions on disposal can be made.

The classification process does, therefore, present a well-established process for assuring the navy that appropriate standards have been selected and consistently complied with and adoption of this approach can reduce the risk exposure, in particular the technical and safety risks, of the project, throughout its life. By delegating some functions to the classification society, which employs professional people with experience of the necessary process steps, the navy will be able to release naval staff from these tasks to use their skills where they are most valuable.

8. CONCLUDING REMARKS

Any transformation means major changes of either what is being done or how it is being done or, more often, both. The desired outcome is to gain a major change and, in industrial parlance, a competitive advantage. In defence terms there is no difference – the aim is to get greater military capability within the available budget and reduce in service costs. When the underlying military doctrine is also changing to match the new world order it is no surprise that the existing well-established approaches are being challenged, but there is also a recognition that change brings risk and that must be managed.

This paper has attempted to set out a rationale where the application of the classification process, which has been developed in a highly competitive, efficient commercial market and has been applied successfully in naval surface ship projects, can be adapted for submarines. This brings into consideration the development of a set of classification rules for submarines

Transformation of procurement and upkeep processes for submarines requires measures to help manage the risks associated with change. The classification process has a number of key attributes, as shown below, which can help manage these risks:-

- Rules which provide a set of coherent standards, maintained with industry, giving clarity, consistency, usability, accessibility and an integrated approach to procurement and upkeep
- An independent assurance process based on an established merchant practice
- A process of progressive acceptance for managing safety hazards and programme and project risk through life which is supported by fully documented and traceable certificates.
- Management of the supply chain through use of approval schemes and survey to ensure compliance with requirements.
- Enhanced availability, reliability and affordability through greater use of COTS equipment.
- Application of industry best practice as appropriate and access to technical expertise and technology transfer from other industry sectors

These attributes make a significant contribution to assurance of submarine safety and act as effective risk mitigation of many of the technical and safety risks a project will face, particularly when the relationships between the various parties involved are changing.

It is advocated that, provided a thorough process for establishing the standards for the submarine is undertaken at an early stage, an independent cost-effective compliance verification regime can be put in place that will deliver benefits in terms of risk management and assurance of submarine safety throughout its life cycle.

9. ACKNOWLEDGEMENT

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10. REFERENCES

[1] Watson, A.W., *Corvettes and frigates* in *Selected Papers on British Warship Design in World War II*, Transactions of the Royal Institution of Naval Architects, Conway Press, 1983

[2] Brown, D., ed, *The Design and Construction of British Warships 1939-1945, vol 2, Submarines, Escorts and Coastal Forces,* Conway Press, 1996

[3] Tucker, J. S., *Glass Reinforced Plastic Submersibles*, Transactions N. E. Cst of Engineers and Shipbuilders, 1978-79, 49-56

[4] *Rules and Regulations for the Construction and Classification of Submersibles and Underwater Systems,* Lloyd’s Register, 1989

[5] *Rules and Regulations for the Classification of Naval Ships,* Lloyd’s Register, 2007

[6] *MoD Ship Safety Management JSP 430 Issue 3*, Ministry of Defence, 2006

[7] *Navy Safety Manual ABR 630,* Royal Australian Navy

[8] Rattenbury, N, Selection and use of standards for naval ships, International Naval Engineering Conference, 2004

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John Cheetham is currently the Submarine Rules Project Manager at Lloyd’s Register responsible for developing the Rules and Regulations for Classification of Naval Ships to include Submarines. He joined Lloyd’s Register in 1990 after working in the naval nuclear programme on the structural integrity of steam raising plant. He has held management positions in Lloyd’s Register since 1994 successively responsible for industrial pressure equipment, marine pressure equipment and London Specialist and Plan Approval Services. He is a Chartered Engineer and Fellow of the Institution of Mechanical Engineers.

Ian Miller is currently the UK MoD Business Manager at Lloyd’s Register, responsible for all business relationships with the Ministry of Defence. He joined Lloyd’s Register’s Graduate Training Programme in 1986 and has held various field positions in the UK and Overseas in the marine sector on existing ships and in the industrial sector on equipment certification and site building projects. He has extensive experience in the UK Nuclear PWR primary and secondary circuit equipment programme and the gas-fired power station building programme. He has held management positions since 1999 including Area Manager for Marine Operations in Scotland and North East England encompassing a number of Naval new building programmes prior to taking up his current role in 2006.

ASSURING SUBMARINE SAFETY FOR THE FUTURE SSBN

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SUMMARY

The 2006 White Paper on the Future of the UK's Nuclear Deterrent stated: "We have therefore decided to maintain our nuclear deterrent by building a new class of submarines". The assurance of safety of such a vessel must start during the concept phase of development and this paper describes the strategy for designing safety into the future submarine. A principal design aim is to reduce physical risk, protect people and protect the environment. To achieve this, the submarine design must: enable control the major accident hazards inherent with delivery of the user requirement; provide a safe working environment for individuals onboard the submarine; and be protective of the environment. This paper describes the development of the SSBN(F) safety strategy and the reports on the experience of implementing that strategy during the concept phase of development.

1 INTRODUCTION

In December 2006, HM Government published a White Paper on the Future of the United Kingdom's Nuclear Deterrent (Reference 1), which stated:

"We have therefore decided to maintain our nuclear deterrent by building a new class of submarines".

The White Paper continues:

"Much has changed since 1980. Safety and regulatory standards have been raised over the last 25 years."

"Safety will be a key element of the design and operation of the replacement SSBNs. The operation of our nuclear-powered submarines is regulated by independent safety authorities within the MOD, whilst the Nuclear Installations Inspectorate license facilities for reactor construction and deep maintenance. A fundamental principle applied by those authorities is that successful safety risk management is founded in a proper understanding of nuclear technologies."

This RINA paper outlines the strategy that is being applied to ensure that the new class of submarine, the SSBN(F), will be safe throughout their life. A key aim of that strategy is to design safety into the future submarine; hence the process must start during the concept phase of development.

A nuclear submarine is one of the most complex machines in the world. To be successful, it must not only be able to counter the range of external hazards it may face in the environment in which it operates, e.g. collision, flood or pressure hull collapse, but must also be able to control the range of internal hazards that will exist, not least the munitions it must carry and the nuclear power plant that will provide its principal energy source.

A range of rigorous safety regulations exist against which the submarine design must be compliant, but those regulations are hazard specific, e.g. ship safety, nuclear safety or munitions safety. Compliance is essential, but as any operator in a hazardous industry realises, compliance on its own is insufficient.

It is very difficult to produce holistic regulations that recognise the demands of all other regulations; hence simple compliance with regulations is not necessarily sufficient to assure the safety of the vessel. The skill of the designer, and the skill of the operator, is equally as important as the skill of the regulator in delivering a safe solution.

2 GOAL BASED SAFETY STRATEGY

The safety strategy adopted for the control of major accident hazards is goal based, as opposed to prescription based, differentiated by the following simplistic examples:

- Goal Based: "People shall be prevented from falling over the edge of a cliff"
- Prescriptive: "You shall install a 1 metre high rail at the edge of the cliff"

2.1 INTERNATIONAL MARITIME ORGANISATION

Such a goal based strategy has been proposed by the International Maritime Organisation (IMO), the Maritime Safety Committee (Reference 4) agreeing a five-tier system comprising:

- Tier 1 - Goals.

- Tier 2 - Functional Requirements.
- Tier 3 - Verification of Compliance Criteria.
- Tier 4 - Technical Procedures & Guidelines; Classification Rules; and Industry Standards.
- Tier 5 - Codes of Practice; Safety & Quality Systems; Operation; Maintenance; Training; Manning.

The future submarine safety strategy is consistent with the IMO approach and the case it is intended to produce will draw upon the concepts of Goal Structuring Notation outlined by Kelly (Reference 1).The case will comprise:

- Goals: articulating the claims that must be achieved to ensure safety.
- Strategies: presenting the argument how the goals are to be achieved.
- Justification: to provide the evidence to substantiate that the goals can be achieved.

Bench-marking the two methodologies:

- Tier 1 Goals; correspond to the goals that the safety case must substantiate.
- Tier 2 Functional Requirements; correspond to the strategy how the safety case will be made.
- Tier 3, 4 & 5 Criteria, Rules and Standards; correspond to the justification to substantiate the safety case.

This paper is focused on the derivation of the Functional Requirements.

2.2 FUTURE SUBMARINE SAFETY GOAL

The top tier safety goal for the future submarine is to:

To develop a cost-effective submarine for which all risks to the workforces, the public and the environment have been reduced so far as is reasonably practicable , when it is operated independently or in conjunction with a shore support facility throughout the life of the submarine.

To achieve this, the submarine must incorporate measures to:

- Reduce the probability of major accidents to a level that is as low as reasonably practicable (ALARP) and tolerable.
- Limit the consequence to people and the environment of any major accidents which do occur.
- Provide a safe working environment for individuals onboard the submarine.
- Impose acceptable environmental impact.

To reduce project risk, the management safety must also:

- Reduce the financial risk of safety driven cost escalation.
- Reduce the risk of programme delays caused by back-fitting safety analysis and back-fitting safety driven changes to the design.

3 SAFETY STRATEGY

A strategy is essential for producing a coherent case that seeks to achieve the top tier safety goal, which must addresses:

- Control of Major Accident Hazards.
- Provision of a Safe Working Environment.
- Protection of the Environment.

The requirement to differentiate between the Control of Major Accident Hazards and the Control of Local Hazards to Individuals to provide a Safe Working Environment is emphasised by Baker (Reference 3) in his assessment of the BP Texas City refinery accident in March 2005, which states:

"BP appears to have established a relatively effective personal safety management system by embedding personal safety aspirations and expectations within the U.S. refining workforce. However, BP has not effectively implemented its corporate-level aspirational guidelines and expectations relating to process risk. Therefore, the Panel found that BP has not implemented an integrated, comprehensive, and effective process safety management system for its five U.S. refineries."

The Baker report presented the findings of an independent investigation into a catastrophic process accident at the BP Texas City refinery on March 23, 2005. It was described as one of the most serious U.S. workplace disasters of the past two decades, resulting in 15 deaths and more than 170 injuries.

In the Baker Report, Process Risk refers to the Control of Major Accident Hazards and Personal Safety refers to the control of local hazards to individuals to achieve occupational health and safety in order to provide a Safe Working Environment. The significance of the report is that while BP believed they had an effective safety management system, it was focused on one aspect of safety only - personal risk. It did not address process risk or the control of major accident hazards.

Implementation of a strategy requires a number of supporting tactics, including:

- Plan, for the Control of Major Accident Hazards.
- Plan, to provide a Safe Working Environment.
- Plan, to enable Environmental Protection.

- Management System, to define Roles and Responsibilities.

The safety and environmental strategy for the future submarine is summarised at Figure 1.

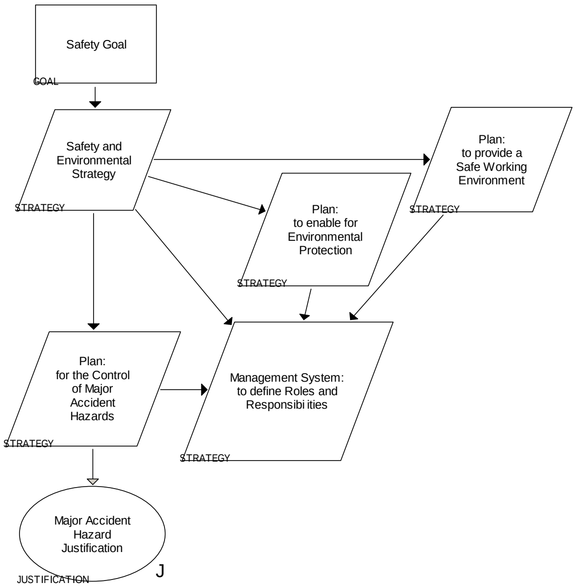

Figure 1. Safety Strategy and Plans

3.1 HAZARDS AND THE CONTROL OF HAZARDS

Hazard, Risk and Safety have the following meanings:

- A Hazard is the intrinsic property of an entity that has the potential to cause harm.
- Risk is the chance that someone will be adversely affected by a Hazard.
- Safety is the state achieved when the Risk arising from a Hazard has been reduced to an acceptably low level.

Hazards are addressed in two categories:

- Major Accident Hazards: hazards that could
  - cause loss of the submarine;
  - cause serious injury or death of multiple persons onboard the submarine; or
  - present a serious threat to life, property or the environment external to the submarine.
- Local Hazards to Individuals: hazards that could
  - cause the death, serious injury or minor injury of an individual person onboard the submarine.

The safety strategy requires the application of different approaches to mitigation of the two categories of hazard, defined as:

- 'Top Down' Control of Major Accident Hazards.
- 'Bottom Up' provision of Occupational Health and Safety.

The strategy for protection of the environment will follow a similar method. A major accident is equally likely to cause environmental damage as loss of life. The Control of Major Accident Hazards is therefore equally applicable to environmental protection as safety. The environmental equivalent of Occupational Health and Safety is:

- 'Bottom Up' Pollution Prevention and Control.

This paper focuses on the Control of Major Accident Hazards.

3.2 'TOP DOWN' CONTROL OF MAJOR ACCIDENT HAZARDS

The strategy for the 'Top Down' Control of Major Accident Hazards is based upon three tenets, shown diagrammatically at Figure 2:

> Tenet 0.1 Function: the functions necessary to control the major accident hazards inherent with delivery of the user requirement will be derived.
> Tenet 0.2 Management: management arrangements will be put in place to enable the design and construction of structures, systems and components to enable the performance of those functions.
> Tenet 0.3 Substantiation: evidence will be presented as justification that the structures, systems and components are able to perform the necessary functions in order to substantiate the case.

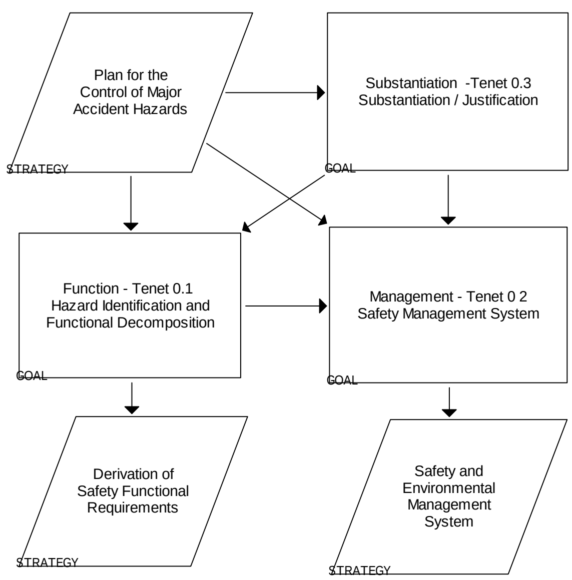

Figure 2. Control of Major Accident Hazard Tenets

The significant points to note are:

- The strategy is safety lead, not compliance lead; i.e the aim of the strategy is to develop a logical argument, supported with appropriate evidence, to demonstrate that the submarine is safe, and thereby satisfy appropriate legislation. The aim is not to simply demonstrate compliance with standards and regulations.
- The strategy aims to inform the design process; i.e the aim is not to retrospectively assess a pre-existing design.
- The strategy is function lead, not system lead; i.e. the aim is demonstrate that those functions necessary to control major accident hazards can be performed, not to simply assess the performance of bounded sub-systems.

The achievement of Tenet 0.1, Function, requires derivation of the Functional Requirements, which involves:

- Identification of those hazards having the potential to cause a major accident that the submarine is required to face in order to deliver the user requirement.
- Challenge of the user requirement to reduce or eliminate the hazards to which the submarine must be exposed.
- Identification of the safety functions that must be performed to control the residual major accident hazards.
- Option generation to propose the combination of submarine systems and sub-systems that could perform the identified safety functions.
- Application of the defence in depth methodology to achieve the safety function integrity commensurate with the unmitigated consequences of each hazard.
- Reduction of the sub-system options to the preferred, chosen, submarine system configuration.

This process requires Functional Decomposition of the User Requirement, and the Safety Functional Requirements necessary to mitigate the major accident hazards inherent with delivery of the User Requirement, to establish the proposed submarine system architecture. Early performance of this exercise will be key to successful implementation of the safety strategy.
The major accident hazards considered include, but are not limited to:

- External Hazards: arising from the environment within which the submarine is required to operate:
  - Sea: pressure creating the potential for hull collapse.
  - Sea: creating the potential for flooding leading to excess submarine weight.
  - Weather: causing extreme motion, acceleration and displacement.
  - Navigation hazards: creating the potential for collision or grounding.
- External Hazards: Impact:
  - Dropped Loads.
- Internal Hazards:
  - Nuclear Materials.
  - Radioactive Materials.
  - Breathable Atmosphere:
    - Temperature and Humidity.
    - Chemical Composition.
  - Flammable Materials.
  - Explosive Materials.
  - Oxidants.
  - Propellants.

4 FUNCTIONAL REQUIREMENTS

An SSBN must perform numerous safety functions in order to control the range of major accident hazards that it will face in service. In order to develop a coherent safety case, it is necessary to derive a logical decomposition of the Safety Functional Requirements (SFR) that are necessary to control the identified major accident hazards. Derivation of that logical derivation is the first challenge facing the SSBN(F) design team.

4.1 FUNDAMENTAL SAFETY FUNCTIONS

Such an approach has been applied by the nuclear industry for a number of years, articulated in the concept of Fundamental Safety Functions. The International Atomic Energy Agency (IAEA) identify three fundamental safety functions that must be performed in order to control the major accident hazards inherent with the delivery of nuclear power (Reference 5):

- Control of Reactivity.
- Removal of Heat from the Core.
- Confinement of Radioactive Materials.

These Fundamental Safety Functions are applicable to the SSBN(F), but address the hazard associated with nuclear materials used for power generation only. There are clearly more fundamental functions required to address the full range of hazards. The question is therefore asked:

- Can a family of Fundamental Safety Functions be defined that describe all of the safety functional requirements for the submarine?
- Can those functions be expressed as a single logical decomposition?
- Can the interaction between those functions be identified and managed?

The first step is to define what constitutes a Fundamental Safety Function, the resultant definition being:

A high level operation that the submarine must perform to control a major accident hazard, and which, if lost, will result in an initiating event that could cause a major accident.

4.2 KEY SAFETY FUNCTIONS

The IAEA Fundamental Safety Functions are applicable to nuclear power. To achieve the aspiration of a whole boat safety functional decomposition it is necessary to start at a tier above the fundamental safety functions. The expression chosen to define such top level functions is 'Key Safety Functions', around which the Fundamental Safety Functions are brigaded. Six Key Safety Functions are identified:

- Vehicle Control:
  Control the submarine vehicle in six degrees of freedom.
- Power and Propel:
  Provide the propulsive power, non propulsive power and waste heat removal required to control the submarine vehicle.
- Generate Nuclear Power:
  Generate the power necessary to control the submarine vehicle from nuclear heat.
- Sustain Life:
  Sustain life onboard the submarine vehicle.
- Handle Ordnance, Munitions and Explosives:
  Control the major accident hazards associated with embarking, handling, storing, discharging and disembarking munitions.
- Control Fire Hazards:
  Fire threatens each of the Key Safety Functions, hence the control of fire hazards is managed as a Key Safety Function in its own right.

The nature of a nuclear submarine is such that a significant major accident hazard remains even when along side, by nature of its propulsion plant and onboard munitions. The safety case must therefore be considered in context of its operating regimes, giving rise to the operating regimes:

- **Sea**:
  Operations under self control in open water.
- **Shore**:
  Operations under external controls when alongside, docked or being manoeuvred by tugs. The Shore case also considered the through life case of maintenance, long overhaul and disposal.

The Key Safety Functions, the major accident hazards they control, and the regimes in which the submarine will be operated are shown diagrammatically at Figure 4.

4.3 VEHICLE CONTROL

The fundamental safety functions to enable vehicle control are shown at Figure 5.
The accidents that the vehicle control function seeks to prevent are:

- Collisions;
- Grounding, either surfaced or dived; and
- Exceeding the submarine's crush depth, caused either by flooding or by uncontrolled manoeuvring.

The function also includes the means to enable external control of the submarine, either by towing or salvage, to regain control the submarine and its installed systems and equipment, should the submarine's ability for self control be lost.

The fundamental safety functions that enable vehicle control are:

- Provide structural integrity;
- Control buoyancy and weight;
- Maintain stability;
- Navigate the submarine, including communication with third parties;
- Self control of submarine manoeuvring, surfaced and dived; and
- External control of the submarine by mooring, berthing, anchoring, towing and salvage.

The key points to note are:

- Vehicle control involves the application of naval architecture disciplines to enable the control of an underwater vehicle, navigation disciplines and communication disciplines.
- Vehicle control makes demands on marine engineering for propulsion, recognising that without forward motion hydrodynamic control surfaces are ineffective.
- Vehicle control makes demands on marine engineering for non-propulsive power, to actuate control surfaces.

The division of analysis by physical system or technical discipline tends to encourage 'stove-piping' of the design, which hinders the construction of a logical case that the submarine is safe.

The benefit of functional analysis is that a logical case can be made to articulate those functions must be performed in order to control the major accident hazards faced by the submarine. The design of systems to enable the performance of those functions can be informed by that analysis and evidence can be collated to provide a justification that those functions can be performed with the correct integrity; hence a substantiated safety case can be made.

4.4 POWER AND PROPEL

The fundamental safety functions brigaded under power & propel are at Figure 6.

The power & propel function differs from the other key safety functions in that its does not directly control any major accident hazards; it is however essential to enabling performance of the other key safety functions.

The three fundamental safety functions brigaded under power & propel are:

- Deliver Propulsive Power: deliver own ship thrust, as demanded by vehicle control.
- Deliver Non-Propulsive Power: generate, transmit, store, distribute, convert and deliver non-propulsive power to perform the key safety functions.
- Remove Waste Heat: remove waste heat and transfer that heat to an ultimate heat sink.

The key points to note are:

- The delivery of propulsive power is in direct support of vehicle control. The integrity of propulsive power is key to safe vehicle control, in particular, in extremis, the ability to provide emergency propulsive power to restore vehicle control in response to a manoeuvring incident or major flood.
- The delivery of non-propulsive power is in direct support of each of the key safety functions:
    - Vehicle control: to actuate control services.
    - Generate nuclear power: to drive rotating machinery necessary to remove heat from the core.
    - Sustain life: to control the internal environment of the submarine.
    - Handle munitions: to control the induced climatic environment in munitions storage compartments.
- The removal of waste heat is in direct support of each of the key safety functions:
    - To transfer nuclear decay heat to an ultimate heat sink.
    - To transfer waste heat from the habitable areas of the submarine to an ultimate heat sink.
    - To transfer waste heat from munitions storage compartments to an ultimate heat sink.
- In order to deliver the power & propel function a number of additional hazards may be introduced into the submarine, including high energy electrical power, lubricating oil, high pressure hydraulic fluid and high pressure air.
- Such secondary hazards may contribute to the onboard fire hazard; hence the control of fire hazards is a supporting function to the delivery of power and propulsion.

4.5 GENERATE NUCLEAR POWER

The fundamental safety functions supporting the generation of nuclear power are shown at Figure 7. The accidents that the nuclear power function seeks to prevent are:

- The uncontrolled exposure of people to radiation.
- The uncontrolled release of energy from nuclear material.
- The uncontrolled release of radioactive material to the environment.

Nuclear power must also be generated with adequate integrity to support the power & propel function, which in turn supports the other key safety functions, most notably vehicle control.

The three fundamental safety functions identified by the IAEA that enable the safe generation of nuclear power are:

- Control of reactivity.
- Removal of heat from the core.
- Confinement of radioactive materials.

In addition, the IAEA identify four radiological protection requirements:

- Shield radioactive materials.
- Minimise human activity in radiation fields.
- Minimise the quantity of radioactive materials produced.
- Treat radioactive materials to reduce the dispersal of radioactive materials within the plant.

The key points to note are:

- The control of reactivity to prevent the uncontrolled release of nuclear energy is synonymous with the control of power generation to support the power & propel function.
- The removal of heat from the core is dependent on the provision of non-propulsive power to drive the rotating equipment employed in the transfer of that heat.
- The removal of heat from the core is also dependent on the provision of heat sink to which nuclear heat can be transferred.
- Claims are made on the structural integrity of the submarine hull for the containment of radioactive materials.
- Claims are made on the confinement, shielding, treatment and minimisation of radioactive materials in order to sustain life onboard the submarine.

- Claims are made on the control of human activity in radiation fields to sustain life onboard the submarine.
- Claims are made on the control of fire hazards to protect nuclear safety critical systems.

4.6 SUSTAIN LIFE

The fundamental safety functions required to sustain life are shown at Figure 8.

The accidents that the sustain life function seeks to prevent are the loss of multiple lives as a result of a gross excursion of the environment onboard the submarine, including:

- Asphyxiation due to loss of atmospheric control.
- Heat exhaustion and heat stoke due to loss of control of the onboard thermal environment.
- Uncontrolled exposure to radiation.

The sustain life function also seeks to:

- Prevent crew fatigue, which would be a contributory factor to the failure to perform other safety functions.
- Enable escape, rescue and abandonment, which may be necessary should it prove impossible to sustain life onboard.

The sustain life function does not encompass occupational health and safety, which is addressed in a separate strategy focused on the control of local hazards to individuals.

The safety functional requirements to sustain life are:

- Control the internal environment of the submarine.
- Provide hotel services to prevent fatigue and illness.
- Protect people from radiation.
- Enable escape, rescue and abandonment.

The key points to note are:

- The sustain life function is dependent upon the power & propel function to drive the equipment required to control the internal environment of the submarine.
- The sustain life function is dependent upon confinement, shielding, treatment and minimisation of radioactive materials.
- The sustain life function is dependent upon the control of human activity in radiation fields.
- The grace time between the failure of certain sustain life functions and catastrophic consequences can be large, but if such failures are not corrected the consequences will be realised. The hazards to sustaining life onboard a submarine must not therefore be underestimated.

4.7 HANDLE MUNITIONS

The fundamental safety functions required to handle munitions safely are shown at Figure 9.

The accidents that the handle munitions function seek to prevent are:

- The uncontrolled discharge of weapons.
- The uncontrolled ignition of fuel and propellants.
- The uncontrolled detonation of explosives.
- The uncontrolled exposure of people to radiation.
- Yield.

The context within which the handling of munitions is addressed is the:

- Embarkation of munitions.
- Storage of munitions.
- Onboard handling of munitions.
- Discharge of munitions.
- Disembarkation of munitions.

The key points to note are:

- The principle strategy for the safe handling of munitions revolves around the provision of a general naval environment within which munitions are demonstrable stable. The general naval environment is defined by the:
  - Natural and induced climatic environment.
  - Chemical and biological environment.
  - Mechanical environment.
  - Threat and accident environment.
  - Electromagnetic environment.
- The provision of a general naval environment is dependent upon other key safety functions, principally the power & propel function for the delivery of non-propulsive power and the removal of waste heat.
- The handling of munitions is also closely linked to the control of fire hazards. A further fundamental safety function is therefore to contain fuels, propellants and explosives in properly constituted storage systems in support of fire prevention.

4.8 NAVAL SHIP CODES

The SSBN(F) strategy is consistent with the concept of 'Naval Ship Codes' (Reference 6), which considers:

- General Provisions.
- Structure.
- Buoyancy and Stability.
- Machinery installations.
- Electrical installations.
- Fire Safety.

- Escape, Evacuation and Rescue.
- Radio communications.
- Safety of Navigation.
- Carriage of Dangerous Cargoes.

Bench-marking the two concepts:

SSBN(F) Strategy	Naval Ship Code
Vehicle Control	Structure
	Buoyancy and Stability
	Radiocommunications
	Safety of Navigation
Power & Propel	Machinery Installations
	Electrical Installations
Generate Nuclear Power	
Sustain Life	Escape, Evacuation and Rescue
Handle Munitions	Carriage of Dangerous Cargoes
Control Fire Hazards	Fire Safety

5 SYSTEM FUNCTIONAL REQUIREMENTS

It has thus been demonstrated necessary to perform thirty two fundamental safety functions in order to achieve the six key safety functions. To relate the fundamental safety functions to the submarine design it is next necessary to further decompose the fundamental safety functions into the functional requirements for physical systems.

Two examples of such decompositions are considered in this paper:

- Control of Buoyancy and Weight.
- Provision of propulsion and non-propulsive power.

CONTROL OF BUOYANCY AND WEIGHT

An obvious submarine function is the control of buoyancy and weight, the functional model for which is at Figure 11.

It is necessary to adjust submarine weight in order to achieve neutral buoyancy when dived in response to:

- Changes in internal weight, including weapons discharge; and
- Changes in buoyancy arising from changes in sea water density and submarine compressibility.

Control of weight is achieved by:

- Coarse control of fixed bodily weight; and
- Fine control, or trim, of variable bodily weight.

In order to control variable bodily weight it is necessary to control the:

- Ingress of water;
- Egress of water; and
- Distribution of weight in order to control pitch and heel.

The control of watertight integrity also supports the control of the ingress of water, the loss of watertight integrity being an uncontrolled ingress of water.

The control of buoyancy and weight also supports the control of depth, the control of depth being dependent upon two functions:

- The control of variable weight; and
- The dynamic control of lift from the hydroplanes.

Dynamic lift is further dependent upon the two functions:

- Control of submarine hydroplanes.
- Control of speed.

5.1.1 Power and Propulsion

The control of submarine speed makes claims on the provision of propulsive power to provide submarine thrust and the control of hydroplanes makes claims on the provision of non-propulsive power for actuation. The control of variable weight is also dependent upon the provision of non-propulsive power, either to pump water out of the submarine, or to blow main ballast.

5.2 PROPULSIVE AND NON-PROPULSIVE POWER

The functional diagram for the provision of non-propulsive power is shown at Figure 12.

5.2.1 Non-Propulsive Power

The option exists to provide non-propulsive power in a number of forms, including:

- Electrical power;
- Hydraulic power; and
- HP air.

With each power source are embodied the supporting functions:

- Generate power;
- Distribute power; and
- Store energy.

Each power source however draws from a common energy source of distributed electrical power, which in turn draws upon the electrical power transmission. Differentiation is made between transmission and distribution:

- Power Transmission: is the process of bulk transfer of electrical power between generators, main switchboards, switchboard inter-connectors and main propulsion motors;
- Electricity Distribution: is the delivery of electrical power to discrete equipments.

The electrical transmission system draws it power from one of a number of sources:

- Onboard generated electrical power.
- Onboard stored electrical power (main battery).
- Over side supplied electrical power (harbour supplies).

Options also exist for onboard generation:

- Turbo-generators; or
- Diesel-generators.

The generation of electrical power by turbo generator is dependent upon nuclear power.

5.2.2 Propulsion

Propulsive power and non-propulsive power are closely linked:

- Main turbines draw upon the same steam source as the turbo-generators;
- Propulsion motors draw upon electrical transmission; and the option exists to use
- Hydraulic motors which draw upon the hydraulic system.

Having established the system functional requirements, it is necessary to establish the means by which the required integrity of function can be achieved, which requires the application of defence in depth.

6 DEFENCE IN DEPTH

Defence in depth is a methodology that has been in use in the nuclear industry for a number of years, the methodology being described in the guidance at Reference 7. The guidance states:

"All safety activities, whether organisational, behavioural or equipment related, are subject to layers of overlapping provisions, so that if a failure should occur it would be compensated for or corrected without causing harm to individuals or the public at large. This idea of multiple levels of protection is the central feature of defence in depth."

The objectives of Defence in Depth are:

- To compensate for potential human and component failures.
- To maintain the effectiveness of barriers by averting damage to the plant and to the barriers themselves.
- To protect the public and the environment from harm in the event that these barriers are not fully effective.

The IAEA identify five Levels of Defence, summarised in Figure 3.

Defence in Depth		
	Objective	Essential Means
1	Prevention of Abnormal Operation and Failures	Conservative Design and High Quality in Construction and Operation
2	Detection of Failures and Control of Abnormal Operation	Control, limiting and protection systems and other protection features.
3	Control of accidents within the design basis	Engineered safety features and accident procedures.
4	Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents	Complementary measures and accident management
5	Mitigation of the Radiological Consequences of significant releases of radioactive materials	Off site emergency response

Figure 3. Defence in Depth

The methodology was developed for civil nuclear power plant, but is equally applicable to other hazardous industries. Levels 1 to 4 are generic to all major accident hazards, whereas level 5 is specific to radiological release. Level 5 can be considered more generic if the means of achievement are considered to include any form of external support in response to a major accident, levels 1 to 4 being achieved by means that are indigenous to the plant.

The concept can also be expressed as a 'bow-tie', as shown in Figure 13.

An accident sequence can be envisaged:

- Normal operation; the failure of which results in
- Abnormal operation; the failure of which is a
- Postulated initiating event; the consequences of which are considered an
- Incident; which if unchecked will result in an
- Accident.

Defence in depth is provided to present barriers to the progression of such an accident sequence. Arrangements must be provided to:

- Prevent deviations from normal operation; which must include the means of
- Detecting a deviation from normal operation; in response to which the means must be provided to
- Prevent deviations from normal operation becoming accidents; which must be reinforced with
- Engineered safeguards; themselves reinforced with onboard
- Severe accident management arrangements; supported by
- External accident management arrangements.

6.1 CONTROL FIRE HAZARDS

The control of fire hazards underpins each of the key safety functions, and hence whole ship safety; fire having the potential to inhibit any or all of the fundamental safety functions. Rather than have multiple strategies for the control of fire hazards, it is proposed to apply one whole boat strategy which will:

- Address the control of fire hazards as a coherent whole ship strategy; but apply
- Targeted strategies in circumstances where specific hazards demand it.

The control of fire hazards is an example of the application of defence in depth, but in recognition of its whole boat significance it is treated as a key safety function.

The fundamental safety functions to enable the control of fire hazards are shown at Figure 10. Those functions are:

- Prevent fire;
- Detect fire;
- Control fire; including the suppression and extinguishing of fire
- Protect safety critical systems; and
- Recover from fire.

7 SUBMARINE SAFETY CASE

The submarine safety case will be made when:

- The key safety functions are defined; the achievement of which requires derivation of
- The fundamental safety functions; the achievement of which requires derivation of
- The system functional requirements; the achievement of the required integrity requires
- Defence in depth.

The amount of defence in depth requires consideration of:

- The consequences of loss of a fundamental safety function; and
- The inherent integrity of systems.

7.1 TOOLS

The management of the SSBN(F) safety strategy is heavily dependent upon information management and information management tools. Reliable relational databases are essential for efficient management, two tools in particular being applied, the:

- Adelard Safety Case Editor; and
- Telelogic System Architect.

The tools are being used in a complementary fashion: the Adelard tool being used for model building in conjunction with facilitated workshops, and for post workshop optioneering and refinement; and the Telelogic tool being used as the archive for agreed solutions to which many users will have access. Both tools enable the presentation of data using graphical techniques, which is essential for functional modelling. Experience shows that complex interactions quickly become difficult to follow when using non graphical databases and spreadsheets.

8 CONCLUSIONS

The strategy for production of a federated whole boat safety case for the SSBN(F) seeks to produce a logical decomposition of the functions that the submarine must be able to perform in order to control the major hazards that are inherent with delivery of the users requirement.

The division of analysis by physical system or technical discipline tends to encourage 'stove-piping' of the design, which hinders the construction of a logical case that the submarine is safe.

The benefit of functional analysis is that a logical case can be made to articulate those functions must be performed in order to control the major accident hazards faced by the submarine. The design of systems to enable the performance of those functions can be informed by that analysis and evidence can be collated to provide a justification that those functions can be performed with the correct integrity; hence a substantiated safety case can be made.

The strategy is consistent with a number of safety methodologies for the control of major accident hazards in a number of hazardous industries, including:

- IMO goal based safety strategy.
- IAEA fundamental safety functions.
- NATO naval ship codes.
- IAEA defence in depth.

The strategy also incorporates the lessons learnt from major accidents, such as the BP Texas accident in March 2004, by differentiating between the control of major accident hazards and the achievement of occupational health and safety.

The strategy is being applied at the earliest point in the design cycle to:

- Inform the design.
- Enable the establishment of the level of defence in depth by the end of the concept phase.

9 REFERENCES

1. *HM GOVERNMENT, 'The Future of the United Kingdom's Deterrent',* Secretary of State for Defence*, 2006*

2. *KELLY, T., 'A systematic approach to safety case management',* University of York*, 2003.*

3. *BAKER, J. A., 'The Report of the BP US Refineries Independent Safety Review Panel',* BP US Refineries Independent Safety Review Panel*, 2007*

4. *INTERNATIONAL MARITIME ORGANISATION, 'Goal-Based Construction Standards for New Ships'* , Maritime Safety Committee, *79th Session, 2004.*

5. *INTERNATIONAL ATOMIC ENERGY AGENCY, 'Safety of Nuclear Power Plants: Design',* IAEA Nuclear Safety Requirements*, 2000*

6. *RUDGLEY, G., BOXALL, P., ter BEKKE, E., and HUMPHREY, R., 'Development of a NATO 'Naval Ship Code',* Transactions of RINA*, 2005*

7. *INTERNATIONAL ATOMIC ENERGY AGENCY, 'Defence in Depth in Nuclear Safety,* International Nuclear Safety Advisory Group*, 1996*

10 AUTHORS

The authors comprise the safety management team for the successor SSBN.

Tony Coverdale (TC Safety Ltd, contracted to the Ministry of Defence) is the Platform Safety Manager for the SSBN(F) and part of the Client Team for development of the submarine.

Tim Roberts (BAE Systems) is the Safety Manager within the Provider organisation, working opposite the Platform Safety Manager to provide Client / Provider collaboration.

Yvonne Stone (Ministry of Defence) is the Assurance Manager within the Client Team, co-ordinating assurance of the work performed by the safety managers on behalf of the Integrated Project Team Leader.

John Williams (FNC) is currently the Independent Safety Advisor supporting the Assurance Manager.

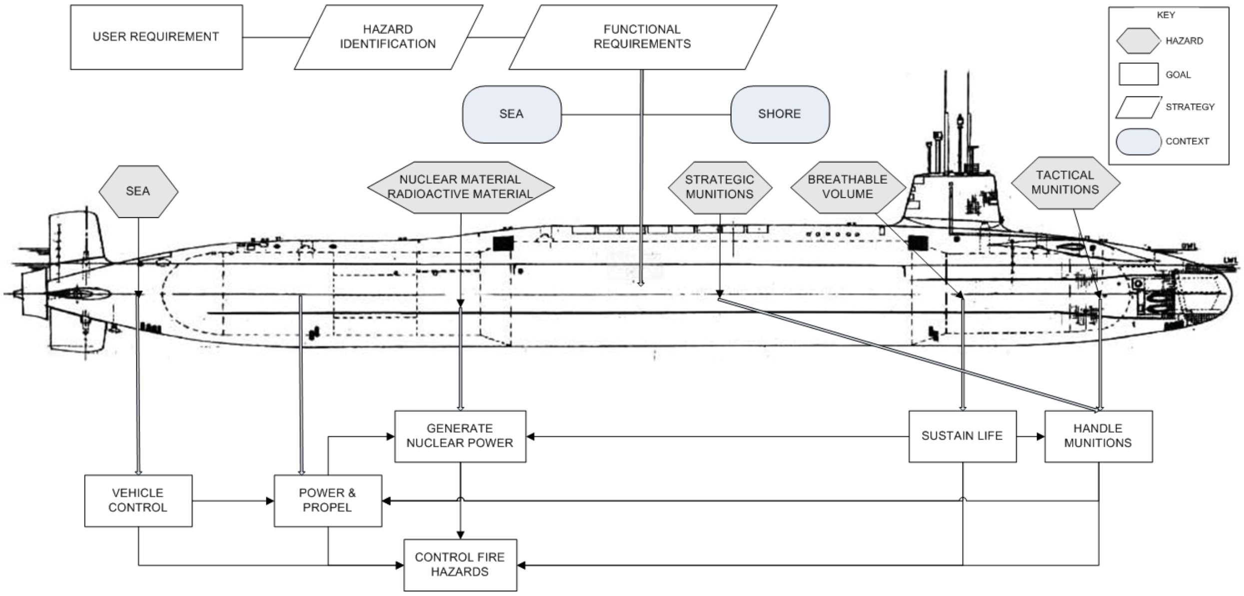

Figure 4. Key Safety Functions

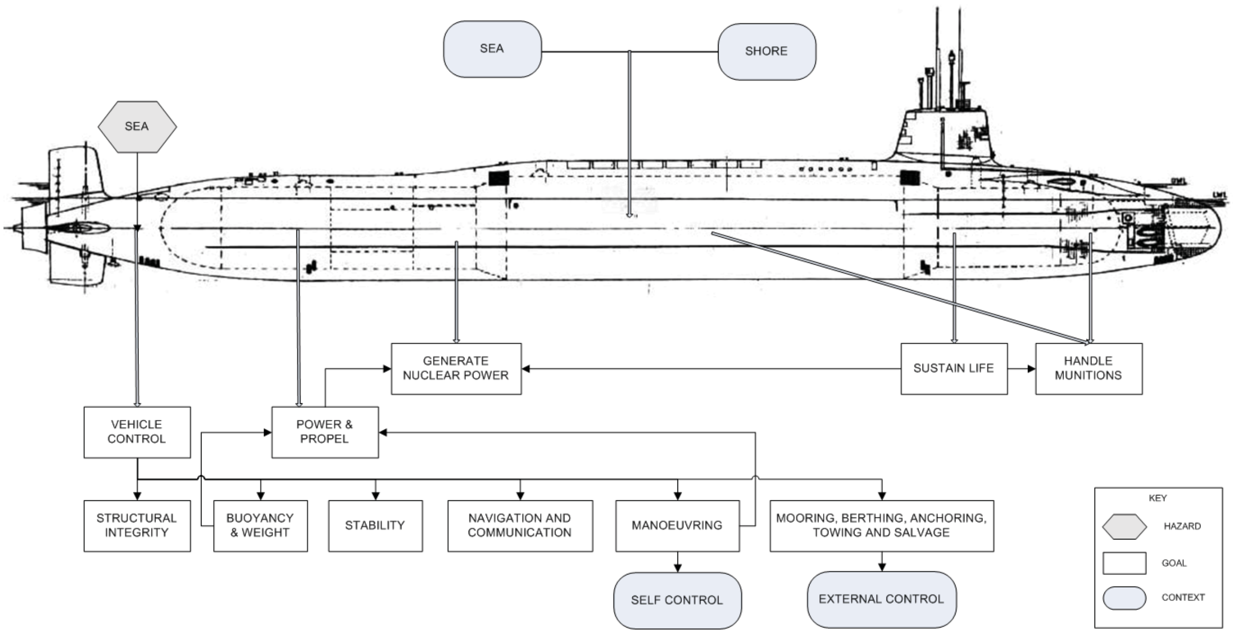

Figure 5. Vehicle Control

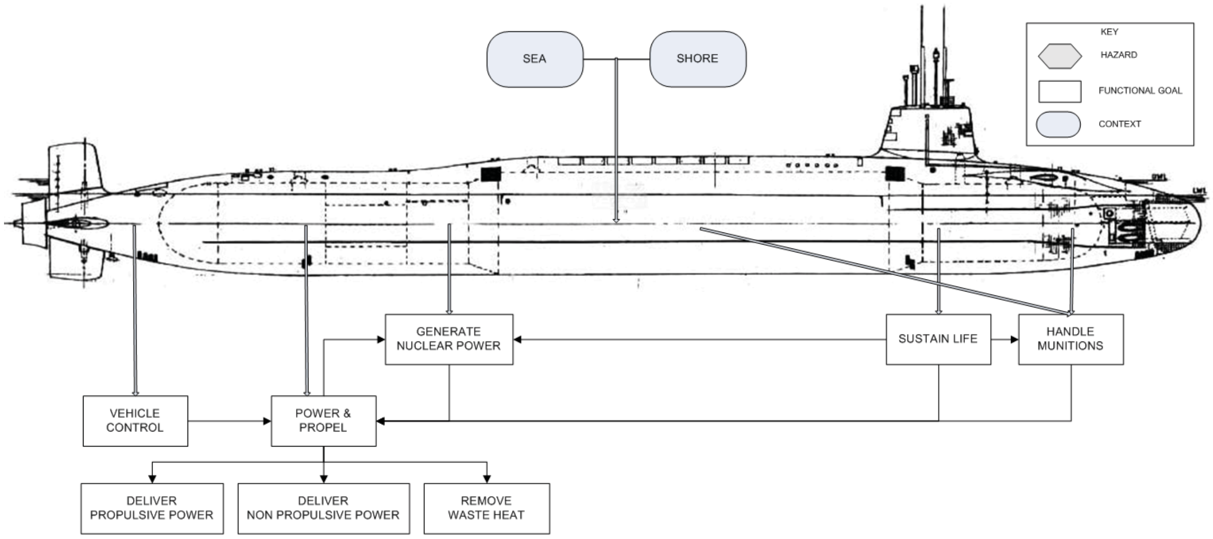

Figure 6. Power and Propel

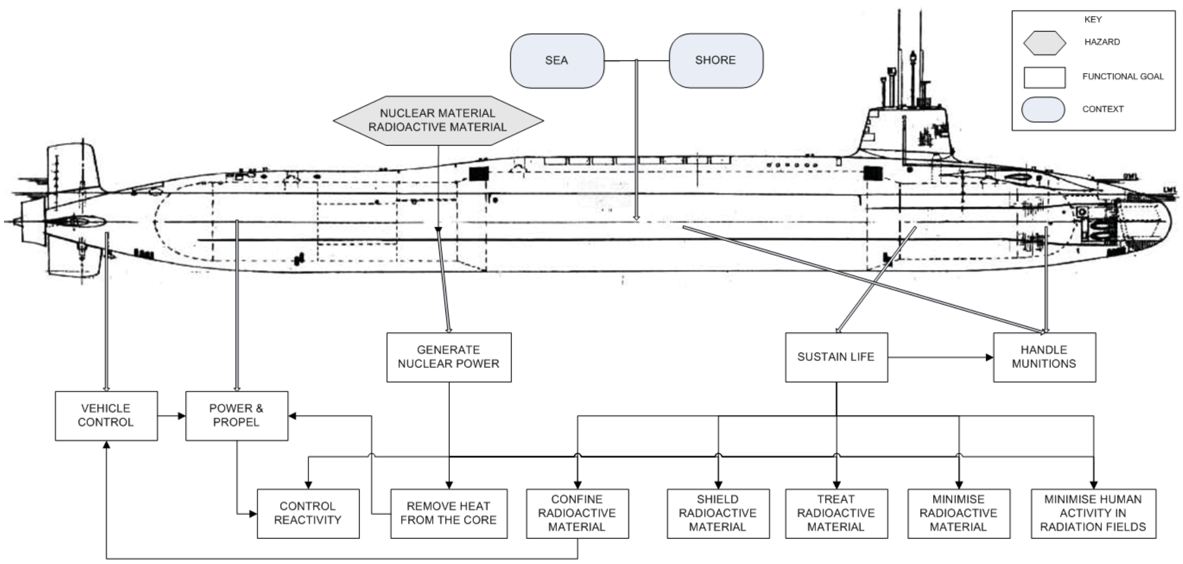

Figure 7. Nuclear Power

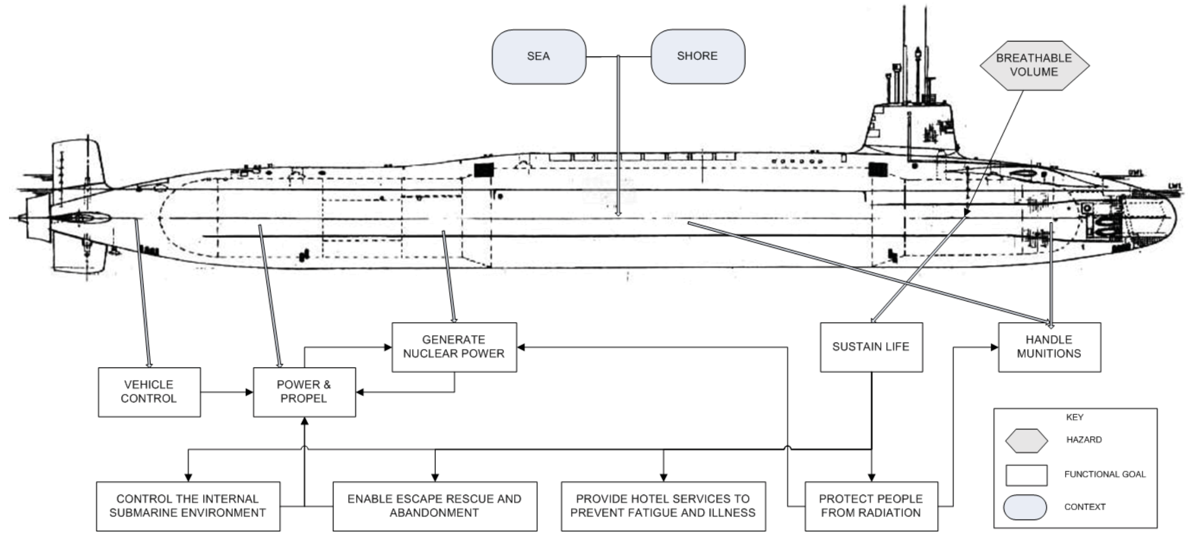

Figure 8. Sustain Life

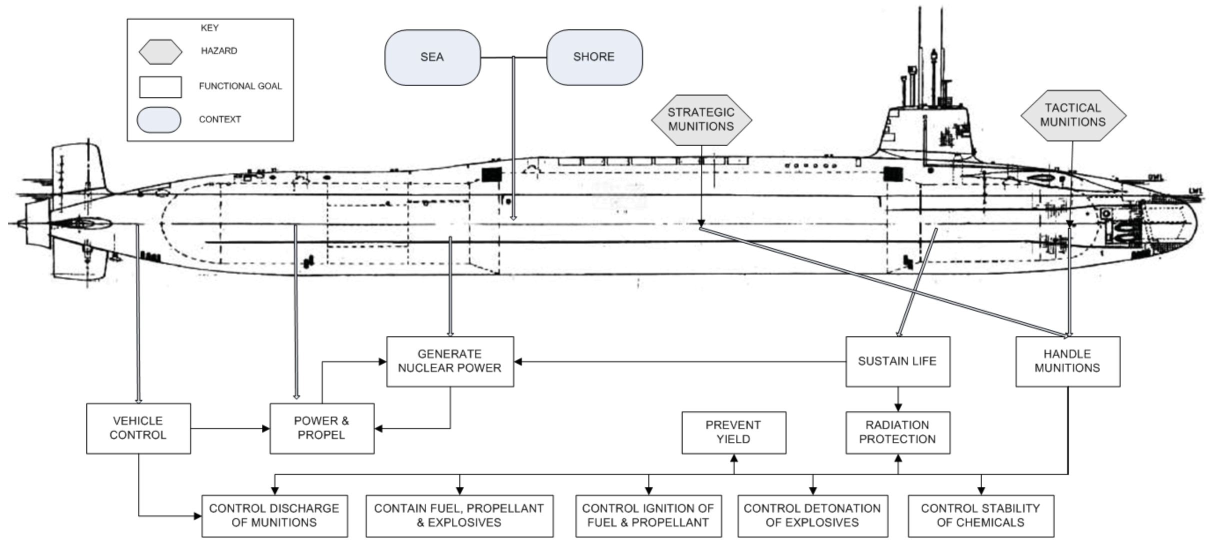

Figure 9. Handling of Munitions

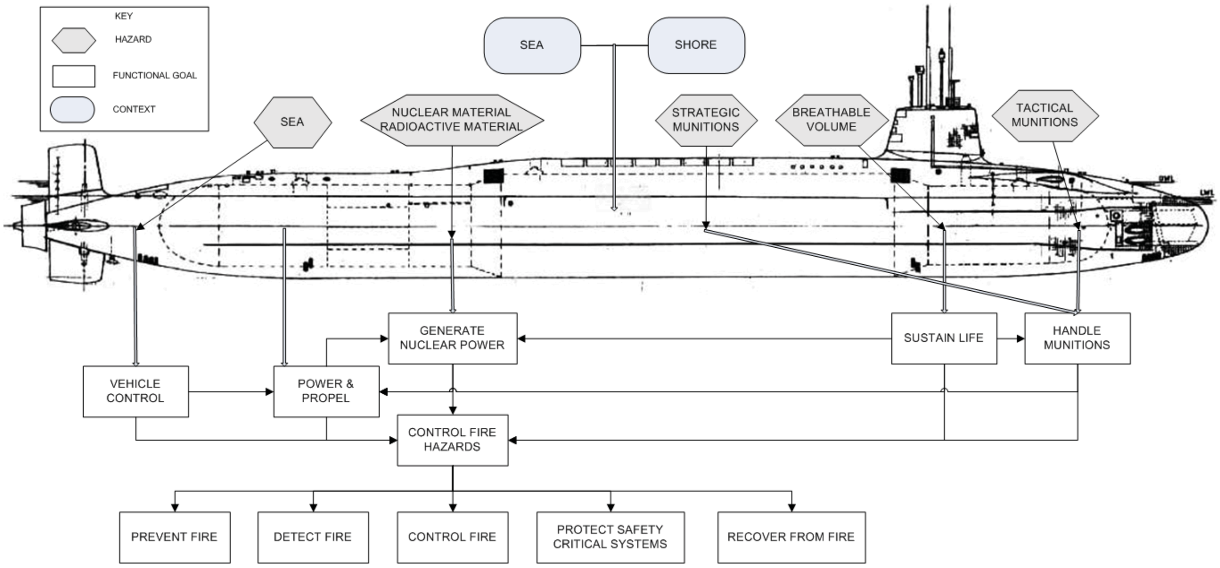

Figure 10. Control of Fire Hazards

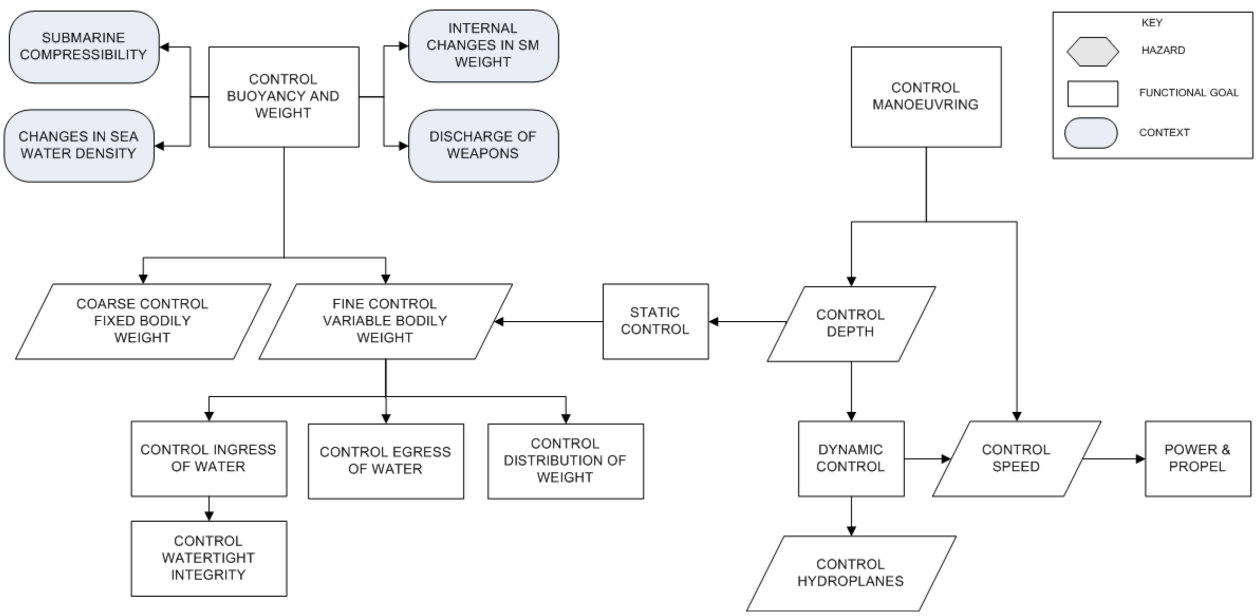

Figure 11. Control of Buoyancy and Weight

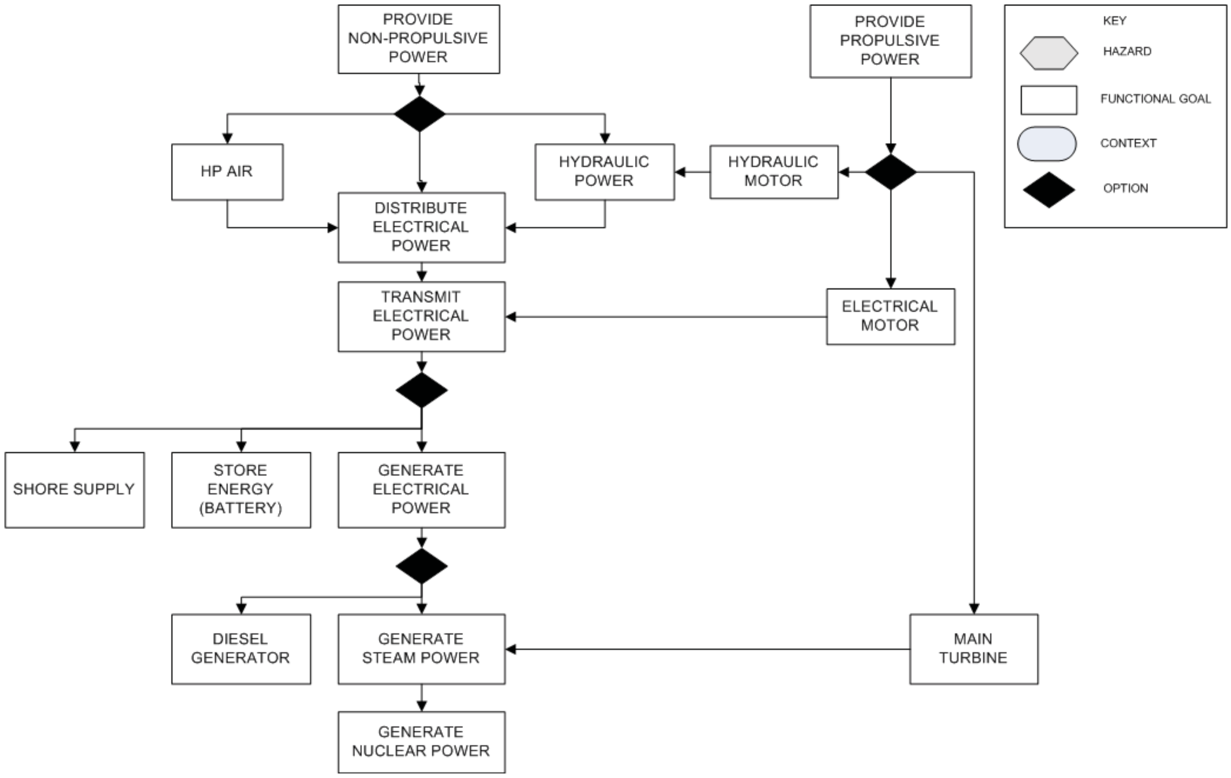

Figure 12. Control of Propulsion and Non Propulsive Power

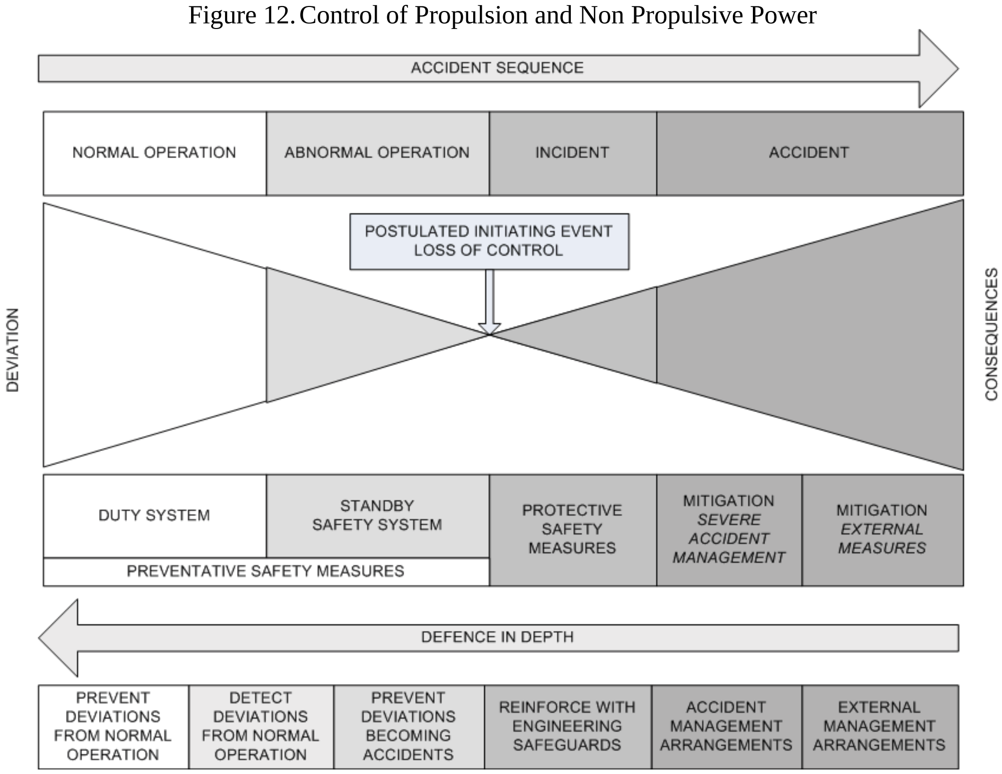

Figure 13. Bow-Tie Diagram

SUBMARINE ESCAPE, RESCUE AND SURFACE ABANDONMENT SYSTEM (SMERAS) REQUIREMENTS OF THE UK ROYAL NAVY

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SUMMARY

This paper describes recent work to capture UK Royal Navy requirements for escape, rescue and surface abandonment capability for the RN submarine fleet.

The submarine service has always managed the risk of submarine casualties, using approaches that are appropriate to the times. The procurement of equipment which provides this capability has changed in the last decade to align with MoD acquisition reform, and the increase in pressure to provide rigorous justifications within taut budgets. The changes have included a new focus on and definition of formal requirements for such equipment. Requirements management, using "User Requirements Documents" (URDs) and "Systems Requirements Documents" (SRDs), is a key tool in modern defence acquisition management.

In the last two years, QinetiQ has facilitated the production of an overarching SMERAS URD and SRD. The paper will describe the approach, stakeholders, background material, context, rationale and arising requirements.

NOMENCLATURE

The following acronyms are used within the paper.

CPG	Capability Planning Group
DEC	Director Equipment Capability
DISSUB	Distressed Submarine (on the sea bed)
FG	Focus Group
FOSM	Flag Officer Submarines
INM	Institute of Naval Medicine
KSR	Key System Requirement
KUR	Key User Requirement
MoD	Ministry of Defence
NSRS	NATO Submarine Rescue System
RN	Royal Navy
SASUB	Surface Abandon Submarine
SMERAS	Submarine Escape, Rescue And Surface Abandonment System
UWE	Underwater Effects

1. INTRODUCTION

This paper reports how, why and what SMERAS requirements were recently defined by the UK Ministry of Defence (MoD), facilitated by QinetiQ. Within the MoD, the Director Equipment Capability (Underwater Effects) - DEC(UWE) – has generated these requirements to support the governance of escape, rescue and surface abandonment capability for the RN submarine fleet. The outcome of the work has been documented in the SMERAS User Requirements Document (URD) [1] and SMERAS System Requirements Document (SRD) [2].

The procurement of escape and rescue equipment in the past was undertaken by a range of separate organisations within MoD, under the guidance of the Standing Committee on Submarine Escape and Rescue (SCOSER) ; when FOSM had control of budgets and equipment acquisition it worked very well and indeed was a formal requirements generation process dating from the loss of HMS THETIS, which presaged the modern trans-line of development approach. The budgetary control centralisation as part of MoD acquisition reform, the increased pressure on budgets and the increased need to provide rigorous justifications all drove a need for change. The committee has now been replaced by a new capability-oriented structure, which must be supported by clearly articulated documentation. Requirements management, through User and System Requirements Documents, is a key instrument of modern defence acquisition management in the UK.

In 2005/6 the absence of a clear, single, agreed statement of requirement owned by the Equipment Capability Customer was found to be allowing inconsistent or inefficient progress on escape and rescue issues. Equally the need to better articulate the requirement for Surface Abandonment needed to be satisfactorily prosecuted with appropriate justification. The most recent review in this area had been CINC FLEET's Submarine Escape and Rescue Policy Review 2005, which was completed and reported in early 2006 [3]. The aim of the review had been to examine all aspects of RN Submarine Escape, Rescue and Abandonment Policy and make recommendations. The relevant conclusions from the study were that:

- SMERAS should be managed as any other capability by a Customer 1 (DEC) led Focus Group for future capability and a Customer 2 (Fleet) led Capability Management Team for current capability[1];

[1] The terms Customer 1 and Customer 2 were removed during the recent Defence Acquisition Change Programme. The MoD

- Surface Abandonment was to be included in the scope of the then SMER Project team and
- Work on a URD and SRD should be re-started. It remains current Navy Board policy that "The requirements of the Policy for a SMERAS are to be expressed as an output-based User Requirement Document (URD)"

QinetiQ was initially tasked, in late 2006, to "develop user requirements that would inform and guide research into escape, abandonment, survivability and rescue capability on board SSN and SSBN submarines". In a second subsequent phase of work, QinetiQ was then tasked, by the SMERAS Project, to produce "a separate detailed System Requirement Documents (SRD) to address Submarine Surface Abandonment and Escape" in early 2008.

The intention of MoD was to develop a first cut of requirements. Changes to these would subsequently be managed internally. MoD asked that the URD and SRD should be developed in accordance with MoD templates for such documents, and with a degree of rigour which would stand up to argument. The techniques which we used for both tasks were similar, although the end results, reported below, were intended for different uses.

The SMERAS URD has been developed with a supporting SMERAS SRD. This SMERAS SRD does not cover the Rescue element, which has been described separately in the NATO Submarine Rescue System (NSRS) project SRD, which focuses on external rescue and intervention capability. It is accepted that the two SRDs will need to be combined (for the RN, noting that the Rescue SRD is also applicable to France and Norway), but this was not a focus for the recent work. The relationship between them is close in terms of User requirements for Intervention – which are partially met by the NSRS SRD, partly by platform System Requirements and partly by the SMERAS SRD. The SPAG (Submarine Parachute Assistance Group) capability also forms part of the current solution for Intervention.

2. UK MOD USE OF REQUIREMENTS ENGINEERING IN ACQUISITION CONTEXT

In normal circumstances, user and system requirements introduce a complete system or service for its whole life and are used to deliver military capability. They are produced in an evolutionary process encompassing input from all relevant stakeholders. They are aligned to support capability governance at different points in the MoD acquisition approvals process[2], as shown in Table 1.

The requirements document consists of a complete set of individual requirements, description of the background, stakeholders etc. It is the means by which the MoD develops, communicates and maintains the requirements throughout the life of the system/service. For each convenient segment of "capability", be it a submarine, training school or sensor network, the user first defines their requirements in terms of the effect that is required. The sponsor (in this case DEC(UWE)) takes the lead on the production, refinement and maintenance of the URD, drawing on the support and endorsement of stakeholders. Most URDs derive from a diplomatic and military policy framework that encompasses Military Tasks, Defence Guidance etc etc. Assumptions, including those on operational need, are defined to support future amendment decisions. Verification criteria are identified against each user requirement and requirements prioritised.

The acquisition authority then defines system requirements to document system characteristics considered necessary to meet all or part of that set of user requirements.

A URD and candidate KURs are required to support the first major investment decision, known currently as "Initial Gate". These are then matured, and the SRD developed, to support the final decision, "Main Gate". Contract specifications for procurement are based on the SRD, and equipment is assessed against it (using Integrated Test Evaluation and Acceptance). Ultimately the MoD will assess the performance at Capability/Effect level against the URD.

In this overall framework, MoD procures submarines and other platforms. Part of the policy that defines the platform system requirements is a level of safety. SMERAS requirements stem from that safety requirement to mitigate risks in operation of the submarine fleet.

In the idealised case, a new capability need is identified, and the Requirements Engineering process is undertaken to identify the needs of Users and System. This is most unusual, especially in the current budgetary climate. More commonly, the out of service date for a capability is anticipated, and the acquisition of replacement capability is initiated. The requirements documentation can start from a known base of measured capability.

now recognises a Unified Customer drawn from the DE&S, Front Line Commands and MoD Centre (see Section 4)

[2] SMART Approvals Guidance –Version 9.1/9.2 dated Nov. 07, http://www.ams mod.uk/aofcontent/tactical/randa/downloads/iabguide.doc

3. APPROACH TO DEFINING SMERAS REQUIREMENTS

In the case of SMERAS capability we recognised that there are four main components of interest. A simple illustration is provided at Figure 1. Rescue is the preferred method of maximising the number of survivors from a DISSUB. Escape is the next alternative. The equipment and training to enable Rescue and Escape are relatively mature. They may be supplemented by Intervention. Surface Abandonment, the fourth component, was to be acknowledged as a new capability; accepting that some abandonment capability does currently exist, although it may be ineffective.

The task of defining requirements for either new or mature capability is not straightforward. Our approach started with the development of a "strawman proposal", which stakeholders could use as the basis to form real, effective requirements.

To generate the strawman, QinetiQ trawled approximately 1100 pages of MoD and other documents, eliciting gems of information convertible into the formal language of user and system requirements. For the mature capabilities, requirements could be derived from supporting documentation, with application of Requirements Engineering rigour, to reformulate the knowledge. For the new capability, it was necessary to identify alternative sources of knowledge. None of the source documents provided information in terms of "The User shall be able to …" or "The system shall…". No word searches help you to winkle out the essence of a standard, manual or book of reference. The content was reviewed to elicit any relevant components that could be adapted to the purpose in hand. Where we identified a statement that looked like a MoD requirement, we extrapolated a strawman statement. This statement would be used by stakeholders to define a real User or System requirement which would in turn generate that requirement. In generating the strawman, we aimed to ensure a full breadth of coverage, so that the framework would capture the complete scope of the requirements. Less important at that stage was depth, which the stakeholders would provide from their domain knowledge and experience.

Existing Escape and Rescue documentation had evolved from reviews undertaken immediately post WW2 and had been progressively amended until the 1980s. Since that time only minor amendments had occurred to the documentation (and Escape related equipment).

For the Surface Abandonment requirements, QinetiQ drew upon Surface Fleet and Merchant fleet practice, and first principles approach to the process of abandoning a submarine. Requirements were drafted from this background into suitable a strawman proposal.

4. UNIFIED CUSTOMER CONCEPT AND KEY STAKEHOLDERS

Having drafted a strawman, our approach now moved on to a second element - presenting it piece by piece to all of the organisations which have a stake in the requirement for the SMERAS capability.

The UK MoD has established, based initially on McKinsey advice, but matured under the recent Defence Acquisition Change Programme (DACP) and subsequent Through Life Capability Management (TLCM) programmes a construct under which Capability decision making is undertaken by the Unified Customer. The "Unified Customer" is a construct which brings together, under the leadership of the Equipment Capability Customer (ECC), the waterfront user (FLEET), the acquisition and support authority (Defence Equipment & Support, DE&S), the scientific support (Science Innovation Technology, SIT) and MoD Centre (Resources, Planning and Policy etc). To develop a fully endorsed requirement set, the whole Unified Customer must provide input and declare satisfaction. This typically occurs before "Initial Gate", and was not strictly necessary for this first cut. The key stakeholders in this case were:

- For Sponsor (ECC) - EC UWE BA/AS
- For DE&S - DES SM IS ER and DES SM IS DASS
- For User - FLEET-FOST, FLEET-CAP and Institute of Naval Medicine
- For SIT perspective – EC UWE Sc1
- The Centre (RPNavy) was represented by EC UWE

Other important stakeholders included those involved in training of Submarine Escape, the platform and equipment acquisition and support authorities, the rescue capability team, and relevant specialists in naval medicine and naval architecture.

These lists produce a diverse range of people and perspectives. The diversity is part of the success of this approach, as it brings together a range of views, all of which can be valid. However, it can also lead to insurmountable difficulties if it is not managed. A few words on the third element of our approach - how we gained consensus - may be useful.

We used three components – a workshop format, the strawman proposal, and an agreed vision of the objective.

The first component is a workshop format. We brought as many of the stakeholders as possible together into a room for a day or two. We displayed the strawman using a laptop & projector combination to enable live editing in front of the stakeholders. Everyone present could see what words were being proposed, and test whether they fitted that person's perspective. Where they did not, stakeholders had sufficient opportunity to propose amendments. Everyone could see what new words were being agreed upon, and thereby influence them. As the facilitator we sought to generate a co-operative spirit among the stakeholders, by establishing a submissive position on the requirements themselves, but driving behaviours and actions towards the common goal.

The strawman becomes the second component. It helps the facilitator to bring focus to the task, and proposes a starting position which should be fairly close to the finishing position. Where disagreement occurred, we sought constructive proposals for new wording or new requirements. We used strawman proposals for everything from the timing of the workshop to the detailed requirement wording.

We started the process with the third component – the stakeholders agreed a simple but clear vision of the objective. This is given by a "Single Statement of User Need". The statement agreed for SMERAS by stakeholders was:

"The user shall be able to maximise the survivors from a submarine that has sunk or that must be abandoned on the surface, whenever and wherever a Royal Navy submarine is operating."

Although somewhat wordy, this sentence encapsulates what all of the stakeholders wanted to do, is based on the high level policy framing the task, and scopes the capability. In fact a further level of scope detail (especially the exclusions) was also agreed. Agreeing a joint goal helped prevent 'scope creep' in the discussion and minimised the possibility of trying to solve different problems. It provided a focussed vision which we returned to often to help guide discussions when uncertainty or conflict arose. It also helped to inspire the work, as it is clearly a worthy cause.

In using these ingredients and generating a cooperative spirit in the workshops, we sought to minimise the normal failure mechanisms of co-operation:

- All assumptions and needs ("win positions", in game theory) could be laid out plainly and understood by all stakeholders;
- Simple criticism was not tolerated – any proposed requirement had to be based on rationale and only constructive proposals were considered; and
- We focussed on common needs, and where apparent differences arose, sought innovative expressions to capture the requirements.

We used email and other simple communication routes to enable stakeholders to provide comments outside the workshops, but found that these were significantly less attractive to the stakeholders. They were used occasionally to make minor amendments, or provide some factual evidence (such as references, or to transfer documentary material).

5. RATIONALE FOR SMERAS

It is worth noting that the UK philosophy on SMERAS stems from the early experience of submarine operations in the Royal Navy. The most direct influence was the loss of HMS THETIS in 1939. The RUCK-KEENE Committee of 1946 initially captured requirements for SMERAS related action. The philosophy generated principles of design, manufacture, maintenance and training which predated the principles of the Health and Safety at Work Act [4]. This Act requires every employer to ensure, so far as is reasonably practicable, the health, safety and welfare at work of all employees, including provision of systems of work that are, so far as is reasonably practicable, safe and without risks to health. There is no general Crown exemption from the act, and MoD is bound by the general duties imposed by it. The SMERAS capability enables the Royal Navy to meet its Health and Safety obligations as described in the Secretary of State for Defence's Policy Statement on Health and Safety [5], for all submarine classes, including the strategic deterrent. It thereby supports Royal Navy delivery to the military policy framework. Since the early days of submarine operations, the RN submarine fleet has been provided with Escape (and later Rescue) capabilities as mitigation for the possibility of an incident. Navy Board policy requires that Escape and Rescue be reviewed at a periodicity not exceeding 10 years, or as directed by the Navy Board. It has therefore been the subject of regular review and improvement, which ensured that the capabilities met the standard expected of the day. However, it does not provide an absolute safety solution, and no guarantee is provided that all submarine personnel will survive an incident. MoD's operational exclusions from the Health and Safety at Work Act allow such a position, given the inherently hazardous nature of submarine operations.

The MoD acquisition process ensures a level of safety in submarine design & construction, developed through life by the operational safety practices of the RN. The level at which this risk is deemed acceptable is referred to as the ALARP (as low as reasonably practicable) risk. Under UK law, ALARP is considered to occur, and risk reduction work may cease, when the cost of any further work becomes grossly disproportionate to the benefits gained. An ALARP risk may involve a hazard with medium probability and very modest consequences, or with very low probability and significant consequences.

History demonstrates, and modern ship safety management [6] recognises, however, that risk cannot be reduced to zero, and that there will always be a residual risk. In accepting that there will be some level of residual risk, it is incumbent on those responsible for the risk to mitigate the consequences of the emergencies that may arise. The ALARP level of risk may be reached when a hazard is deemed to be very low probability, even though it may be of relatively high consequence. This level of consequence especially must be fully assessed and mitigated where possible.

The SMERAS capability is required by the Royal Navy to provide mitigation for a "Distressed Submarine" (DISSUB) or a Submarine which must be abandoned on the surface. DISSUB refers, by international convention, to a submarine lying on the seabed, and excluded a surfaced submarine. We therefore introduced, and stakeholders adopted, "SASUB" for a Submarine which must be abandoned on the surface.

6. MAIN SMERAS USER REQUIREMENTS

The most significant ("Key") User requirements are listed at Appendix 1. These were selected by the stakeholders as being the most significant requirements, which would have to be delivered if the capability was to be delivered. Other requirements were also defined at lower priority levels.

Four priority levels were used, to represent the relative levels of need that the user may have for the individual requirements. Each level was defined and agreed by stakeholders, to support interpretation of requirements as they were gathered and judged for inclusion. Guidance was provided to support governance of requirement against other considerations (for example, affordability). The level within DEC / Unified Customer at which this decision may be taken was particularly provided. The priority levels (initially for the URD, and later for the SRD) were agreed as shown in Table 2.

High Level Characteristics were used to expand on, and bound, the SMERAS Single Statement Of User Need.

- Survival – The ability of the user to maximise the Survivors from those alive after the initial accident. A Survivor is defined as "A member of the ship's company who has survived the DISSUB/SASUB event, reaches a Safe Haven, and whose prognosis is that he will live".
- Escape and Surface Abandonment – The ability of the user to facilitate the escape of personnel from a DISSUB or SASUB in the range of conditions and scenarios likely to be encountered.
- Rescue – The ability of the user to rescue personnel from a DISSUB in the range of conditions and scenarios likely to be encountered.
- Recovery and Intervention – The ability of the user to retrieve personnel to medical triage and care, and provide the minimum conditions for survival within the DISSUB or for a SASUB by external means comprising a breathable atmosphere, survivable pressure, food, water and medical supplies sufficient for the duration of the SMERAS operation.
- Operational Readiness and Availability – The ability of the user to deploy sufficient SMERAS capability for a DISSUB or SASUB emergency, on any occasion and in sufficient time to maximise the Survivors.
- Command and Control – The ability of the user to exercise command and control over the SMERAS capability.
- Training – The ability of the user to operate the SMERAS capability effectively and safely.

The High Level Characteristics are presented in Figure 2.

The numbering system used in the list of KURs refers to the overarching hierarchy in which they sit, the top level of which is described by these High Level Characteristics.

7. SMERAS SYSTEM CONCEPT

The complete Escape, Rescue and Surface Abandonment system consists of infrastructure, people, equipment, processes and information. This section describes the context in which the system exists, the high level architecture of the system itself, and the boundaries and interactions between the two.

Figure 3 illustrates the system context.

A process based approach was taken to outline the principle areas of need for the System. To aid comprehension of the system, a contextual process diagram has been defined. This is shown in Figure 4.

The system includes the directly applicable physical entities, people, end-to-end processes, infrastructure etc, as defined in the Defence Lines of Development. Based on this consideration, and the process above, the SMERAS systems architecture may be shown as the matrix in Appendix 3. Note that this architecture does not address the Rescue element of SMERAS, which is subject of a separate SRD.

The most significant external interdependencies for the Escape, Rescue and Surface Abandonment system are between the system and (a) the submarine crew which the system is helping to protect, (b) the maritime environment and (c) the submarine platform in which the crew operate.

The physical extent of the system includes the submarine platform, mobile elements of safe haven, and external support. The main systems boundaries are summarised in Figure 5.

8. MAIN SMERAS SYSTEM REQUIREMENTS

The definition of Key Requirements for SMERAS is that the "Requirement is essential to mitigate an intolerable submarine personnel risk (for example to fulfil duty of care, equivalence with commercial safety legislation etc)". These Key Requirements MUST be implemented for the capability or system to succeed. The Key System Requirements are shown at Appendix 2.

The main system requirements follow the process based approach. First the Command must have sufficient information to recognise whether there is a need for survival, escape and or abandonment, the extent, and the timescale. Then the decision must be communicated to all on board. The system must support preparation , and enable warning of the shore authorities. The system requirements then focus on the immediate priority - Survival on board. The requirements support and enable the well-known Royal Navy Submarine Survival guidance. The next priority is how to get out of the submarine, and requirements cover (a) Surface abandonment from deep inside the submarine, to the casing and thence to a temporary safe haven; and (b) unassisted Escape with minimum barotrauma and DCI. The concept of a temporary safe haven was used to give some flexibility to designers of the surface survival system. Solutions may include one-man or multi-man liferafts, but other solutions may yet be found. The intent is to protect survivors at the sea surface that have escaped or abandoned without the provision of external support. Having dealt with the principal issues, the Requirements also include needs for Availability, Operating environment, Training and operability and Safety. Finally, the relationship with the Rescue SRD is cemented by a requirement to enable mating of NATO standard Rescue Systems with the platform.

The numbering system for the URD and SRD was self-contained. However, the SRD was assessed for completeness using a two dimensional UR-SR matrix, which could also be used to relate the URD and SRD numbering system, as well as forming one step towards full traceability.

9. BENEFITS FOR SMERAS GOVERNANCE

The requirements documents have not been produced to replace existing standards such as the Submarine Escape and Rescue Handbook or NATO standards. They were developed to aid in MoD governance of SMERAS capability for SSN and SSBN submarines. Although more usually associated with large complex capabilities, the URD and SRD have been agreed to ensure the right management processes and outcomes are in place, and to enable gaps to be identified. They will enable MoD to:

- Demonstrate compliance with MoD high level policy responsibilities;
- Coherently manage capability, acquisition and support;
- Affirm a formal requirement for new and ongoing SMERAS acquisition;
- Negotiate equipment supply with platform IPTs;
- Undertake Cost-Benefit / ALARP analysis where required;
- Develop contractual requirements for SMERAS equipment supply; and
- Inform and guide relevant research.

MOD has been making use of both the URD and SRD, as in the following practical examples.

In parallel with the finalisation of the URD Director In Service Submarine's personnel analysed the existing systems against these requirements and documented the shortfalls or Voids. These Voids have then been collated, categorised and prioritised. This now, more clearly, allows the focusing of effort and resources to those areas were the greatest benefit can be achieved. This Void list has become one of the main matrixes used for the management of the In Service capability.

The additional granularity that the recently completed SRD will deliver allows the analysis above to be re-visited. This will ensure that the original focus remains extant and the deeper granularity may expose lesser voids.

The main driver for the SRD was not re-analysis described above (as the URD had achieved this). However the current Defence Standard for Escape and Rescue describes, in great detail, the system that is currently delivered and does nothing to drive innovation into future build. With the advert of the Future SSBN Project it was essential that a capability based requirement, for SMERAS, was established to ensure the best possible solutions could be considered in this area rather than just replicating the systems of the past. This is currently an active area of work.

10. CONCLUSIONS

A coherent set of User and System level requirements have been established by the UK Ministry of Defence for Submarine Escape, Rescue and surface Abandonment Systems. We have described the definition process, and the Key requirements. The process is replicable for other navies. The outcomes may in some cases be relevant to other navies, although determining a complete rationale and stakeholder input would be necessary before assuming this to be true.

11. ACKNOWLEDGEMENTS

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12. REFERENCES

1. CARNIE, P.K. & TAYLOR J.W., 'User requirements capture for Submarine Escape Rescue and Surface Abandonment Systems (SMERAS) (UC)', *Unpublished QINETIQ/D&TS/SEA/TR0615927/1.0, 20 Dec* 2006.

2. CARNIE, P.K., 'SMERAS System Requirement Documentation Production - WP2 Report', *QINETIQ/EMEA/TS/LR0804518, 28 Mar* 2008.

3. Submarine Escape and Rescue Policy Review Committee 2005, *MoD unpublished FLEET/0250/012,* 8 Feb 2006

4. Health and Safety at Work etc. Act 1974

5. Secretary of State's policy statement on Safety, Health and Environmental Protection, *MoD, now in Annex A to JSP815, Oct 06 (and updates)*

6. MoD Ship Safety Management System, JSP 430, Issue 3 Parts 1-3, 2005

13. AUTHORS BIOGRAPHY

Patrick Carnie is a Consultant at QinetiQ. He was responsible as project leader for the work described in this paper. Prior to joining QinetiQ, Patrick was programme manager for embryonic surface ship and equipment projects at MoD DPA Future Business Group. He previously managed the development of Human Factors guidance to the Navy. He recognises the potential for complexity and conflict between requirements, and the need to understand how the requirement will be tested.

James W Taylor is a Principal Engineer working on a diverse range of marine engineering projects, such as a feasibility study on escape systems. From 2000 to 2003 James was the Chief Design Engineer in Babcock Design and Technology. Prior to this he worked for Rolls-Royce in Derby for 14 years as a stress engineer on the mechanical and structural aspects of the Trent range of engines and other large gas turbines.

Andrew Dent is a programme and opportunity manager at QinetiQ. From his previous experience as a systems engineering manager in the Royal Navy and in the defence & rail industries, he provided guidance on the requirements process, contributed to the workshops and strawman and compiled the traceability matrix.

Cdr Mark Adams, RN is currently DEC UWE-BA and was primary Sponsor for the generation of the SMERAS URD. His experience includes 20 years submarine operating experience and previous appointments as head of Design Authority Ship Systems within the Submarine Support IPT (2003-06) and in a much earlier guise, Equipment Desk officer for Submarine Atmosphere Control (including SMERAS) equipments.

Cdr Stephen Birchall, RN is a serving RN Submarine Marine Engineer. As the SMERAS Project leader he is responsible of the integration of all technical aspects of Escape, Rescue and Surface Abandonment for the Royal Navy. Following the acceptance into service of the NATO Submarine Rescue System this summer he will also be responsible for the management of the Rescue system to UK, France and Norway. He is the UK Head of Delegation to the NATO Working Group on Submarine Escape and Rescue.

Appendix 1

Key User Requirements (KURs) (from [1]).

The user's highest priorty requirements for Submarine Escape Rescue and Abandonment Systems (SMERAS) are provided in the table below.

LB = Lower Bound (Minimum acceptable performance) and UB = Upper Bound requirements (Maximum targeted performance).

ID	Descriptor	User Requirement	Justification	Validation Method	Priority	Status	Remarks
1	**Survival**	The user will be able to maximise the number of lives saved from those surviving the initial accident, without the provision of external support, until recovered to place of safety	Following the initial accident leading to a DISSUB or surface abandonment situation, the remaining crew must survive in the ensuing environment until intervention/rescue forces arrive and start recovery operations. "This capability area presents the greatest risk to the crew of a DISSUB in both rescue and escape scenarios." (Draft SCOSER - SMER Policy Paper dated February 2002).	Completion of acceptance trials, at sea demonstration of system effectiveness, operational work-up; periodic validation through structured exercises, some of which may be unalerted and should include wider participation from within the MoD and industry; analysis of the effectiveness of through-life performance and end to end system trials.	KUR	Endorsed	Retain existing capability to maximise the number of lives saved from those surviving the initial incident.
1.1	Survival Capability - Subsurface	The user will be able to effect the survival of DISSUB personnel (with atmosphere, water, food) for 7 days (LB) following the initial accident without external assistance. (UB= 16 days)	Rescue removes the inherent risks associated with buoyant ascent but several days may lapse before a DISSUB may be reached. Hence, it is vital that the capability exists within the DISSUB for personnel to survive whilst awaiting rescue during this period. SPAM scenario- South Pacific time to achieve rescue 16 days.	Completion of acceptance trials, at sea demonstration of system effectiveness, operational work-up; periodic validation through structured exercises, some of which may be unalerted, and should include wider participation from within the MoD and industry;	KUR	Endorsed	Extant endorsed requirement from SERPRC 92 report.
1.2a	Survival Capability – following Surface Abandonment	The user will be able to effect the survival of personnel in the water at the surface for 5 days, following surface abandonment.	Personnel may have to remain in the water and await the arrival of rescue/intervention forces. Survivors are likely to be fit and capable for 5 days, with deterioration thereafter.	Completion of acceptance trials, at sea demonstration of system effectiveness.	KUR	Endorsed	Having abandoned a stricken submarine on the surface it is essential that personnel survive for a further minimum 5 days (potentially in liferafts), whilst awaiting the arrival of rescue/intervention forces to effect recovery, and that they are able to be quickly located by such forces.

ID	Descriptor	User Requirement	Justification	Validation Method	Priority	Status	Remarks
1.2b	Survival Capability – following Escape	The user will be able to effect the survival of personnel in the water at the surface for 24hrs (LB) following escape, with a UB of 5 days.	Personnel may have to remain in the water and await the arrival of rescue/intervention forces. 24hrs based on intervention and recovery capability	Completion of acceptance trials, at sea demonstration of system effectiveness.,	KUR	Endorsed	Having escaped from a DISSUB it is essential that personnel survive on the surface for a further minimum 24 hours without external assistance, in a range of challenging environmental conditions, whilst awaiting the arrival of rescue/intervention forces to effect recovery and then that they are able to be quickly located by such forces.
2	Escape and Surface Abandonment	The user will be able to affect the escape of all able personnel (LB) [all personnel (UB)] from a DISSUB without external assistance, from depths of 0 -200 metres (LB) [up to a maximum depth of 600m (UB)].	Fulfil duty of care and save lives. Most of the Continental Shelf is at a water depth up to 200m and there is no military requirement beyond 600m.	Completion of acceptance trials, at sea demonstration of system effectiveness, operational work-up; periodic validation through structured exercises, some of which may be unalerted and should include wider participation from within the MoD and industry; analysis of the effectiveness of through-life performance and end-to-end systems trials. This has to be within safety and ethics, and may include comparative trials, unmanned demonstration of system effectiveness or training for skills validation.	KUR	Endorsed	Escape is defined as any method by which a man leaves a DISSUB and makes his way to the surface without direct assistance from outside agencies. (ATP-10(D) Brit-Supp 2). The 200m limitation is based on the average depth of the UK continental shelf and bulkhead design. In-service RN submarines and ASTUTE Class escape compartment bulkheads are rated to a pressure equivalent of 180 metres sea water (+/- 10%). A recent policy paper has reinforced the need for a robust and reliable escape capability to 180m +/-10%, with the facility for the entire crew to escape from either of the two escape sections of RN submarines.
3	Rescue	The user shall be able to effect the Rescue of all able DISSUB personnel (LB), using devices external to the incident submarine, with a UB of all personnel.	During the last 100 years there have been over 170 known peace time submarine losses world-wide. Caused by material failure, operator error, collision, fire and a variety of other reasons, 85 percent of these accidents have been in waters where the submarine could bottom without reaching its crush depth. However, there would be severe risk to personnel attempting escape from such depths.	Completion of acceptance trials, at sea demonstration of effectiveness and operational work-up.	KUR	Endorsed	Rescue system currently provided by UKSRS, soon to be replaced by the NATO NSRS system.

ID	Descriptor	User Requirement	Justification	Validation Method	Priority	Status	Remarks
4	Recovery	The user will be able to recover DISSUB/SASUB survivors from the water to medical triage and to appropriate medical care, before safe haven is compromised.	The purpose of surface intervention is the saving of life once the crew has left the DISSUB. (DRAFT SCOSER SMER Policy Paper dated Feb 2002). Duty of care to reduce the loss of life of those surviving the initial DISSUB incident to As Low As Reasonably Practicable.	Completion of acceptance trials, at sea demonstration of system effectiveness, operational work-up; periodic validation through structured exercises, some of which may be unalerted and should include wider participation from within the MoD and industry; analysis of the effectiveness of through-life performance.	KUR	Endorsed	Safe Haven is 7 days if no intervention has occurred. Currently Surface intervention includes: Primary - SPAG air drop or by fastest means possible/the arrival of First Intervention stores and remaining SMERAT to the scene of incident by the fastest means possible; Secondary - the arrival of second reaction stores and the transfer of casualties to a medical reception centre or Primary Casualty Receiving Ship for treatment.
5	Operational Readiness and Availability	The user will be able to react to a DISSUB/SASUB emergency on any occasion with sufficient readiness and speed of response. The SMERAS capability shall be designed to be continuously available.	An emergency may occur at any time, and SMERAS must be ready to respond with worldwide capability.	Completion of acceptance trials, at sea demonstration of system effectiveness, operational work-up; periodic validation through structured exercises, some of which may be unalerted and should include wider participation from within the MoD and industry; analysis of the effectiveness of through-life performance.	KUR	Endorsed	Navy Board Policy on Submarine Escape and Rescue requires the system to be continuously available. UK submarines that are worked up and are operational at sea, by definition, have an escape system continuously available. This includes not only the capability to deploy on a global scale within an appropriate timescale, but also the ability to operate in the range of environmental circumstances and conditions likely to be encountered anywhere in the world. UK submarine rescue and intervention forces are maintained at specified notice for mobilisation/deployment. Readiness also implies the need for training, together with the periodic demonstration and validation of availability and capability.

ID	Descriptor	User Requirement	Justification	Validation Method	Priority	Status	Remarks
6.1	Localise DISSUB/SASUB	The user will be able to localise the position of the DISSUB/SASUB. Within x minutes.	The precise location of the DISSUB/SASUB may be unknown.	Completion of acceptance trials, at sea demonstration of system effectiveness, operational work-up; periodic validation through structured exercises, some of which may be unalerted and should include wider participation from within the MoD and industry; analysis of the effectiveness of through-life performance.	KUR	Endorsed	The position of the DISSUB/SASUB should be known within 1000m of a datum established by the On-Scene Commander. EPIRBS requirements reference SOLAS Chapter 4 Regulation 7.

Appendix 2

Key System Requirements (KSRs) (from [2]).
The following indications of rationale are used in the Priority column, to show why each Key System Requirement is considered to be of such high priority:

a. It encapsulates and characterises the system,
b. It identifies the primary (performance) characteristics of the system, against which options will be evaluated,
c. It is critical to the satisfaction of the associated URD (e.g. as performance / cost / time drivers),
d. It is for some other reason assessed as of particular interest to management, e.g. represent a major risk dependency

ID	System Requirement or Constraint description	Measure of Performance (MOP) / Performance Envelope	Justification	Verification Criteria	Priority	Status	Remarks
1	DECISION The system shall supply sufficient information and guidance for Command to recognise whether there is a need for survival, escape and or abandonment, the extent, and the timescale.	Command trained personnel interpret the information and guidance and make the correct decision	The balance of risk must be determined to maximise the number of survivors in different circumstances	Acceptance by relevant Subject Matter Experts based on table top exercise.	Key a	Candidate	
1.3	The system shall clearly communicate the escape and abandonment orders (including routes) to all on board.	All able bodied survivors (min) All survivors (max) receive the orders	Personnel will not escape or abandon unless ordered to do so by Command (SA) Senior Survivor (Escape). URD 2.3.1/2.	Test exercise demonstrates that all on board receive orders	Key b c	Candidate	Clarity of command communication will support abandonment
2	PREPARATION The system shall support preparation to escape and abandon the submarine.	All able bodied survivors (min) All survivors (max) correctly prepare the submarine, themselves and their equipment for escape or abandonment	Where time permits, preparation will enhance the no. of survivors and limit other damage	Achieve Abandonment EOP recommended actions in harbour test. Achieve Escape guardbook recommended actions in harbour test and training facility.	Key a	Candidate	EOP.52 (SA) Guardbook (Escape)

2.1	The system shall clearly alert the escape and abandonment decisions and geolocation to external authorities.	International distress signal (min) decision and geolocation alerted to OPCOM (max)	URD 6.1 Reduce loss of life by mobilising external support	Test exercise demonstrates that external authority receives alert	Key b c	Candidate	International standard applies
3	SURVIVAL ON BOARD The system shall enable the survival of DISSUB personnel.	All survivors continue to survive for 7 days (min) 16 days (max) following the initial accident without external assistance.	URD 1.1	Physical inspection of systems and stores by Subject Matter Experts demonstrates MOP likely to be met.	Key a b c	Candidate	16 days is a SPAM projection based on SSN operating in Pacific Ocean. If agreed, then apply to subsequent Survival requirements (perhaps with reduced requirement?) STANAG 1301Minimum conditions for survival in a distressed submarine prior to escape or rescue
3.1	The system shall ensure that breathable Atmosphere is available to all DISSUB survivors	Maintain atmosphere within BR241 Part 3 requirements throughout survival areas for 7 days (min) 16 days (max) following the initial accident	URD 1.1.1	Test of installed system demonstrates effectiveness over complete envelope of performance	Key b c	Candidate	
3.1.1	The system shall be able to monitor the DISSUB atmosphere	Survivors can monitor oxygen, Carbon dioxide and absolute pressure (min), all likely key contaminants (max) and detect increased risk early enough to take required action	URD1.1.1.1	Verify that BR241 Part 3 is being complied with	Key b	Candidate	Currently achieved by various means. However, there are shortfalls in the ability to effectively analyse and monitor for carbon monoxide and other contaminants such as chlorine.

3.1.2	The system shall replenish oxygen in the DISSUB atmosphere to support survivors for 7 days (min) 16 days (max)	Survivors have sufficient oxygen to survive for 7 days (min) 16 days (max)	URD 1.1.1.2	Test of installed system shows that oxygen remains within BR241 Part 3 limits.	Key b c	Candidate	There is a shortfall in the capacity of current ELSS oxygen generation in that insufficient can be carried to sustain a DISSUB crew for 7 days.
3.1.3	The system shall remove carbon dioxide (CO2) from the DISSUB atmosphere to a level not to threaten Survivors for 7 days (min) 16 days (max),	Survivors do not suffer incapacitating CO2 effects	URD 1.1.1.3	Test of installed system shows that CO2 remains within BR241 Part 3 limits.	Key b c	Candidate	There are shortfalls in current capability. Firstly, insufficient stores are carried to remove sufficient carbon dioxide to sustain a breathable atmosphere for a DISSUB crew over a 7 day period; secondly, the effectiveness of present systems is significantly degraded at high ambient pressures and low ambient temperatures.
3.2.1	The system shall monitor DISSUB absolute pressure	Survivors can monitor the atmosphere and detect increased risk early enough to take appropriate actions	URD1.1.2.1	Verify that BR241 Part3 is being complied with	Key b	Candidate	
3.3.1	The system shall ensure survivors have on board sufficient hydration for 7 days (min), 16 days (max)	All survivors have at least 1 litre per day for 7 days (min) 16 days (max)	URD 1.1.3. STANAG 1301 commits to 7 days on board stores. – to prevent acute renal failure	Inspection demonstrates compliance with STANAG 1301 (para 19: the minimum fluid intake should be 1 litre per day per man.)	Key b c	Candidate	

3.3.2	The system shall ensure survivors have on board sufficient nutrition for 7 days (min), 16 days (max)	All survivors have at least 1250kcal per day for 7 days (min) 16 days (max)	URD 1.1.3. STANAG 1301 commits to 7 days on board stores.	Inspection demonstrates compliance with STANAG 1301 (para 19: the minimum calorific intake should be 1250kcal per day per man. In addition, 1000kcal should be available to be eaten just prior to escape)	Key b c	Candidate	
3.4	The system shall enable survivors to monitor radiation levels and take appropriate action	Survivors are able to identify that exposure to radiation is within safe levels	Statutory duty of care, (Ionising Radiation Regulations (1999), and JSP391)	Test of installed system demonstrates compliance with safe exposure limits	Key b	Candidate	BR241 Part 3 provides advice.
4	SAFE ABANDONMENT The system shall support abandonment from the submarine casing either immediately or as directed by Command, to the temporary safe haven.	All able bodied survivors (min) All survivors (max) abandon from casing	URD 2.3.1/2 Need to maximise survivability by minimising damage to personnel and equipment while reaching a safe haven from platform.	Modelling analysis (criteria tbd). Trial demonstration that full complement is able to abandon from casing in good conditions.	Key a c	Candidate	Trial conditions should be more protected than for Egress test (eg Horsea Lake) for safety reasons
4.1	The system shall support egress from the submarine	All able bodied survivors (min) All survivors (max) achieve egress within 20 minutes (in good conditions with all routes available)	URD 2.3.1/2. Contributes to egress and abandonment in 30 mins - extrapolated from civilian (SOLAS) reqt for evacuation from high density of passengers on ships	Harbour trial demonstration that full complement is able to egress (using all access routes) within 20 minutes. Modelling analysis (criteria tbd).	Key b c	Candidate	“Egress” completes when whole body is outside casing. Egress route is any appropriate route out of the submarine as selected by Command above. Timings may be class specific. Future SMs may trade-off hull design vs equipment. 30 mins is linked to SOLAS

5	ESCAPE The system shall enable the escape of survivors from the DISSUB without external assistance.	All able bodied survivors (min) All survivors (max) escape from water depths of 0-200m (min) 600m (max).	URD 2	design review, pressure test at build, and in service validation against AS301 (tower functional trial)	Key a c	Candidate	
5.2	The system , where pressurised escape is used, shall minimise barotrauma and DCI	Pressure is not raised at a rate greater than double in 4 seconds	duty of care to survivors	system demonstration modelling and FITT (Fully instrumented Tower Trial)	Key b	Candidate	FITT is how system validation is undertaken
5.4	The system shall enable all survivors to escape within 8 hours (min) 4 hours (max), once the decision has been made to escape.	All survivors escape within 8 hours from all depths	IRR 1999 BR241 Part 3	FITT and systems validation/modelling demonstrate that MOP is likely to be met.	Key b c	Candidate	8 hours is based on the reactor accident radiation dose rate of 200 milli Seiverts per hour, such that all survivors escape before they are exposed to 2 Seiverts. Reduction of this time will enhance survival rates. The parameters should be reviewed, and related to 5.1. Current system limitations enables 4 minutes tower cycles (ie 15/30 escapes per hour, depending on single or two man tower.)
6	TEMPORARY SAFE HAVEN The system shall include a temporary safe haven on the surface to protect survivors that have escaped or abandoned without the provision of external support.	All able bodied survivors (min) All survivors (max) have a temporary safe haven in the ensuing environment available for 24 hours (min) 5 days (max)	The submarine is no longer a safe haven. URD 2.3.1/2 URD 1.2a	Demonstration that sufficient temporary safe havens are provided for maximum potential number of personnel that could be carried in the platform	Key a c	Candidate	System should allow egress, but support morale, collocation, environmental protection, medical support, food. Note injured people may require supporting equipment/medical supplies to enable this.

7	AVAILABILITY The system shall be continuously available to react to a DISSUB or SASUB emergency with sufficient readiness and speed of response.	99.99% effective availability for 120 days at sea	URD 5 and 5.3	AR&M review and inspection of system.	Key a b c	Candidate	NSRS requirement is 98% availability. Maintenance, inspection and redundancy is used to achieve levels.
8	OPERATING ENVIRONMENT The system shall be capable of operating in a world-wide environment.	The (min) performance is for operation except for ice-covered waters, (max) performance is worldwide.	URD 1.2.1, URD 5.5, and RN submarine operation world wide	Evidence provided that system can achieve MoP	Key a b c	Candidate	NP100 Mariners handbook definition of sea ice. “ice-covered” is defined as greater than one tenth sea ice. NB SOLAS has temperature requirements.
9	TRAINING AND OPERABILITY The system shall ensure all personnel on board have knowledge of Escape, survival and Surface Abandonment procedures and equipment according to their status.	All potential Senior Survivors and lead Damage Control personnel are able to initiate and direct Escape, survival and surface abandonment. All ship’s company are familiar with the use of Escape, survival and surface Abandonment procedures and equipment. All visitors are made aware of Escape, survival and surface Abandonment procedures and equipment. Personnel required to conduct defined maintenance, inspections, etc to meet Availability requirement are SQEP.	URD section 7. Maximising opportunity for personnel to become survivors	Realistic training has been completed by all submarine personnel, to a training performance standard defined as consequence of Training Needs Analysis	Key a b c	Candidate	Training facilities could include physical simulator, which could test personnel and potential solutions. “Familiar” means to be trained to an approved, recognised or certified level. Training should be undertaken on a cycle sufficient to prevent significant knowledge loss. Future developments may include Human Factors review to better define the knowledge levels used here.

10	SAFETY The system shall be as safe as reasonably practical.	System is complaint with JSP430.	Safety is a mandatory requirement	System safety case is approved	Key a c	Candidate	
11	RESCUE The system shall enable mating of STANAG 1297 Rescue Systems with the platform	Rescue seat is compliant with STANAG 1297	Rescue cannot be conducted without this seat	seat mating exercise preceded by build test form and design review.	Key b c	Candidate	

Appendix 3

SMERAS System Architecture

Component	**Decision**	**Preparation and mustering**	**Survival within submarine**	**Safe Abandonment**	**Escape**	**Sea Survival**
Infrastructure	Training facility (simulator?)	Training facility	Trials and exercises facilities?	Training facility, and on board	Trials and exercises facilities? Training facility	Training facility.
Personnel (inc training and organisation)	DCHQ team recommends to the command. OPCOM authority possible Providers of damage information – all in existing DC Organisation. TNA training	All personnel (civilian & naval) likely to be on board submarine – incl casualties. (tho SA may be partial/staged). Specialist maintainers. Visitors.	Training facility	All personnel (civilian & naval) likely to be on board submarine – incl casualties. (tho SA may be partial/staged). Specialist maintainers. Visitors.	All civilian & naval personnel likely to be on board submarine – incl casualties. (tho Escape may be partial/staged). Specialist maintainers.	All personnel (civilian & naval) likely to be on board submarine – incl casulaties. (tho SA may be partial/staged). Specialist maintainers. Visitors.
Equipment & Technology (inc logistics and Interoperability)	Decision aids equipment. If still operating - existing Damage Control system. Atmosphere Monitoring system.	Assume DC equipment etc is sufficient Equipment to enable future phases. (inc positioning)	All civilian & naval personnel likely to be on board submarine – incl casualties. (tho Escape may be partial/staged). Specialist maintainers.	Options for egress routes (incl existing, marked, lit), sufficient for no. of survivors, expectation for time of egress. Collocation of abandonment items. Decision aid Safe entry to water/survival solution.	Equipment to support escape at depth escape, eg Escape towers, SEIE, etc.	Environmental protection (temp loss, injury, drowning); Comms/tracking; Survival supplies (physiological & medical); Tracking, Min dispersion; Evade platform
Concepts and doctrine (inc Processes and information)	QRs and EOP to support decision. Operating Instruction. Guidance, based on scenarios	EOP (relationship with existing other EOPs, indicators, guidance), Prompt cards for equipment.	Survival stores, atmosphere management system (SAM URD), radiation monitoring, habitability,	EOP, Map of egress route options Process cards provided next to equipment	communications systems	EOP, Survival tactics and communications routines

Appendix 4 Tables and Figures

Governance	**Requirements**
Project Initiation	Outline URD with candidate KURs
Initial gate	URD with candidate KURs
Main gate	URD, SRD, KURs
Contract let	Contract

Table 1 Governance and Requirements

Priority level	**Definition**	**Trade-off Guidance & level**
Key	Requirement is essential to mitigate an intolerable submarine personnel risk (for example to fulfil duty of care, equivalence with commercial safety legislation, or comply with international agreements on SMERAS)	Requirement MUST be implemented for the system to succeed. Considered untradeable by the capability sponsor.
1	Requirement is important to mitigate a significant submarine personnel risk.	Requirement WILL be implemented for the system to succeed. Trading will require reference back to the DEC via CPG and SMERAS FG.
2	Requirement mitigates a submarine personnel risk.	Requirement SHOULD be implemented for the system to succeed. Trading will require reference back to the CPG and SMERAS FG.
3	Requirement is useful to mitigate ALARP submarine personnel risks.	Requirement MAY be implemented for the system to succeed. Trading can be decided by the SMERAS FG.

Table 2 SMERAS Priority levels

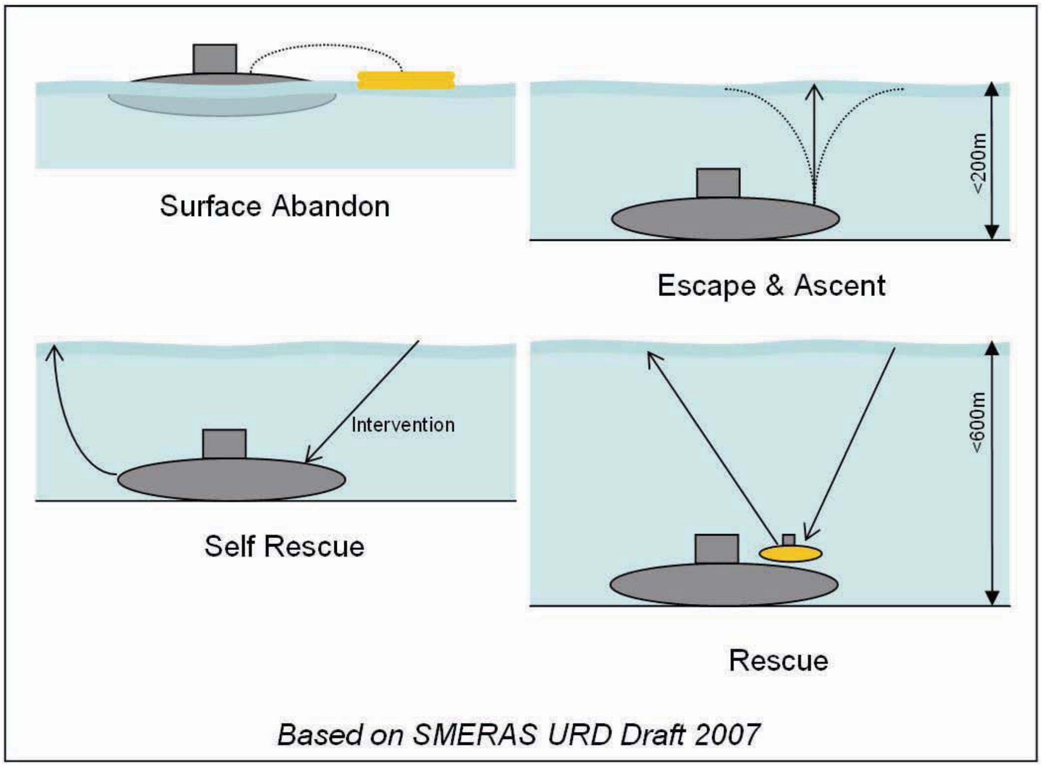

Figure 1 SMERAS scenarios

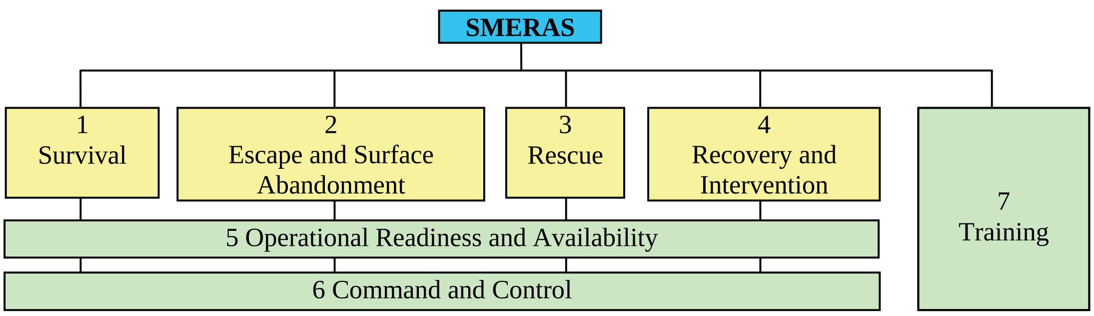

Figure 2 SMERAS High Level Characteristics

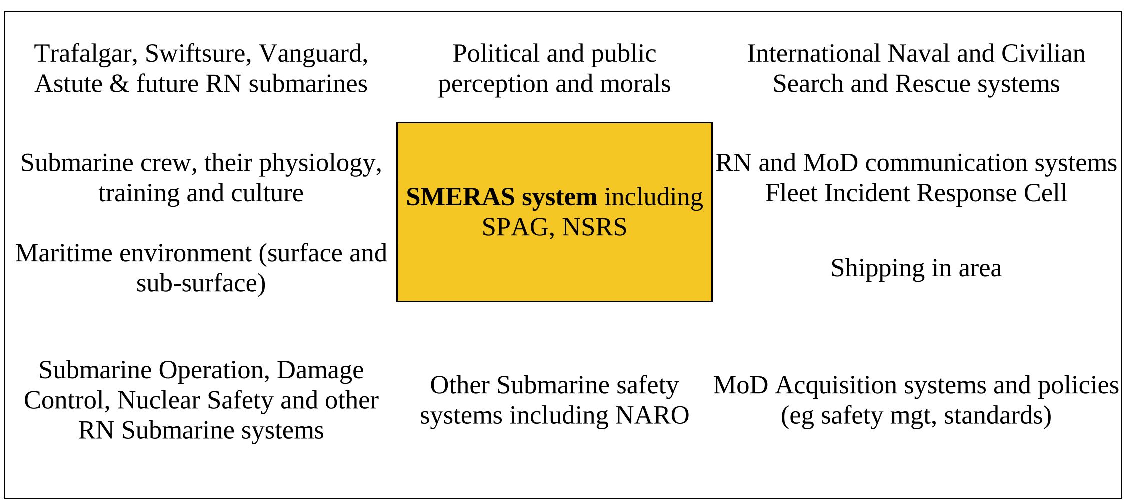

Figure 3 SMERAS system context

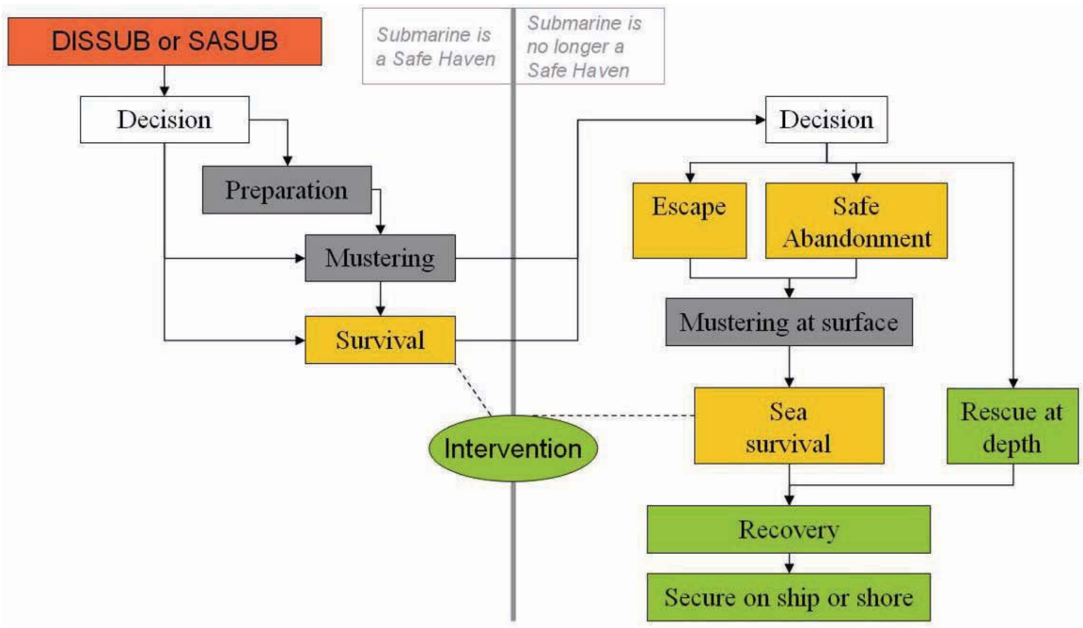

Figure 4 SMERAS process diagram

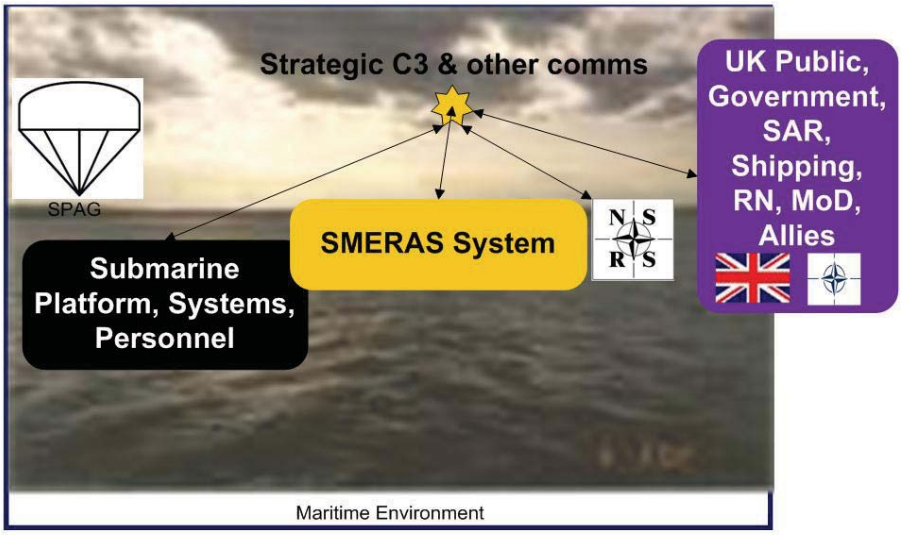

Figure 5 SMERAS systems boundaries

SUBMARINE ESCAPE AND RESCUE OPERATIONS - THE HOLISTIC APPROACH TO SAFETY

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SUMMARY

Escape and/or rescue from a submarine is an emergency activity that is undertaken only rarely and, by its very nature, is hazardous. Such operations will naturally attract wide industry and media attention, focusing on both the outcome and the approach taken. A successful escape and rescue mission is the objective, and it is consistent with this to require that such a mission must not unduly endanger the lives of anyone involved. Consequently, the effective safety management of the entire escape and rescue system capability (covering both the equipment and the operations) is essential.

An extensive range of equipment is required for the rescue system. For example, a Mother-ship is required to transport the rescue vehicle with its launch and recovery equipment and associated mission support equipment in order to provide a platform for rescue operations. The major elements of the capability (the rescue vehicle, launch and recovery system etc) will normally be expected to have a validated design, be manufactured and maintained in accordance with a classification society's rules (and obtain subsequent certification as such), thereby providing an element of assurance of the inherent safety of their design. However, the interfaces between the equipments that make up the rescue system (for example the rescue vehicle, the launch and recovery system etc), their operation and the operating environment are not covered by classification society rules. Consider the condition of the watertight integrity of the rescue vehicle when it mates with the distressed submarine. This condition is not covered by classification society rules for either the disabled submarine or the escape and rescue system, nor would the particular combination of rescue vehicle with every submarine have been considered in the design process of either component. However, in order for the owner of the rescue system to discharge their safety responsibilities they must be able to demonstrate that this condition has an acceptable level of risk attached to it.

This paper reviews the elements that, together, provide a versatile overall capability, and discusses how the safety aspects of this specialist type of capability present some particular challenges. It describes the assurance applicable to equipments that are 'in-class', and suggests how, with correct management of the hazards and risks associated with this intrinsically dangerous capability, the interfaces between the escape or rescue equipments and the disabled submarine can also be proven and reported to be acceptably safe.

1. NOMENCLATURE

ALARP	As Low As Reasonably Practicable
CASEVAC	Casualty Evacuation
CS	Certificate of Safety
DISSUB	Distressed Submarine
DNV	Det Norske Veritas
ELSS	Emergency Life Support Stores
HARMS	Hazard and Risk Management System
HAZID	hazard Identification
HAZOP	hazard and Operability Study
JSP	Joint Services Publication
LR	Lloyds Register
MCA	Maritime and Coastguard Agency
MoD	Ministry of Defence
MOPORT	Port used to embark the SRS onto the MOSHIP
MOSHIP	Mother-ship
NSRS	NATO Submarine Rescue System
RAN	Royal Australian Navy
ROV	Remotely operated Vehicle
SERS	Submarine Escape and Rescue Service
SOLAS	Safety of Life at Sea
SQEP	Suitably Qualified and Experienced Personnel
SRS	Submarine Rescue System
SWIFT	Structured What If Technique
TUP	Transfer Under Pressure

2. INTRODUCTION

2.1 SUBMARINE ESCAPE AND RESCUE

Many Navies across the world have a submarine capability. The submarines are designed to fit the requirements of each Navy and the areas in which they operate. There are submarines currently in-service which are nuclear powered and can remain on submerged patrols for months at a time, there are also submarines that are powered conventionally and only patrol littoral waters for short durations.

The wide scope of submarine designs dictates the need for many and varied designs of Submarine Rescue Systems (SRS). Fourteen countries (including the UK) are known to have some form of SRS capability, with the soon to be introduced into service NATO SRS (NSRS), fulfilling the requirements of three participating Navies (i.e. France, Norway and the United Kingdom).

The rescue systems in service range from Remotely Operated Vehicles (ROV) to free-swimming submersibles. Some nations operate ROVs which have the capability to act as a rescue vehicle, able to transfer personnel from the DISSUB into a chamber integral with the ROV.

ROVs may also be used to provide the facility to replenish Life Support supplies at the intervention stage of a rescue, in advance of a rescue vehicle being deployed. These ROVs use manipulator arms to allow them to 'post' Emergency Life Support Stores (ELSS) into the DISSUB and to assist with clearance of debris thus enabling the rescue vehicle to attempt to mate with the DISSUB.

Manned submersibles may also be used; these usually have a two man crew and one or two rescue chamber attendants – the number being consistent with the number of survivors that can be rescued during each dive.

All of these different types of rescue system are supported by a Mothership (MOSHIP) which provides a platform for the rescue equipment such as a Launch and Recovery System, Transfer Under Pressure Facility, Hyperbaric Facilities, Communications equipment, Power Generation Systems etc.

This paper considers those rescue systems that use a rescue vessel to mate with a DISSUB and how that type of SRS has been designed to meet specific requirements, whether these are Classification Society Rules or international requirements. It then goes on to discuss how these design requirements can be used to help provide assurance of safety. It also considers the equipments of the SRS and their interfaces with each other and the DISSUB and how their safety can be assured.

2.2 BMT ISIS' EXPERIENCE

BMT Isis has extensive experience of supporting both the design and operation of submarines and their respective rescue systems. BMT Isis' most recent experience includes providing a specialist Safety Engineer for the NSRS (See Figure 1), focusing on the rescue vehicle and its launch and recovery system and the production of the submissions for Certificates of Safety for key hazard areas, as required by the UK MOD Naval Authorities.

BMT Isis has also produced an initial Safety Case Report for the Royal Australian Navy (RAN) Submarine Escape and Rescue Service (SERS) (See Figure 2). Additionally, BMT Isis has undertaken safety assessments for elements of the UK SRS (See Figure 3), covering TUP and the launch and recovery system. It should be noted that the RAN SERS is an ROV with a manned rescue chamber whilst the NSRS and LR5 are both independently powered free swimming submersible rescue vehicles.

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Figure 1 - The NATO Submarine Rescue System Being Launched from a MOSHIP

© Royal Australian Navy

Figure 2 - Royal Australian Navy Submarine Escape and Rescue System

Figure 3 - United Kingdom LR5 Submarine Rescue Vehicle

2.3 SUBMARINE RESCUE SYSTEMS

Although the various SRS are designed to meet each Navy's specific requirements they all have the same basic operational requirements and modes of operation, and would typically be required to respond to a DISSUB incident and to be 'on site' above the DISSUB, ready for initial intervention operations, within say 48 hours.

Not all of the SRS systems in the world are international in capability, for example the Japanese rescue system is not air transportable as the design requirement is to support its submarine operations within limited areas.

A SRS that has been designed to mate with a STANAG mating seat will be able to mate with another country's submarine. Within the submarine rescue community it is likely that the most local country with an SRS capability to the DISSUB would at least attempt an intervention whilst waiting for the country of ownership to deploy their SRS.

Figure 4 shows a typical, integrated Submarine Rescue System.

These elements of the SRS are described below.

2.3 (a) The Base Facility

The Base Facility is where the SRS is stored and maintained (either for readiness for a mission or after completion of a mission) and from where the system is deployed for missions or exercises.

2.3 (b) Mobilisation

Mobilisation covers the activities required to take the SRS from storage at the Base Facility, and make it ready for the exercise or mission and transportation to the point of embarkation onto the MOSHIP (MOPORT).

2.3 (c) Transportation

This aspect of the SRS capability covers transportation of the SRS from the Base Facility to the MOPORT for embarkation. Transportation would normally be expected to be a combination of road and air, depending on the distances involved and the suitability of an appropriate MOPORT.

When a rescue system is transported via air there are three stages to the transport:

- Transport to the airport including loading the system onto the aircraft(s);
- Flight to the destination airport;
- Loading the system onto appropriate transportation at the destination airport and the subsequent journey to the MOPORT.

2.3 (d) Embarkation

When the mobilised SRS assets reach the MOPORT it is embarked upon the MOSHIP. Two MOSHIPS may be used, one to deploy the Intervention system (which may comprise an ROV, ELSS and boats to rescue the DISSUB crew if they have instigated a "rush" escape for example) and another to deploy the rescue capability (the rescue vessel and hyperbaric treatments etc.).

2.3 (e) Commissioning and Setting To Work

Once the SRS has been embarked onto the MOSHIP the rescue team (who deploy with the SRS and will comprise for example, the SRS maintainers, the rescue vessel crew and rescue compartment attendees etc) will begin to commission and set to work all of the systems associated with the SRS.

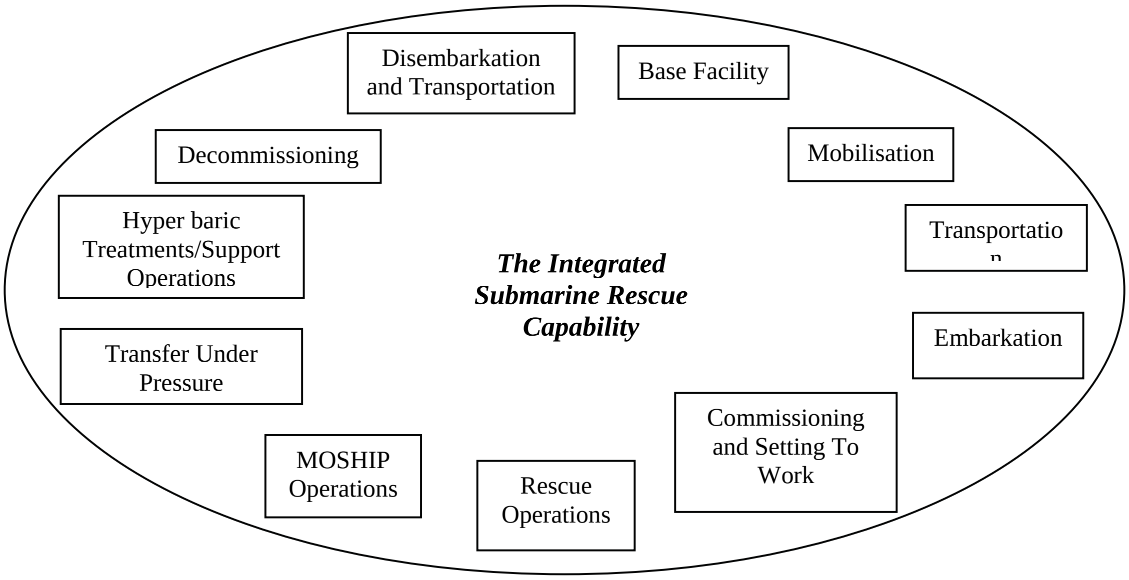

Figure 4 - The Integrated Submarine Rescue Capability

2.3 (f) Rescue Operations

Rescue operations cover all the activities associated with the launch and recovery of the rescue vehicle from and to the MOSHIP and whilst it is undertaking operations in the water.

2.3 (g) MOSHIP Operations

The MOSHIP undertakes a far greater role than just transporting the SRS to the site of the DISSUB. It provides the platform to launch and recover the rescue vehicle, carries the TUP facility, hyperbaric facilities (where relevant) and supports other elements of the SRS such as air compressors and communications equipment.

Whilst facilitating the transportation of the SRS and its associated equipment the MOSHIP is also required to support it's own crew, the Rescue team associated with the SRS, TRIAGE and immediate medical support and, of course, the rescued submariners.

2.3 (h) Transfer Under Pressure

In order to undertake rescue operations with the internal atmosphere of the submarine rescue compartment at pressures above surface, the rescue vehicle needs to be pressurised to match the pressure within the DISSUB. A TUP system allows rescuees, and post rescue operations the rescue compartment crew, to be transferred for decompression in a constant pressure environment.

2.3 (i) Hyperbaric Treatments / Support Operations

Decompression chambers are provided for the hyperbaric treatment of rescuees and the rescue compartment crew as necessary, to undergo decompression within a safe and controlled environment.

The MOSHIP also provides other support activities such as launching and recovering a small boat to assist in the launch and recovery of the rescue vessel and divers/swimmers to assist with emergency escape from the rescue vessel. In some instances the MOSHIP is also able to support helicopter operations to provide casualty evacuation (CASEVAC) to other support assets.

2.3 (j) Decommissioning

Upon completion of the exercise or mission, the SRS needs to be decommissioned prior to disembarkation when the MOSHIP returns to port.

It should be noted that for the SRS decommissioning refers to the processes involved in returning the system to a state of immediate readiness as opposed to end-of-life decommissioning.

2.3 (k) Disembarkation and Transportation

Disembarkation and transportation covers all of the activities associated with removing the entire SRS from the MOSHIP and transporting it back to its Base Facility.

2.4 WHY WE NEED A ‘SAFE’ SYSTEM

As it is not possible to build a system that is absolutely safe, there is a need therefore to define a ‘safe’ system with regards to the SRS. A ‘safe’ system is a system that has an associated level of assessed safety risk that is acceptable to the stakeholder community. It should be noted that the stakeholder community may include the general public.

All SRS equipments and operations need to be proven to be ‘safe’ to operate under all expected operating conditions. The principle behind a submarine rescue system is to provide a safe and secure method of rescuing the crew of a submerged and disabled submarine.

A stricken submarine will gain significant media attention wherever it is in the world and with 24 hour media coverage of such an event, any rescue mission will be followed with interest, worldwide. Therefore it is essential that any SRS is able to respond safely and rapidly, with a typical time for initial equipment to leave the base facility of within 12 hours. A SRS that results in injuries to the rescue team whilst getting to the site of the incident would obviously gain very negative media attention. Similarly, an SRS that undertook a rescue but lost crew due to unsafe design or operational practices would, in addition to very significant human losses, also attract negative media coverage for the Navy and nation involved.

It is not however, just media attention that requires the rescue system to be safe. The owner of the SRS will generally have a legal, and always a moral, duty of care not only to the crew of any SRS but to the crew of the stricken submarine to ensure that any rescue attempt will not put their lives in further danger.

In order to achieve a ‘safe’ SRS, the following aspects need to be taken into account:

- The benefits brought by distinct equipment being ‘in class’ to various Classification Society Rules;
- The risks posed by elements of the operations that are not covered by being ‘in class’ but may well be controlled by national and/or international legislation;
- The risks associated with the interfaces between the SRS equipments.

It is the first two of these elements that form the basis for a safe system, however due to their legislating approach they are unable to cover the interfaces between the SRS equipments. The safety of the SRS relies upon a holistic approach to ensure that all aspects of the numerous equipments are considered.

3. SAFETY REGIMES APPLICABLE TO A SRS

Because of the many and various equipments comprising a SRS, there are similarly many and varied safety regimes that can apply to them.

Major elements of a SRS, such as the rescue vehicle, launch and recovery system and the decompression facility, may be designed in accordance with relevant Classification Society Rules. All elements of the SRS will need to meet international legislation such as The Safety of Life at Sea (SOLAS) and local maritime agencies such as the UK Maritime and Coastguard Agency (MCA). Additionally, the procurement process for nations may require adherence to in-country or owner requirements (for example the UK MoD key hazard area certification).

The timelines associated with the design and construction of the submarines that may require rescue, their escape and rescue systems and the SRS that is to be used to effect any rescue will also impact how the systems interface. It is possible that a newly in-service SRS may be required to mate with a DISSUB that was designed to requirements, specified many years ago. In this time it is quite feasible that Classification Society Rules, statutory requirements and design techniques may have changed adding additional challenges to the SRS.

For these reasons it is essential that the interfaces between these requirements are managed through design or operational measures to achieve the safety requirements.

3.1 CLASSIFICATION SOCIETY RULES

The use of “Rules” as defined by the Classification Societies has been the accepted route of checking a design and building ‘safe’ vessels across the world’s fleet of commercial (and some naval) vessels. These “Rules” were derived from the need to provide assurance to insurers that their vessels were fit for purpose. Therefore the “Rules” developed are prescriptive and detail specific requirements that have been developed and proven over time. These “Rules” if implemented will provide a significant degree of assurance that the vessel is fit to operate within the conditions of class.

It is to be noted that this prescriptive approach does not currently require any risk justification. Classification provides assurance that a design is fit for purpose and in a regime that is recognised by society. However, there is no consideration given as to whether the risk can be reduced further or indeed, whether the level of safety achieved is As Low As Reasonably Practicable (ALARP) - this concept includes a cost benefit element. Within the SRS environment, Classification applies to a limited part of the overall system and therefore can only provide mitigation for risks associated with the specific element of the system that is in-class.

The SRS includes a number of major equipments which may be in-class with a number of different classification societies, for example:

- Lloyds Register (LR) may cover the submersible rescue vehicle;
- Det Norske Veritas (DNV) may cover diving systems and marine lifting appliances.

The design of a vessel that is in-class demonstrates that equipment is fit for purpose as long as it operates within the Conditions of Class. However, the definition of in-class does not normally say how close the equipment is to exceeding the limits required for compliance with each rule, for example it does not specify the factor of safety that has been applied - this information is essential to identifying whether a risk is ALARP.

3.2 KEY HAZARD AREAS

The UK MoD is required by the Secretary of State for Defence to ensure that all work they undertake, whether this is the design or operation of equipment, meets, or is at least as good as, that required by current statutory requirements. To this end the MoD has required the development of risk based safety cases since 1998. This requirement is detailed in Joint Services Publication (JSP) 430 [1].

JSP 430 has developed over the years and now includes the requirement for key hazard area certification to be included within the safety case. The key hazard areas associated with submarines and therefore a SRS are:

- Submarine Structural Strength;
- Submarine Stability;
- Atmosphere Control;
- Watertight Integrity
- Manoeuvring and Control
- Propulsion and Manoeuvring;
- Fire.

Two alternative approaches are used to obtain Certificates of Safety (CS) for these key hazard areas;

- The prescriptive (standards based) approach;
- The performance (risk based) approach.

The risk based approach requires that the Platform Duty Holder demonstrates, through a formal submission, that the risks pertinent to the key hazard area are ALARP and either broadly acceptable or tolerable. This contrasts with the prescriptive approach that provides assurance by compliance with agreed and accepted standards identified through a risk-based selection process. It is to be noted however, that even the prescriptive approach may still require risk-based assessment to comply with

JSP430 [1]. An example of this would be that prescriptive standards exist for the key hazard area of fire, however there is a need to conduct a risk assessment to identify the appropriate standards to be used.

Whilst this approach has been adopted by the UK MoD other countries may approach safety certification in different ways.

3.3 INTERNATIONAL STANDARDS

There are a number of international, flag state and port state standards that apply to all seagoing vessels such as SOLAS [2] and (for the UK), the MCA. As with classification society rules, these standards have developed over time often in response to incidents and accidents at sea. They are able to provide assurance that specific aspects of a vessel's design or operation provide adequate mitigation to potential hazards e.g. navigation lights.

3.4 WHY USE A RISK BASED APPROACH WITHIN THE CLASSIFICATION PROCESS?

It is a straightforward and well known exercise to build a vessel that is fit for purpose and therefore "In-class" with a classification society, and also to gain in-country approval, for example the UK MoD require a SRS to have key hazard area certification and follow a risk based safety management process. However, providing assurance to the owner, operating authority, crew and rescued submariners that the interfaces between these "known" areas are safe is a more complex problem.

The fact that the design of the SRS meets, for example the required standards for key hazard area certification provides significant assurance that the system is adequately safe. In other cases, for example that the

vessels is "In-class" or meets MCA navigational requirements, this only provides evidence that certain areas of the SRS have mitigation against hazards. If we consider the submersible rescue vehicle, it may be in-class with LR Rules for Submersibles, however the Conditions of Class for this certification will not detail the factor of safety that has been applied to the pressure hull design. If risks associated with this area of the system are to be justified as being ALARP, it is essential that the factor of safety is known. It may be, for example, that by increasing the thickness of a section (which at the design stage would have minimal cost), the factor of safety could be increased to a point whereby further improvements would not be cost effective and hence the risk of pressure hull collapse can be justified as being ALARP.

All of the elements of the SRS must be shown to be safe with all the risks mitigated to ALARP and either broadly acceptable or tolerable. The interfaces between elements covered by "Rules" and key hazard certification can therefore be easily missed. It is irrelevant that both the submersible rescue vehicle and the DISSUB are certified as meeting all appropriate rules and regulations if the interface between them cannot be proven to be safe.

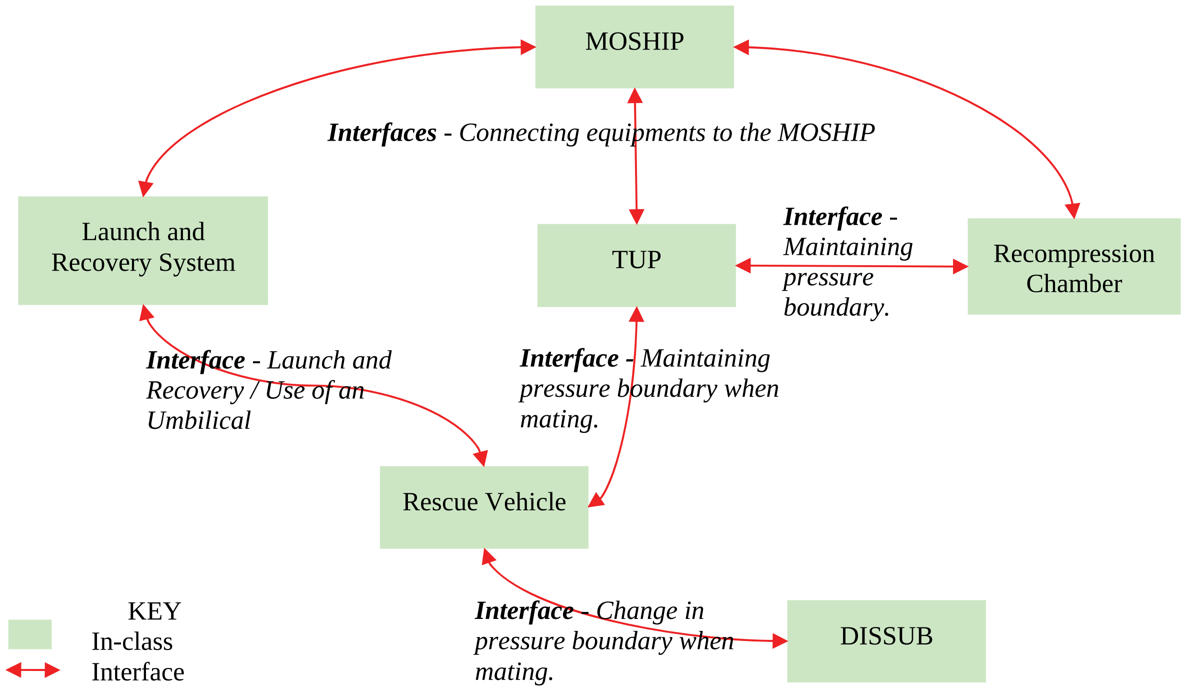

Figure 3 - The Types of Interfaces That Require a Risk Based Approach to Safety

Both vessels for example, have the appropriate approval of their pressure boundary, but when the two vessels mate that pressure boundary changes. Figure 4 identifies some of the more significant interfaces that exist between the various equipments of a SRS, it should be noted that this does not cover all of the interfaces and is for illustrative purposes only. It is these interfaces that require a SRS to have a whole system safety case which utilises the risk based approach to ensure that all hazards have been identified and subsequently mitigated to ALARP and either broadly acceptable or tolerable when the SRS is deployed under a defined range of operational scenarios. The risk based approach is that mandated to the UK MOD for all Naval Vessels by JSP 430 [1].

4. THE RISK BASED APPROACH TO A SRS AND OPERATION

4.1 WHAT IS THE RISK BASED APPROACH?

The Risk Based Approach identifies Safety Targets based on tolerability, acceptability and performance criteria specific to the system.

The risk based approach requires experienced personnel to identify the safety targets which must be agreed with all interested parties, for example the designer, operator and owner. This approach requires the identification of hazards, the safeguards and mitigation that control the risks, risk assessment and analysis and ALARP justification. The following paragraphs describe the various aspects of the risk based approach.

4.2 HAZARD IDENTIFICATION

There are a number of methods of Hazard Identification (HAZID) that can be applied to a risk based approach to safety, for example a Hazard and Operability Study (HAZOP) or a Structured What If Technique (SWIFT). Each technique has its merits and its application must be tailored to suit the system under study.

A successful HAZID is heavily dependent on the personnel involved in the exercise. This means the use of Suitably Qualified and Experienced Personnel (SQEP). These SQEP will bring to the HAZID their own skills and experiences together with their own view of hazards and issues discussed. This body of SQEP should represent all stakeholders of the SRS element under study from the designer, the user and the customer.

These SQEP then use a suitable HAZID technique to identify hazards and their associated accident scenarios or causes. For example, during lifting operations there is a potential hazard of a dropped load, resulting in injury to personnel and damage to the equipment.

The use of SQEP minimises the likelihood of hazards being missed during the identification process, it should also ensure that only credible hazards are identified and taken forward for risk assessment. For example a SRS operator might identify a hazard from their experience whist the designer may know that the cause of this hazard has now been designed out of the system.

In order to ensure that the results of the HAZID are meaningful it is important that a structured approach is taken to recording the outcomes as this will form part of the ‘Body of Evidence’ to support the Safety Case for the system.

4.3 RISK ASSESSMENT AND ANALYSIS

Once the hazard and it’s cause has been identified it is then necessary to assess the risk to individuals, the equipment, the mission or the environment. This assessment allows risks to be categorised by identifying a severity and consequence for each risk.

In undertaking this risk assessment it allows risks to be ranked to identify those that are initially not tolerable. From this ranking the risks that require effort to reduce them to ALARP and either broadly acceptable or tolerable can be clearly identified.

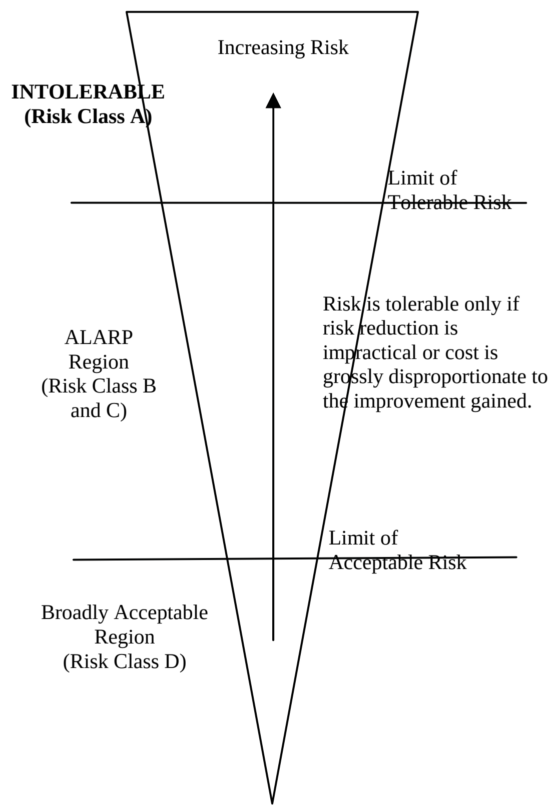

Figure 4 - The ALARP Principle

In reducing the risk there is a known hierarchy of risk reduction techniques, these are:

- Eliminate the hazard;

- Reduce the risk by implementing an engineered mitigation strategy;
- Reduce the risk by implementing a mitigation strategy based on human factors.

It should be noted that the definition of ALARP and either broadly acceptable or tolerable may differ according to the system being assessed. For example in the UK a SRS will have a significantly different definition of ALARP and either broadly acceptable or tolerable even compared to that of another military system, whereas the RAN utilise the same assessment criteria for all of their equipment. The use of different risk classification regimes is required to reflect the various environments in which systems operate and the number of people etc that are at risk. Every time a SRS is mobilized it is entering a potentially dangerous situation as it's mission is to rescue a crew from a DISSUB. The risks to the SRS have the potential to be further exacerbated by the use and mission of the DISSUB, for example risks to the SRS may be increased if the rescue mission is to mate with a nuclear powered submarine that has suffered damage to its reactor.

The risk matrix applied to a SRS should reflect that there may be a greater risk to, for example the crew, than under normal submersible operations. This means that although still undesirable, there may be a greater appetite for risk with respect to the rescue mission compared to the potential benefit of rescuing the crew of the DISSUB.

4.4 SAFEGUARDS

Once hazards and causes have been identified and initially assessed it is then necessary to identify appropriate safeguards and mitigating activities which have the potential to reduce the likelihood of the cause of the hazard occurring and/or the severity of the accident.

Three types of safeguard can be considered to exist;

- ”Existing” safeguards that are currently known to be in place and evidence can be provided to confirm this e.g. the submersible vehicle has diverse atmosphere control systems for which drawings and specifications are available;
- “Intended” safeguards that are expected to be in place but there is currently no evidence to confirm this e.g. a planned maintenance schedule would be expected to be developed (to provide mitigation for equipment failure for example) but has not yet been developed;
- “Proposed” safeguards are those that are considered to have a potential risk reduction effect if implemented. These safeguards would be expected to be subject to a cost benefit analysis to allow an ALARP justification to be developed.

As has been discussed in the previous paragraphs, relevant aspects of Classification Society “Rules” can be claimed as an ‘existing” safeguard e.g. compliance with DNV Rules for Marine Lifting Equipment [3] would provide sufficient justification that the equipment has adequate strength for its intended scope of operation. Classification to a ‘rule’ should also provide assurance that the equipment will be periodically surveyed (and tested as necessary). It is to be noted however that the survey and test requirement of a rule would still require evidence (in the form of a relevant entry in the maintenance schedule) before the safeguard can be considered to have been implemented.

Classification society rules therefore have the potential to provide confidence that the risks from a particular hazard are adequately managed. However, in order to use these rules as part of the body of evidence for a safety case, they need to be fully understood with regards to how they are mitigating the hazard.

4.5 HAZARD MANAGEMENT

An essential element of the safety management process is the management of hazards and their risks. As soon as hazards are identified they should be recorded in a Hazard Log. There are a number of different ways of recording hazards, for example a simple Excel spreadsheet could be used or alternatively a more complex bespoke Hazard Management tool. Figure 6 below shows a screen shot from one such tool the BMT Isis Ltd Hazard and Risk Management Tool (HARMS). The appropriate method of recording should be based on the detail and complexity of the hazard log.

During the life of the system changes will occur for many reasons, for example, design changes may have to be made, there may be changes to the operating environment or statutory law may change, which have an impact upon the system. To this end it is essential that the evidence used to claim that a risk is ALARP is periodically reviewed. The Hazard Log is therefore a “live” document that should reflect the risk status of the system at any point in time.

4.6 THE HOLISTIC RISK BASED APPROACH

Many approaches are taken to ensuring the safety of the equipment interfaces however these tend not to consider the concept of a ‘system of systems’. The holistic risk based approach ensures that all elements of the SRS are addressed. It allows for the interfaces between the equipments and systems that make up the SRS to be clearly identified, risk assessed and managed.

The holistic approach also recognises the importance of the equipments being “In-Class” and how this can be used to validate the argument that appropriate mitigation is in place to ensure the system is ALARP.

5. THE SAFETY CASE

A Safety Case is the body of evidence that is gathered to support the claim that the system is adequately safe. The Safety Case must present a clear, comprehensive and defensible argument that a system is safe to operate in the specific context. It is essential that the Safety Case clearly communicates the ideas and information that is required to demonstrate the Safety Argument.

The Safety Case for a SRS therefore needs to cover all the elements comprising the particular system and be developed through a series of Safety Case Reports, covering the lifecycle of the system.

The Safety Case Report, at whichever part of the lifecycle of the system, is used to bring together all of the aspects of the risk based approach to provide a comprehensive argument that the system is safe. The following paragraphs describe the Safety Case Reports that are required throughout the lifecycle of the equipment.

5.1 THE PRELIMINARY REPORT.

This is written very early in the design in order to obtain an understanding of the major hazards and the potential level of risk that they present. This allows design effort to be applied to achieve risk reduction at a time when design changes are least costly. At this stage the higher levels of risk reduction forming the ‘hierarchy of risk reduction’ would be applied e.g. elimination of the hazard.

5.2 THE PRE-CONSTRUCTION REPORT.

This is used to identify and resolve the design issue hazards, prior to construction, after which ‘hardware’ changes become significantly more costly. This Safety Case report aims to confirm the potential that each hazard has to become ALARP and either broadly acceptable or tolerable.

5.3 THE PRE-OPERATIONAL REPORT.

This is written when the system is ready for say initial trials. The difference between this and the two previous reports is that to support this report the operational design and controls associated with trials (but not necessarily for full in-service operation) will be in place but may not have been tested. This confirms that the risks from the identified hazards have been reduced to ALARP and either broadly acceptable or tolerable.

5.4 THE OPERATIONAL REPORT.

This reflects the safety status of the operational system and draws on the evidence supporting the claim that all identified safeguards are in place and there is evidence to support their effectiveness. It should also describe the Safety Management System (SMS) that is in place to manage the safety of the system throughout its life. This report validates the ALARP status of the hazards for an in-service system and confirms that the ALARP status has the potential to be maintained.

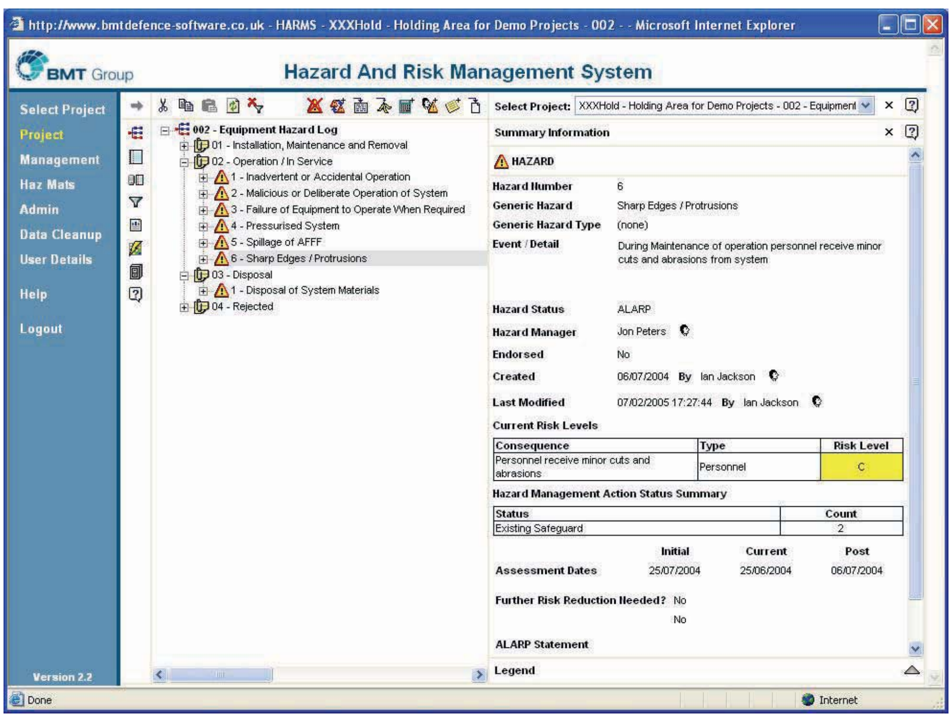

Figure 5 - A Screen Shot From the Hazard and Risk Management Tool HARMS

6. CLAIMS-ARGUMENT-EVIDENCE

The Claims-Argument-Evidence approach to the development of a Safety Case provides a justification framework to substantiate the Safety Claim. The Safety Case must detail the Claim that is being made, the Evidence to support this claim and the Argument as to how the evidence supports the claim.

When the UK MoD first promulgated the requirement to develop Safety Cases for their platforms, systems and equipment, a large number of these Safety Cases were necessarily "retrospective", in that the Safety Cases had to be developed to support the safety argument for in-service systems, at a stage in their lifecycle where designing out the hazard was not a practicable solution.

BMT Isis has used the Claims-Argument-Evidence approach to the development of several safety cases including the Whole Submarine Safety Case (WSSC) for Trafalgar and Vanguard class submarines and the RAN SERS.

Figure 7 presents an illustrative example of how the Claim-Argument-Evidence approach can be used for an element of an SRS.

The Claims-Argument-Evidence approach to the Safety Case can be managed and represented graphically utilising commercially available tools such as ASCE™, developed by Adelard LLP. Any graphical representation should be supported by a clear and concise narrative of the claims and arguments together with the references to the supporting evidence.

As Figure 7 shows, the use of Classification Society rules can be used within a safety case to provide evidence (the certificate) of an argument that the safety claim is true. However, as previously discussed, Classification Society rules cannot provide assurance of the operational capability of a SRS in its entirety. The use of the Claim-Argument-Evidence approach allows multiple arguments, with their associated evidence, to be used supported by sub-claims, each of which will have their own argument and supporting evidence.

The risk based approach to hazard identification provides further evidence to support a safety claim. The argument supporting this approach must have as evidence a description of the process, including a record of the SQEP involved, and the results e.g. the hazard log, together with the ALARP justification.

As has been demonstrated each safety claim is supported by any number of safety arguments. These multiple arguments and their supporting evidence provide a comprehensive justification for each safety claim. This type of notation is particularly powerful in allowing disparate elements of evidence (e.g. compliance with Class requirements, historical safety records, elements of engineering assessment that support a risk assessment, etc) all to be taken into account within an overall, or holistic, Safety Case approach. It is essential that these multiple arguments are clearly communicated to ensure that the full justification is understood.

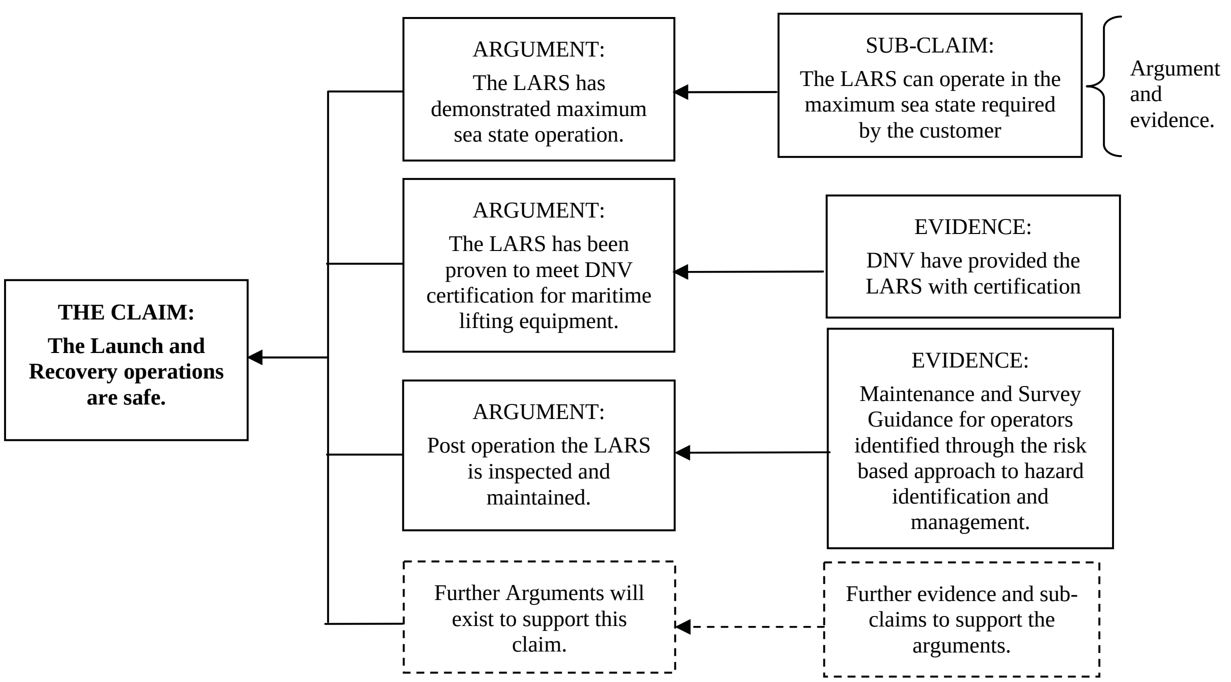

Figure 6 - An Example of The Claims-Argument-Evidence Approach to a Safety Case for a SRS.

7. CONCLUSIONS

This paper has considered the key aspects that need to be considered in order to provide a comprehensive and complete safety argument for an entire SRS system, and it has demonstrated that there are a number of methods that can be applied to provide evidence to support the safety argument.

Compliance with classification society rules goes a long way to assuring the safety of individual aspects of the SRS and it provides compelling evidence to support the safety argument for them.

The use of in-country standards and certification requirements (such as the UK MoD key hazard area certification) can also validate the safety claims made for certain equipments.

However, many other hazards and associated risks are not managed by compliance with certification requirements alone, particularly where these "certified" equipments interface. Therefore in order to provide a complete safety argument one must take a holistic view of the system. If the risk based approach is followed and a comprehensive Claims-Argument-Evidence structure is built up for the system it will provide assurance to the owner and operator that the SRS as a complete system has a level of associated risk that is ALARP and either broadly acceptable or tolerable.

8. ACKNOWLEDGEMENTS

The views expressed in this paper are those of the author and are not necessarily those of BMT Isis Ltd or the BMT Group.

9. REFERENCES

[1] JSP 430: MoD Ship Safety Management Policy. Issue 3 dated September 2006.

[2] International Convention for the Safety of Life At Sea (SOLAS)

[3] DNV Rules for the Certification of Lifting Appliances 2007.

10. AUTHORS BIOGRAPHIES

Loren Roberts (CEng, MRINA) has 13 years experience in Naval Architecture and Engineering with BMT. She has worked as a safety engineer for the past 6 years and is now a Senior Consultant with BMT's Safety and Environmental Consultancy, BMT Isis Ltd. Her recent experience has included developing three of the six submissions for UK MoD key hazard area certification for the NSRS.

John Turner (MSaRS) has 40 years of experience in Engineering with the past 27 years involved with safety and reliability engineering and management, covering the defence, nuclear and off-shore industries and is currently a member of the Senior Management Team of BMT Isis Ltd. He is a member of the Safety and Reliability Society and is a past chairman of the Western Branch. His recent experience of Submarine Escape and Rescue safety has been gained from assignments covering the UKSRS, NSRS and RAN SERS.

FUTURE CORROSION SIGNATURES MODELLING

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SUMMARY

Minimisation of electromagnetic signatures is an important consideration in future submarine design. Electric and magnetic fields play an important role in the detection of a submarine. This paper identifies and outlines methods for improving the computational modelling of corrosion related submarine signatures.

1. INTRODUCTION

In recent years the technology for detecting electromagnetic signatures associated with submarines has improved significantly. As such, it has become necessary to reduce the electromagnetic signatures of future submarines. While this can be aided with computational tools, the capability to model smaller signatures, more accurately, has become a necessity.

In addition, the capability to model conditions in which submarines are likely to operate has become important to designers. This has been brought about as the operational environment in which submarines function is constantly changing. For example, it has become important to be able to model the signature of a submarine based in the littoral environment.

Corrosion of a submarine is closely linked with electromagnetic signatures as both are caused by the galvanic potential differences that exist between the metallic structures in contact with the seawater.

The US Department of Commerce estimated that the economic cost of corrosion in 1975 was approximately 5% of the Gross National Product (Reference 1). Repair time and costs as well as replacement part costs are just some of the expenses incurred by corrosion of marine structures. Corrosion also presents an environmental threat via leakage of toxic chemicals and can lead to loss of life due to structural collapse. The ability to model corrosion – and in particular its effect from long term coating damage – has therefore become increasingly important.

In particular, the capability to model end-of-life conditions of a submarine has become essential. Such conditions, in which coating damage is at a maximum, are likely to lead to the largest signatures being produced and hence the greatest chance of detection.

The increasing importance of corrosion and signature management has resulted in the modelling of corrosion related signatures progressing from being a research activity into the commercial engineering field. To support this, a variety of computer tools (such as FNREMUS (Reference 2) and BEASY-CP (Reference 3)) and techniques (such as physical scale modelling (Reference 4)) have been developed, refined and validated over the past decade and a half. As well as modelling corrosion, current computational tools are also capable of modelling impressed current cathodic protection (ICCP) systems. A well designed ICCP system will provide both corrosion protection and reduced signatures throughout the life of a submarine.

Computational tools allow designers to simulate real-world conditions – many of which would otherwise be prohibitively expensive to model experimentally – to predict and/or minimise the signature and corrosion of a submarine.

While computational tools allow users to simulate problems that would not otherwise be possible, areas in which they could be further improved have been identified. One such area is associated with the lack of processor power and memory available for solving models. Despite doubling approximately every two years – as stated by Moore's law – the processor power and memory available in the current generation of computers is still insufficient for solving the desired problems using current computational tools. Alternative methods – such as optimising algorithms used for modelling corrosion – for running models of the desired size must therefore be sought. This will allow the designer to run increasingly detailed models leading to more accurate corrosion and signatures prediction.

If left unchallenged, as coating damage and degradation of a submarine occurs, the corrosion and associated electromagnetic signatures will increase. Computational models allow designers to run a range of "what-if" scenarios corresponding to variations in coating damage and operating conditions (i.e. salinity and water depth). This provides a through-life profile of the corrosion and electromagnetic signatures of a submarine allowing designers to determine possible worst-case scenarios, and the effectiveness of control algorithms. Performing such analyses requires running a number of models at high cost and the overall process can be significantly improved by being able to run in less time.

Another area in which current day computational tools need to be improved is in the modelling of the corrosion electrochemistry. This is currently achieved using a simplistic method which is unable to adequately model electric fields in enclosed spaces. Improvement in the modelling of electrochemistry would again allow more accurate predictions of corrosion and signatures of a submarine.

This paper identifies the limitations of the current generation of computational tools used for modelling corrosion and signatures of submarines and outlines methods for improving them.

2. COMPLEX ICCP SOLUTIONS

Corrosion and signatures are intimately linked as they both result from electrochemical currents flowing in seawater. Electric and magnetic fields are signatures of a naval vessel that play an important role in its detection. The static electric (SE) signature is the electric field associated with corrosion. The corrosion-related magnetic (CRM) field is the coupled magnetic field caused by the corrosion-related electric currents flowing in the seawater. The SE and CRM signatures are caused by the galvanic potential differences between the metallic structures in contact with the seawater. For example, the relative position in the electrochemical table of steel and Nickel-Aluminium-Bronze (NAB) provides a sufficient driving potential to create an electric field.

Cathodic protection inhibits corrosion of a material that would otherwise act as an anode by forcing it to behave as a cathode. This may be achieved by attaching anodes to the structure and drawing current away from the area to be protected. An impressed current cathodic protection (ICCP) system ensures that on-board power supplies provide controllable anodic currents to "inert" anodes. Electrical potential is monitored through reference cells placed at strategic locations on the structure. An ICCP system provides flexibility under widely varying operating conditions to reduce corrosion. Unfortunately, the relative complexity of the system demands a high level of design understanding. Skilful arrangement of the individual components is required for the design of an effective ICCP system. Analytical evaluation of ICCP system performance, either by computational simulation techniques or scale model experimental testing, can be a powerful tool in the development of ICCP systems but can also be prohibitively expensive.

An ICCP system generally consists of several anodes, reference cells and power supplies. Each of these is grouped into zones – each of which is defined as a single controller that adjusts the output of a power supply through anode(s). Reference cells monitor the potential on the hull potential and provide information to the control algorithm. The current of each anode is determined from the potential at its reference cells using separate algorithms. The control of each zone acts independently of the others.

Despite the term "zone" implying that discrete zonal boundaries exist, this is not the case. Indeed the hull is a continuous structure without physical barriers defining individual zones. The effect of one zone's power input on the reference cell of another therefore becomes a concern for both the physical and computational model.

Consequently, ICCP systems are moving away from the traditional zonal systems to a single "complex zone" in which the anodes and reference cells are regulated by a single controller. Algorithms capable of modelling these complex zone ICCP systems have been incorporated into the FNREMUS software.

3. OPTIMISING CORROSION MODELLING

Traditional computational methods for modelling corrosion and signatures have previously required sacrificing problem size (i.e. the number of elements) in order to run models in a reasonable amount of time. As a result, the mesh resolution is generally below the level of detail desired by code users. While this may be sufficient for smooth regions – such as the hull, smaller areas that require greater resolution – such as hull mounted equipment and free-flood areas – are often sparsely represented. The accuracy of the predicted corrosion and signatures is therefore compromised at these sites.

3.1 NUMERICAL SOLVERS

Current corrosion modelling software is based upon Laplace's equation for the potential distribution throughout the seawater with the electrochemistry being modelled using non-linear polarisation curves. An example of a polarisation curve is shown in Figure 1. The solution process (illustrated in Figure 2) involves iterating between Laplace's equation and the polarisation curves until the potential distribution between iterations is sufficiently small. The bottleneck in this process is solving Laplace's equation. Initially, the Finite Element Method (FEM) was used to solve the open boundary Laplace problem that arises in corrosion modelling. However, the requirement to analyse the, effectively, infinite domain of seawater results in a prohibitively large model or inaccurate solution in which the open domain is insufficiently represented.

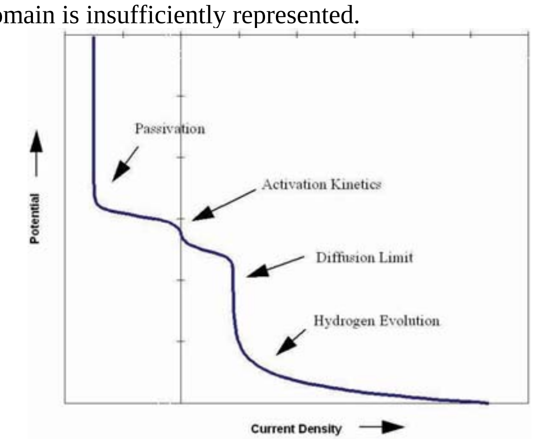

Figure 1: An example of a polarisation curve.

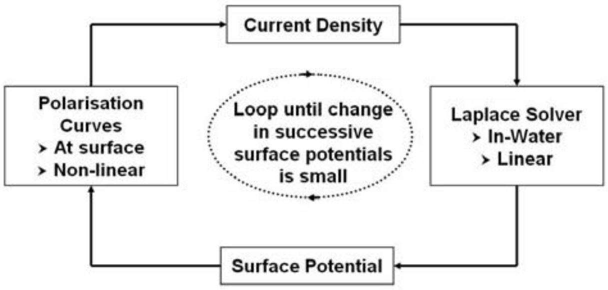

Figure 2: Solution process for corrosion modelling.

An alternative approach is to use the Boundary Element Method (BEM) for solving Laplace's equation. In this approach the governing differential equations are transformed into integral identities based on Green's fundamental solution for the three-dimensional Laplace equation. These integrals are numerically integrated over the boundary of the problem which is divided into a number of elements. These elements, which tend to be triangular or quadrilateral, are defined by a number of nodes that are also common to the surrounding elements. As in other numerical approaches, provided the boundary conditions are satisfied, a system of N linear algebraic equations (one for each node) emerges for which a unique solution can be obtained.

The BEM has predominantly been used in recent years to solve Laplace's equation within corrosion modelling software. Unfortunately, the solution matrix resulting from the BEM formulations is asymmetric and fully populated with non-zero coefficients. This means that the entire BEM solution matrix, of size N^2, must be saved in the computer core memory for efficient direct solving. The storage and computational cost of iteratively solving such a matrix equation scales with *Order* N^2. A problem with twice as many elements will therefore take four times as long and require four times as much memory to solve.

One method employed in recent years to reduce the computational and storage cost of the BEM is the Fast Multipole Method (FMM). The FMM can be thought of as an accelerated form of the BEM in which Green's function is represented in terms of a Taylor Series expansion. While every element interacts with every node in the BEM, the FMM approach involves averaging elements in groups (thereby creating "pseudo-particles") which then interact with nodes. The size of each group of elements is proportional to the distance from the group centre to the node with which it interacts. This approach allows a single group of elements to interact with many nodes, thus reducing the number of interactions that take place between elements and nodes. The computational and storage cost of employing the FMM to solve Laplace's equation can be shown to scale linearly with the size of the problem. Increasing the mesh resolution at areas of interest will therefore have a significantly smaller impact on the computational cost of the FMM compared to that of the BEM.

When applied to solving Laplace's equation in corrosion modelling software the FMM allows problems that were previously prohibitively large to be solved. In addition, the nature of the FMM allows the user to sacrifice solution accuracy for a decrease in run time by reducing the number of Taylor Series terms used to represent Green's function. This is ideal for sensitivity analyses in which the user may wish to reduce the run time for initial studies at the expense of the solution accuracy.

3.2 RESULTS

The corrosion modelling software FNREMUS has previously been used to demonstrate the speedup possible when employing the FMM to solve Laplace's equation (Reference 5). The geometry, provided by the US Naval Research Laboratory (NRL) is representative of vessels with one propeller and one rudder located along the centreline. The mesh, shown in Figure 3, consists of approximately 3,600 elements and 15,000 nodes. As mesh size increases the difference in computational cost between the BEM and FMM is exacerbated due to the *Order* N^2 and N cost scalings, respectively. Large and complex models such as those envisaged for future systems will therefore demonstrate much larger cost savings with the FMM than the modestly sized mesh used in this example.

The vessel is outfitted with a 2 zone ICCP system. Exposed surfaces are limited to the propeller and docking block areas. These make up approximately 3% of the total surface area of the vessel corresponding to newly painted conditions. The coated areas of the vessel are considered to be perfectly dielectric surfaces. The docking block and propeller areas are assigned the polarisation response of steel and NAB, respectively.

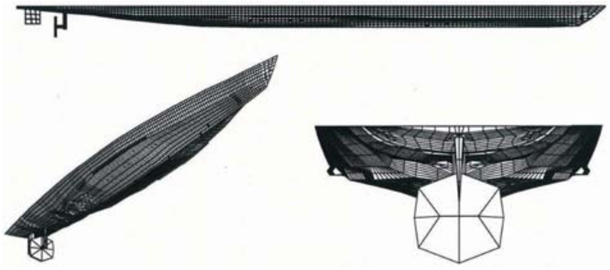

Figure 3: Boundary element mesh.

Two Laplace solvers were employed in the FNREMUS corrosion software. These are:

- BEASY-Thermal, a commercial boundary element solver; and
- An FMM solver developed by Frazer-Nash at Imperial College, London.

These will henceforth be referred to as FNREMUS-BEASY and FNREMUS-FMM, respectively.

Of particular interest when comparing the two solvers are their relative run-times and accuracy. Since the FMM uses a Taylor Series approximation of Green's function it might be expected that this is not as accurate as the conventional BEM solver. However, the time required to run FNREMUS-FMM should be far less than that for FNREMUS-BEASY. In order to compare the performance and accuracy, the results calculated using FNREMUS-FMM were obtained using different numbers of expansion terms. While increasing the number of terms in the Taylor Series expansion will generally increase the accuracy of the solution, the benefit of doing so must be offset against the additional computational cost of calculating the extra expansion terms. In addition, experimental results, obtained using physical scale modelling (PSM), were also used to validate the computational results. Results calculated using both PSM and FNREMUS-BEASY were calculated as part of the paper by DeGiorgi et al (Reference 6).

Key results obtained using PSM and computational methods are shown in Table 1 and illustrated in Figure 4. Of importance here is the comparison between the two calculated results. As expected, the anode currents are equal to the sum of the current from the propellers and docking block for each of the solvers. The total anodic currents are equal to 1.97mA and 2.01mA for FNREMUS-BEASY and FNREMUS-FMM, respectively. The difference between the FNREMUS-FMM and PSM anode currents is greater than the differences calculated for FNREMUS-BEASY and PSM. However, this is offset by the smaller difference between the total cathodic currents. Indeed, the FNREMUS-FMM values of anodic/cathodic currents are closer to the average of the PSM anodic/cathodic currents than FNREMUS-BEASY.

	PSM	FNREMUS-BEASY	FNREMUS-FMM			
			p=2	p=3	p=4	p=5
Total anode current (mA)	-1 97	-1 97	-2 01	-2 01	-2 01	-2 01
Docking blocks (mA)	0 89	0 89	0 92	0 92	0 91	0 91
Propeller (mA)	1 15	1 08	1 10	1 10	1 10	1 10
Total	2 04	1 97	2 01	2 01	2 01	2 01

Table 1: Corrosion results from ship hull calculated using Physical Scale Modelling (PSM), FNREMUS-BEASY and FNREMUS-FMM.

Figure 5 shows the CPU times required to run the model using the FNREMUS-BEASY and FNREMUS-FMM solvers. As discussed previously, FNREMUS-BEASY employs the conventional BEM to solve Laplace's equation. FNREMUS-BEASY is therefore expected to take longer to solve problems than FNREMUS-FMM. Indeed, the total CPU time taken to run FNREMUS-BEASY for this case is approximately 24,000 seconds. This is at least twice as long at it takes to run FNREMUS-FMM. The time taken to solve the problem using FNREMUS-FMM with two expansion terms is approximately 3,000 seconds or eight times quicker than FNREMUS-BEASY.

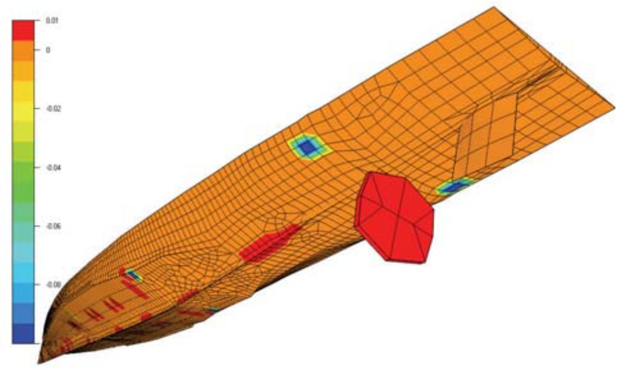

Figure 4: Current density on the aft-end of the vessel

While this relatively small example demonstrates the improvement in CPU-time achieved by using the FMM, greater savings in performance have been shown for larger problems. Unfortunately these results are not available for publication.

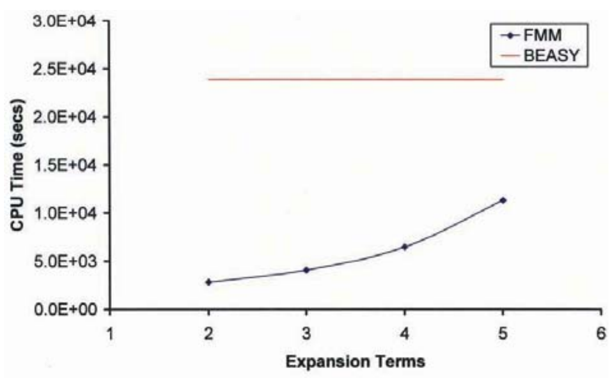

Figure 5: CPU time required to run FNREMUS using different Laplace solvers. FNREMUS-BEASY was only run once but has been shown here for comparison with FNREMUS-FMM.

3.3 SURROGATE OPTIMISATION

Iterative processes commonly occur within computational corrosion solvers. The non-linear nature of the boundary conditions that arise as a result of the polarisation curves require an iterative procedure for solving the problem. Meanwhile, within this iteration, BEM or FMM indirect solvers also require solving a set of matrix equations iteratively.

Traditional global optimisation techniques generally perform a large number of function evaluations before converging to a solution. However, this is not practical when the objective function involves a computationally

expensive analysis; for example, a BEM, FEM or CFD analysis.
Surrogate models (approximate responses to the underlying model) are well-suited to the optimisation of expensive objective functions since they generally require far fewer function evaluations.

These optimisation techniques have been successfully employed by Frazer-Nash to determine a set of optimum empirical parameters to use in a code which predicts the mechanical properties of irradiated graphite. Traditional optimisation schemes would be computationally too expensive since evaluating the objective function requires an FEM analysis.

Frazer-Nash is currently investigating surrogate optimisation techniques that could be used to reduce the number of iterations to convergence within the outermost iterative loop or the BEM/FMM Laplace solver.

4. IMPROVED ELECTROCHEMISTRY MODELLING

Protective anticorrosion coatings are the first line of defence against corrosion for submarines. In addition to anticorrosion coatings submarines also employ cathodic protection as secondary corrosion protection. Successful corrosion modelling of coated areas such as ship hulls and seawater ballast tanks will require the ability to incorporate these two corrosion protection strategies into the modelling paradigm.

The present generation of corrosion modelling software currently uses a simplified representation of the corrosion electrochemistry, and it is not readily capable of dealing with issues of seawater chemistry, coatings chemistry, or progressive substrate degradation. The present platforms for corrosion modelling represent seawater, coatings, and corroding steel substrates as coupled electrical resistors. The interactions between these coupled resistors are then analysed using Laplace's equation to obtain potential distributions and current flow throughout the seawater. The electrochemical corrosion reactions of metallic surfaces are modelled as non-linear resistors through the use of polarisation curves. In effect, the seawater is treated as a homogenous conductive fluid and Ohm's law is applied. This is a reasonable model of the overall effects of corrosion of a submerged structure in a large volume of electrolyte and is valid for smooth surfaces of hulls in open ocean conditions. However, it is not capable of predicting coatings failure or the spread of corrosion damage at known coatings defects.
Seawater is an electrolytic conductor that allows passage of electrical current through movement of dissolved ionic species. The Laplace approach does not allow for the flow of ions within the seawater which is the basis of electrochemistry. Nor does it allow for variations of chemical species within the seawater electrolyte. This variation in seawater chemical species of composition becomes critical in enclosed spaces where there is limited or no exchange between the enclosed fluid and the larger body of seawater surrounding the structure. Examples of such geometries range in size from cracks and crevices to enclosed spaces such as sea chests or other geometric features on hulls. In all cases, depravation of chemical species plays an important role in corrosion behaviour. At the micro and meso scales this limitation of Laplace's approach results in errors in modelling the local environment. This has implications on accurately modelling using lower scale techniques that depend on macro-scale model information. At the engineering system level, the limitations of Laplace's approach have a significant effect on design of corrosion protection and signature of the whole vessel.

The inability of Laplace's equation to adequately capture the enclosed space electrical fields has been demonstrated through physical scale modelling experiments. These experiments investigated the effects of anode within an enclosed space (such as a sea chest) on the on-board and off-board electrical field of the structure.

There are significant similarities between crevice corrosion and corrosion of coated metals. In some cases a coating will blister or flake by a crevice corrosion mechanism, but even other mechanisms (e.g. diffusion through porous coatings or local attack at damage sites) show strong parallels in the electrochemical and ion transport involved.

Frazer-Nash has developed a quasi-one-dimensional hybrid Finite Element (FE)/Finite Difference (FD) computational crevice model that incorporates the necessary elements of chemical transport and simple passivity. Figure 6 shows typical predictions for the computational crevice model. This model uses the following approach:

- The underlying FEM allows the basic crevice geometry (i.e. depth, variation of width and branching) to be represented. In this respect it is "quasi-one-dimensional" because it represents true geometry but with only a single cell across the crevice. The FEM calculation includes electrochemical reactions at the surfaces.
- The FD method is employed for calculating the migration and diffusion of species within the crevice, and for modelling chemical equilibrium and ion hydrolysis. This method was chosen because of the form of the equations employed.
- Iteration between the two methods allows a full transient solution to be derived.

The modelling method has a number of useful features which can be used to simulate a variety of scenarios. These features include:

- Stainless steel or aluminium alloy simulation

- Linear or radial geometry
- Insulated, single or multi metal wall geometry
- Multiple crevice branching
- Variable gap and gap discontinuity
- Bulk solution inhibitors

Techniques such as the crevice model provide a better understanding of the electrochemistry of coatings. This can be used to improve the existing corrosion models by enhancing the empirical coating model. Alternatively, the crevice model can be incorporated into the existing BEM corrosion models to produce a hybrid model.

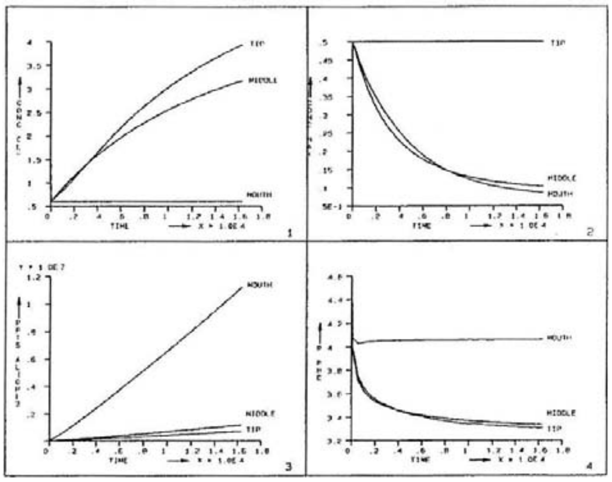

Figure 6: The four graphs show the variation with time at the mouth, middle and tip of the crevice of Cl^- concentration (top left), Na^+ concentration (top right), precipitation of $Al(OH)_3$ (bottom left) and pH (bottom right).

5. CONCLUSIONS

The reduction of corrosion related signatures is of particular importance in the design of future submarines. In order to aid the submarine design process, computational tools need to be capable of modelling smaller signatures more accurately.

This paper has identified several key areas in which today's generation of computational tools for modelling signatures can be improved.

The first area identified as requiring improvement is in the setup of ICCP systems. The components of ICCP systems are generally grouped in zones. However, the effect of one zone's power input on the reference cell of another becomes an issue for both experimental and computational modelling. An alternative method, successfully employed in the FNREMUS, is to employ a single "complex zone" in which the anodes and reference cells are regulated by a single controller.

A further area in which considerable improvement in accuracy can be achieved is in the computational performance of the software used for modelling corrosion related signatures. This will enable more detailed models – which were previously prohibitively large – to be solved. In addition, this will allow designers to perform more effective through-life analyses of future submarines with a view to profiling signatures. Two possible methods for improving the computational performance have been outlined in this paper. The first of these include replacing the current generation of BEM Laplace solvers with those employing the FMM. The result of implementing the FMM within FNREMUS has been shown to give significant improvement in computational performance for a modestly sized problem. Secondly, the performance of computational solvers can be further increased by employing surrogate optimisation techniques to speed-up the many iterative processes that take place within signature modelling software. This area is currently under investigation at Frazer-Nash with a view to employing it in FNREMUS.

The final area identified for improving the current generation of computational tools for modelling signatures relates to improving electrochemistry modelling. A simplistic approach is generally used in which electric fields are not adequately modelled in enclosed fields. An alternative method outlined in this paper and under investigation by Frazer-Nash involves employing a crevice model to improve corrosion models.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

1. Economic effects of metallic corrosion in the United States, in NBS Special Publication 511-1. 1978, National Bureau of Standards, U.S. Dept. of Commerce.

2. Frazer-Nash Consultancy, *FNREMUS Detailed Modeller User Guide*, FNC 5421/21133R, Issue 4, 2007.

3. *BEASY User Guide*. 1994, Computational Mechanics: Southampton, UK and Boston, USA.

4. Lucas, K.E., Thomas, E.D., & Hogan, E.A., "Physical Scale Modelling for the Design of Impressed Current Cathodic Protection (ICCP) Systems", *UMIST Advances in Corrosion and Protection Conference*, Paper # 199, Manchester, England, July 1992.

5. Keddie, A.J., Pocock, M.D., & DeGiorgi, V.G., 'Fast solution techniques for corrosion and signatures

modelling', *Simulation of Electrochemical Processes II*, 225-234, 2007.

6. DeGiorgi, V.G., Pocock, M.D., Wimmer, S.A., & Hogan, E.A., 'Zonal ICCP System Control Interactions,' *Simulation of Electrochemical Processes*, 15-24, 2005.

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Early validation of remus - algorithms

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Warship 2008: Naval submarines 9, Glasgow, UK

DEVELOPMENT OF AN ASSET INTEGRITY MANAGEMENT STRATEGY FOR MARINE PROPULSION SHAFTS

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SUMMARY

The propulsion tailshafts fitted to submarines are potentially at risk from environmentally-assisted cracking in service due to the combination of a large number of rotating-bending stress cycles in conjunction with the possibility of exposure to seawater. Contact with seawater will cause corrosion pits to form which could act as fatigue initiators. To prevent this occurring, the exposed parts of the shaft are protected by an epoxy bandage. However, previous experience with older shafts has shown that the bandage may not entirely prevent ingress of seawater throughout the life of the shaft. In order to manage the risk of environmentally-assisted cracking, an Asset Integrity Management (AIM) strategy has been developed that defines a through-life inspection procedure intended to maintain shafts at their target level of operational safety. This paper describes the processes used to develop the AIM plan, establish user and system requirements, and select the optimum inspection technology for the application. The potential for transfer of this knowledge to future designs is also discussed.

NOMENCLATURE

a	Crack depth (m)
c	Diameter of corrosion pit (m)
C_P	Corrosion pitting constant (m/s$^{1/3}$)
$\frac{da}{dN}$	Crack growth per cycle (m/cycle)
$\frac{dc}{dN}$	Pit growth per cycle (m/cycle)
f	Apparent cyclic frequency (Hz)
K	Stress intensity factor range (MNm$^{-3/2}$)
Q	Shape parameter
$_a$	Alternating stress amplitude (MN/m^2)
t	Time (s)

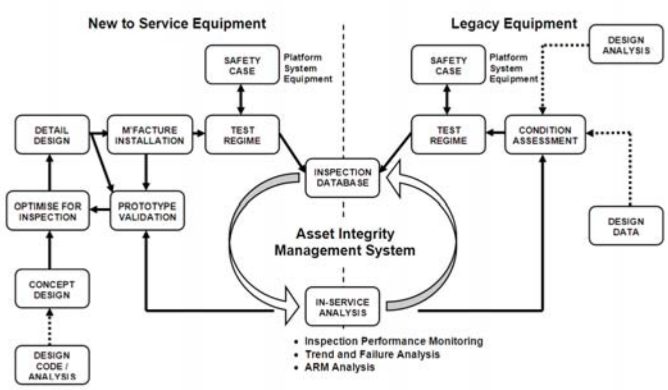

Figure 1: Asset Integrity Management process

1. INTRODUCTION

Many types of structure are expected to deteriorate during their anticipated working life. This deterioration may affect the ability of the structure to perform its design function in the manner intended either it terms of a reduction in performance or operational safety or both.

Marine propulsion shafts are potentially at risk from environmentally-assisted cracking in service due to the combination of a large number of rotating-bending stress cycles in conjunction with the possibility of exposure to seawater.

In the event that the protection afforded by the epoxy bandage becomes compromised, contact with seawater may cause corrosion pits to form which could act as fatigue initiators. Once initiated, cracks are expected to grow rapidly to a size at which shaft failure is possible.

In order to manage this risk across all legacy submarine platforms, Asset Integrity Management (AIM) principles originally developed within the petrochemical industry have been used to develop an integrity management strategy for tailshafts.

AIM calls upon a wide range of engineering skills and Non Destructive Testing (NDT) techniques to deliver intelligent information systems and hardware that enable operators to maintain assets at the required levels of performance and integrity at minimum through-life cost. The AIM process can be applied equally to new-to-service assets and legacy equipment, as shown in Figure 1.

In the specific case of submarine tailshafts, the AIM strategy is required to deliver both the through-life safety and performance targets, whilst maximising platform availability by minimising the impact on existing maintenance cycles.

2. ASSET INTEGRITY MANAGEMENT PROCESS

The basic stages in the Asset Integrity Management process shown in Figure 1 are:

- Establish the design intent of the assets;
- Quantify the operating environment;
- Understand how assets age or deteriorate;
- Rank assets to identify areas of real risk;
- Specify optimal methods for condition assessment;
- Derive appropriate reliability and performance targets;
- Predict when asset condition will fail to meet target;
- Develop a strategy to maintain assets just above target;
- Implement AIM strategy within a data infrastructure.

Gaining a solid understanding of the early stages of the AIM process is crucial to achieving a cost-effective through-life integrity management solution. Over the past 15 years, several previous attempts to deal with tailshaft cracking have largely failed to deliver because there was insufficient initial consideration given to the likely nature of shaft defects and their criticality with respect to tailshaft integrity. The order of the tasks given above places relatively low cost review and research tasks early in the process, in order to define robust User and System Requirements for the more costly activities associated with development and formal qualification of NDT inspection equipment for condition assessment. The overall intention of following this process is to develop optimum systems and procedures that will allow the integrity of all legacy submarine tailshafts to be managed at the lowest cost.

The following section describes the current understanding of shaft deterioration mechanics once seawater has penetrated under the epoxy bandage, and shows how probabilistic analysis can be used to estimate the risk of shaft failure in this condition. The predicted failure probabilities may be used to assist in defining the overall Asset Integrity Management strategy and the System Requirements for the development of inspection methods, as described in subsequent sections of the paper.

3. THROUGH-LIFE INTEGRITY OF SHAFTS

This section outlines the various issues that govern shaft life, and reports the key findings from research and modelling tasks in this area.

3.1 TAILSHAFT DESIGN LIFE

UK submarine tailshafts are designed and repaired in accordance with Defence Standard 02-304 [1, 2]. A fatigue life of 10^8 to 10^9 cycles is required depending on the particular application. The dominant alternating stress component which determines the fatigue life of the shaft is the rotating bending stress; for outboard portions of the shaft which are immersed in seawater, this is recommended not to exceed +/-20MPa. This value assumes that the epoxy bandage remains intact for the life of the shaft.

If the epoxy bandage is compromised, however, the design fatigue life is no longer assured. The nucleation and growth of corrosion pits of sufficient size to prematurely initiate fatigue cracks means that the safe operating life of the shaft may be significantly curtailed. There have been a small number of instances where fatigue cracks have developed in older classes of submarine shaft; however, no catastrophic failures have ever been reported.

Deterministic calculations to predict the useful life of a shaft assuming water ingress occurs will generally produce very conservative estimates of shaft life. For example, pitting rates for ferritic steels can be up to 2mm per year. Using fracture mechanics and upper bound corrosion fatigue data for ferritic steels it can be shown that a 2mm corrosion pit could initiate a fatigue crack and lead to shaft failure in less than 2 years. Together these numbers suggest that once water ingress occurs, shaft failure would be expected within 3-4 years. This is not consistent with service experience since water ingress under the bandage terminations is a relatively common observation at refurbishment (see Figure 2), and yet only a very small proportion of shafts have been found to contain cracks.

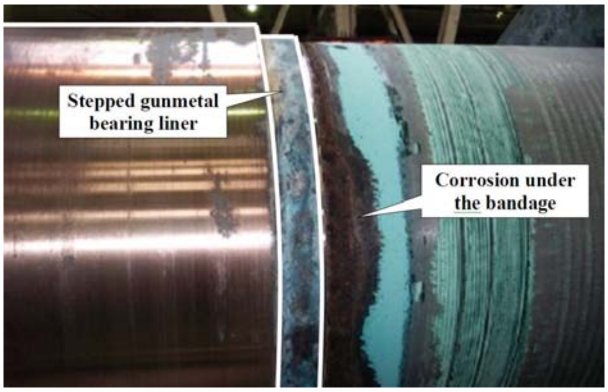

Figure 2: Corrosion Observed after Bandage Removed

3.2 PROBABILISTIC MODEL OF TAILSHAFT LIFE

The rates of growth of corrosion pits and of fatigue cracks in the near threshold region that dominate shaft life are known to be subject to considerable statistical variation. A more representative estimate of the risk of premature failure of shafts can be gained though the use of probabilistic analysis. The following probabilistic model is based on the four stages of shaft life shown schematically in Figure 3.

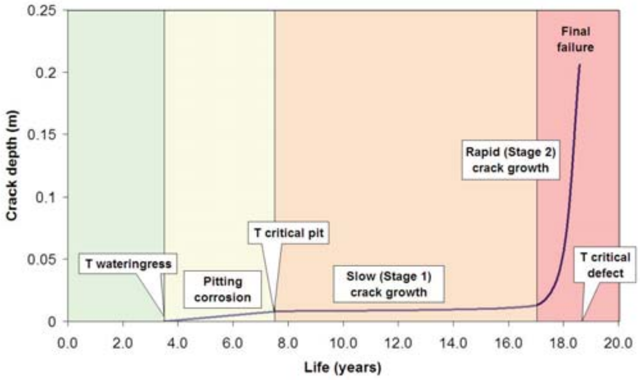

Figure 3. Schematic of the Tailshaft Lifecycle

The first stage of shaft life is experienced prior to water getting under the bandage. Once this has occurred, corrosion pitting is expected. As the pits grow and start to form chains, fatigue crack initiation becomes increasingly likely. Cracking will proceed relatively slowly at first in the near threshold region, until the cracks reach a size at which very rapid growth is expected due to the large number of shaft revolutions experienced annually. This sequence of events can be represented mathematically as:

$$t_{failure} \quad t_{wateringress} + t_{criticalpit} + t_{criticaldefect}$$

The probabilistic model attempts to predict each stage of the shaft life using empirical data and equations, in order to develop statistics for the probability of shaft failure that can be used to formulate the integrity management strategy.

3.2 (a) Water ingress stage

No information, empirical or otherwise, has been found that allows prediction of the length of time that the epoxy bandage will remain effective in keeping water out. Effort in this area has been focussed on design improvements such as more effective bandage terminations, and ensuring that best practice is followed in application of the bandage. No benefit is taken in the model of a period without seawater in contact with the tailshaft.

3.2 (b) Corrosion pitting stage

A number of published pitting corrosion models which aim to quantify the initial rate of pitting and the pit to crack transition stage of corrosion life were reviewed [3]. The pit growth behaviour and the near threshold crack growth rate are both dependent on the material and environment, and there is often considerable scatter in the data. The absence of any published pitting data specific to tailshaft steels in seawater means that the model needs to retain a large amount of uncertainty in this stage of shaft life prediction.

It was concluded [3] that the mathematical model derived by Kondo [4] provides the most appropriate means of predicting the growth of corrosion pits and the subsequent transition into fatigue cracks. The rate of increase of corrosion pit diameter, c, per cycle of shaft rotation is expressed as a function of fracture mechanics parameters (a, Q, K, $_a$) for an equivalent crack-like defect of the same dimensions using:

$$\frac{dc}{dN} = \frac{1}{3} C_p{}^{3} f^{\ 1} a^2 \pi^2 Q^{\ 2} (2.24\sigma_a)^4 \Delta K^{\ 4}$$

where constant $C_p = c/t^{1/3}$ is obtained from corrosion pitting measurements taken over a period of several years [5], and f is the apparent frequency of the fatigue cycling.

The fatigue stresses in tailshafts are relatively low, which is likely to promote a significant period of growth by pitting corrosion prior to transition to fatigue cracking. This means that the size of the corrosion pits that can exist in the shaft without initiating fatigue cracks are large relative to many other corrosion pitting scenarios.

3.2 (c) Corrosion fatigue cracking stage

Near threshold corrosion fatigue data were also reviewed for steels tested in air and immersed in seawater [3]. The effects of specimen thickness, R-ratio and frequency on the crack growth threshold for medium strength, low alloy and carbon manganese steels under freely corroding seawater conditions were investigated. An upper bound for corrosion fatigue crack growth rates was identified:

$$\frac{da}{dN} = 2.33 \times 10^{\ 19} (\Delta K)^{16} \ for\ \Delta K \le 4MPa\sqrt{m}$$ Stage I growth

$$\frac{da}{dN} = 1.48 \times 10^{\ 11} (\Delta K)^{3.06} \ for\ \Delta K > 4MPa\sqrt{m}$$ Stage II growth

A mean fatigue crack growth curve corresponding to two standard deviations below this upper bound was established by shifting the Stage 1 fatigue curve to stress intensity factor values increased by 2MPa√m. The fatigue behaviour is then assumed to be lognormally distributed between the mean and upper bound curves. This recommendation is supported by test data, and by growth rates estimated for the limited number of cracks that have been found in earlier tailshafts.

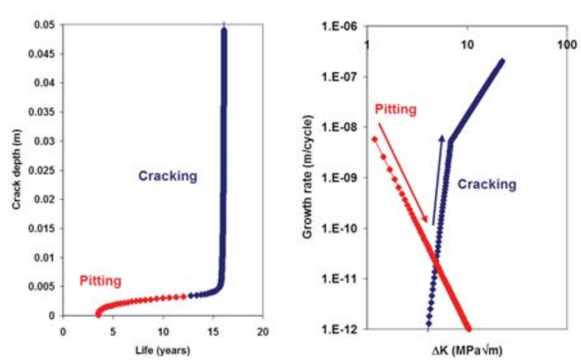

Figure 4: Schematic of Probabilistic Shaft Life Model

When combined with the pitting rate equation, a model for predicting the growth of fatigue cracks from corrosion pits can be formulated. The relationship between actual defect growth and the corresponding defect growth rates is illustrated in Figure 4, which shows that the transition from a pit to a crack occurs once the predicted fatigue crack growth rate exceeds the rate of pit growth.

3.2 (d) End of shaft life

The end of the useful life of the tailshaft is determined by the onset of one of two conditions:

- The shock performance of the shaft is compromised;
- The fatigue crack growth rates are so high that failure is likely within six months.

Calculations show that both of these conditions are reached when defects are relatively small, in the order of a 5mm crack fully extended around the shaft circumference.

3.3 SHAFT LIFE PREDICTIONS

The probabilistic model described above uses Monte Carlo simulation to obtain a probabilistic distribution of the time taken for a shaft to contain maximum defect sizes of 1mm, 2mm, 3mm *etc* following water ingress. The model is run up to 50,000 times with the pitting and fatigue variables randomly sampled from suitable probability distributions. Figure 5 presents an example of predicted defect populations in a shaft after up to 10 years operation.

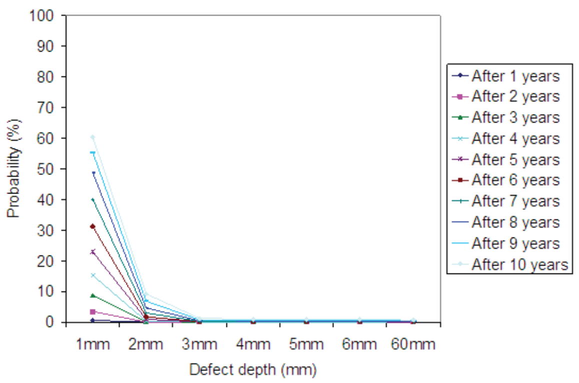

Figure 5: Example of Predicted Defect Populations

The model can be used to predict the defect population if a shaft is re-used for a second commission, having received NDT inspection to eliminate defects above a certain size. Calculations show that if the presence of no pits or cracks greater than 2mm deep can be assured using NDT, then the risk of reaching the estimated end-of-life defect size of 5mm during a second commission is acceptably low.

It is also possible to extract statistics for the defect size at which pit to crack transition takes place, Figure 6, which provides additional information to support the development of the optimum NDT system.

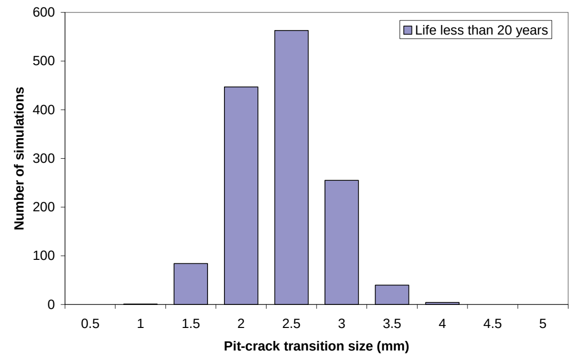

Figure 6: Predicted Pit to Crack Transition Sizes

3.4 NDT INSPECTION STRATEGY

The defect predictions support the adoption of an NDT inspection strategy based on a highly sensitive inspection method for location and sizing of small defects, most likely deployed with the boat in dry dock to enable access to either the outside or the bore of the shaft. Providing this can eliminate the presence of significant (>2mm) defects in the critical areas of the shaft with confidence, it should be possible to demonstrate safe operation of the shaft for a further commission.

As a further safeguard against failure, it may be possible to develop a less sensitive technique that can be deployed at any time whilst the boat is at sea, to provide an alarm if very large defects develop in the shaft. Guided wave ultrasonic technology shows some promise in this respect, but is not discussed further in this paper.

4. NDT INSPECTION SYSTEM DEVELOPMENT

This section describes the systems engineering techniques used to capture User and System Requirements, establish System Attributes, and to evaluate and select the most appropriate NDT technologies and suppliers for development of the Inspection System. A programme to develop the Inspection System is currently underway.

4.1 NDT INSPECTION SYSTEM CONCEPTS

The defect predictions have been used to define the detection capability requirements for the NDT Inspection System, together with further aspects such as access and operational availability restrictions.

4.1 (a) User / System Requirements

The process of Requirements Capture is a systems engineering process of correctly capturing and expressing the functionality required from a system to provide the user with a desired capability. The requirements for the Inspection System were captured during a stakeholder workshop and subsequently refined to provide a clear and concise declaration of the performance requirements and constraints of the desired system.

4.1 (b) System Attributes and Functional Diagram

Following the requirements capture phase, the next stage of the process was to translate requirements into a suite of desirable attributes to be sought in a candidate solution. The attributes articulate what the system aims to achieve in terms of the overall output of the inspection and the constraints within which the system must operate.

The requirements management process ensures that no particular solution is pre-judged and that an auditable link between requirement and solution is maintained that can be used in the acceptance of the final system. The set of requirements was interrogated and the following attributes were extracted:

- High performance sensor(s)
- High performance real time processing
- Adaptable to different shaft geometries
- Accurate positioning
- Available
- Self contained & compact
- Robust
- Reliable, repeatable coupling
- Reliable data capture

In order to provide structure to the assessment of candidate systems and technologies, a System Functional Diagram was constructed which identifies the principal elements of the overall Inspection System. This diagram groups the necessary system attributes into functional sets to allow technical, operational and support requirement relationships and dependencies to be clearly identified and evaluated. From the analysis of the requirements set it was clear that satisfying the majority of the requirements would be primarily dependent on sensor performance.

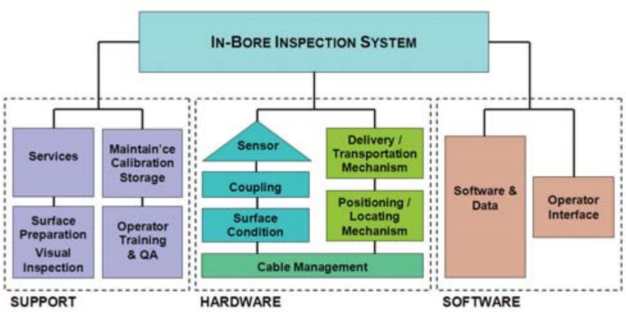

Figure 7: NDT Inspection System Functional Diagram

Through on-going discussions with suppliers and operators of NDT equipment and sensors it emerged that it was highly unlikely that a complete off-the-shelf system existed that could meet the demands of the inspection performance requirements, and that development would be required.

4.2 NDT TECHNOLOGY / SUPPLIER EVALUATION

Various NDT sensor technologies were considered for the inspection application. In order to achieve the desired confidence in the results and compatibility across all submarine platforms, it was apparent that inspection of the outer surface of the shaft from inside the shaft bore would be the preferred approach. This would permit the use of ultrasonic techniques, which are generally considered to be the most mature and reliable of all inspection methods.

Three ultrasonic inspection technologies were explored:

- Pulse Echo;
- Time of Flight Diffraction (ToFD);
- Phased Array.

In addition to sensor technology the capability to develop a delivery mechanism to facilitate remote in-bore inspection was also evaluated. An initial market research survey identified the most promising suppliers of ultrasonic technologies operating in the UK market. 20 companies were asked to respond to a detailed Request for Information (RfI) which included questions to establish commercial ability in addition to technical competence.

In a parallel exercise, the three ultrasonic techniques were trialled on a scrapped section of shaft with artificial pits (dimples) and small slots machined into the outer surface. Using manual probes from within the bore, the pulse echo and ToFD operators were both able to reliably detect 1.0mm deep hemispherical dimples and a 0.8mm deep slot in the outside of the shaft from within the bore, see Figure 8. This was deemed to be adequate proof of concept for proceeding with these techniques. The results using phased array equipment were less convincing.

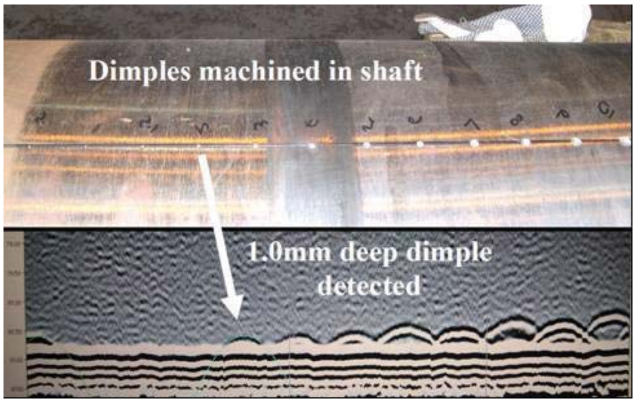

Figure 8: Detection of Dimples using ToFD Ultrasonics

Selection of the successful partnership of IMES Ltd of Aberdeen with Sonovation of The Netherlands was based on evaluation of all of the weighted scores for each question in the RfI, together with a demonstration of capability and previous experience in deployment of at least two of the three ultrasonic techniques.

The in-bore NDT Inspection System (see Figure 9) is being developed through a series of independent design reviews and staged trials. It is anticipated that the system will be fully qualified and available for use by the end of 2008.

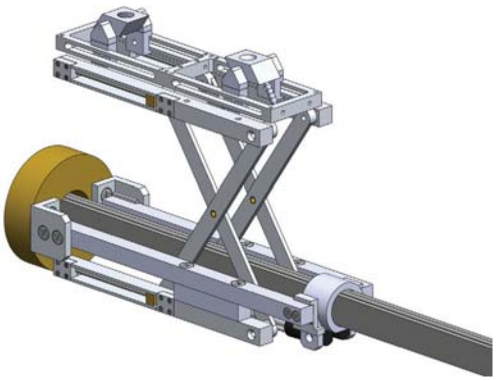

Figure 9: Concept Model of In-bore Inspection System

5. INTEGRITY MANAGEMENT OF SHAFTS

Figure 10 shows a process diagram for managing the legacy fleet of submarine tailshafts from commissioning activities through a period in-service and onwards to de-commissioning,

At the hub of the process is the Asset Integrity Management software system that allows all shafts to be maintained in a fit-for-purpose condition.

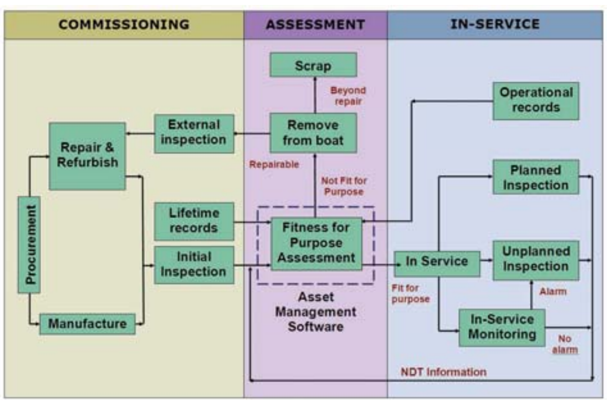

Figure 10: Through Life Shaft Management Process

5.1 COMMISSIONING

At start of life or during repair and refurbishment, an inspection of the condition of the shaft is required to be carried out using surface NDT methods. It is proposed to improve the robustness of this inspection by using the in-bore Inspection System currently under development. External inspection using existing near surface techniques will also continue to be carried out for comparison.

In addition to documenting the outer surface condition, the NDT inspection system can also be used to perform a through-wall volumetric scan to record the condition of the entire shaft. The benefit of this is to ensure that when shafts are inspected in service to determine whether they require replacement, a baseline set of NDT records will be available for comparison with the in-service data.

5.2 ASSESSMENT

The NDT data produced using the Inspection System will be run through the integrity model and evaluated by a suitably qualified and experienced integrity engineer. The output of this assessment will support a risk-based decision on whether the shaft is fit for purpose or not.

The most critical decision to be made at this point is whether a shaft is fit for purpose, or whether it requires to be replaced, as this is a very expensive process. It is therefore crucial that the level of operational risk is demonstrated to be ALARP.

If the shaft is deemed unfit for a further commission, it would be removed for repair and subjected to inspections both before and after refurbishment, and finally assessed again for fitness for purpose before being returned to service.

5.3 IN-SERVICE

If the shaft is deemed fit for purpose then it is accepted into service with planned inspection dates for future dockings and inspections using the in-bore NDT Inspection System. These planned inspection dates are calculated from the knowledge of the current state of the shaft and the predicted growth of shaft defects over time. The integrity model would be continually updated and validated by the supply of in-service inspection data and operational usage, and by laboratory testing exercises as deemed appropriate.

The Asset Integrity Management system described in this paper will provide MES with a complete risk management and procurement plan for each tailshaft in the legacy submarine fleet. A further inspection capability is also in development to allow continuous in-service monitoring of the shaft without docking the boat.

6. CONCLUSIONS

- The design basis and historical performance of submarine tailshafts have been reviewed, and the deterioration processes that may curtail shaft life have been critically examined. Shaft life is governed by localised corrosion pitting which may initiate fatigue cracks, which ultimately could lead to final failure.

- A probabilistic integrity model for tailshafts has been developed to predict the growth of defects in the event that the epoxy bandage loses its corrosion protective function in service. The integrity model predictions are broadly consistent with the in-service experience, and confirm that the risk of shaft failure is low but finite.

- The integrity model predictions highlight the safety and commercial benefits of optimum shaft bandage application.

- The risk predictions have been used to define a set of User and System Requirements for an inspection capability for tailshafts. A technology and supplier evaluation exercise has selected a prime contractor team to develop a highly sensitive in-bore NDT Inspection System.

- An Asset Integrity Management strategy for tailshafts has been developed, which uses the NDT inspection system to periodically measure the material condition of tailshafts, and an integrity model to assess whether shafts are fit for purpose and to schedule when they require to be inspected again.
- The knowledge of tailshaft design parameters and their effect on shaft life, together with the NDT Inspection System being developed, provide valuable information and equipment to facilitate the design of support solutions for future submarine tailshaft designs.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

1. NES 304, “Shafting Systems & Propulsions, Part 1, Design Requirements for Main Propulsion Shafting”, Issue 2, August 2002.

2. NES 304, “Shafting Systems & Propulsions, Part 4, Requirements for Repair of Main Propulsion Shafting”, Issue 2, September 2002.

3. FNC 33017/32133R Issue 1, “S and T Class Submarine Tailshafts - Literature Review of Pitting Corrosion and Near Threshold Fatigue Data”, Frazer-Nash Consultancy Ltd, January 2007.

4. Kondo, Y, Prediction of Fatigue Crack Initiation Life Based on Pit Growth, Corrosion Science, Vol. 45 No 1, 1989 pp7-11.

5. Boyd, W.K, Fink, F.W, Corrosion of Metals in Marine Environments an Overview, Metals and Ceramics Information Centre, Ohio.

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Warship 2008: Naval Submarines 9, Glasgow, UK

THE APPLICATION OF A LOW SIGNATURE PROPELLER CAPABILITY TO NAVAL SUBMARINES

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SUMMARY

QinetiQ is currently developing, on behalf of the UK MoD, the Low Signature Propeller Capability (LSPC) for the Royal Navy. The LSPC is currently directed towards surface ship propellers, in particular those with specific signature targets for Radiated Acoustic Noise (RAN) and Cavitation Inception Speed (CIS). The LSPC includes a significant element of experimental and analytical study in order to establish a suitable model to full scale correlation for CIS. This correlation includes factors relating to the respective 'Water Quality' present during cavitation tunnel experiments and ship range trials.

The paper details the rationale behind the LSPC programme of work and relates how the current research and outputs may be applicable to future propeller designs and RAN and CIS trials for RN submarines. Such work may become more directly applicable to submarine designs as the possibility of increasing littoral operation of submarines is considered.

NOMENCLATURE

CFD	Computational Fluid Dynamics
CIS	Cavitation inception speed
DERA	Defence Evaluation & Research Agency
K	Nuclei effect parameter (equation 1)
LISST	Laser In-Situ Scattering and Transmissometry instrument
LSPC	Low Signature Propeller Capability
LSPIF	Low Signature Propeller Industry Forum
n	Empirical exponent in inception scaling (equation 1)
RAN	Radiated Acoustic Noise
RANS	Reynolds Averaged Navier Stokes
R_{es}	Reynolds number, ship (equation 1)
R_{em}	Reynolds number, model (equation 1)
RN	Royal Navy
TVI	Tip Vortex Inception
MoD	Ministry of Defence
σ_{if}	Tip vortex cavitation coefficient at inception, full scale (equation 1)
σ_{im}	Tip vortex cavitation coefficient at inception, model scale (equation 1)

1. INTRODUCTION

The reliable prediction of CIS for full scale surface warship propellers based on either cavitation model testing or by analytical methods has always been an extremely difficult and emotive subject for designers where, in most cases, the results of full scale trials are not readily available for correlation due to the classified nature of the data. In addition the knowledge and control of the full scale environment is difficult to measure or predict with any real sense of reliability, thus achieving a required CIS is judged by designers and customers alike to contain significant risk.

QinetiQ is developing for the UK MoD a Low Signature Propeller Capability, which will enable model tests undertaken in a prescribed manner to be used with a mandated scaling method as the basis for accepting that the propeller design meets the specified full scale CIS. The MoD rather than industry would then accept the risk that the ship or submarine fails to meet the CIS specification, thus procuring a successful vessel at lower risk to the manufacturer and at a consequential lower cost to the MoD.

2. QINETIQ'S LOW SIGNATURE PROPELLER CAPABILITY

Previously, low signature propeller designs for the RN were developed and designed by MoD agencies such as DERA. This process, prior to 'Smart Procurement' allowed the designs to be developed, model tested and trialled within the MoD/RN fraternity, knowledge from the process could be fed back directly and design evolutions developed to provide in-service improvements which could be accommodated within the surface ship programmes. This 'closed loop' process ensured that developments in low signature design and knowledge gained from in-service use could be accommodated in future designs. The risk of non-performance was therefore held by the MoD; however, the 'feedback' process provided a form of 'constant improvement' to be possible, albeit at the additional cost of new designs if necessary. Industry input was therefore limited to providing the manufacturing element for low signature propellers. The advent of 'Smart Procurement', effectively 'broke' the established process, resulting in a more traditional performance contract let to industry. Inevitably, this move towards a more commercial procurement approach has led to increased risk to industry for RN propellers as the responsibility for such performance is no longer held by the MoD. The LSPC was developed to enable industry to deliver low signature propeller designs to the MoD without the prohibitive costs involved with holding significant risk for meeting CIS performance. The LSPC is being developed to provide a propeller acquisition process that will cover in broad terms:

- The technical specifications for a propeller to capture any special requirements that are additional to normal manufacturing requirements, class rules etc.
- Guidance, when necessary, on suitable design methodology for low signature propellers
- Model testing methods, including model manufacture to adequately represent the full scale configuration and a prescriptive model test methodology
- Scaling to full scale by means of a prescribed methodology
- Acceptance of a propeller design by the MoD on the basis of predicted full scale propeller CIS that meets the specification

The process will also cover the manufacture of the full scale propeller, through development with the MoD and industry.

Confirmation of the vessel's performance will be by sea trial and the acquisition process will define the requirements for water quality measurements, ship condition and environmental conditions during the trial.

The LSPC is currently based on the assumption that low signature propellers for submarines and ships have tip vortex cavitation as the first onset. This is often (but not always) the case at model scale. Consequently it is possible to use a scaling methodology based on the Reynolds number of the flows over the model and full scale blades.

3. PROPELLER INDUSTRY FORUM

As part of the LSPC, a Low Signature Propeller Industry Forum (LSPIF) has been developed which includes representatives from the MoD, European propeller industry, UK warship builders and the UK Classification Society. This forum was established to both promote and ensure that the eventual process output from the LSPC has the understanding, backing and ownership from all the relevant stakeholders. The forum is held biannually and has proved invaluable to gaining the appropriate views on both a wide range of elements ranging from propeller model tolerances to scaling methodologies and manufacturing requirements and standards.

A key element of the LSPIF is the ability to collate different experience and views with respect to developing an appropriate manufacturing standard for such low signature propellers. In particular, ensuring that modern manufacturing and measurement methods are taken into account and only those relevant elements identified in existing standards such as [1] are addressed in developing a suitable manufacturing standard. In addition to overall accuracy, better definition of blade edges and tip areas will be addressed, possibly by making use of modern surface representations of the propeller blades. Such high quality definitions and use are relatively common place within the industry.

4. TEST METHODOLOGY

QinetiQ's current practice for cavitation inception tests of model propellers involves the manufacture of large scale hull and propeller models (Figure 1) that are installed in a large cavitation tunnel. The propeller is viewed under various operating conditions, usually at a constant water speed and at various static pressures, and the inception conditions noted as a result of varying the propeller shaft speed. Water quality has, as in many organisations, been limited to solely measuring dissolved gas content at the test conditions and it is usual practice to de-gas the water in order to improve the viewing conditions within the tunnel such that reliable visual estimates of CIS can be made. Such a process has a direct effect on the cavitation susceptibility of the water in the cavitation tunnel.

Figure 1: Model test arrangements for cavitation viewing in the QinetiQ Cavitation Tunnel

It is, however, not usual to routinely measure water quality during sea trials (e.g. noise rangings) in which cavitation inception speed is assessed.

It is widely accepted that water quality affects the cavitation performance of propellers and measurement of appropriate parameters during model tests and during sea trials is crucial to the development or validation of a scaling methodology. It is also evident that the water quality during contractual sea trials must be defined in order to predict the performance of the vessel before it is built and a means of scaling the actual sea trial results to those expected under the defined conditions must also be addressed.

The presence of nuclei (mainly bubbles) in the water has a greater effect on inception than the presence of dissolved gas. In the LSPC, a LISST (an optical device) and a Minisonde (Figure 2), both portable devices, are being used to measure water quality parameters during model tests.

Figure 2: Minisonde (left) and LISST (right) for water quality measurements

The measured parameters include:

- Nuclei (bubble and particle) concentrations
- Dissolved gas content
- Temperature (to evaluate vapour pressure)

The same parameters have been measured during routine noise rangings of surface ships, although these measurements were performed about 150m to the side of ships' tracks to avoid any disruption to the rangings. The data from comparable model and ship trials was then used in the scaling method.

There is value in evaluating a single parameter that describes the water's cavitation "susceptibility". One such device is the 'vortex nozzle', effectively a venturi where the susceptibility of the water to cavitate is evaluated in terms of the pressure at inception. An alternative to be investigated by QinetiQ is a novel use of the Dynaflow Acoustic Bubble Spectrometer (ABS) (Figure 3). In normal operation, the ABS measures the bubble size concentration by the effect of the bubbles on the propagation of sound through the water and these measurements will be made for comparison with the nuclei concentrations measured by the LISST. In addition, QinetiQ are procuring a more powerful amplifier with the intention of increasing the emitted sound level until cavitation is created in the water; the susceptibility can then be evaluated in terms of the power required to drive the source hydrophone at this condition. Figure 4 illustrates some initial results showing the measured output voltage variation as the power applied to the source hydrophone is increased. A sharp increase in hydrophone output voltage is evident when cavitation is initiated and so the applied voltage is a measure of the susceptibility of the water to cavitate.

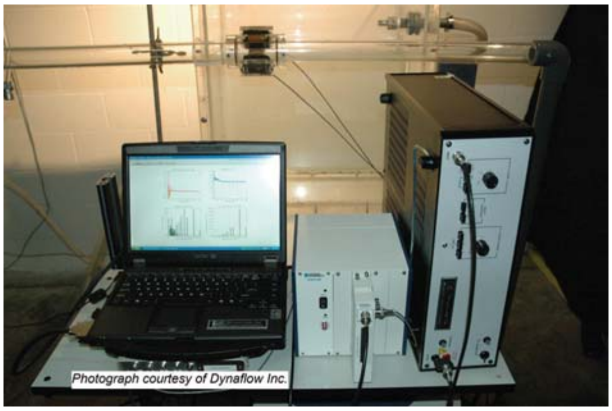

Figure 3: Dynaflow Acoustic Bubble Spectrometer

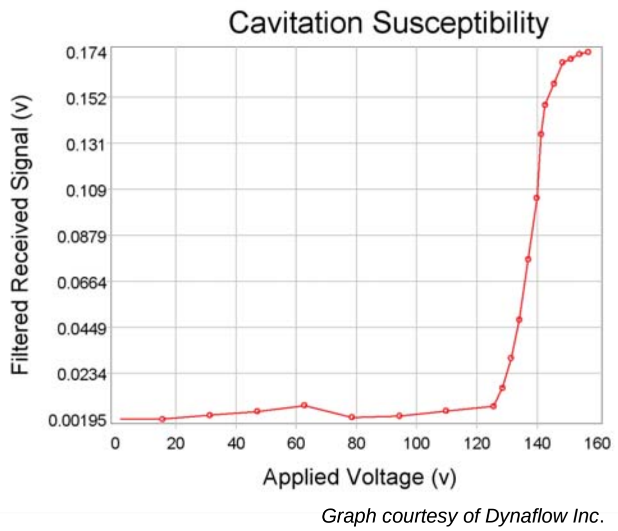

Figure 4: Cavitation susceptibility measured by the Dynaflow ABS

The ABS device is relatively portable unlike traditional venturi devices used within cavitation tunnel facilities and therefore provides the opportunity to determine the susceptibility of the water to cavitate during full scale sea trials.

5. SCALING METHODOLOGY

The scaling methodology adopted within the LSPC is that of Shen et al, [2], which follows closely that of the ITTC, [3].

$$\sigma_{if}/\sigma_{im} = K\,(R_{ef}/R_{em})^n \qquad (1)$$

The scaling on Reynolds number is appropriate for cavitation in the blade tip vortex. Shen evaluates the exponent n from theory for vortical flows to give n = 0.4, which agrees with some experimental results. The nuclei size parameter K is evaluated from its calculated variation with nuclei size ratio as shown in Figure 5.

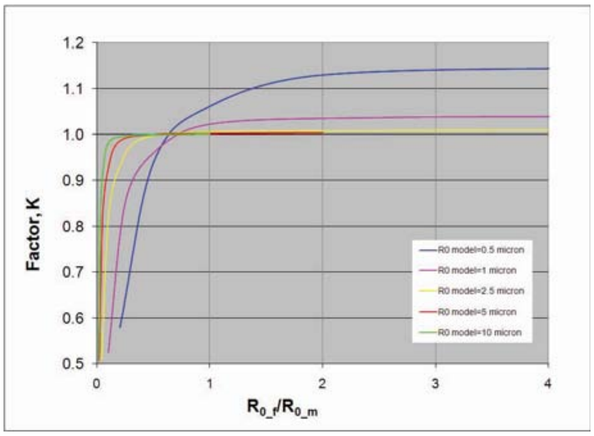

Figure 5: Variation of calculated nuclei parameter K (taken from [2])

Measurements of nuclei concentrations in both model tests and full scale trials (Figure 6) have enabled the nuclei size parameter to be evaluated for the purposes of applying the methodology.

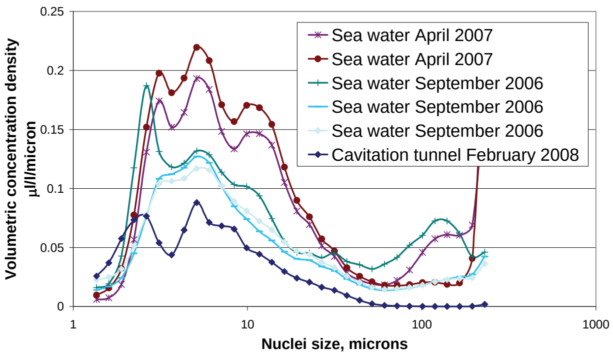

Figure 6: Nuclei concentrations at sea and in the water tunnel

To date, these values have been used without modification and reasonable correlation has been obtained for a particular ship class. Figure 7 shows the full scale cavitation inception (bucket) diagram obtained from model tests of a surface ship and use of the proposed methodology. It shows the common forms of cavitation on the back and face of the propeller blades. Inception data obtained from noise rangings of ships of the same class are also shown on the graph to indicate the current level of correlation obtained.

There is scatter in model and ship data; the former needs to be reduced through a more detailed understanding of water quality effects; the latter needs to be reduced through a more detailed assessment of the trial conditions, particularly the vessel's operating condition (speed through the water) and water quality. It should also be emphasised that noise rangings are not primarily intended to precisely determine the CIS of the vessel.

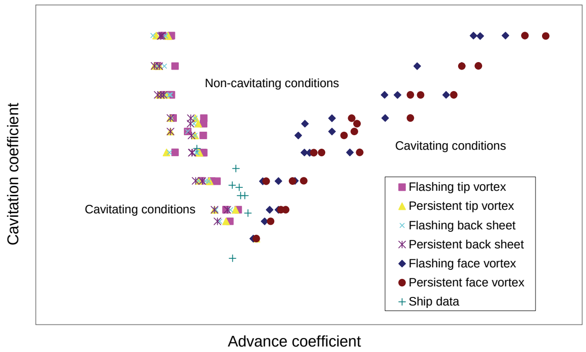

Figure 7: Typical cavitation bucket diagram comparing model and full scale results

It is common for cavitation inception to be determined by visual inspection of the propeller and the flow in its vicinity during model tests, but acoustically during full scale trials (particularly for a submarine). The scaling methodology proposed uses these two means of inception detection on the basis that visual inception at model scale will generally give earlier inception than that derived acoustically because of the difficulty in making suitable noise measurements in a noisy environment. Additionally, it is not usually possible to determine onsets of other cavitation forms once first inception has occurred. At full scale, acoustic measurements are the only feasible means of detecting inception (e.g. for a submarine) or will give an earlier inception that visual means (for a surface ship). Thus the correlation methodology will relate the earliest inception of cavitation at the two scales.

6. SHIP TRIAL

A bespoke CIS ship trial is proposed that will provide more reliable and detailed data to confirm the validity of the proposed scaling methodology and hence the water quality measurements necessary during future model tests and during future first-of-class trials. Currently, RAN trials are used routinely to determine the noise levels at a range of frequencies for a range of ship speeds, usually achieved by a predetermined range of shaft RPM. CIS is determined from a review of this data as either 'first audible' or 'developed', the latter is when a noticeable rise in sound pressure level occurs for a given change in shaft RPM. This method is not sufficiently precise for determining CIS from audible means for the purpose of delivering an appropriate correlation between model experiments and full scale trials. The proposed CIS trial will (for a ship) involve viewing of the propeller to identify cavitation inception, the form of the cavitation and, if possible, additional cavitation data from radiated noise measurements, hull vibration measurements and hull surface pressure measurements. It is proposed that future first of class ship trials will be similar. For submarines, determination of inception by acoustic means, using either an onboard hydrophone or a static array on a noise range, will be required.

The essential water quality measurements would ideally use water sourced from the vicinity of a propeller. In practice, this will be achieved during the proposed ship trial by using sea water drawn into a sea chest from a position ahead of the propellers. Whilst measurements of sea water at a position directly ahead of an operating propeller may be possible, any intrusion into the inflow will modify local flow conditions directly affecting the CIS and thus rendering the correlation invalid.

7. COMPUTATIONAL TOOL

A computational tool is also being developed as part of the LSPC which has required the development of a number of associated aspects of computational fluid dynamics. This tool is a combination of a RANS flow solver with theory for calculating bubble trajectory and size variation. The tool, [4], calculates the trajectories of a cluster of bubbles injected in the flow upstream of a propeller (Figure 8) and calculates the radiated sound as they travel around the propeller blade tip, growing and collapsing as a result of the pressure field that exists around the blade.

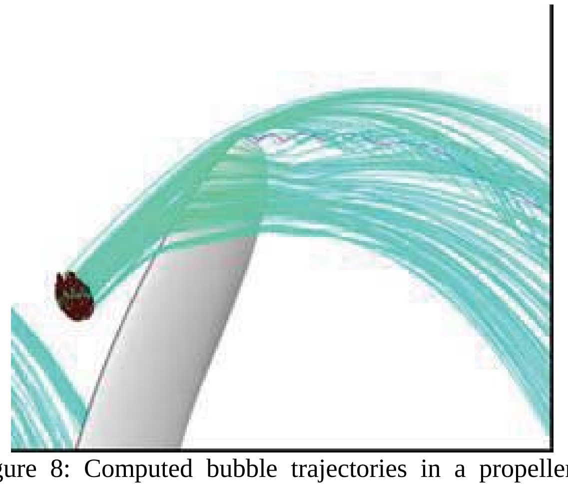

Figure 8: Computed bubble trajectories in a propeller blade tip vortex

This tool will initially be used to calculate cavitation inception speeds at various model and full scale conditions to compare the scaling with that derived from physical model tests and full scale trials, so absolute accuracy is not required. In addition to this, limited variations in blade design will be assessed in order to evaluate whether the tool can be used as a means of 'ranking' prospective designs and therefore be used for preliminary design evaluation. Ultimately, it is expected that the tool will be used to predict the actual CIS of a propeller operating behind the hull of a ship or submarine.

8. REQUIREMENTS FOR SHIP ACCEPTANCE TRIAL

It is clear that the full scale propeller CIS predicted from model scale test results must be confirmed by full scale trials that must include precise measurement of:

- Vessel operating condition, particularly speed through the water, draught and trim
- Water quality, particularly nuclei/bubble concentration, temperature, salinity and dissolved gas content
- Environmental conditions e.g. sea state, wind speed and direction, tide/current speed and direction

Acceptable limits on some of these parameters will have to be set, such as a maximum permitted sea state and wind speeds. The measurement of other parameters, such as speed though the water, can pose significant demands for a sea trial.

9. LSPC APPLICATION TO SUBMARINES

The LSPC is designed to deliver knowledge over a relatively broad range of aspects for the design and procurement of low signature propellers. Two process documents will deliver the capability to the MoD:

1. 'Standard Template', which is a comprehensive low level document to prescribe all the appropriate technical aspects related to the development and procurement of a low signature propeller. It is proposed that this will look much like an existing standard but be specific to low signature propellers.

2. 'Acquisition Process', which is a high level document designed to support the justification behind the adoption of the detailed process laid down in the 'Standard Template'. This is directed towards forthcoming MoD programmes which require low signature propellers.

Whilst the LSPC is directed towards surface ship propellers, the ultimate output from the programme, provided in the two process documents, will be generic. In particular, the water quality aspects, the scaling process, the CIS trial process and the bespoke manufacturing standards and requirements will be equally applicable to future submarine propellers and indeed other types of propulsors. It is recognised that some modification will be required to the CIS scaling methodology currently based on TVI; however, this will form the basis of an additional study as required.

10. CONCLUSIONS

A process by which full scale propeller CIS can be determined reliably in a consistent manner from model tests is being developed so that low signature propellers can be procured for warships and submarines with a reduced risk of failing to meet contractual requirements than is currently possible. The reduced risk is beneficial to the prime contractor, ship builder, propeller manufacturer and to the MoD since the financial implications of the risk of failure to meet CIS targets are significant. Agreeing and accepting CIS at model scale early in the overall procurement cycle allows much earlier 'sign off' of risk than is currently the case.

Currently the scaling methodology assumes tip vortex cavitation will be the first inception and uses measurement of water quality parameters at both model and full scales.

The development of a CFD tool for the prediction of CIS should provide a basis for a better understanding of the mechanics and geometry which drive TVI. Such a tool can be used to evaluate prospective blade designs for CIS.

Agreement of a suitable manufacturing standard for low signature propellers in co-operation with industry should reduce the possibility of over specification and ultimately non-acceptance of the manufactured propeller.

Knowledge gained from the conduct of a bespoke CIS trial should provide the basis for a working process where CIS can be more accurately determined, the output being fed back into the correlation process.

11. ACKNOWLEDGEMENTS

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Any views expressed are those of the authors and do not necessarily represent those of QinetiQ ltd.

12. REFERENCES

1. Manufacturing and Detail Design Requirements for Propulsors – Shafting Systems and Propulsors - Defence Standard 02-304 Part 3. Ministry of Defence. Issue 2. 9th September 2002

2. Shen Y., Chahine, G., Hsiao C-H., Jessop S. Effects of model size and free stream nuclei on tip vortex cavitation inception scaling CAV2001:SESSIONA1.004

3. International Towing Tank Conference, 1990 19th ITTC Cavitation Committee Report Madrid, Spain

4. WATSON, SJP. & BULL, PW. 'Aspects of the Modelling of the Inception of Tip Vortex Cavitation', RINA Marine CFD, 2008.

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DESIGNING A FLAT END FOR A ROUND HOLE: INNOVATIVE SOLUTIONS FOR PRESSURE HULL ENDS USING OPTIMISATION METHODS

W Christie and **J Hobson**, QinetiQ, UK

SUMMARY

This work addresses the use of optimisation methods to find appropriate design solutions for flat end closures on large diameter submarine pressure hulls that are likely to dive to depths greater than continental shelf. Current approaches to end closure design are discussed, and the basis for the optimisation approach is presented. Three main design variants are considered; an externally and internally framed orthogonally stiffened design and a conceptual solution. Two main optimisation approaches are used; size optimisation and topology optimisation. The optimised design approach is configured to produce solutions that are competitive with a traditional torispherical dome design. The results indicate that optimisation methods provide a better method of design than traditional sizing calculations for complex structural problems but that, using the approach adopted, use of these methods cannot determine a design solution that is as structurally efficient as a dome solution. However, the results indicate that there is potential to derive effective flat end design solutions that are between two and three times as heavy as a dome solution. Given the anticipated savings in manufacturing cost offered by a flat end closure, this increased mass may be considered a small price to pay.

NOMENCLATURE

DBA	Design By Analysis
DBF	Design By Formula
FEA	Finite Element Analysis
FEC	Flat End Closure
RAN	Royal Australian Navy
SSN	Attack Submarine, Nuclear
SSK	Hunter Killer Submarine, Conventional

1. INTRODUCTION

Flat End Closure (FEC) design for naval submarine pressure hulls, though by no means the most structurally efficient option, does offer benefits in terms of ease of manufacture – for both the end closure itself and the adjoining structure, improved volume utilisation, and, reduced construction costs. The potential impact of these benefits necessitates a re-examination of the available methods of design, and begs the question – is there a rational means to derive more efficient structural FEC design solutions?

The use of FECs on naval submarine pressure vessels dates back to the earliest examples of submarine warfare in modern history. The pressure hull of the H. L. Hunley, the first submarine to sink a warship, was constructed with flat ends, a fact which probably contributed to the legend that it was made from a cast-off steam boiler. Flat ended submarine pressure hulls are, however, uncommon in modern naval submarine construction, especially on large diameter pressure hulls with diving requirements in excess of continental shelf depths. The larger the pressure hull diameter, and the deeper the required dive depth, the greater the structural imperative for a domed end closure, typically in the form, or combined forms, of torus, spherical, and conical sections. Typical variants of end closure adopted by the US Navy are shown in Figure 1.

UK Navy submarines typically use torispherical end closures across full or truncated main pressure hull diameters.

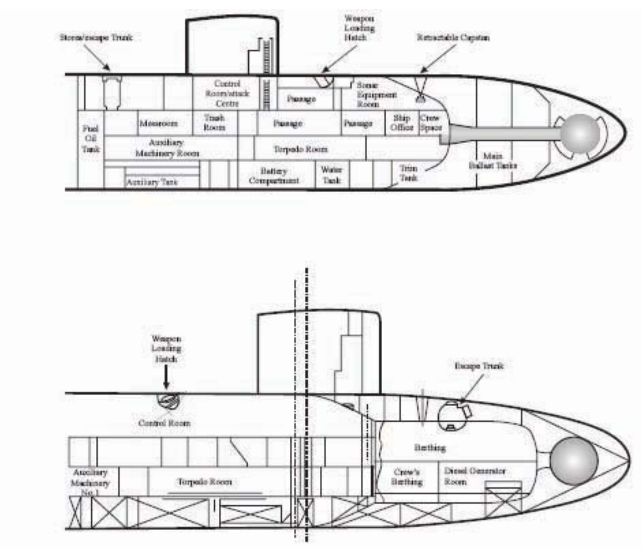


Figure 1: End closure arrangement on US Los Angeles (top) and Sturgeon (btm) class SSNs [1].

There are, of course, exceptions to the rule, and perhaps the most significant of these is the Royal Australian Navy's (RAN) Collins Class conventional submarine, the second largest conventional submarine in active service, the layout of which is shown in Figure 2 below.

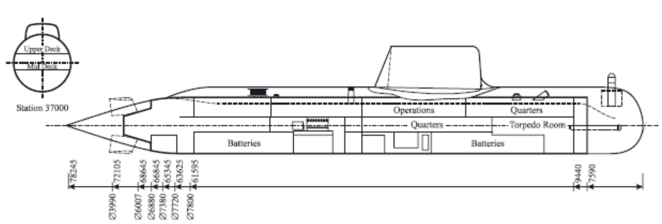


Figure 2: RAN Collins class conventional submarine, Kockums design [2].

Table 1 gives a broad-brush comparison of SSN/ SSK type dimensions and end closures, where known.

Submarine (SSN/SSK)	End Closure	L, m	B, m	Disp., tonnes
RN Astute, SSN	Torisphere	97	11	7800
USN Virginia, SSN	Cone-Torisphere	115	10	7800
Oyashio, SSK	Domed	82	8.9	4000
RAN Collins, SSK	Flat	78	7.8	3353
HDW 209, SSK	Domed	65	6.5	1800

Table 1: End closure, length, beam and submerged displacement for a selection of attack submarines.

Figure 3 indicates the main design approaches for UK submarine pressure hull end closures.

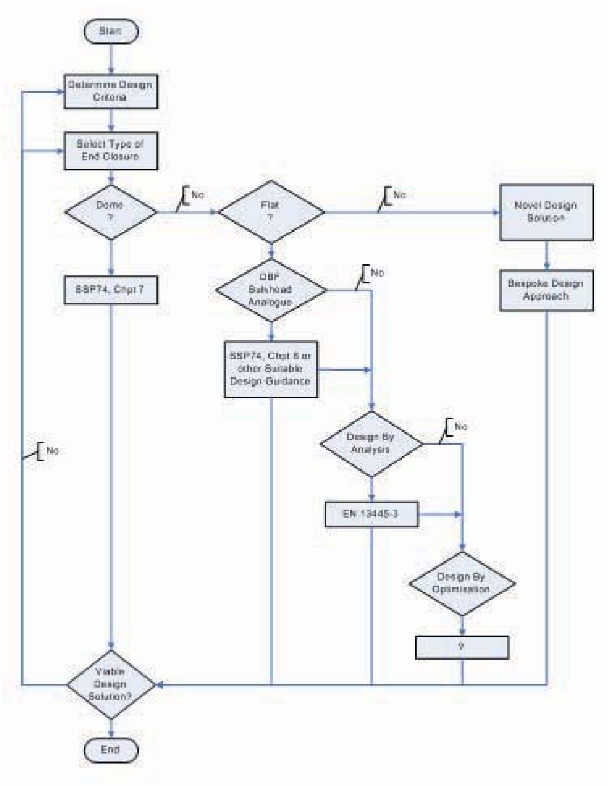


Figure 3: Design approaches for UK submarine pressure hull end closures.

Typically, torispherical dome ends are designed according to guidance laid out in SSP74 [3]. However, design guidance is also available for a variety of externally pressurised domes in both PD 5500 [4] and EN 13445 [5].

However, there is comparatively little guidance when it comes to the design of flat end closures. Specifically, SSP74 suggests that FEA be used to develop suitable designs. It is also possible to adopt guidance for internal safety bulkheads though it is important to understand the differences in design assumptions for the different structural purposes: a safety bulkhead is likely to experience an extreme event only once and can tolerate some plastic deformation, whereas a flat end closure will experience repeated load reversals over its lifespan, at depths likely greater than continental shelf, and its response must remain elastic throughout.

In terms of using FEA to establish a design, EN 13445 provides guidance for two Design By Analysis (DBA) approaches; a stress characterisation approach – an approach which has been available in the ASME boiler code [6] for decades, and, perhaps in this instance, a more appropriate direct approach.

Finally, this paper examines the application of FEA based optimisation tools to design practicable yet sufficiently light FEC designs. Optimisation tools are the mainstay of design in a number of industries, particularly the automotive and aerospace industries. Though optimisation methods capable of ship section sizing have been available since the 1970's, modern optimisation tools are comparatively poorly integrated into the design of ship and submarine structure. Optimisation methods provide a means of establishing "right first time" economical design solutions for problems with a large number of design parameters that are otherwise intractable - other than by making gross simplifications concerning structural decomposition into forms that can be treated using either classical or empirical solutions. Optimisation methods therefore have the potential to establish more economical structural design solutions than can otherwise be derived by traditional methods. This paper seeks to answer what impact optimisation methods have on FEC design.

2. APPROACH

2.1 OVERALL DESIGN EXTENTS

Viable design solutions were sought for a single notional hull diameter of 10 m throughout. With regard to Table 1, a 10 m diameter was chosen as being an upper limit on likely hull diameter.

2.2 CONSTRUCTING THE OPTIMISATION PROBLEM FOR DESIGN

For structural problems, optimisation methods are used to amend the topology of a structure (i.e. it's overall form), the shape of a structure (i.e., the profile of it's existing boundaries), or its section sizes.

The mathematical description of an optimisation problem can be phrased as follows;

Minimise f(x), subject to:

	$g_j(x) \leq 0$, $j = 1,\ldots, n_g$	Inequality constraints
	$h_k(x) = 0$, $k = 1,\ldots, n_h$	Equality constraints
	$x_i^L \leq x_i \leq x_i^U$	Side constraints
for,	$x = \{x_1, x_2,\ldots,x_n\}$	Design variables

The function f(x) is termed the objective function, and it can either be maximised or minimised by the optimisation method. Some optimisers allow multiple objective functions but one is sufficient for these studies. The objective here was to minimise the overall mass of the end closure design.

No equality constraints were imposed in these studies, though there were a number of viable options for inequality constraints. The possibilities included setting limits on: maximum displacements, maximum stresses, the minimum critical buckling factor, and minimum non-linear collapse pressure. Furthermore, displacements and stresses could have been broken down into component vectors or combined scalars. These constraints could have been considered individually or in combination, however, it was important to run through a variety of design configurations in this study, and each configuration has sufficient design variables to make execution times lengthy. The method adopted was therefore to use von Mises stress at the extreme plate fibres in the end closure structure as a single constraint. To ensure that fatigue problems were guarded against, the optimisation method had to seek viable designs with peak stresses below three quarters of the tensile yield stress of the material.

The only side constraint considered was to restrict section sizes to those specified in SSP74 to guard against torsional buckling experienced by flanges.

The selection of design variables was influenced by the design approach, and these are discussed in the next section.

2.3 DESIGN APPROACH

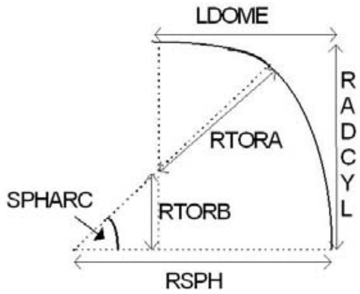
The intent of this work was to determine the influence of alternative optimisation design configurations and to compare the resulting solutions with a traditional dome solution, particularly in terms of mass.

A high tensile steel material was used throughout with an assumed yield value of 550 MPa. An elastic-perfectly plastic material model was used for all non-linear collapse analyses.

To develop competing optimisation alternatives three main variants were considered. The first two variants were based upon a conventional orthogonally stiffened grillage type structure, the first and second variants being differentiated by the grillage being external or internal to the pressure hull enclosure. The third variant imposed no preconceptions on optimal form, other than assuming structure external to the flat plate is in free flood, and offered the potential for a more conceptual alternative.

2.3 (a) Dome design

A notional 10 m torispherical dome was designed, in accordance with SSP74, to be a baseline alternative. The dimensions of this dome design are shown in Figure 4.



Attribute	mm
LDOME	3414
RTORA	2028
RADCYL	5000
RTORB	2972
SPHARC	50 deg
RSPH	5908
Thickness	64

Figure 4: Torispherical dome geometry

The empirical collapse pressure for a dome of this design is 7.11 MPa, based upon SSP74 guidance. Abaqus [7] was used to carry out a non-linear collapse calculation on this design, which included an N=12 out-of-sphericity imperfection representative of the dome construction. This imperfection is exaggerated in Figure 5. The resulting collapse pressure was found to be 8.09 MPa.

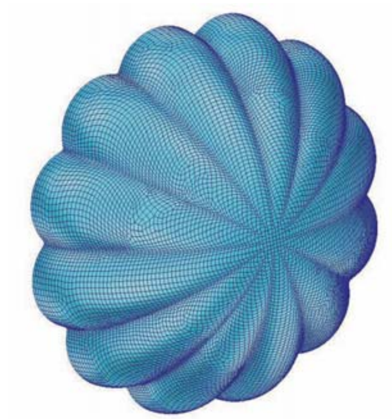


Figure 5: Out of sphericity imperfection for non-linear dome collapse calculation.

Given the empirical curve is thought to be accurate to within 10%, this therefore is a significant difference which is likely the result of the modelled imperfection. The empirical curve assumes the worse case to be a flat indentation in the spherical portion of the torisphere, whereas the imperfection modelled here is mostly within the toroidal section; hence, though more in keeping with the imperfections arising during manufacture, it suggests a higher collapse pressure is achievable than the empirical curve predicts.

It is important at this point to note the following concerning the design approach.

First, a dome is designed for collapse because, for the anticipated loading, its shape makes buckling the most critical failure mode. A grillage is usually designed to minimise peak stresses within the plating to prevent failure by fatigue or rupture, and the plating is thereafter checked for collapse. The design intent is different for the different forms of structure, based upon their most critical failure mode, and subsequent comparison of designs based upon collapse pressure alone is inferential.

Second, though it is possible to use non-linear collapse pressures as a design constraint within the optimisation problem, it was thought uneconomical to do so given the nature of the study and the large number of runs required; using a Newton-Raphson iteration scheme can require upwards of 15 iterations per calculation, and each optimisation study can run to between 25 and 90 cycles. Therefore it was necessary to find a more economical means of driving the optimisation. It was therefore decided that the design load for the optimised solutions would be 7 MPa – the minimum collapse pressure for the dome design. With a constraint to keep stresses below yield, adopting this design load would ensure that the collapse performance was equivalent, or better, than that of the dome.

2.3 (b) Orthogonal framing external to pressure hull

The configuration of shell properties and initial plate section sizes are shown in Figure 6 and the imposed loads are shown in Figure 7. The imposed load conditions are shown in the lower image. Quarter symmetry is applied to the structure in the XZ and YZ planes, and the structure is fully restrained in the XY plane at the other end of the pressure hull from the end closure.

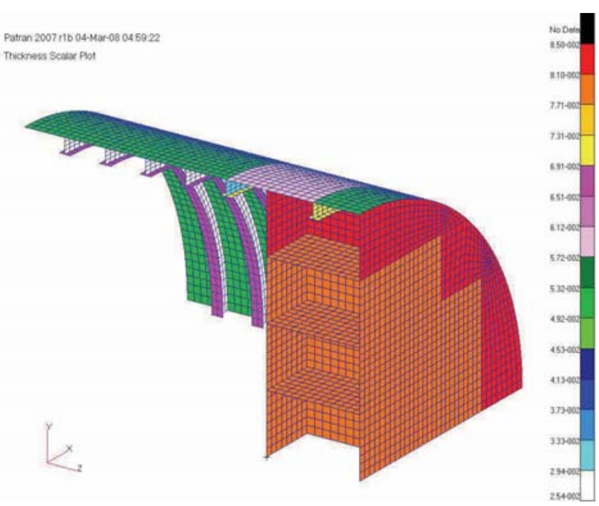


Figure 6: Material property definitions for externally framed design variant (mid grillage panels removed to reveal detail).

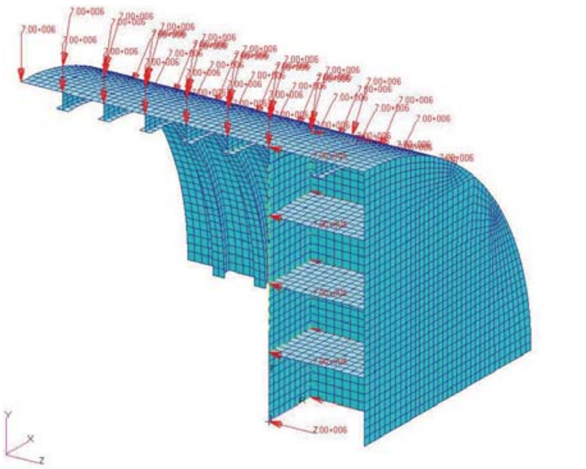


Figure 7: Load conditions for externally framed design variant (mid grillage panels removed to reveal detail).

The design is configured for size optimisation and the design variables are taken as the plate section sizes for the grillage, two sizes of fwd and aft bulkhead plating, three sizes of pressure hull plate, and section sizes (flange and web sections) for two frames.

2.3 (c) Orthogonal framing internal to pressure hull

The shell properties are substantially the same for this variant as for the externally framed variant, the only difference being that this variant has no aft-bulkhead plating and an additional frame. Figure 8 shows the load conditions. The applied boundary conditions are exactly the same as those for the internally framed variant.

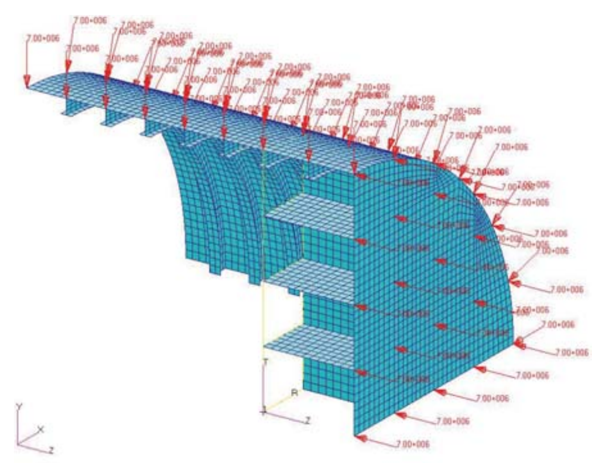


Figure 8: Load conditions for internally framed design variant (mid grillage panels removed to reveal detail).

As for the externally framed variant, the design is configured for size optimisation and the design variables are the plate section sizes for the grillage, two sizes of fwd bulkhead plating only, three sizes of pressure hull plate, and section sizes for two frames.

2.3 (d) Conceptual solution

Though the boundary conditions remain the same, the design problem configuration to generate conceptual solutions is different.

Topology, as opposed to shape or size, optimisation is used in this instance. Topology optimisation proceeds by calculating the degree to which the available material is used to resist the imposed load (based upon strain energy). If the material is deemed to be under used then an underlying mathematical model, in effect, removes material by increasing the porosity of the element. Conversely, if an area of high strain energy is developed within elements of low porosity, material is added by decreasing the element porosity. Over a number of iterations material is effectively redistributed until the desired design criteria are achieved, however, material cannot be added outwith the extents of the original design mesh. Consequently, using topology optimisation to develop conceptual solutions requires an over large design domain. If, by intent or accident, the design domain is insufficiently large then the resulting optimised solutions will, in effect, have been developed with a geometric constraint.

The configuration of the model for topology optimisation used in this study is shown in Figure 9.

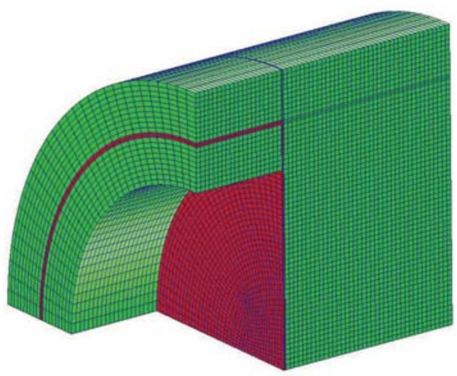


Figure 9: Model used to generate conceptual solutions using topology optimisation

The design volume is shown in green. The non-design volume is shown in red. The non-design volume represents the pressure hull and bulkhead plating. The design area extends both internally and externally to the cylindrical section of the pressure hull, and externally to the flat plate of the end closure. This configuration was adopted to provide space for alternative support arrangements to develop at the flat end–cylinder transition.

The pressure load is applied to the outside of the non-design domain, which assumes that any structure developed outside the pressure hull will be in free flood.

2.2 SEQUENCE OF EXECUTION

At Rosyth, QinetiQ has two pieces of software capable of carrying out size, shape and topology optimisation, namely MSC.NASTRAN [8] and Altair Hyperworks [9]. A process map showing, in general, how optimisation studies are configured is shown in Figure 10.

The predominant sequence of operation is shown by the red path; the secondary sequence is shown by the yellow path, and other lesser used alternative routes are shown in black.

In this study, for both framed variants, the procedure was to build the geometry in PATRAN; import the resulting FE model into Hypermesh; configure the model for size optimisation; run the study using Hyperstudy as the optimisation engine and NASTRAN as the proprietary solver.

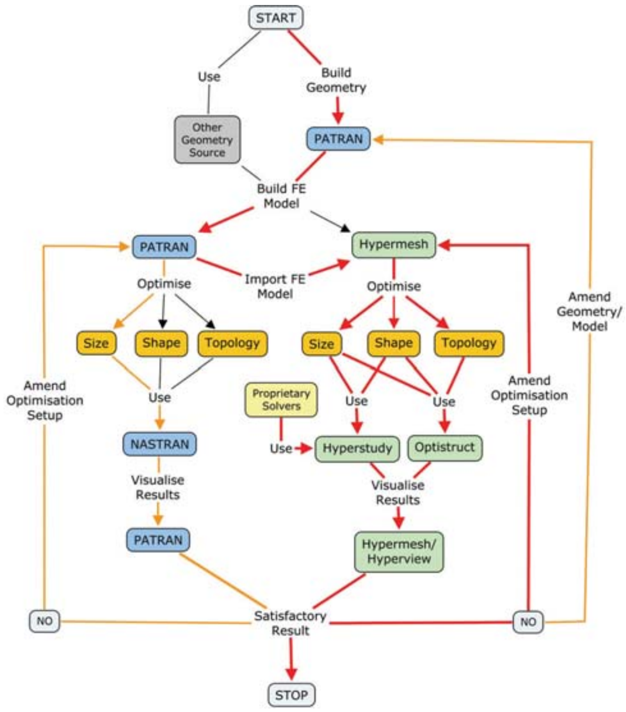


Figure 10: Possible configurations for performing optimisation studies.

For the conceptual variant the process was: build the initial geometry in PATRAN; import the resulting FE model into Hypermesh; configure the model for topology optimisation using Optistruct as both optimisation engine and solver. Once a topology optimised solution was established, a shell idealisation was created in PATRAN and the resulting FE model was read into Hypermesh where it was then configured for size optimisation. This time Hyperstudy and Abaqus were used as the optimisation engine and proprietary FE solver respectively.

3. RESULTS

3.1 ORTHOGONALLY FRAMED VARIANTS

Figure 11 shows the objective (mass) and constraint (von Mises stress) responses during the optimisation of the externally framed design variant.

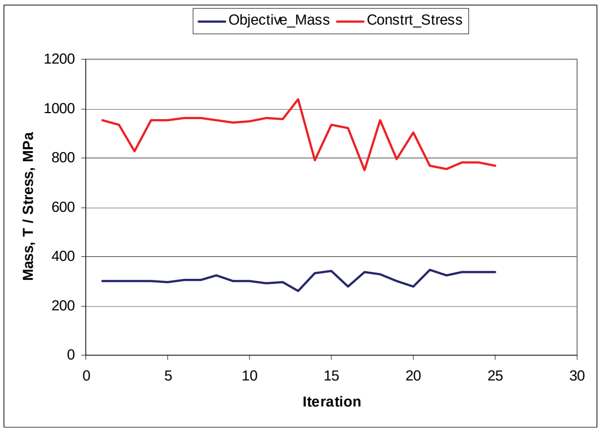


Figure 11: Design responses at each optimisation iteration for the externally framed design variant.

The method proceeds by first perturbing the design variables to establish the sensitivity of the design objectives. Thereafter the design variables are perturbed in a rational manner, based upon the sensitivity results, in an attempt to find a solution satisfying the objective and constraint functions.

As Figure 10 shows, after 25 iterations, and given the constraints on section sizes, the optimisation process cannot find a configuration having a mass equivalent to the dome which satisfies the stress constraint.

Though peak stresses were reduced by approximately 200 MPa, they were still in the order of 200 MPa in excess of the design constraint. Also, reduction in stress level was achieved at the expense of a slight increase in mass.

Figure 12 shows the design responses for the internally framed design variant. The development of the design responses can be seen to be different from that for the externally framed variant.

In this instance, though approximately 50 Tonnes has been shaved off the mass after 35 iterations, it was not possible to achieve a robust solution with significantly lower stress levels. Again, overall, the mass of the resulting structure is still well in excess of the dome mass, and the stress levels are well in excess of yield.

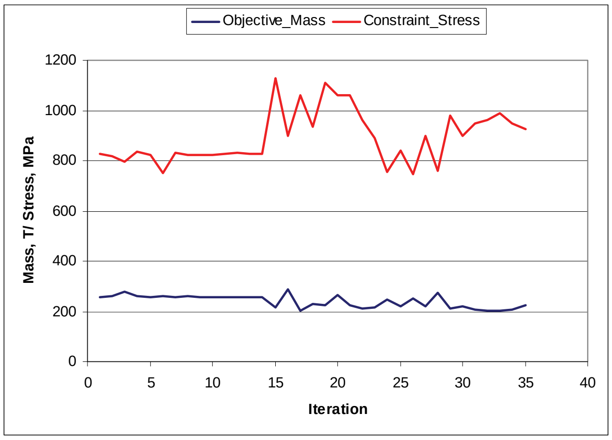


Figure 12: Design responses at each optimisation iteration for the internally framed design variant.

It should be noted that for both variants it was assumed that further iterations would not reveal a satisfactory design solution. Also, though the design intent was not achieved, optimisation did provide a more effective method of design than one based upon empirically derived guidance.

3.2 MODIFIED EXTERNAL FRAME DESIGN

Clearly, too much was being asked of both framed design variants. To derive a workable solution it was necessary to relax some aspect of the design. Revisiting the externally framed solution, it was decided to reduce the applied load from 7 MPa to 4 MPa. Figure 13 shows the resulting design responses.

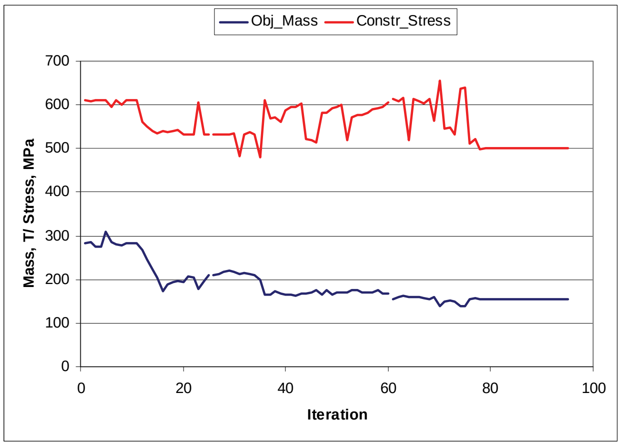


Figure 13: Design responses at each optimisation iteration for the externally framed design variant with reduced load.

Minor alterations were made to the constraints imposed upon the loaded bulkhead plate section size at iterations 25 and 60. Without these modifications the optimisation process would have reduced the bulkhead plate stresses by increasing their section size, rather than restrict the overall displacement by increasing the section sizes of the grillage.

As Figure 13 shows, the optimisation method converged upon a stable solution after approximately 75 iterations. The peak stress in the structure was reduced by over 100 MPa, bringing it down to the target level. Simultaneously, the mass of the structure was reduced by approximately 140 Tonnes.

Further mass savings were possible by next carrying out a topology optimisation. The structural forms resulting from this optimisation are shown in Figure 14.

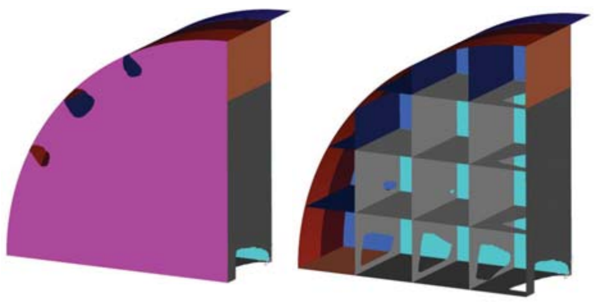


Figure 14: Structural form resulting from the topology optimisation of the size optimised external frame design under reduced load, with outer grillage plating (left) and without (right).

As can be seen, material considered redundant has been removed from the outer plating of the grillage, and from within the grillage itself. While this removed material further reduces the mass of the structure by 20 Tonnes overall, it does increase the peak stresses in the material, though not in excess of its yield value.

3.3 CONCEPTUAL DESIGN SOLUTION

Figure 15 shows the conceptual solution derived from topology optimisation of the solid FE model shown in Figure 8 for an imposed load of 7 MPa. Figure 16 shows a reverse view of the same structural arrangement.

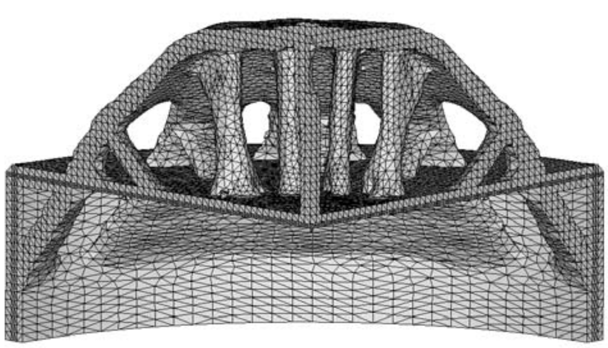


Figure 15: Solid mesh representation of topology optimised conceptual design solution, internal perspective.

Figure 16: Solid mesh representation of topology optimised conceptual design solution, external perspective.

Conceptually, the solution is trying to produce a through bulkhead arch, which supports the central bulkhead plate with ties.

Clearly the form shown in Figures 15 and 16 does not represent a practicable structural solution; therefore some idealisation of this solution was required. Assuming the structure was to be built up from simple to manufacture geometric shapes, the derived shell idealisation is shown in Figure 17, the outer casing is transparent to reveal internal detail.

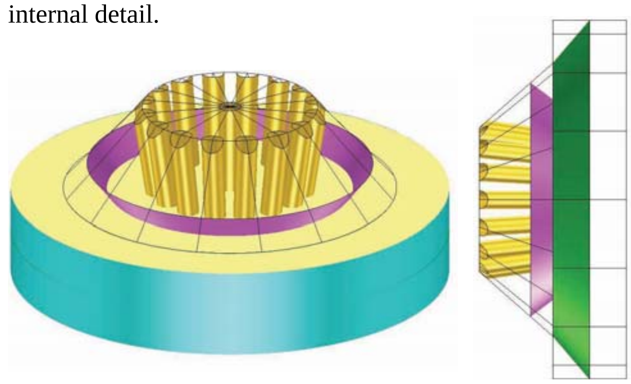


Figure 17: Shell idealised conceptual structural form, with transparent outer casing.

The section sizes for this idealisation were taken from the solid geometry. This structure was then size optimised for a 7 MPa pressure loading, to seek the lightest possible structural arrangement.

The von Mises stress field for the resulting structure, adopting cyclic symmetry conditions, is shown in Figure 18. It is worth noting that the structure can be seen to be remarkably under stressed.

Figure 18: von Mises stresses in 10 m size optimised conceptual solution under 7 MPa load.

This conceptual solution was found to have a maximum peak stress 12% lower than the material yield value, however this was achieved at the expense of increased mass; the solution was found to be approximately six times the mass of the dome structure.

It should be noted that no secondary reinforcement is assumed in this solution. An alternative solution may be to use stiffened plate sections rather than plane plate sections.

4. CONCLUSIONS

A comparison of results for the design alternatives considered is given in Table 2.

Model	Design	Load, MPa	Peak $_{vm}$, as a fraction of yei	Mass, as a proportion of Dome mass	P_c, As a proportion of dome
Dome	-	-	-	1.00	1.00
Ext. Frame	SSP74	7	1.74	4.93	-
	Size Opt.	7	1.37	5.29	0.97
Int. Frame	SSP74	7	1.50	4.19	-
	Size Opt.	7	1.38	4.07	0.97
Modified Ext. Frame	SSP74	4	1.11	4.66	-
	Size Opt.	4	0.91	2.55	-
	Top. Opt.	4	0.97	2.23	0.66
Conceptual	Top. Opt, Size Opt.	7	0.88	5.98	2.61

Table 2: Comparison of design alternative results.

Peak stresses are expressed as a fraction of the material yield value. Mass is expressed as a fraction of the baseline dome mass, and non-linear collapse pressure is expressed as a fraction of the modelled dome collapse pressure.

Optimisation based design can be seen to offer better design solutions than traditional design methods for the selected design responses.

However, the only optimised designs that satisfied the stress constraint were those for the conceptual solution and for the external frame variant with the reduced design load. In the conceptual study, the cost of achieving the stress constraint was a six fold increase in mass compared to the dome design, however, an additional benefit was an increase in collapse pressure to over 2.5 times that of the dome.

Though the conceptual solution performed well structurally it was the heaviest design alternative. This raises issues in terms of manufacturability. Excessively thick plate is expensive to weld and the solution would have to be reconfigured using stiffened plate in an attempt to derive a practicable alternative.

The inability to find universal satisfactory results raises the following questions. First, it is possible to find a sufficiently economical orthogonally stiffened end closure design for a large diameter pressure hull subject to deep dive depth? Second, is the design approach too severe to realise viable designs? Third, have sufficient design variables been declared with constraints that allow potential solutions to emerge?

No flat end solution is ever likely to be as structurally economical as a domed solution; however, the results indicate that there is potential for finding suitable flat end design solutions for large pressure hull diameters capable of achieving deep dive depths. Optimisation methods are likely to be the only means of realising this potential, though a different approach may be required in three respects. First, framed solutions may prove more viable if frame spacing is also incorporated as a design variable along with each inter-frame bulkhead plate section. Second, more economical designs may emerge if a non-linear collapse constraint is placed on the optimised solution, certainly this is likely for the conceptual solution where the non-linear collapse pressure is well in excess of that for the dome, and the design is so much heavier. Third, the design of the adjacent cylindrical pressure hull should be included in the design to a greater extent than was possible in these studies; increasing the section of the adjacent ring stiffened cylinder would provide added support to the end closure design, and, using optimisation methods, it would be possible to reduce the stiffness differential between the two components and thus minimise shear effects around their interface.

Finally, a more rigorous approach may be possible by configuring end closure design requirements in terms of a direct design by analysis scheme, as developed in EN 13445. This would provide a clear rationale for integrating optimisation based design.

5. ACKNOWLEDGEMENTS

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Any errors in approach and reporting are the responsibility of the authors.

6. REFERENCES

1. Joubert, P., ‘Some aspects of submarine design. Part 1. Hydrodynamics’, *DSTO-TR-1622, http://dspace.dsto.defence.gov.au/dspace/handle/1947/3919 (as of 4th March 2008),* 2004

2. Joubert, P., ‘Some aspects of submarine design. Part 2. Shape of a submarine 2026’, *DSTO-TR-1920, http://dspace.dsto.defence.gov.au/dspace/handle/1947/8027 (as of 4th March 2008),* 2006

3. Sea Systems Publication No. 74 (SSP74), Design of Submarine Structures, *Sea Technology Group, Defence Procurement Agency*, MOD, June 2001.

4. PD 5500 2002, Unfired fusion welded pressure vessels, *British Standards Institute*, 2002.

5. BS-EN 13445-3 2002, Unfired Pressure Vessels – Part 3: Design, *British Standards Institute*, 2002.

6. American Society of Mechanical Engineers, Boiler and Pressure Vessel Code, ASME, New York.

7. Abaqus v6.7, Abaqus Inc., http://www.simulia.com, (as of 2nd March 2008).

8. MSC Software Corporation, http://www mscsoftware.com/, (as of 2nd March 2008).

9. Altair Engineering Inc., http://www.altair.com, (as of 29th January 2008).

7. AUTHORS’ BIOGRAPHIES

Crerar Christie is currently a Senior Engineer within QinetiQ. After studying for a PhD in optimisation at Newcastle University Engineering Design Centre he joined QinetiQ, then DERA, in 2000 and has since been responsible for a wide variety of numerical analysis work, including dispersion modelling, explicit equation of state blast modelling, and non-linear collapse analysis. He maintains his interest in all manner of optimisation techniques and is associated with the UK Association for Structural and Multidisciplinary Optimisation. Recently, his work has been concerned incorporating optimisation methods to find more economical design solutions for various aspects of UK submarine design.

John Hobson holds the current position of Senior Structural Engineer within QinetiQ. He is mainly responsible for carrying out linear and non-linear FEA of submarine structures. Previous work includes successfully predicting collapse pressures and buckling mode shapes for detailed experimental submarine models. His most recent work includes optimization and impact analyses of submarine fore end structure.

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Advances in Experimental Techniques for Understanding the Manoeuvring Performance of Submarines

Nick Kimber, Paul Crossland
QinetiQ, UK

RINA WARSHIP 2008: NAVAL SUBMARINES 9

QinetiQ/CON/MPP/CP0800200

10 June 2008

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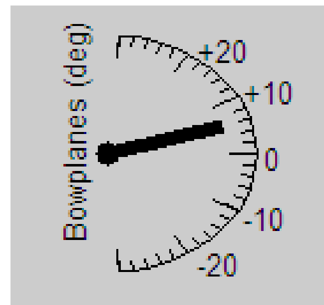
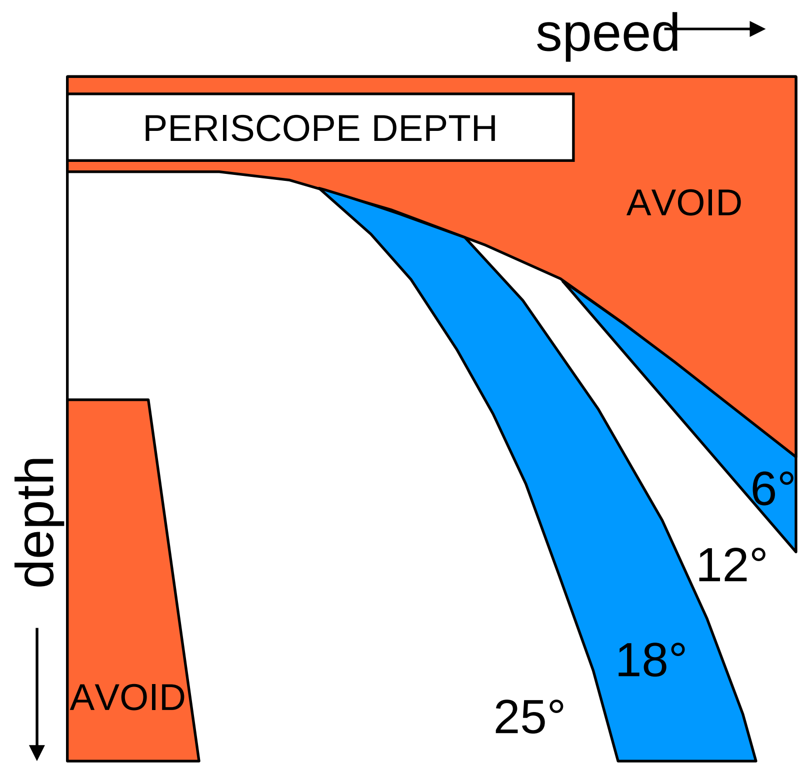
Contents



01 Introduction

- Development of numerical models
- Simulations used outside currently validated limits
- Quality of predictions degrades as manoeuvre becomes more extreme
  - e.g. emergency recovery following hydroplane jam
- Simulations used to provide operational limits
  - Manoeuvring Limitation Diagram
  - Safe Manoeuvring Envelope
  - Conservative factors built in
- Fidelity therefore of utmost importance
  - on a class basis, sometimes even boat-specific
  - validation through free-manoeuvring model tests and full-sale trials



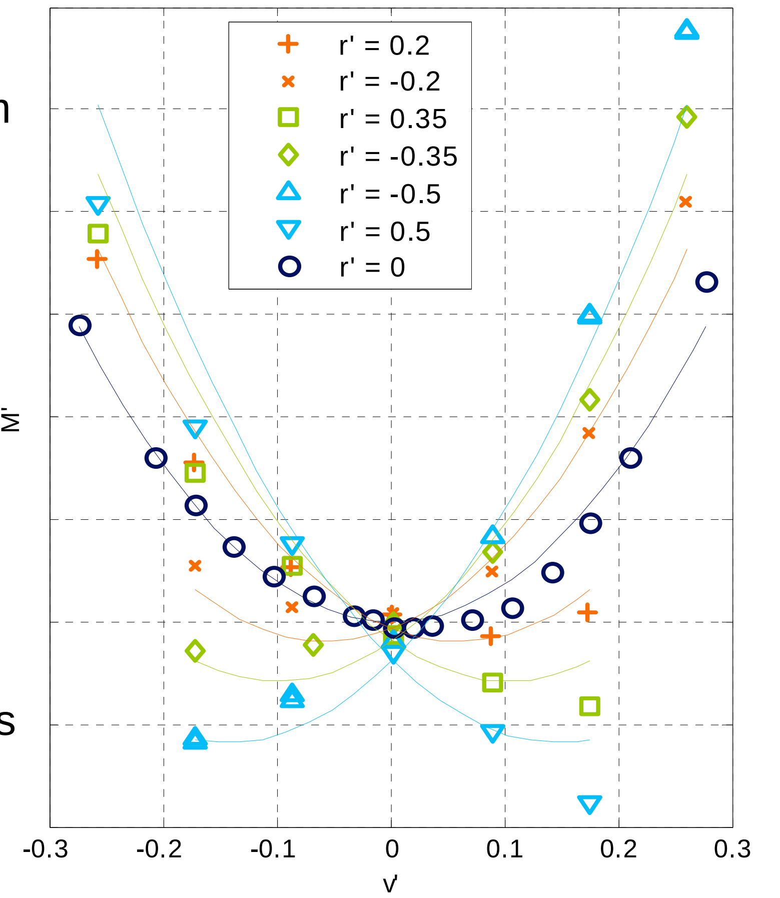
01 Introduction

- As the complexity of the mathematical model increases:
  - may introduce new independent parameters
  - may require testing over wider range of existing parameters
  - more tests ⇒ longer experiment programme ⇒ increased cost
- This paper looks at one area where this is a concern, and how it has been addressed
- The paper also looks at one area of the validation process
  - what to do when predictions do not match observed behaviour
- Common theme is maintaining fidelity in a cost-effective manner

02 Background

Tank testing

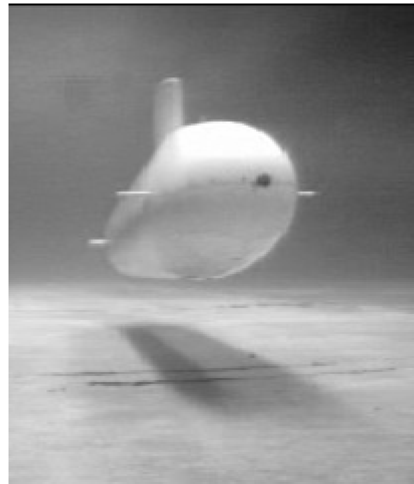
- Constrained tests in Ship Tank and on Rotating Arm
- Conducted over a range of
  - pitch angles
  - pitch rates
  - yaw angles
  - yaw rates
  - hydroplane angles
  - rudder angles
  - rpm
- Non-linear polynomials fitted through data points
  - re-creates force or moment within simulation for a given state
- Figure: 17 Ship Tank runs and 36 Rotating Arm runs
  - generates 3 pitch moment coefficients, 3 lift and 3 drag
  - typically around 100 coefficients required in total

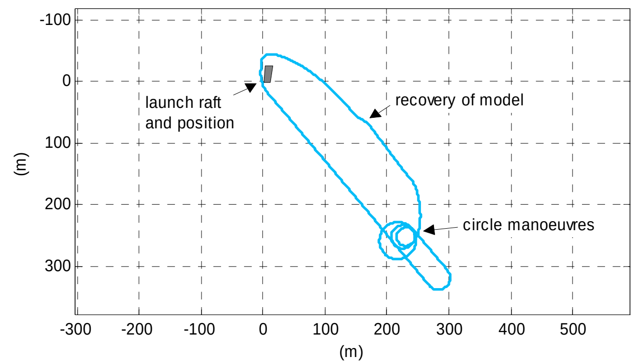


02 Background

Free manoeuvring model tests

- Simple tests in an Ocean Basin
  - Confirmation of manoeuvring performance
  - Can be run in controlled waves
  - Test-bed for real-time non-linear control
  - Initial source of data for simulation validation
- More extreme manoeuvres in a deep water facility
  - e.g. high speed hydroplane jam recovery
- Accurate measurements needed (and achieved)





03 Cross-coupling behaviour

In this context, cross-coupling refers to the vertical force and moment acting on the submarine body during a horizontal plane turn

- Typically, the force is downwards, but causes the submarine to pitch up
- Mathematical model for this comes from constrained experiments

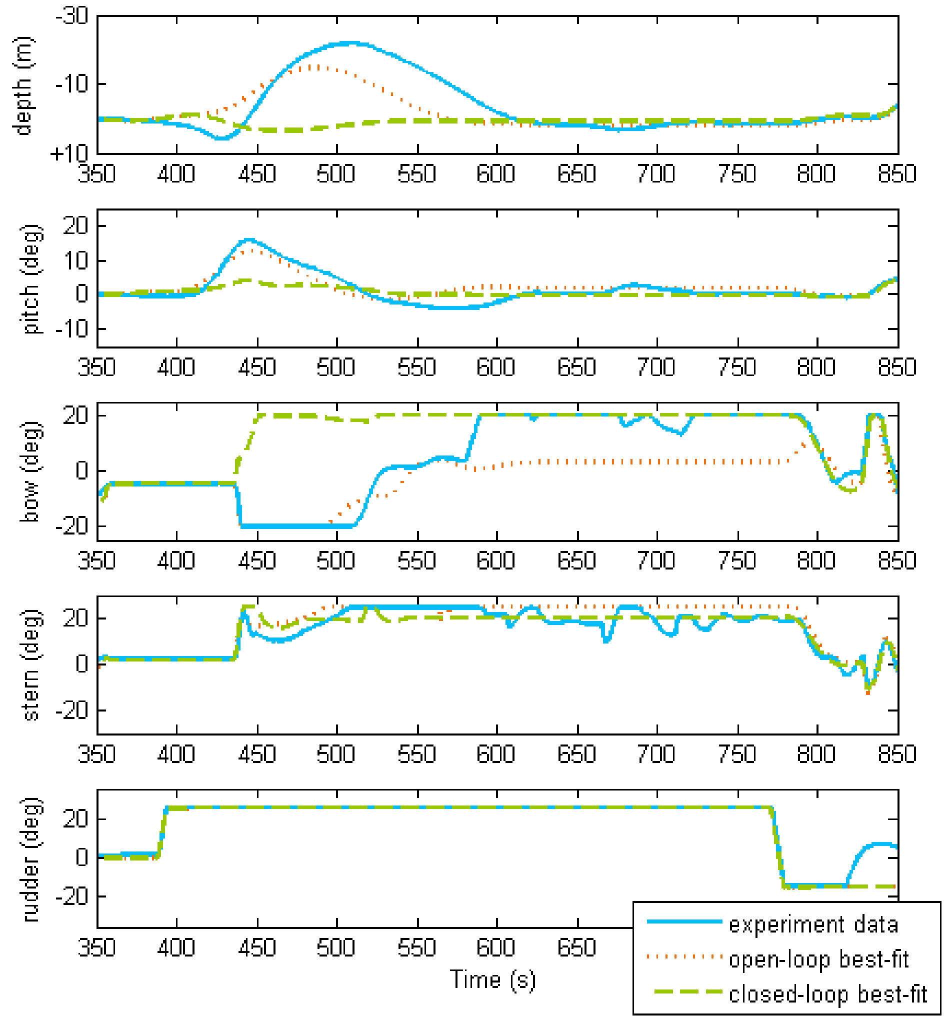
Free-manoeuvring experiments include turns

- free-turns, open-loop manoeuvre, no depth control
- simulations significantly over-predict the pitch (and subsequent depth) responses
- controlled turns, motion appears well-predicted, different hydroplane angles

Need to understand why and improve the predictions

03 Cross-coupling behaviour

- This example (typical of many) includes a free-turn and a controlled turn
- Initial attempts to improve prediction based on parametric search
- Coefficients found which improved open-loop prediction
  - wrong hydroplanes when active
- Coefficients found which matched closed-loop control
  - hardly any excursion during open-loop phase
- Concluded that hydroplane effectiveness is different in a turn



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03 Cross-coupling behaviour

Increased sternplane effectiveness

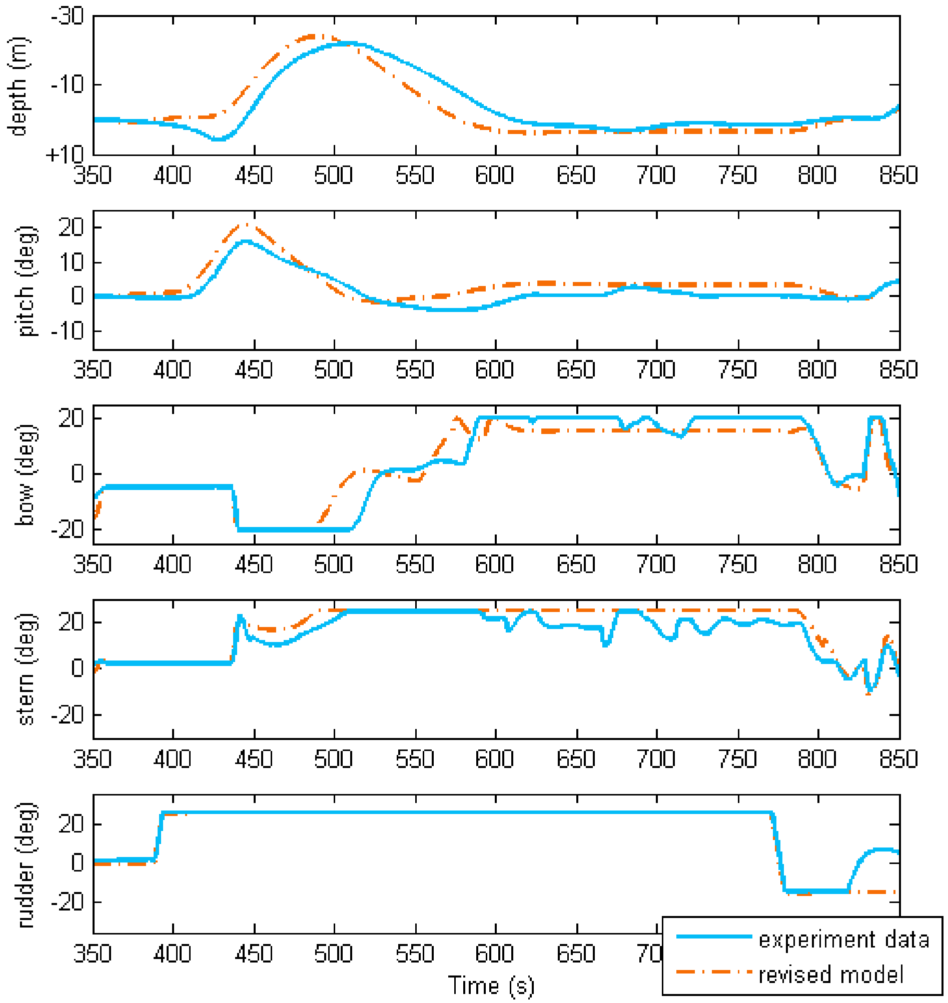
- During a turn, the drift angle means that the aft end is on the outside of the circle
  - increased local flow velocity?
- original model

$$Z = Z_{uu\delta s} u^2 \delta s$$

- replaced by

$$Z = Z_{uu\delta s} \left(\sqrt{u^2 + v^2} - |r| x_{\delta s} \right)^2 \delta s$$

- Currently no constrained model experiments to support evidence



03 Cross-coupling behaviour

Identification from free-running model data

- Conducted steady, controlled turns over range of speeds and rudder angles
  - autopilot guaranteed constant depth and level pitch
  - obtained an equilibrium condition i.e. net force = net moment = zero

$$Z_{uu}u^2 + Z_{uw}uw + Z_{uu\delta b}u^2\delta b + Z_{uu\delta s}\left(\sqrt{u^2+v^2} - |r|x_{\delta s}\right)^2\delta s + \left(Z_{uq} + m + \Delta m\right)uq + \Delta mg\cos\phi\cos\theta + Z_{turn} = 0$$

- All velocities, rates and angles measurable
- Resolve all forces
- Assuming faith in the other coefficients, cross-coupling force can be calculated directly
  - same for moment measurement
- Tabulate the results from each run and plot…

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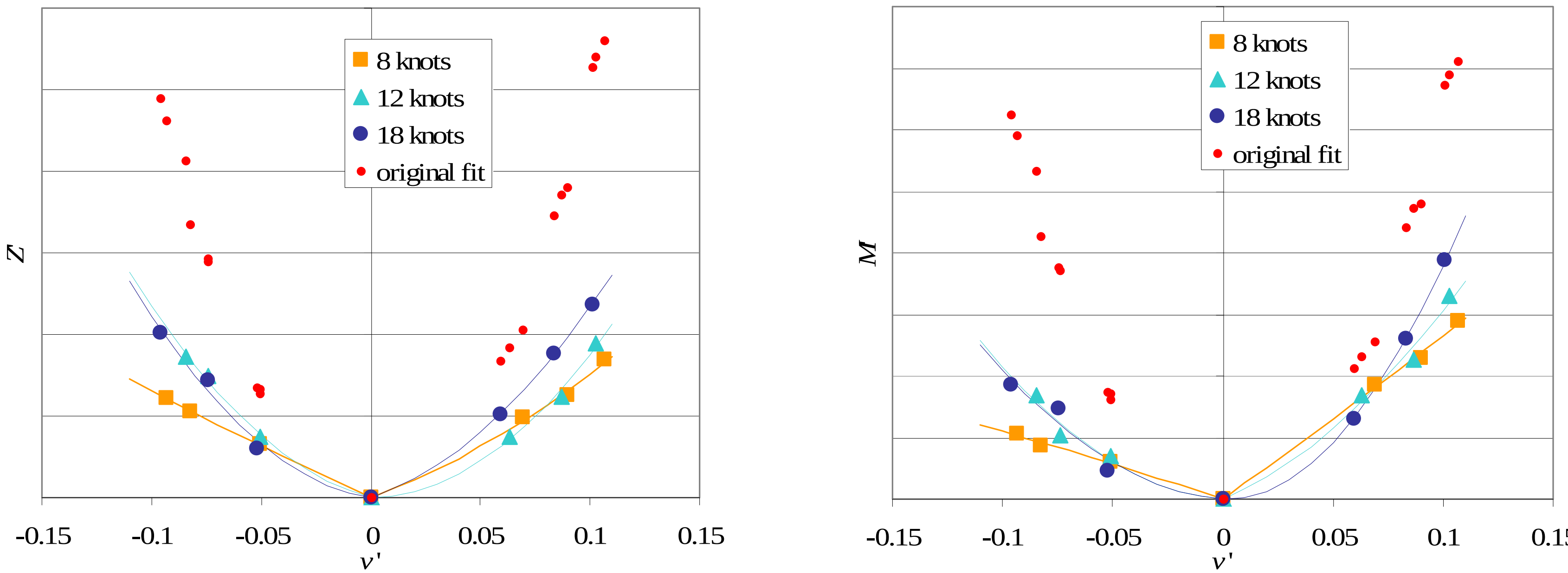
03 Cross-coupling behaviour

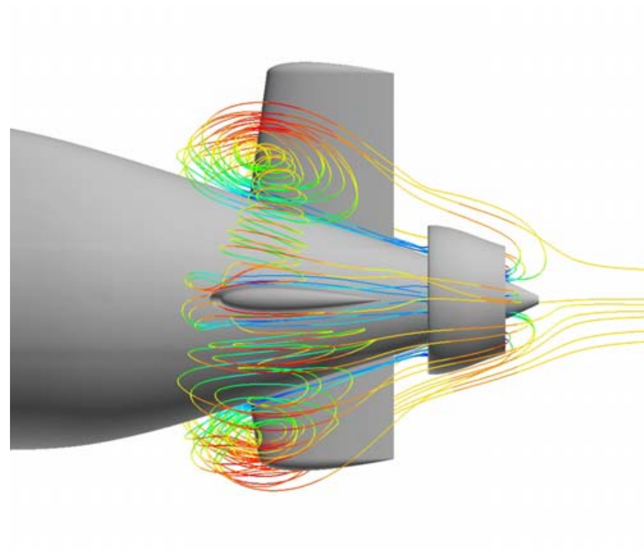
Identification from free-running model data



- Equations are of the form $Z_{turn}' = Z_{vv}'v'v' + Z_{u|v|}'u'|v'|$

04 Ramp tests

Interest in modelling forces and moments generated under braking



- Complex flows
- Current mathematical model known to break down
- Coefficients for self-propulsion no longer valid
- Change to model based on propulsor state
  - defined as

$$n' = \frac{Instantaneous\ rpm}{rpm\ \ for\ self\ \ propulsion\ at\ instantaneous\ speed}$$

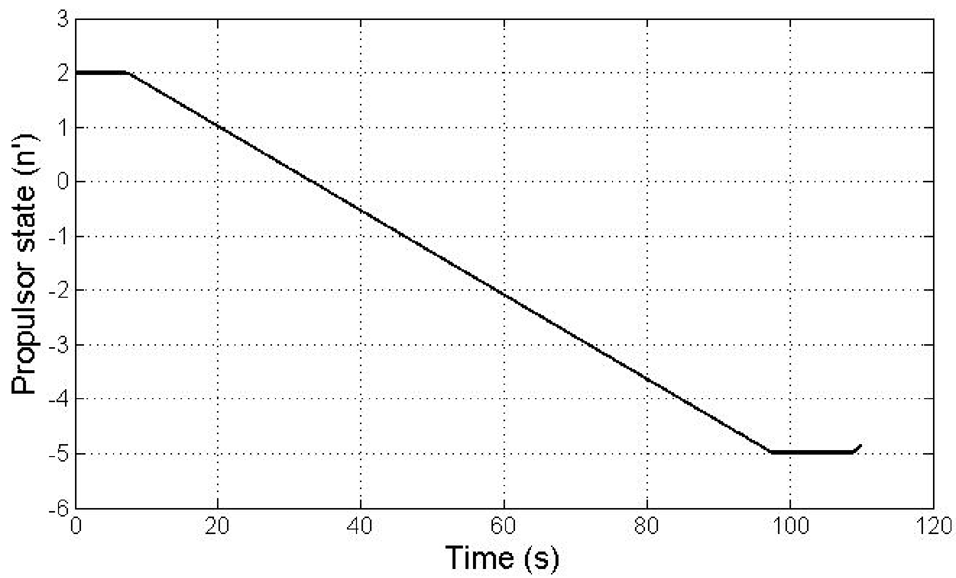
- Nominal coefficient is modified thus, for example

$$Y_{uu\delta r}{}' = Y_{uu\delta r0}{}' + (n' - 1)Y_{uu\delta rn}{}'$$

- But what range of n' to test?

04 Ramp tests

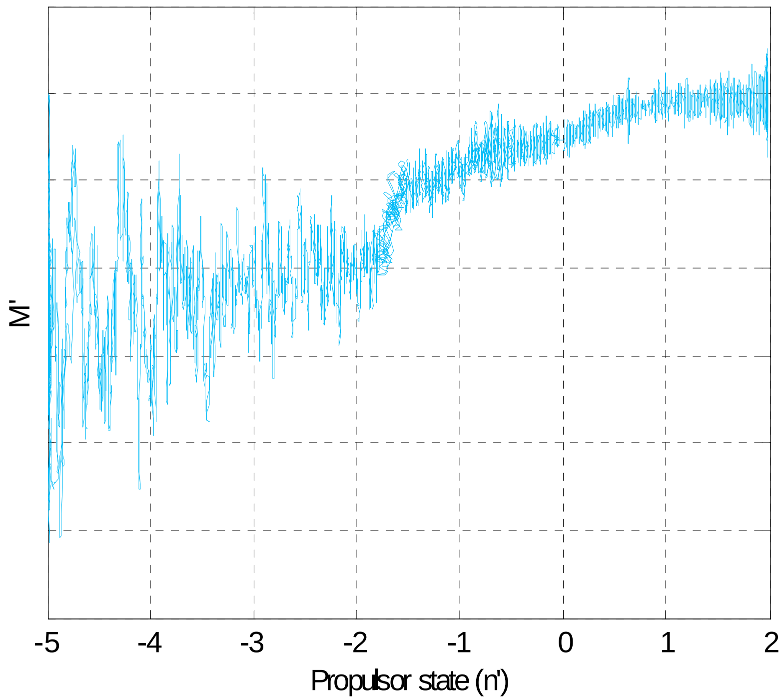
- Traditionally select 2 or 3 fixed values of n'
- Replace with dynamic variation of rpm over single tank run



- How can these be analysed within the format of the steady-state model?

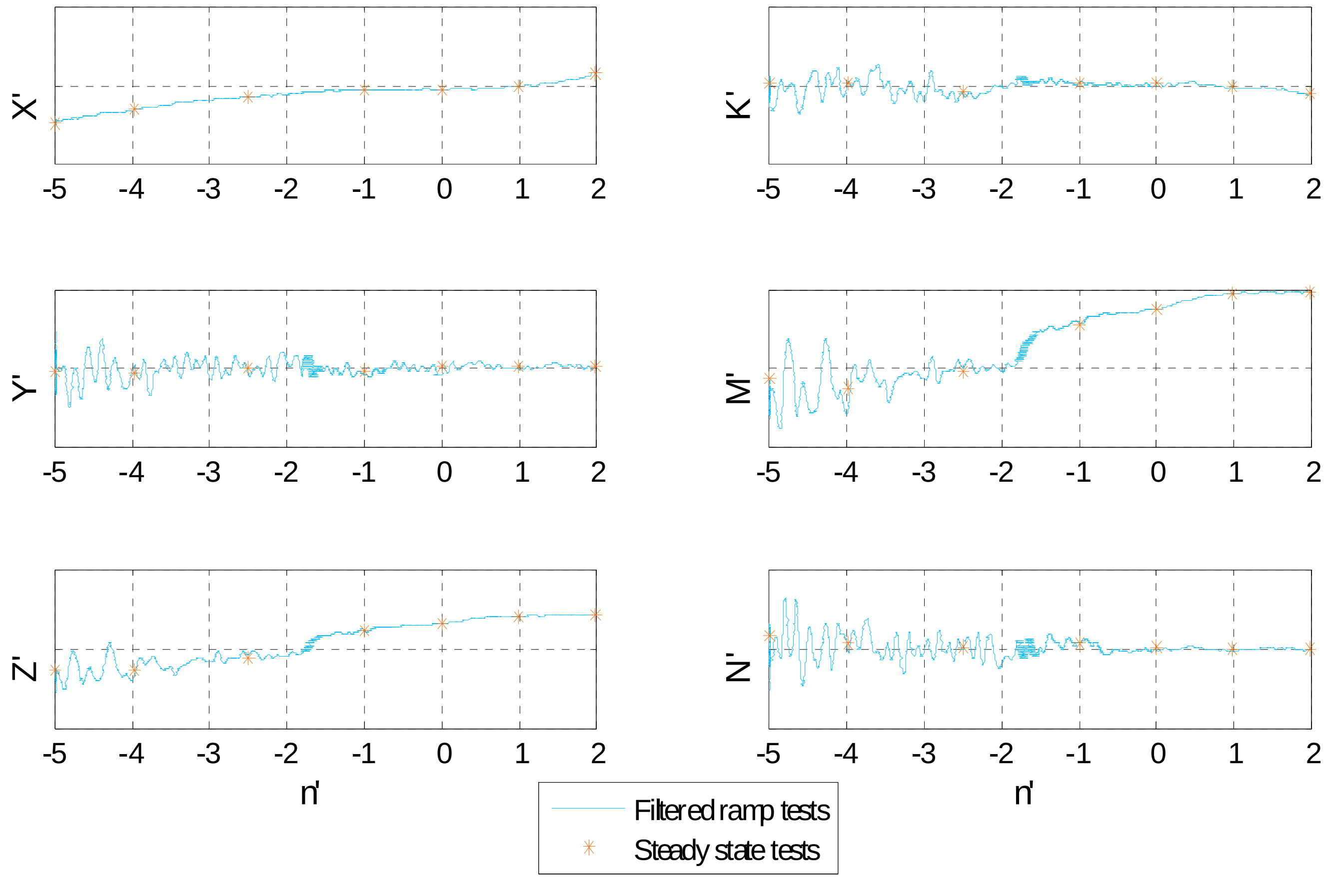
04 Ramp tests

- Example results – pitch moment
- Requires filtering



04 Ramp tests

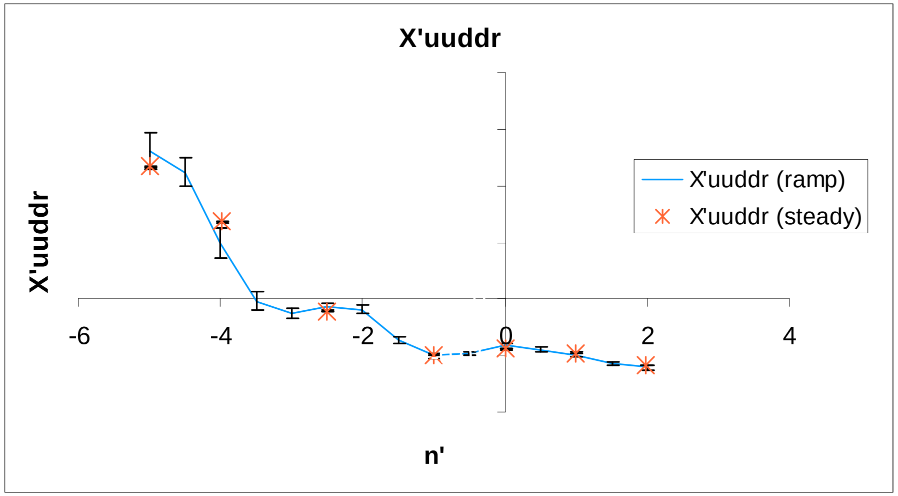
Comparison with steady state fixed points

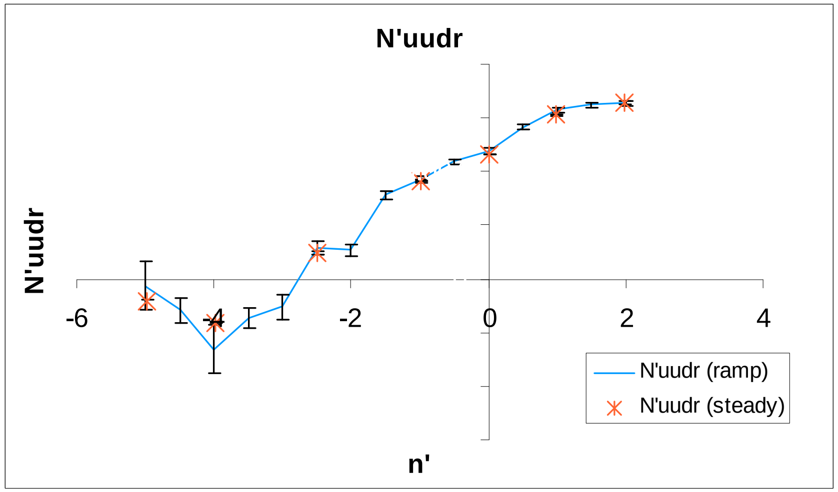


04 Ramp tests

Processing ramp test data

- Choose discrete n' values
- Extract and average several points around each discrete n' value
- Can now apply standard regression techniques
- Compare with original steady state experiment results





05 Conclusions

Presented two different experiment techniques

- Each aims to improve understanding where simulations are known to be poor

Cross-coupling behaviour

- Constrained model results do not predict free-manoeuvring response
  - Reason for this is still not clear
  - Predictions improved if stern hydroplane effectiveness increases in a turn
- Cross-coupling model can be derived from free-manoeuvring model
  - demonstrates asymmetry and dependence on speed

Ramp tests

- Development of mathematical models can increase number of parameters and test range
  - meets requirement to keep physical experiments to a realistic number
  - dynamic tests shown to successfully reduce number of steady state runs

05 Conclusions

Recent times have seen major full-scale trial programmes

- manoeuvres repeated using free-running model
- simulations compared at both scales
- improvements made

Drive to improve simulation fidelity

- confidence in predictions
- establish reliable operational limits
- provide appropriate advice to submarine operators

The Global Defence and Security Experts

www.QinetiQ.com

Assurance of Submarine Safety in a Changing Environment

by

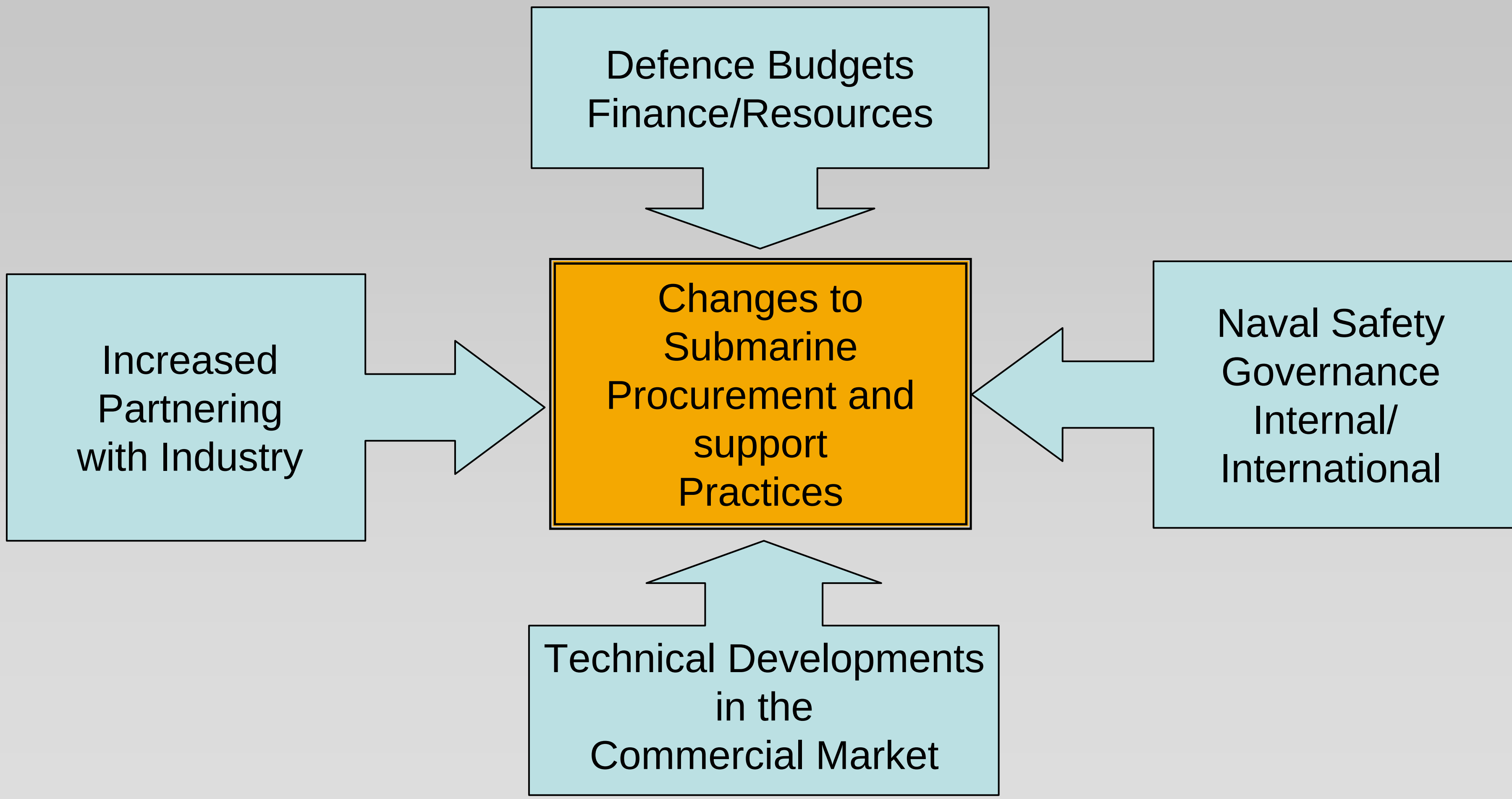
John Cheetham
Ian Miller

11th June 2008

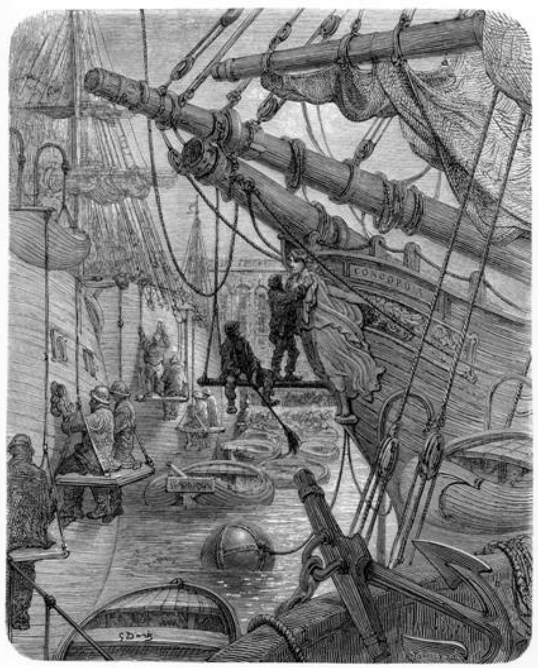
Lloyd's Register

- Changing environment
- Classification and naval platforms
- Challenges facing the safety regulators
- Project risk management
- Classification process applied through life
- Key attributes which contribute to assurance of submarine safety

Changing Environment – Drivers for Change



245 years of development of Classification

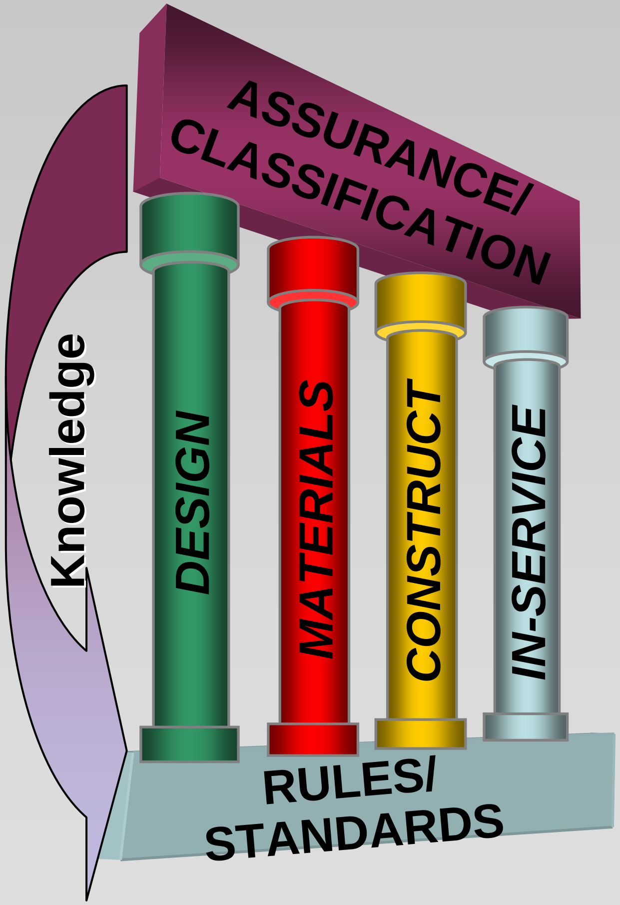


Le vaisseau *Concordia*, dans un bassin des docks

Lloyd's Register

Classification Process

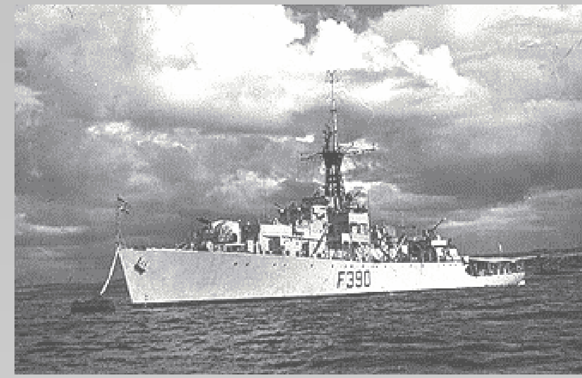
- Development of Rules –
  The Standards
- Development of Regulations –
  The route to verification of compliance
- Verification activities –
  The collection of evidence
- Certification –
  The confirmation of compliance



Lloyd's Register

Development of Naval Ship Classification

- By the end of the second world war 2400 naval ships had been constructed under survey
- More recently involvement focussed on auxiliaries
- Interest in combatants led to the development of the Rules for Naval Ships

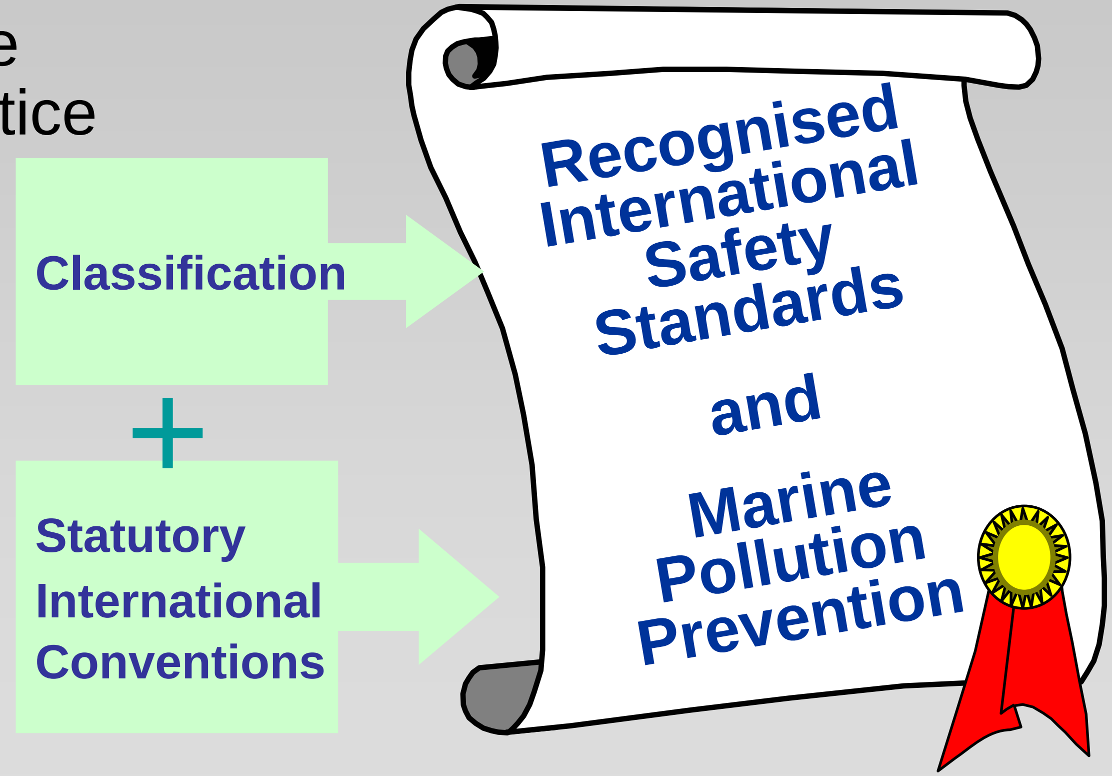


Rules for Naval Ships

- Military loads, engineering systems and operational requirements not applicable on merchant ships
- Survivability and vulnerability assessments
- Redundancy and reconfigurable systems
- Residual damage strength
- Rules for submarine specific structure and systems are being developed

Safety Regulation

- The naval classification process replicates the merchant sector practice
- Scope is increased to embrace the IMO regulations
- Covers the acquisition lifecycle



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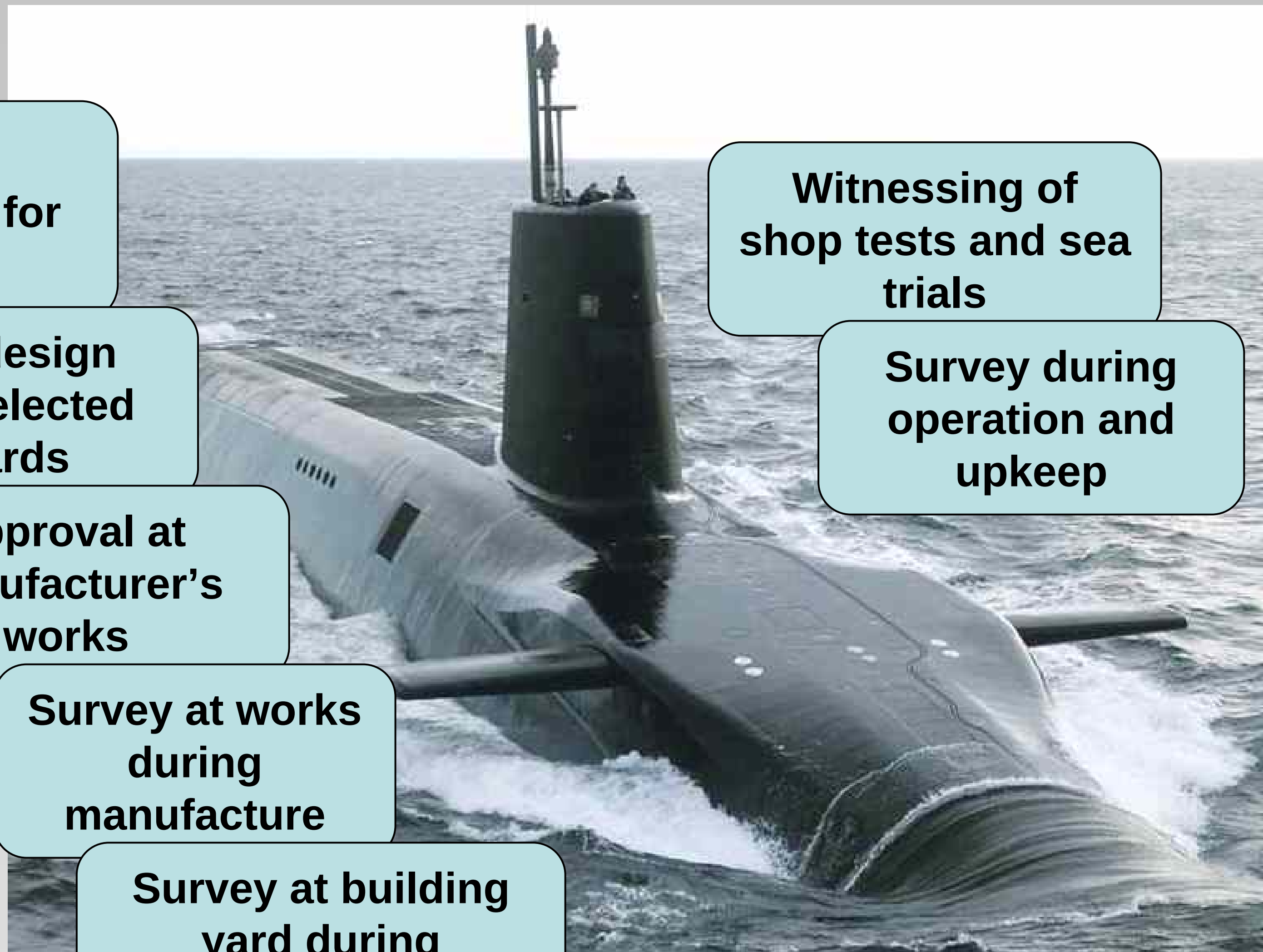
Comparison with the commercial sector

- Command structure and freedom to regulate, with sanctions
- Lack of external supporting pressures
- Unfamiliarity of purpose and goal
- High risk acceptance spreading to normal operations



Review of standards set for platform

Review design against selected standards

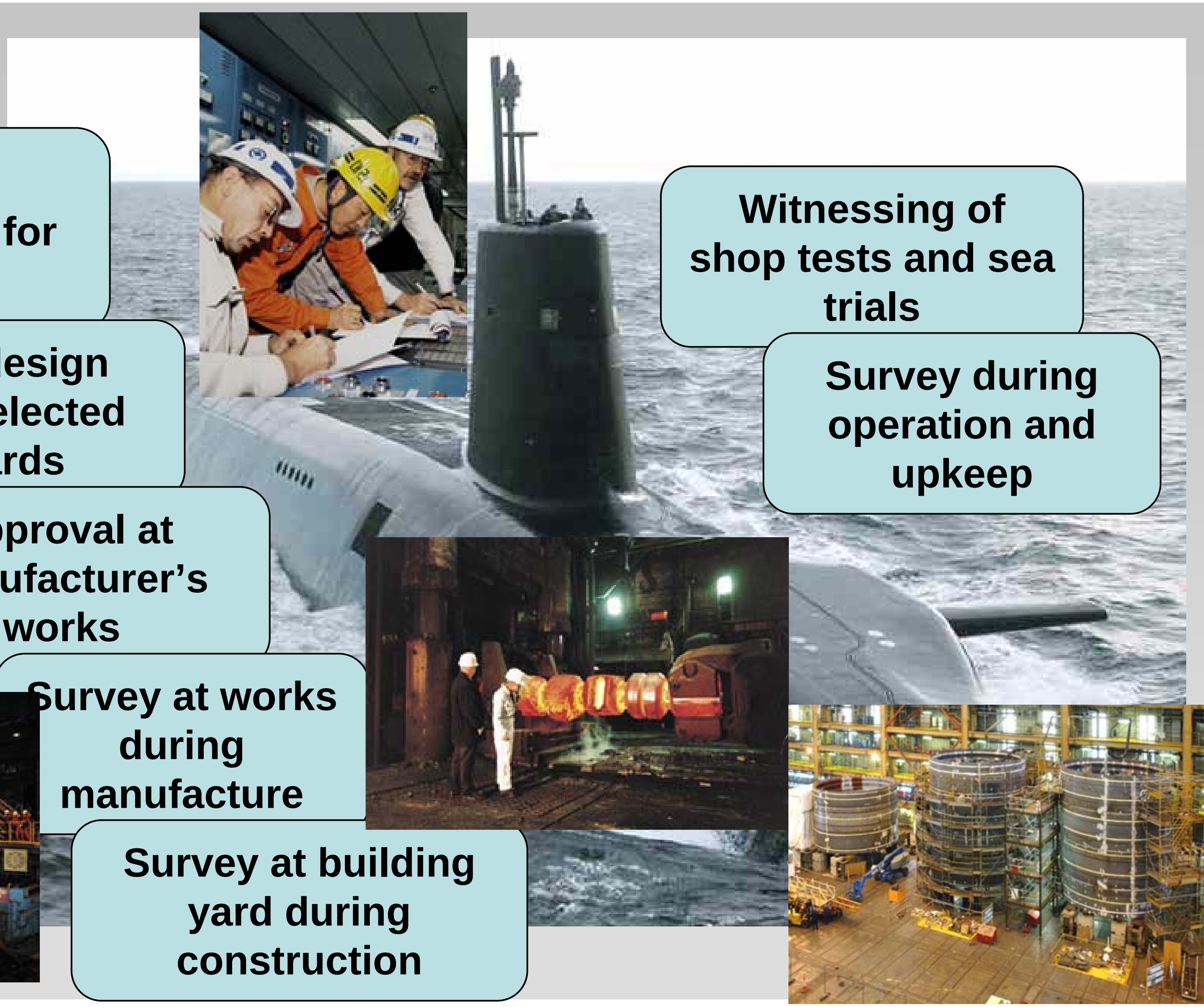
Approval at manufacturer’s works

Survey at works during manufacture

Survey at building yard during construction

Witnessing of shop tests and sea trials

Survey during operation and upkeep



Review of standards set for platform

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Approval at manufacturer's works

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Survey at building yard during construction

Witnessing of shop tests and sea trials

Survey during operation and upkeep

Regulation and management

- Regulation imposes an external control on management
- Management of risk is a business imperative
- Regulation becomes more invasive when management is perceived to be weak or ineffective

Development of safety regulation

- Post-event investigation, apportionment of blame and imposition of requirements

- Safety by prescription and compliance

- Commitment to active management of safety beyond imposed prescription

- Imposed regulation or self-regulation

Principles of good regulation

- Don’t make rules unless the smallest company will be able to cope
- Don’t make rules unless the benefits justify the imposed costs
- Don’t make detailed prescriptive rules when a goal can be defined and industry can decide how to achieve it

The burden of safety regulation

- Cost of regulation
- Bureaucracy and complexity of regulatory process
- Verification industry
- Challenge to professional responsibilities and loss of control
- Risks associated with non compliance

Safety regulator's challenge

- Convincing that safety regulation has real business benefits
- Demonstrating that commercial sector practices can provide good models
- Showing that classification is much more than developing a set of Rules
- Understanding that there is no unique route to managing safety and risk

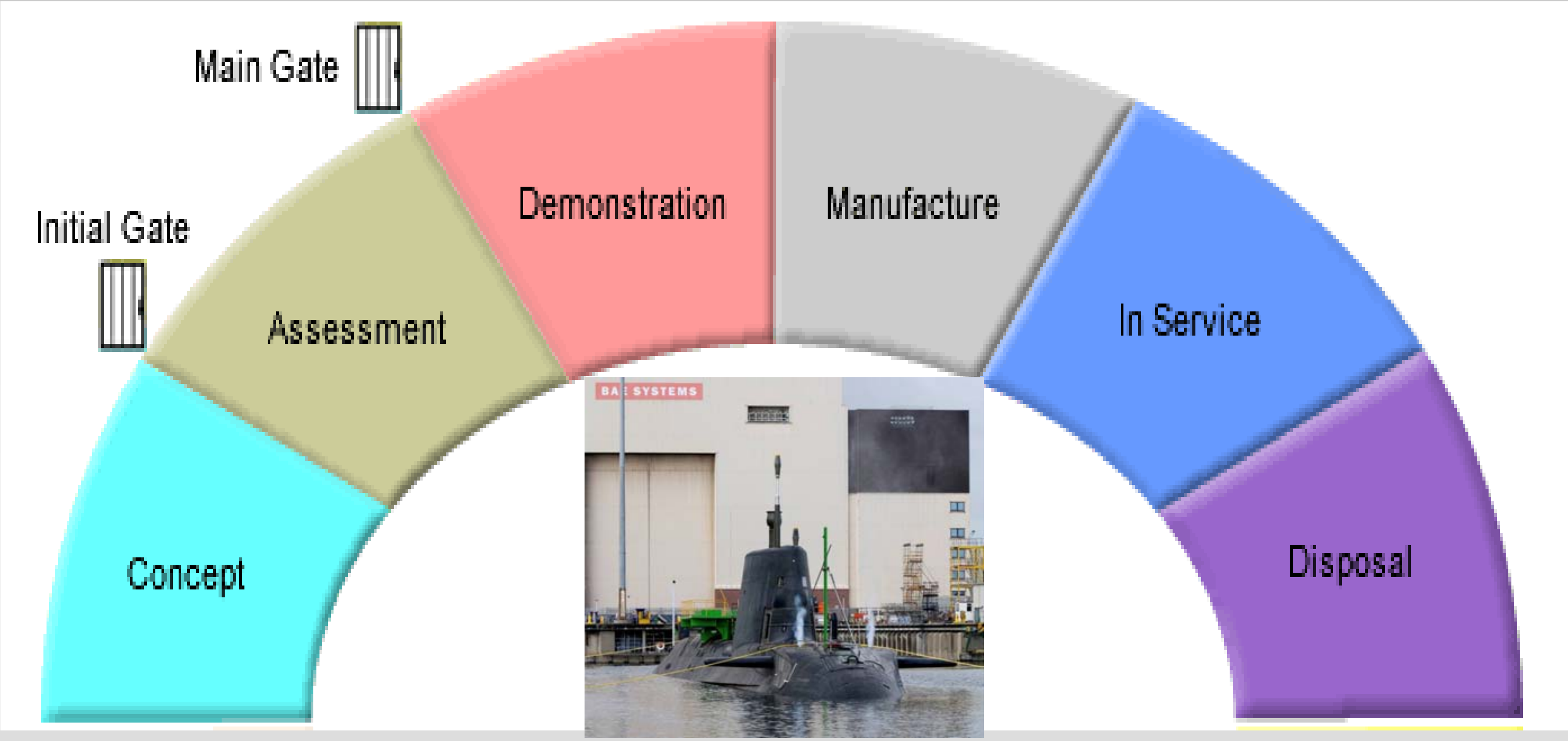
Project risks

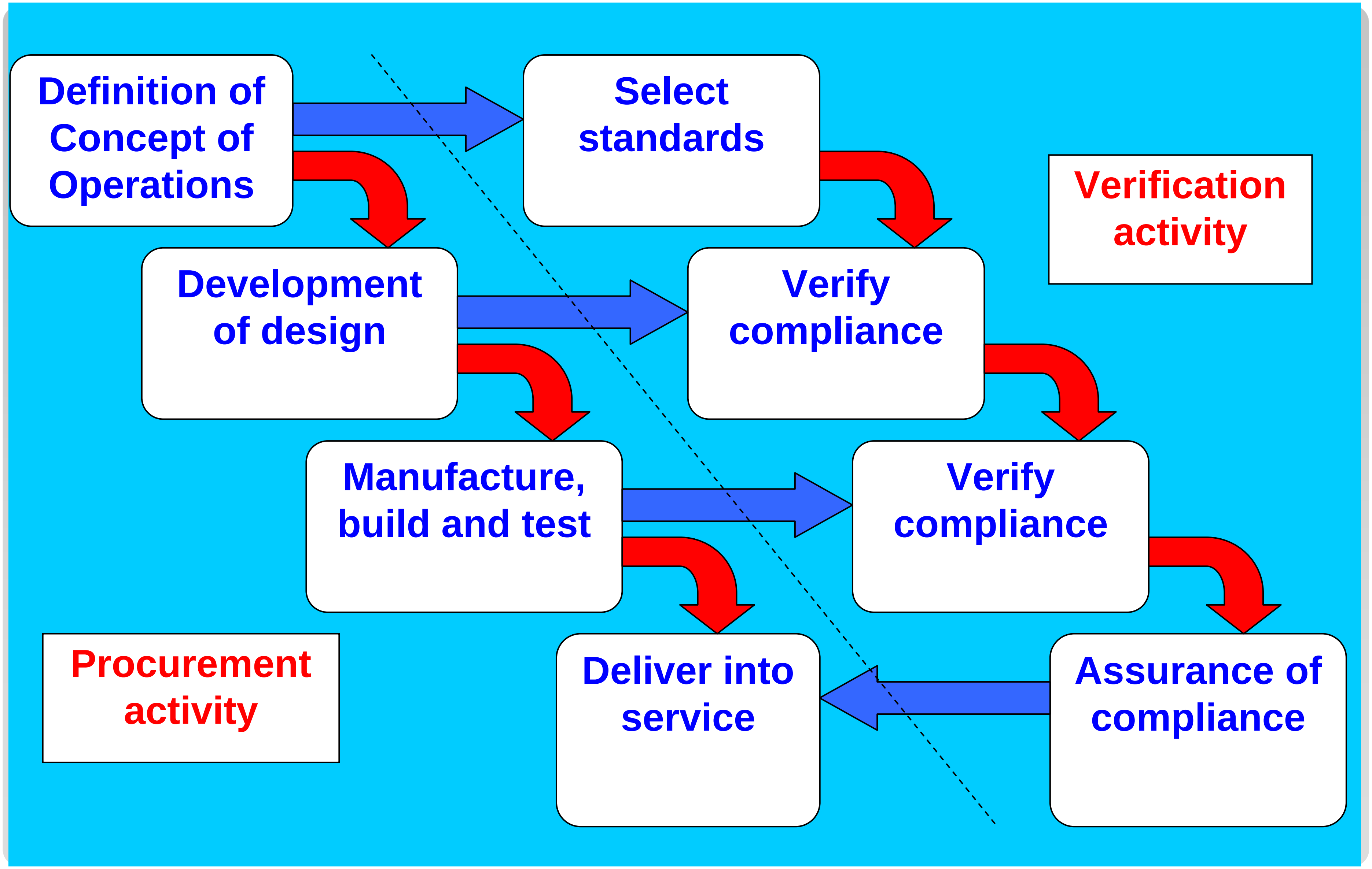
- Programme
- Cost
- Delivered capability
- Operability
- Technical
- Safety

Non-safety benefits of safety regulation

- Inherent risk management support
- Similarity of risk mitigation measures
- Risk management depends on robust processes and intervention
- Traceability aids retrospective fault elimination
- Documentation trail provides solid foundation

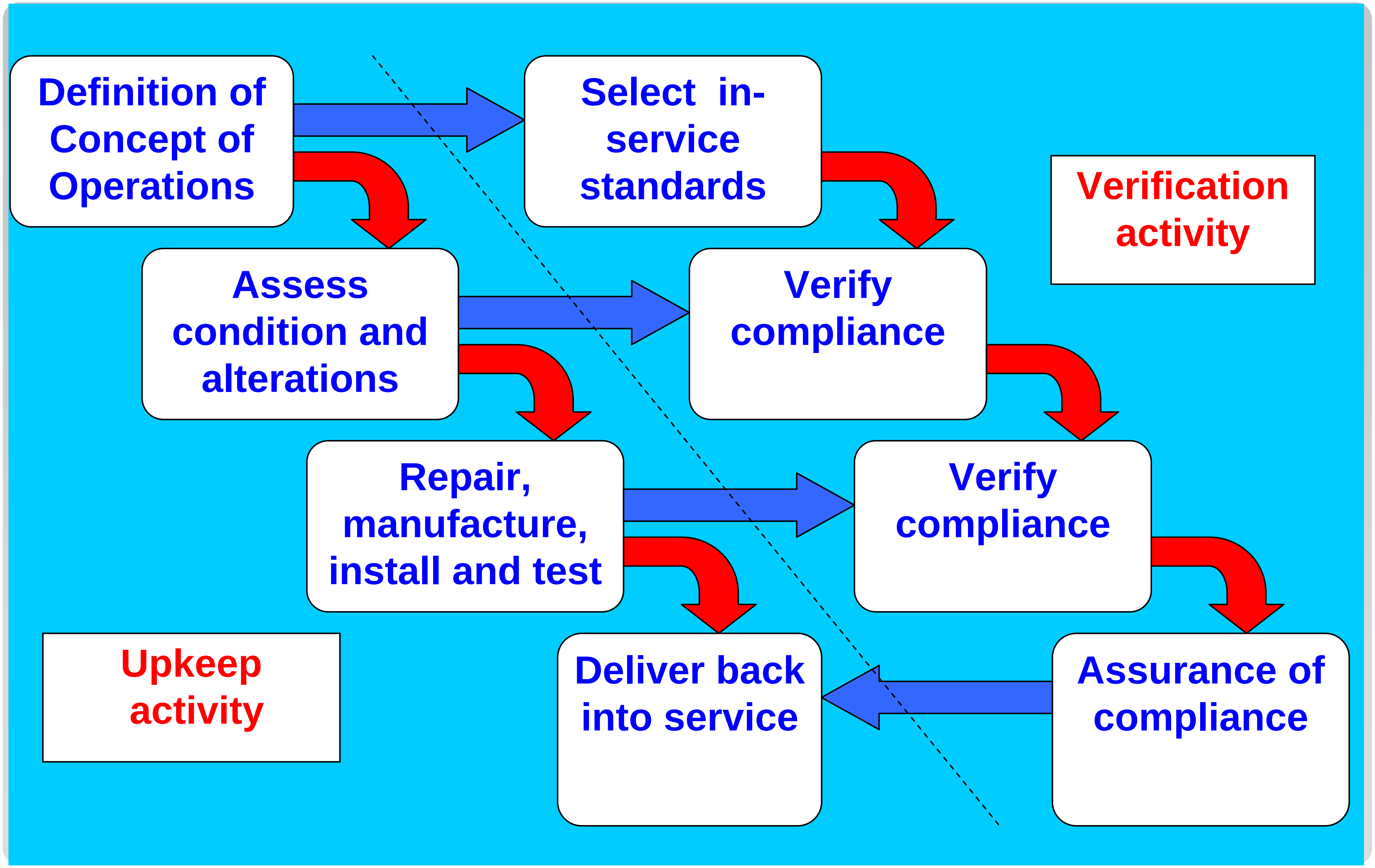
Support through life




Definition of Concept of Operations
Select standards
Verification activity
Development of design
Verify compliance
Manufacture, build and test
Verify compliance
Procurement activity
Deliver into service
Assurance of compliance

Procurement

- Selection of standards to suit capability
- Progressive assessment during design development
- Traceability throughout supply chain
- Monitoring of manufacture and construction
- Monitoring of testing and commissioning


Definition of Concept of Operations
Select in-service standards
Verification activity
Assess condition and alterations
Verify compliance
Repair, manufacture, install and test
Verify compliance
Upkeep activity
Deliver back into service
Assurance of compliance

Upkeep

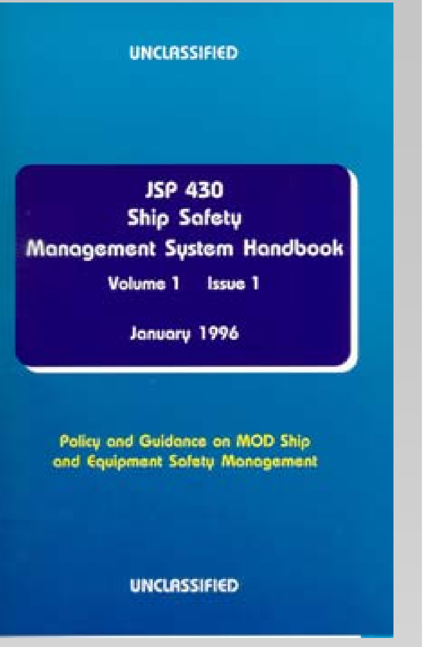
- Baseline standards against which proper assessment can be made of condition and alterations
- Traceability of materials and components
- Identification of necessary repairs to maintain standards
- Monitoring of repair and alterations

Contribution to project risk management

- Project technical risks and safety share key characteristics
- Assuring safety can mitigate project risks
- Clarity of requirements throughout the supply chain reduces programme, cost and technical risks
- Traceability provides audit trail

Relationships

- Support for platform safety case
- Provision of appropriate maintained standards
- Deficiency and defect management



Classification process - key attributes

- Rules which provide a set of coherent standards
- Independent safety assurance process
- Progressive acceptance
- Assurance in the supply chain
- Enhanced availability and reliability through use of COTS equipment
- Access to technical expertise and technology transfer

Classification - processes for managing risk and assuring safety through life

Warship 2008, Naval Submarines
Glasgow, June 2008

Lloyd's Register

FRAZER-NASH CONSULTANCY

End-of-Life Preparation for Submarines

Dr Trevor Perry CEnv MIEMA

Systems and engineering technology

Overview

- Key Issues & Drivers
- New IMO Requirements
- UK Interpretation
- Implications for Submarines
- MOD Implementation

Issues & Drivers

- Exposure to Hazards
  - Asbestos
  - Polychlorinated biphenyls
  - Heavy metals
  - Organotin compounds
  - Hydrocarbon contamination
  - Toxic fumes (NOx, dioxins, furans, PAHs)
- Lack of Personal Protective Equipment

Issues & Drivers

- **Poor decommissioning**
- **Lack of controlled working practices**

- **Lack of engineered shipbreaking facilities**
- **Lack of engineered waste disposal sites**

Photo courtesy of Greenpeace / Berstorff

New IMO Requirements - Aims

- Aims
  - Safe & environmentally sound recycling of ships
  - **Also** covers
    - Minimisation of operationally generated potentially hazardous waste
    - Emergency contingency planning

New IMO Requirements - Scope

- Cradle to Cradle (grave)
  - Vessel Design, Construction
  - Operation
  - Vessel Recycling, Disposal.

New IMO Requirements

- IMO Guidelines
  - Recommendatory guidelines on “Green Passport” to be made mandatory
  - Other new guidelines to be introduced by Joint IMO/ILO/Basel Convention Working Group
  - These new ‘guidelines’ will also be mandatory
  - Ratification due July 2009?

Joint Working Group 'New' Guidelines

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- New guidelines
  - Communication of information
  - Control of hazardous materials
  - Ship inspection
  - Surveys & certification
    - International Ready for Recycling Certificate
  - Ship Recycling Plan
  - Gas-free-for-hot-work conditions
  - Ship dismantling/Recycling standards
    - Authorisation of Ship Recycling Facilities
    - Statement of Completion of "Ship Recycling"
  - Others?

UK Interpretation

- DEFRA Ship Recycling Strategy
  - Vessels intended for further use
  - Vessels destined for recycling & disposal

  - Commits MOD to IMO Requirements

The Million Dollar Question…..

Does it apply to Submarines ?

YES

- Explicit Reference in MOD interpretation

Photo courtesy of DISM

Implications for Submarines

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- New Submarines
  - Design considerations
    - Hazard elimination/minimisation through:
      - Increased COTS application/ systems
      - Increased automation
      - Elimination/substitution of hazardous materials
    - Ease of maintenance v ease of dismantling conflicts
  - Surveys
    - Initial survey prior to service entry.

Implications for Submarines

- In-Service Submarines
  - Minimisation of operationally generated hazardous waste
  - Review adequacy of contingency planning
  - Develop Green Passport
    - On-board materials
    - Operationally generated potentially hazardous waste
  - Surveys
    - Initial survey – verification of Green Passport
    - Periodic surveys – 5 yearly verification of continuing applicability of Green Passport
    - Other surveys – following significant modifications

Implications for Submarines

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- End-of-Life Submarines (Recycling)
  - Update and complete Green Passport
  - DDLP & final survey
  - Obtain 'Ready to Recycle Certificate'
  - Develop Ship Recycling Plan
    - Owner / disposer
  - Draft disposal contractual agreements
    - Minimum standards
  - Inspect/Audit ship recycling operations
  - Receive Statement of Completion of Ship Recycling.

Implications for Submarines

- End-of-Life Submarines (Resale)
  - Update Green Passport
  - Conduct verification survey
  - Obtain government's consent

- Contractual agreements
  - Include disposal contractual agreements
  - Statement of Completion of Ship Recycling.
- Default by new owner?

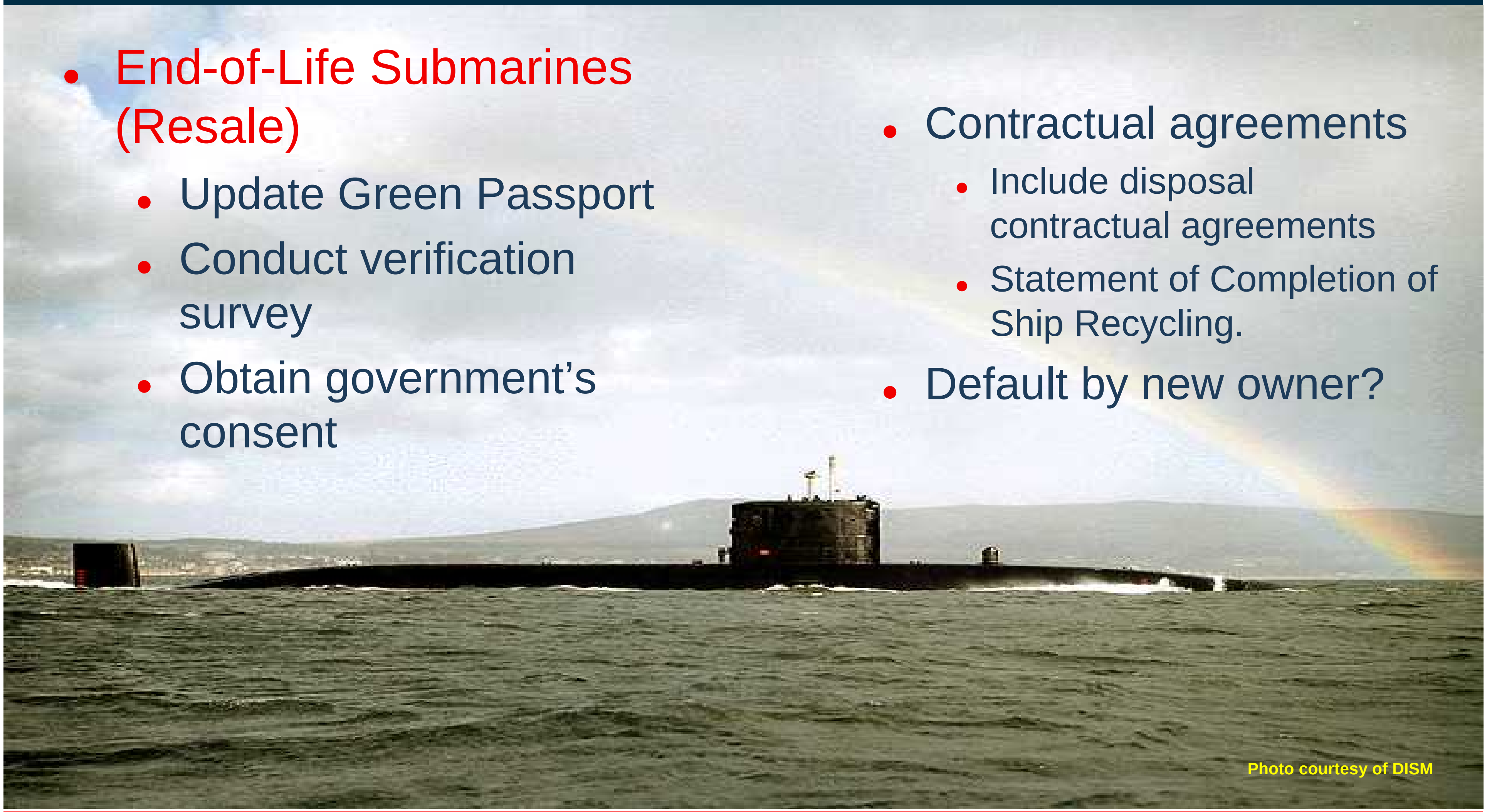
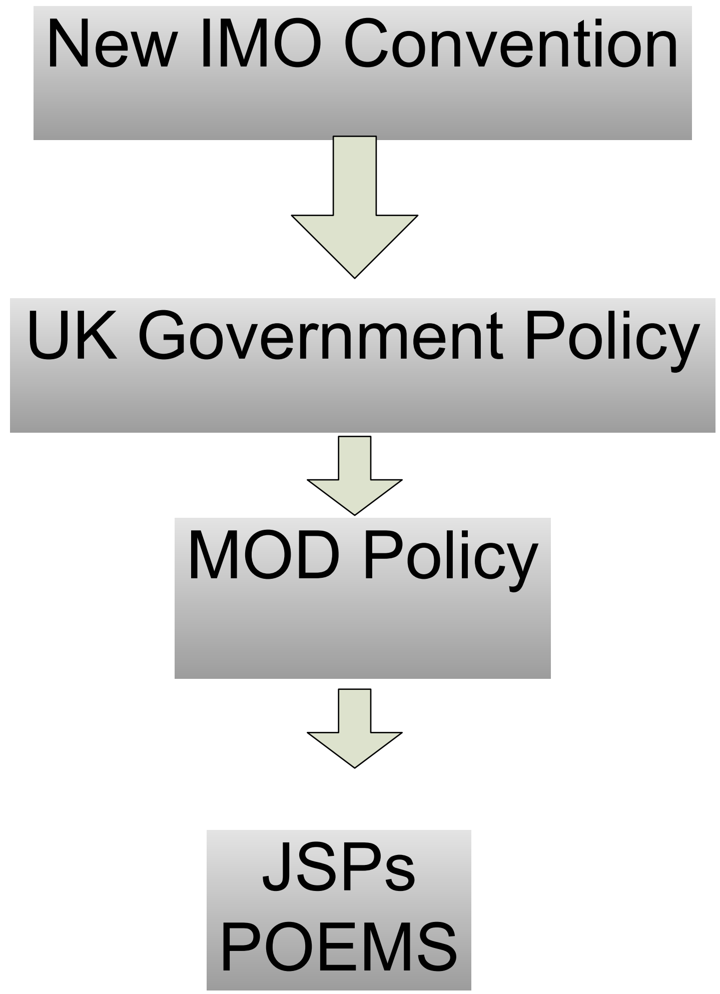


Photo courtesy of DISM

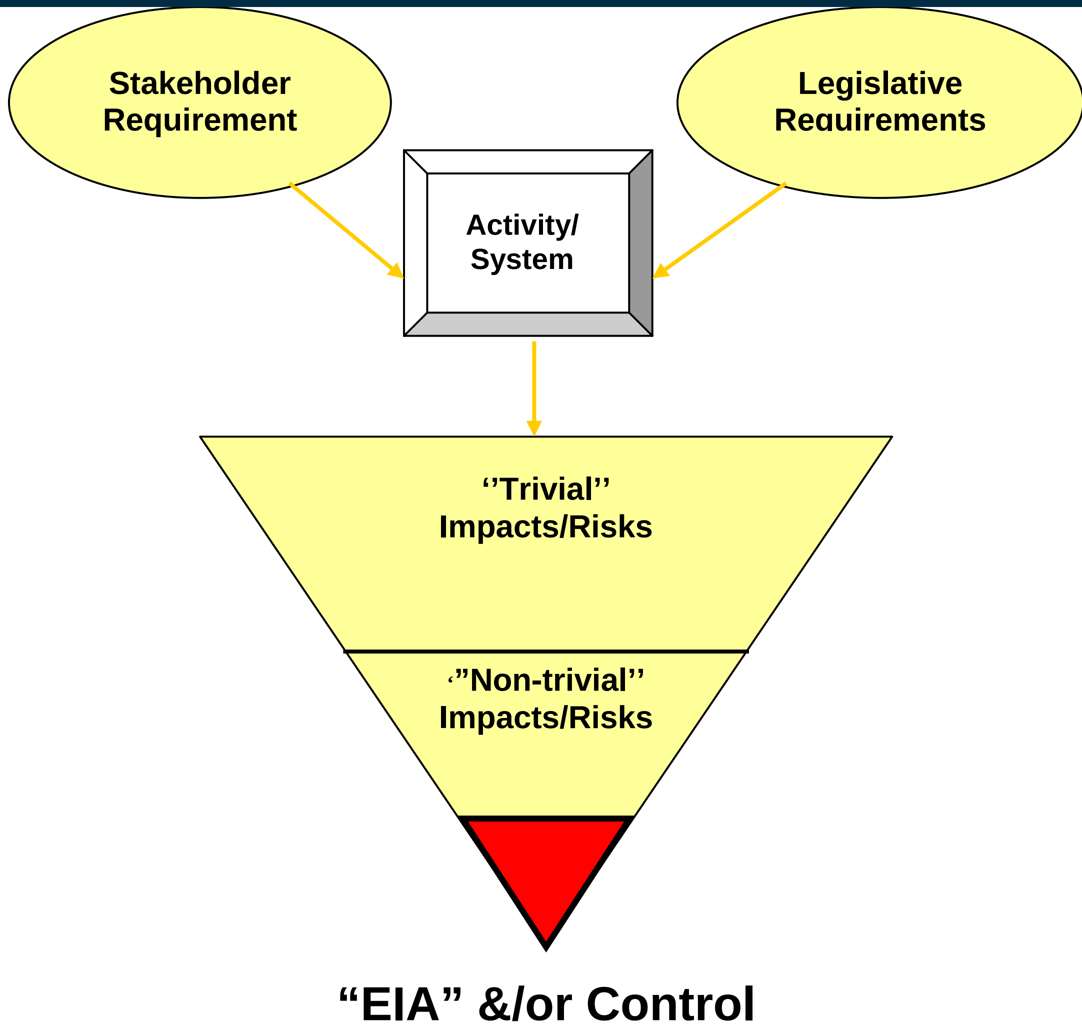
UK MOD Implementation



UK MOD Implementation

- Project Oriented Environmental Management System (POEMS)
  - Systematic framework for managing statutory requirements;
  - Effective tool for driving continuous improvement.

Overview of POEMS



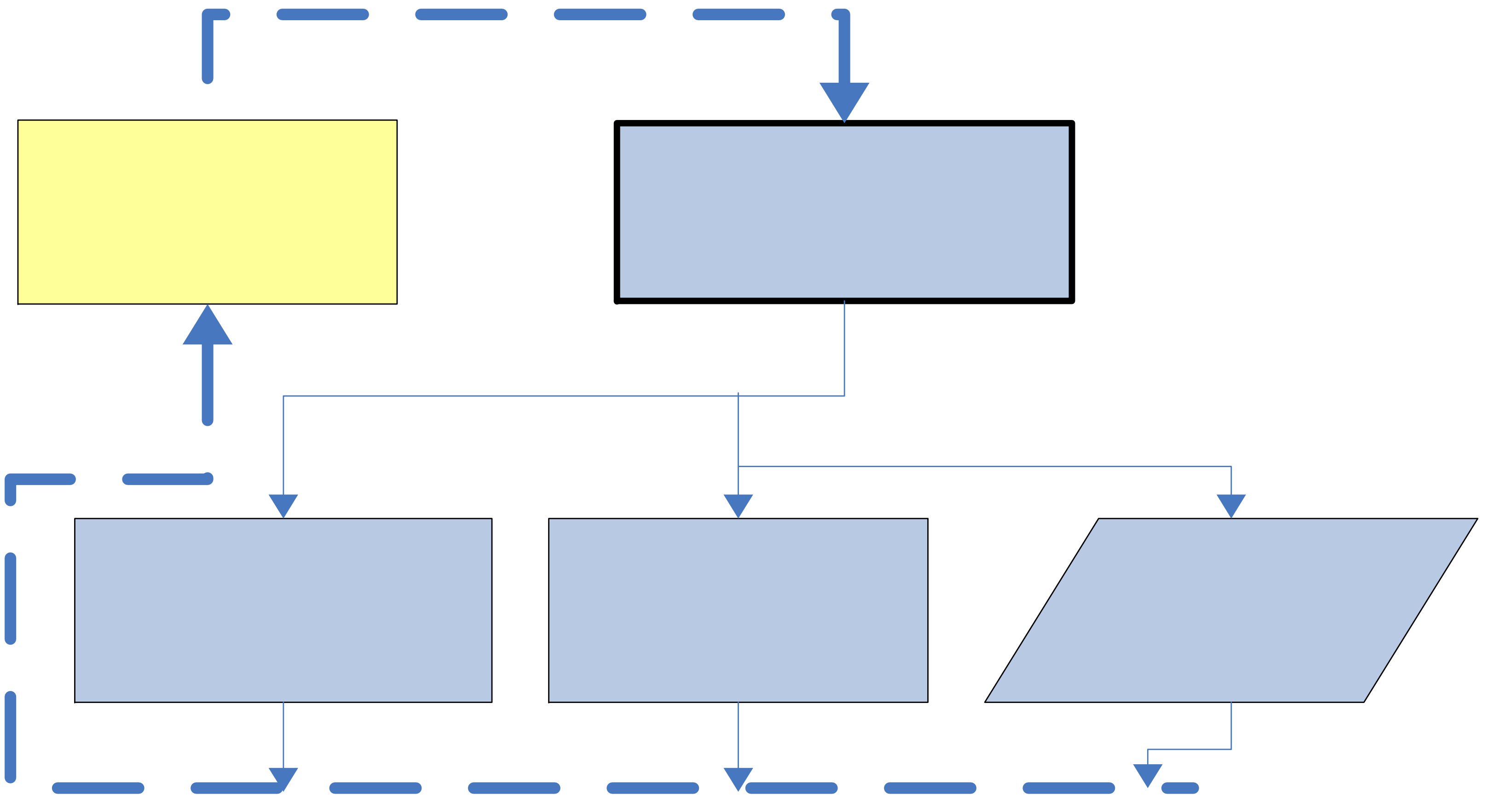
Requirements

System

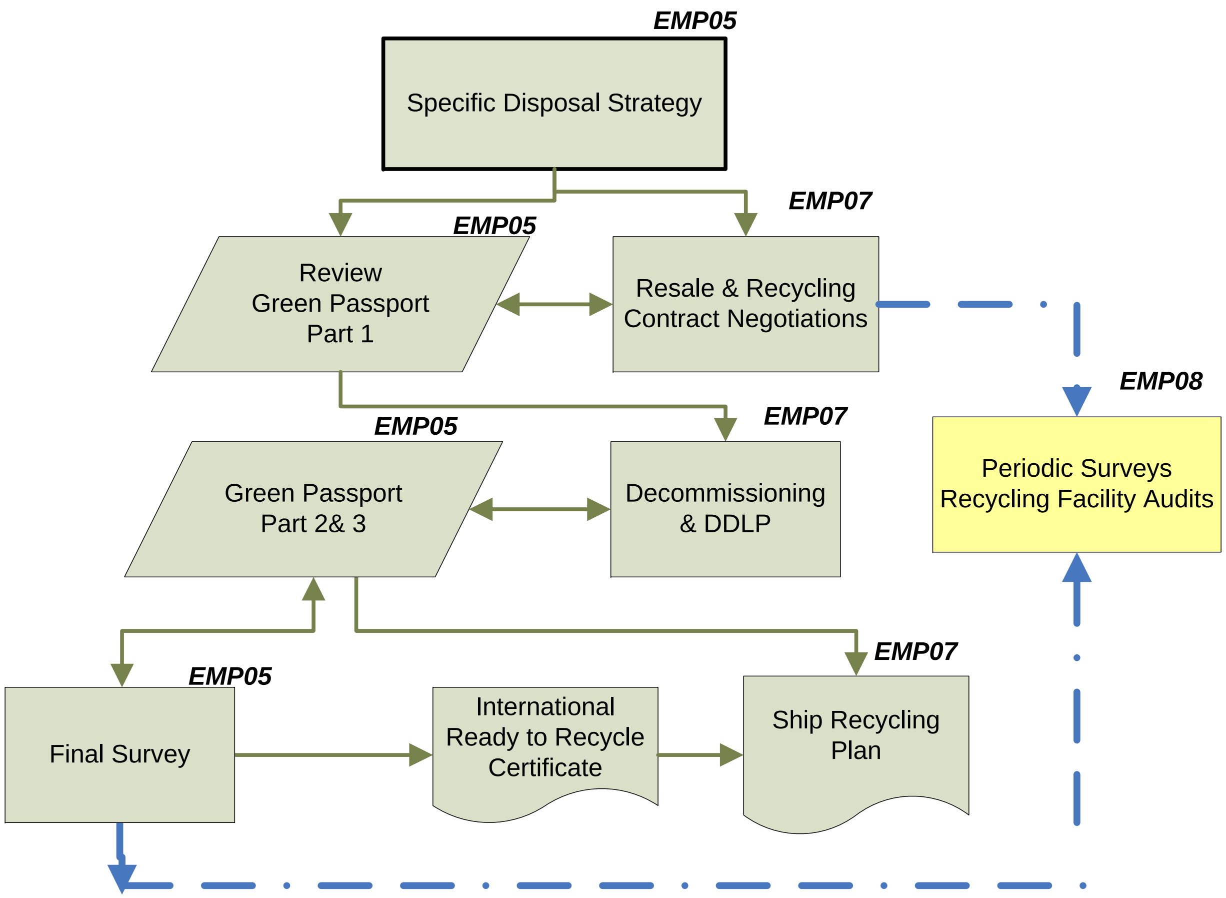
"EISS"

Action

New/ In-Service Vessels



End-of-Life Vessels



Focus on Proactive Action

- Legislation demands it
- Public opinion expects it
- Increased efficiency requires it
- Human health depends on it
- Local ecosystems and global cycles are preserved by it
- Reputation of MOD and Services relies on it
- MOD Policy insists on it

Inaction is Not an Option!

Don't get Bogged Down….

End-of-Life Preparation for Submarines

Dr Trevor Perry CEnv MIEMA

Systems and engineering technology

Finite Element Modeling of Collapse Experiments of Ring Stiffened Cylinders with Simulated Corrosion Damage

L Jiang[1], JR MacKay[2,3], J Wallace[1], MJ Smith[2], M Norwood[1] and TN Bosman[3,4]

1. Martec Limited, Canada

2. Defence R&D Canada – Atlantic, Canada

3. Delft University of Technology, The Netherlands

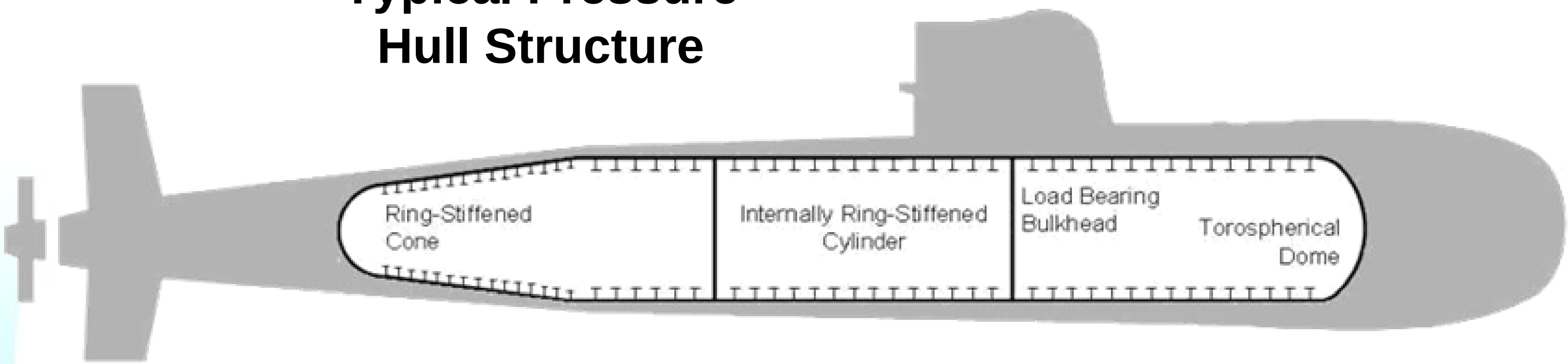
4. TNO Built Environment and Geosciences, The Netherlands

Presentation Outline

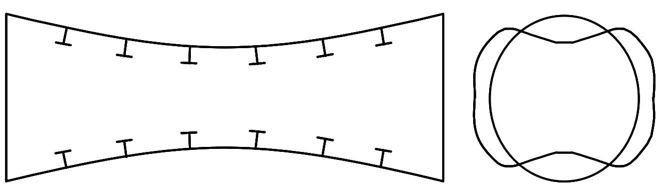
- Introduction
- Experimental collapse testing
- Numerical modeling
- Conclusions

Pressure hull strength and corrosion damage

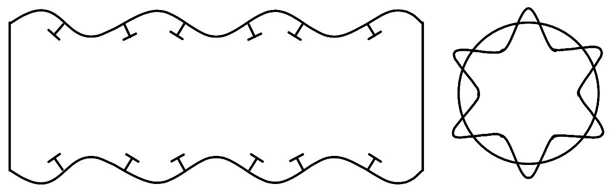
Typical Pressure Hull Structure



Failure Modes for Ring-Stiffened Cylinders



Overall Collapse



Interframe Collapse

- Elasto-plastic collapse sensitive to:
  - geometric imperfections
  - Residual stresses due to fabrication

Cylinder testing program

- CAN/NL collaborative program for destructive testing of ring-stiffened cylinder specimens
- Timeframe: 2005-09

Purpose

- Database for validating submarine structural analysis methods
- Better understanding of corrosion effects on pressure hull strength

Status

- 22 cylinders tested to date
- Approximately 25 additional cylinders will be tested

Cylinder testing program

Test Specimens

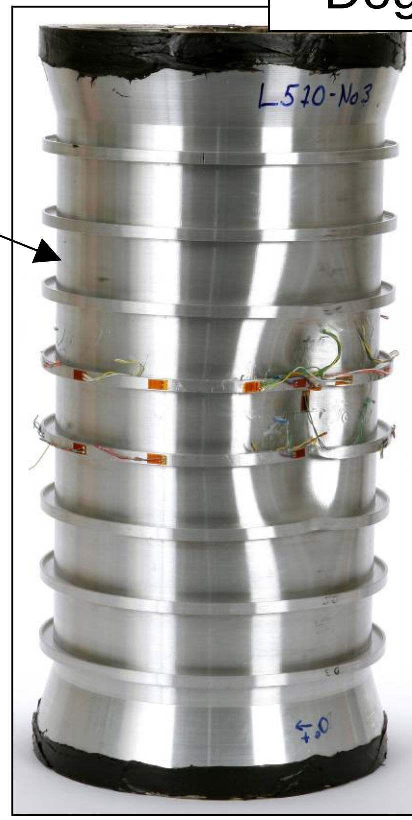
- Designed with collapse properties similar to actual submarine compartments
- Short and long cylinders
- Internally and externally stiffened specimens
- Machined thinning to simulate corrosion
- Strain gauged to measure deformations and stresses
- Specimens machined from solid Al pipe
- Tested at DRDC pressure tank facility

Cylinder Testing Program Results

Short Cylinder with no Corrosion

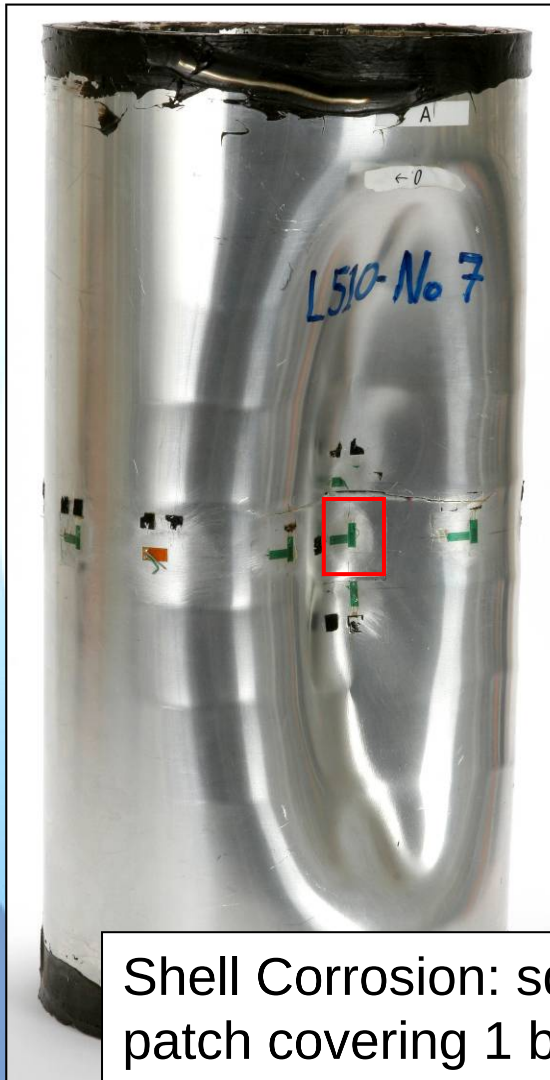
Volume-Control Pressure Testing

Long Cylinder with ‘Dog-bone’ Corrosion

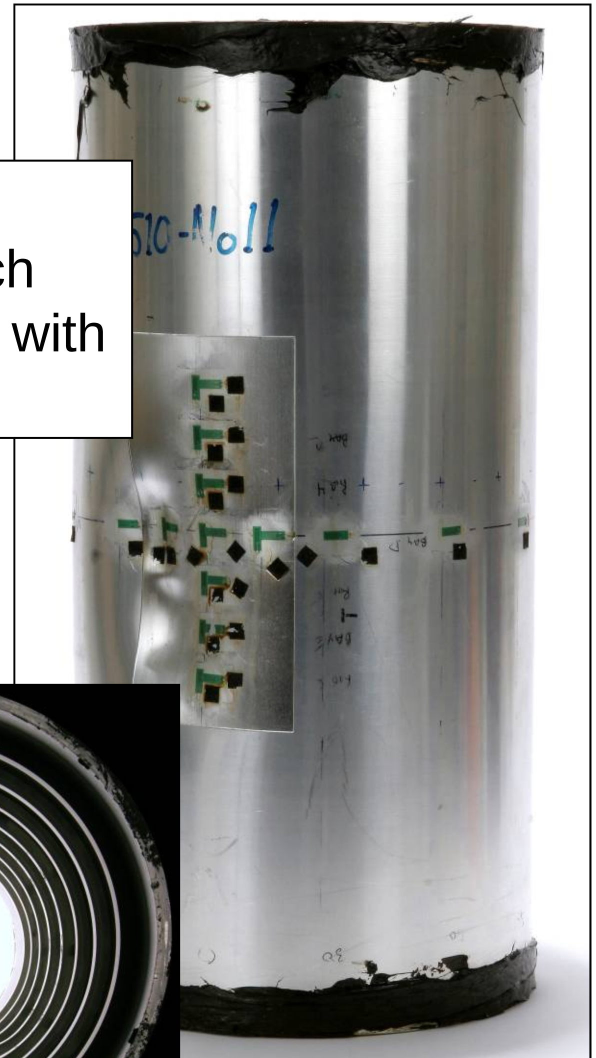


Conventional Pressure Testing

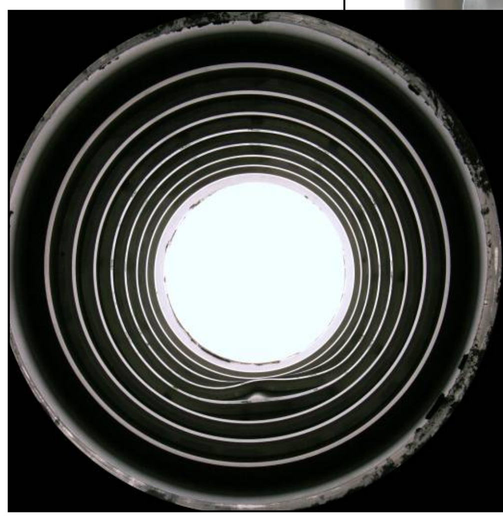
Cylinder Testing Program Results



Shell Corrosion: square patch covering 1 bay with 20% thinning

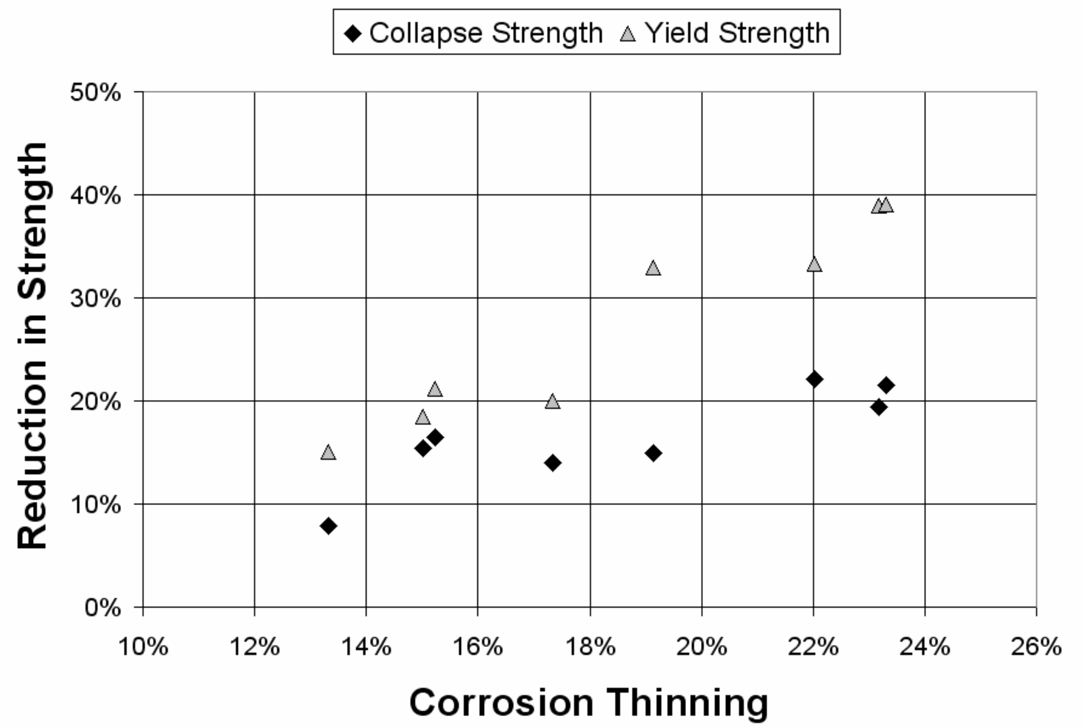


Shell Corrosion: rectangular patch covering 5 bays with 13% thinning



Cylinder Testing Program
Preliminary Conclusions

- Loss of collapse strength due to corrosion is on the order of the shell thinning
- Yield strength is more greatly affected by thinning than collapse strength
- Eccentricity due to one-sided shell thinning may have a strength-reducing effect in addition to the thinning itself
- Magnitude of thinning is more significant for strength considerations than the total volume of material lost to corrosion



Results for cylinders with small amounts of imperfection

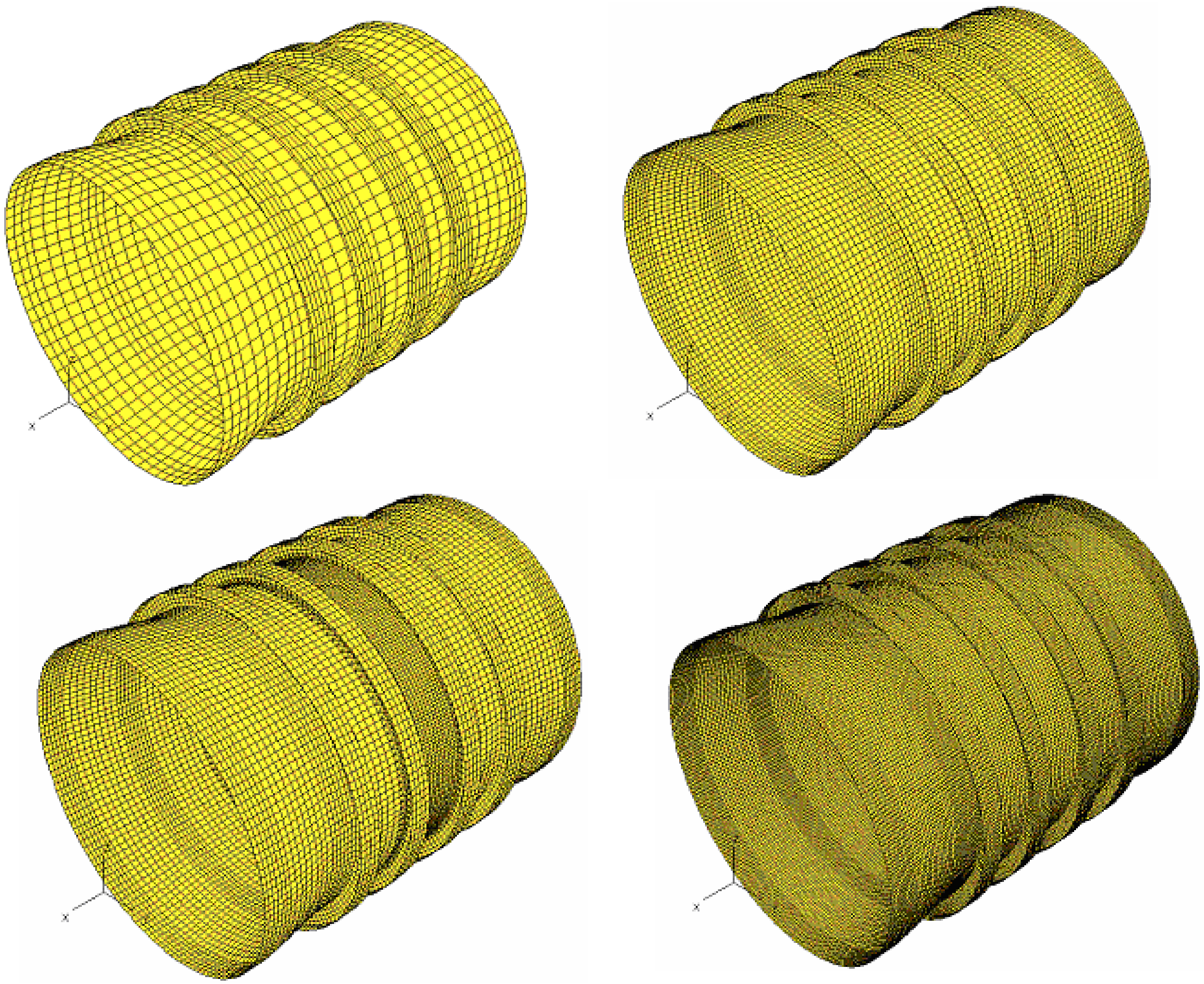
Finite Element Model Generation

- FE models generated by SubSAS program
- Measured geometric imperfections (out-of-circularity) included
- Measured thickness variations included
- Elastic-plastic material properties with bi-linear and multi-linear stress-strain curves extracted from test data
- Clamped boundary conditions to simulate heavy endcaps
- External pressure on shell and equivalent end forces
- Simulated corrosions in shell were modeled by reducing thickness and applying offset
- Mesh density determined through convergence study

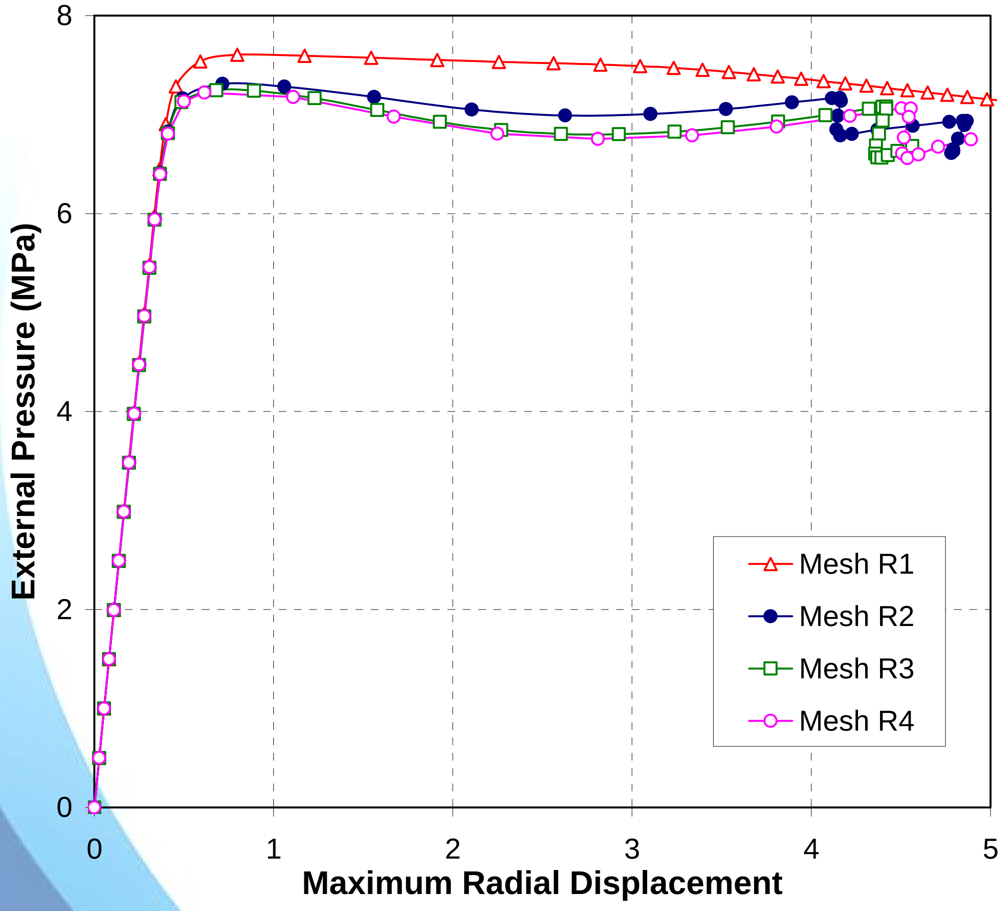
Finite Element Solver

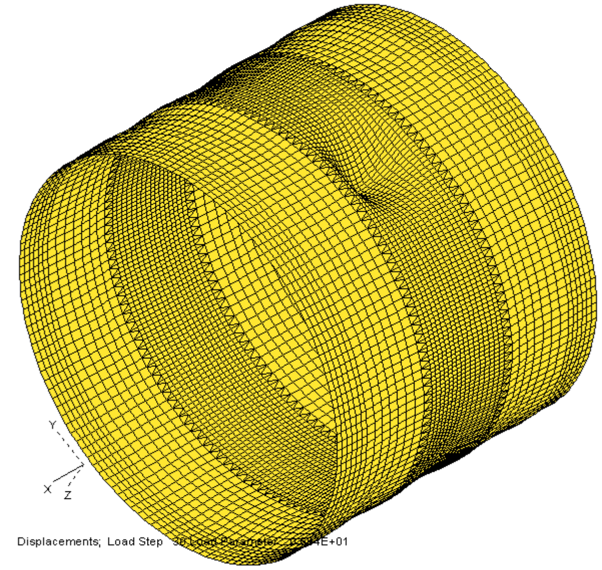
- VAST: a general-purpose nonlinear finite element program developed by Martec over the past 30 years in partnership with DRDC Atlantic
- Four-noded quadrilateral shell element with mixed interpolation of transverse strain component (MITC4)
- Consistent co-rotational formulation used for geometric nonlinearity
- J_2-flow theory used for elastic-plastic material property
- Overlay model used to represent multi-linear stress-strain properties
- Orthogonal trajectory solution procedure used to obtain solution in the post-collapse range

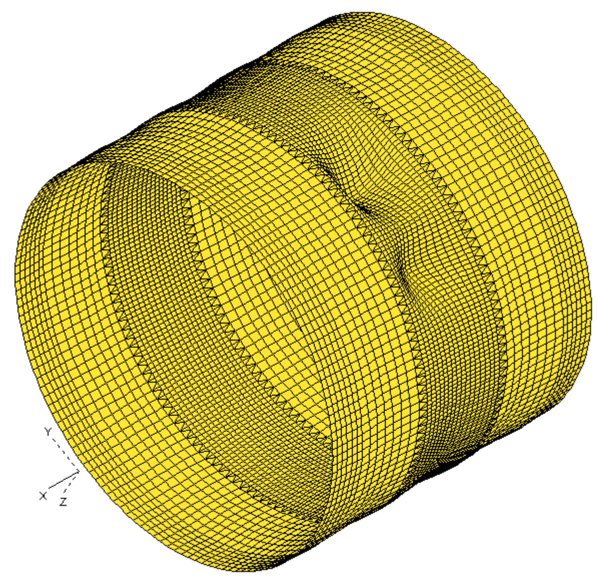
Short Cylinders with External Stiffeners



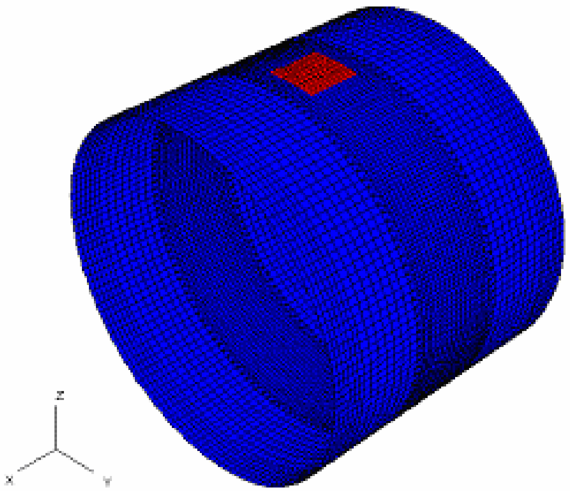
Short Cylinders with External Stiffeners

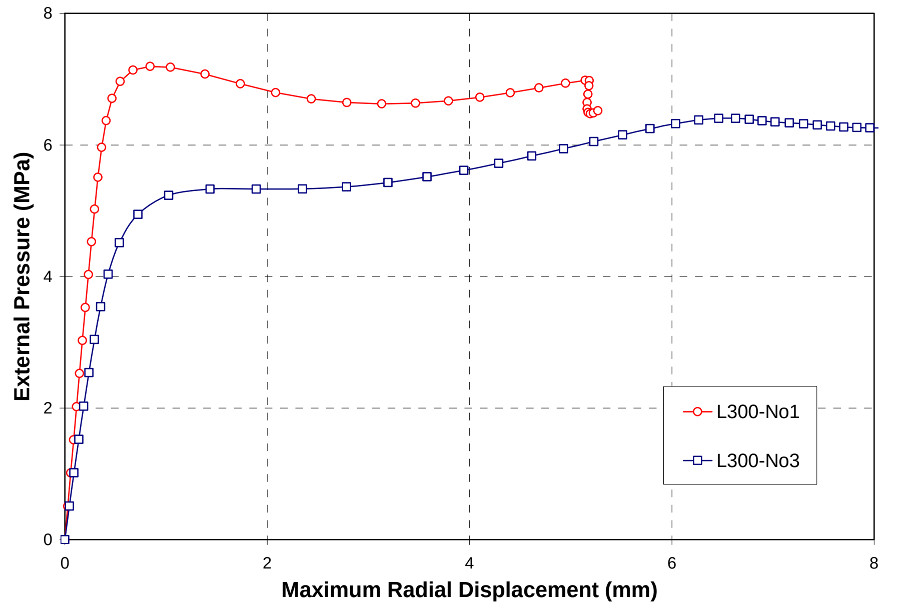


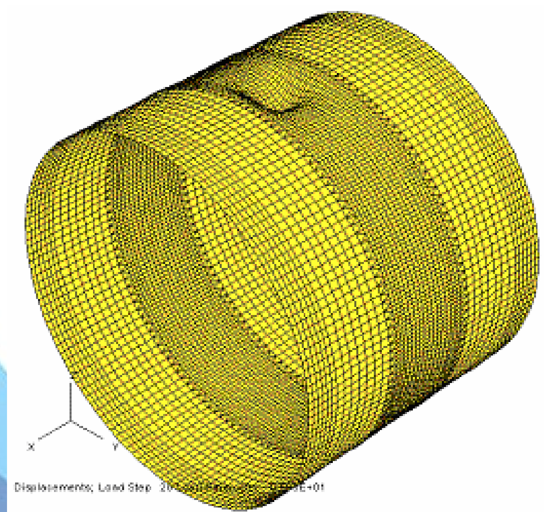


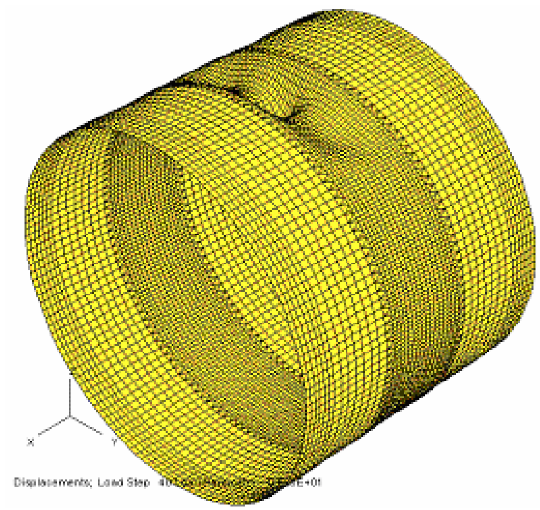


Short Cylinders with External Stiffeners

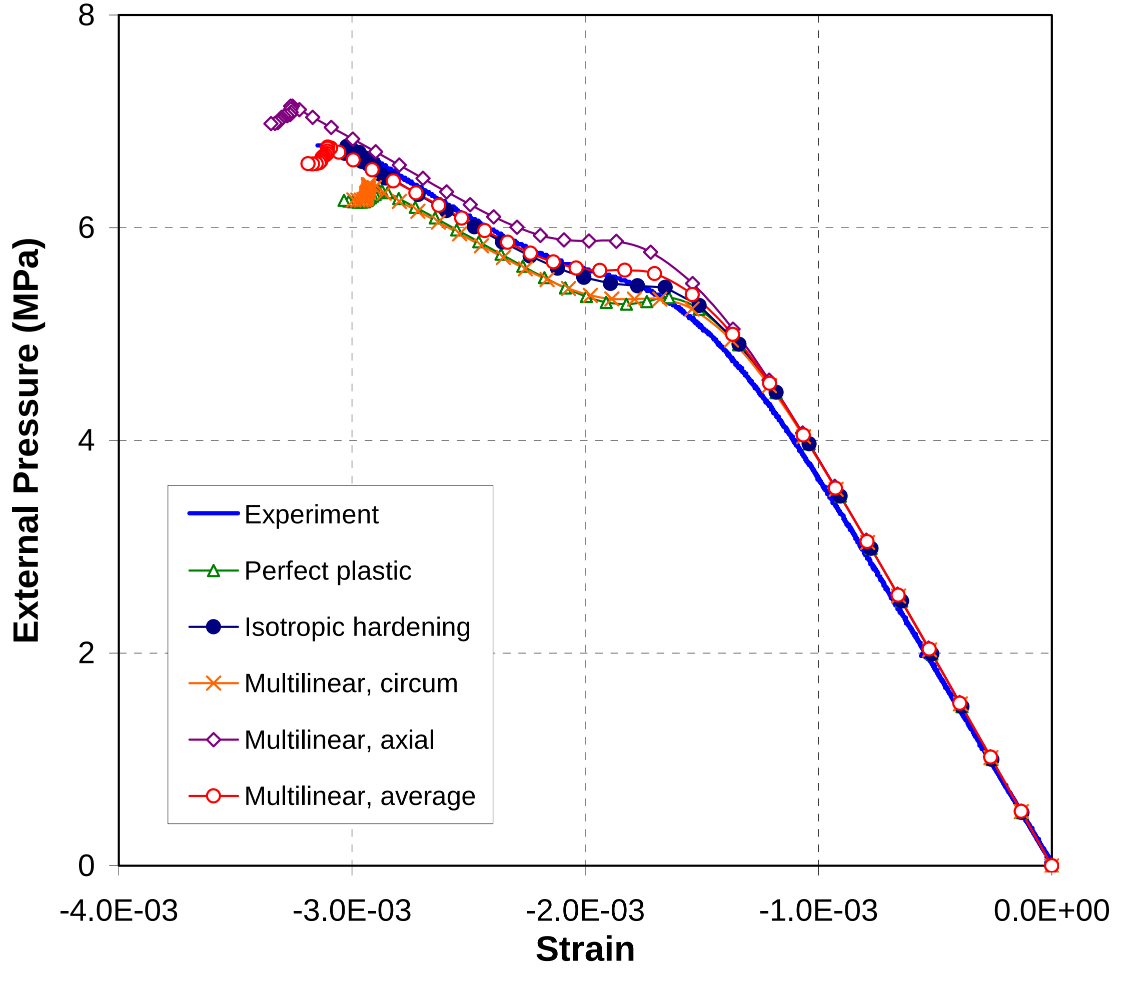






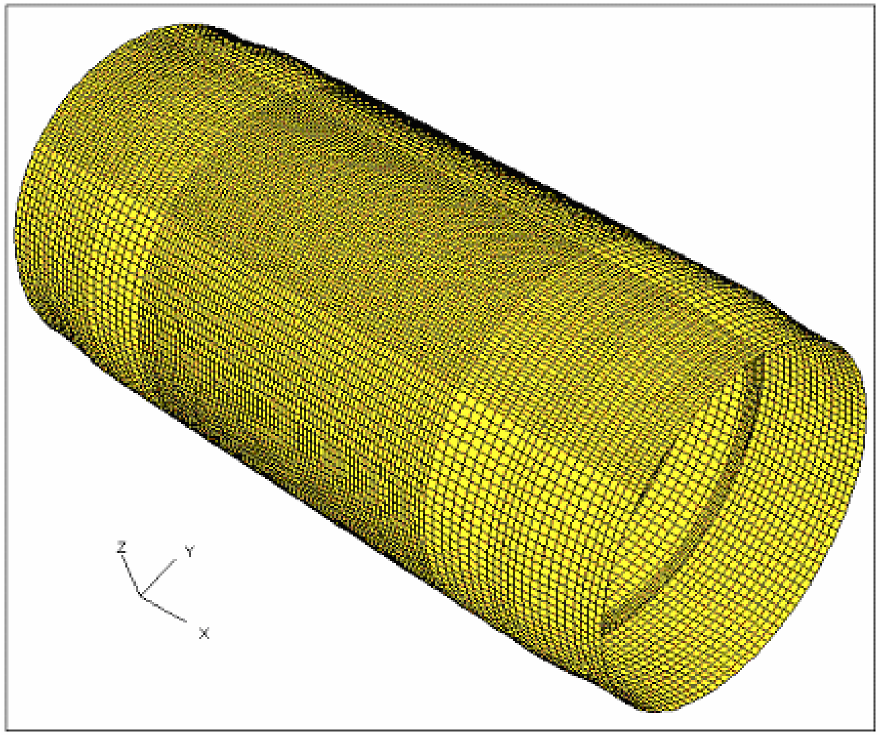


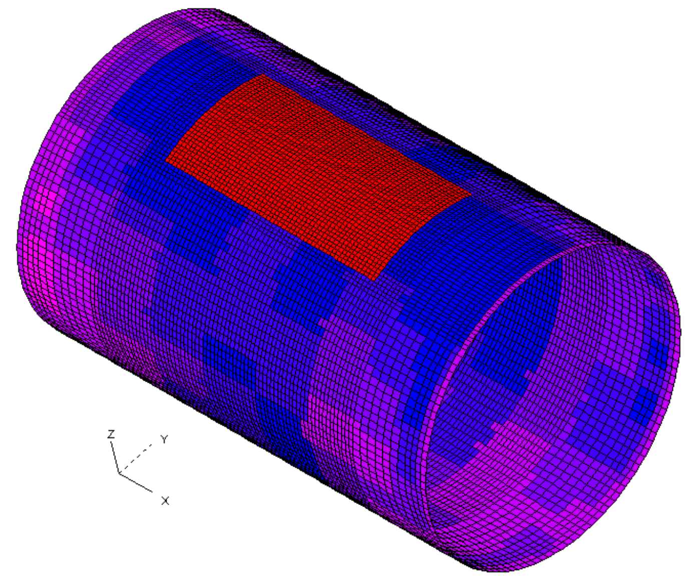
Short Cylinders with External Stiffeners



Circum. Strain in Flange of Frame # 2

Long Cylinders with Internal Stiffeners





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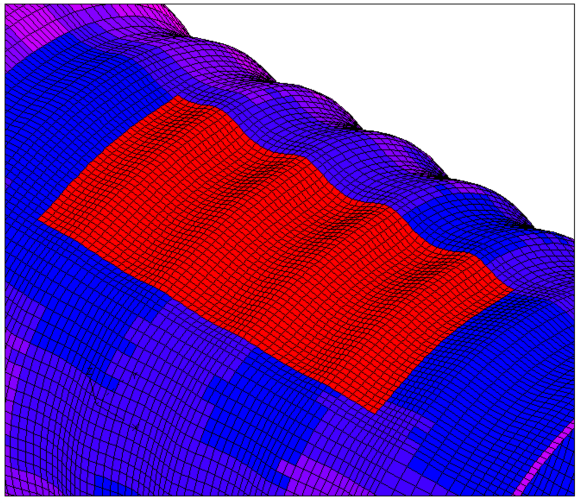
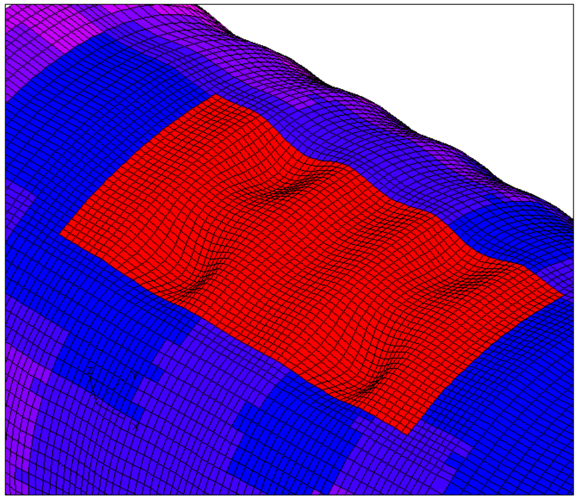
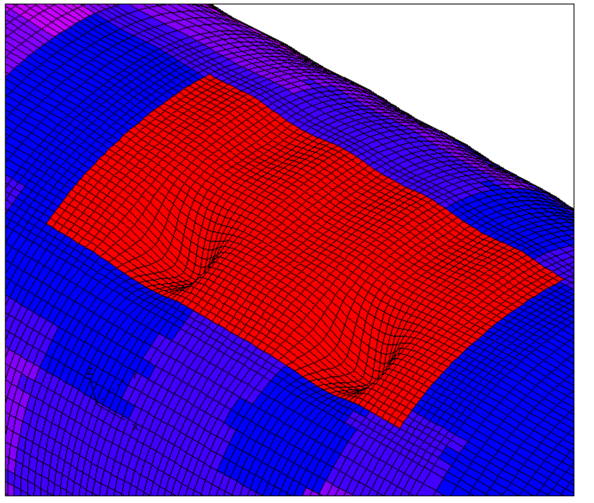
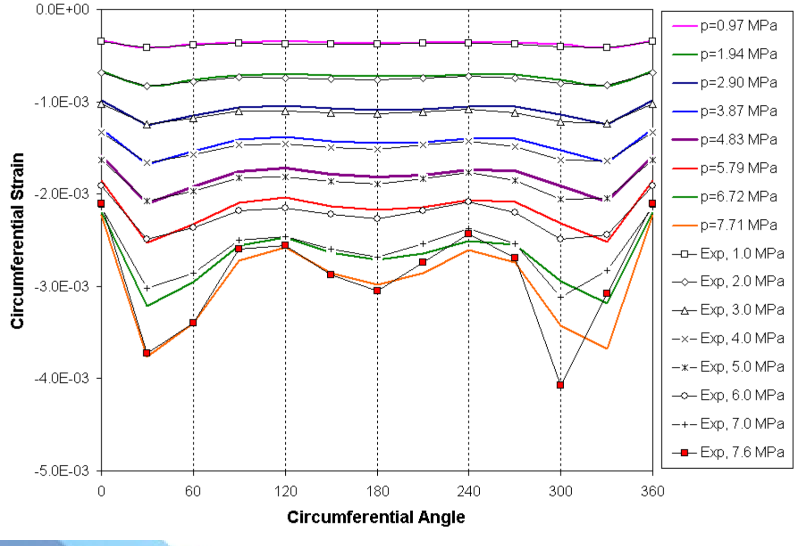
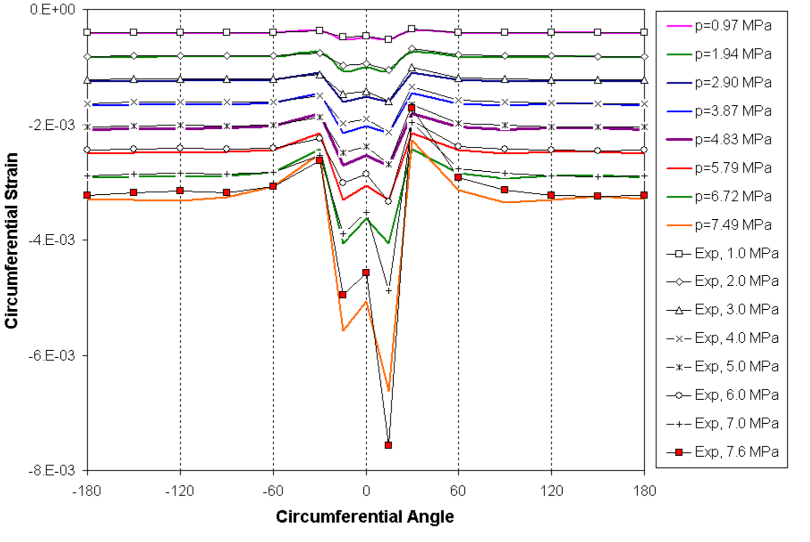
Long Cylinders with Internal Stiffeners



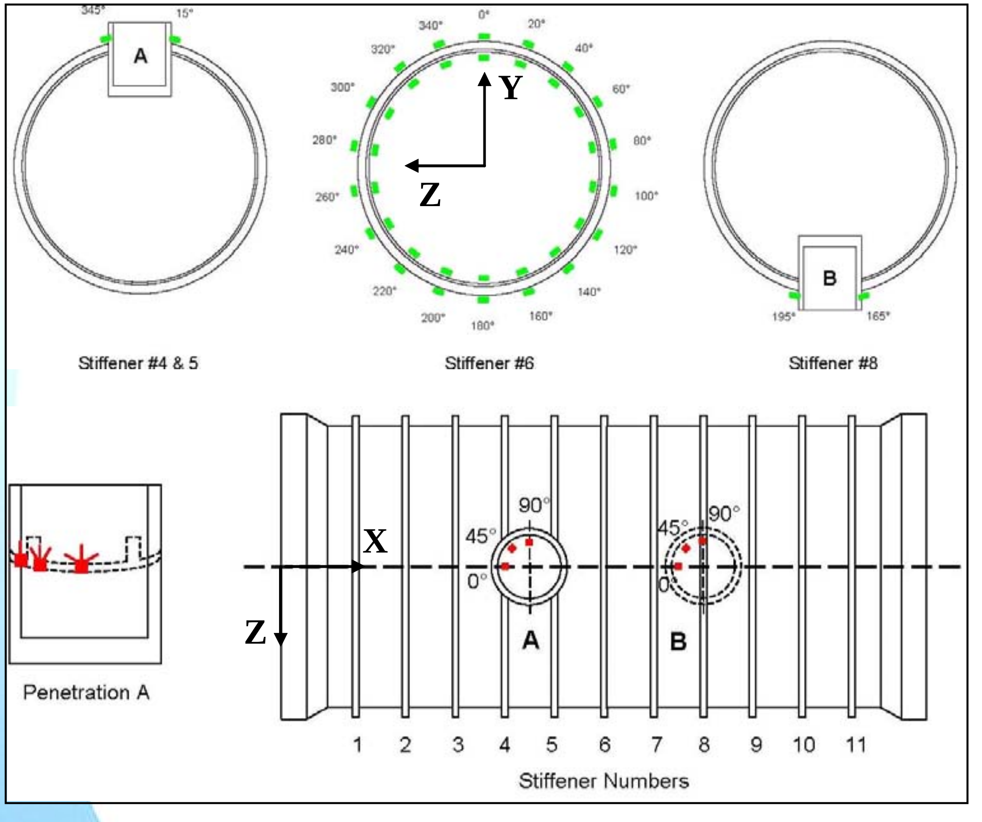


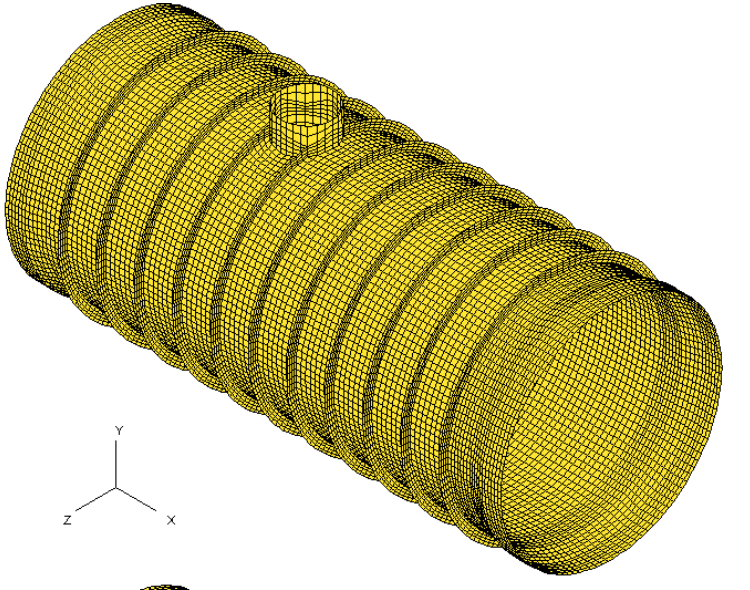


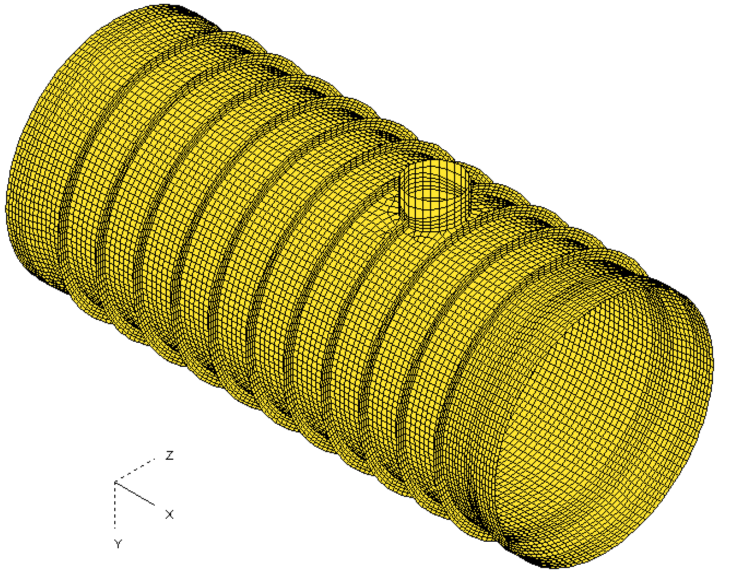




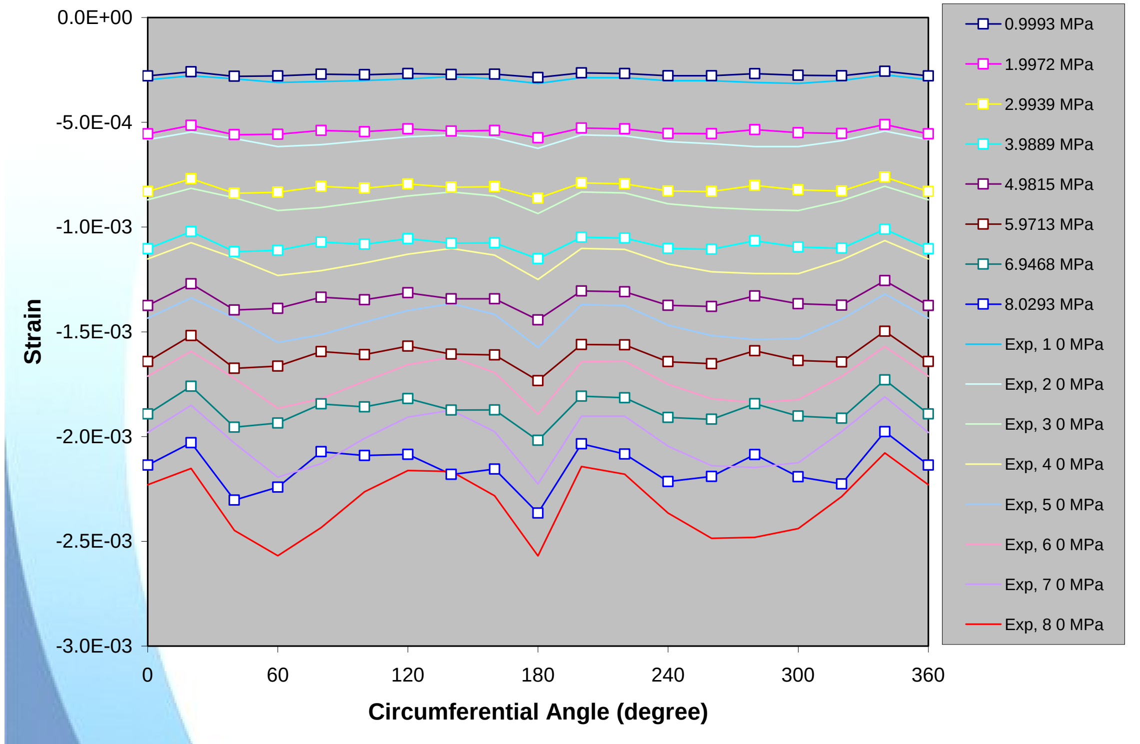
Cylinder with Penetrations



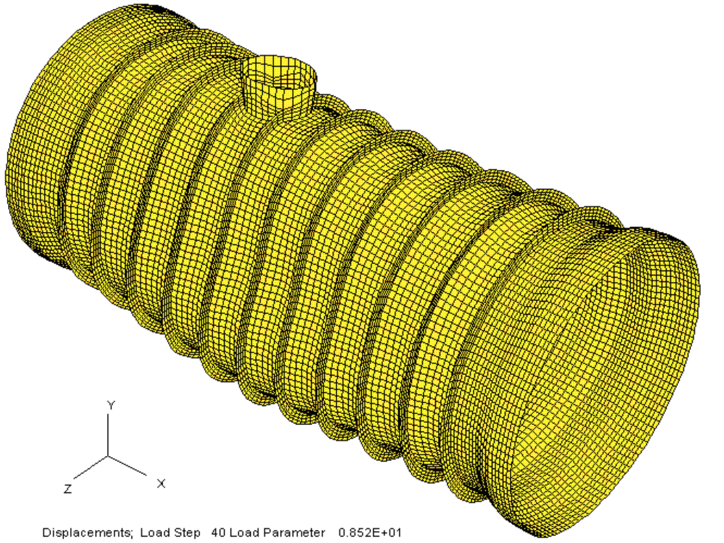


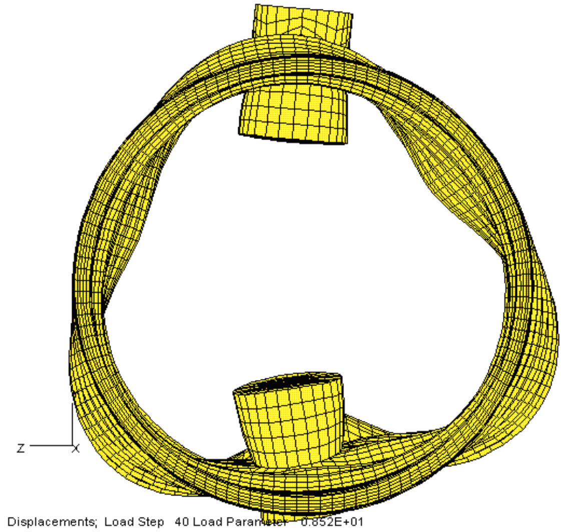


Cylinder with Penetrations



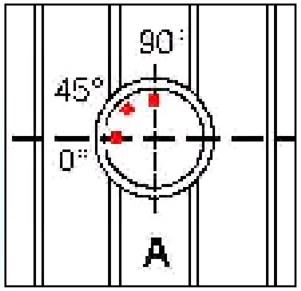
Circum. Strain in Frame # 6

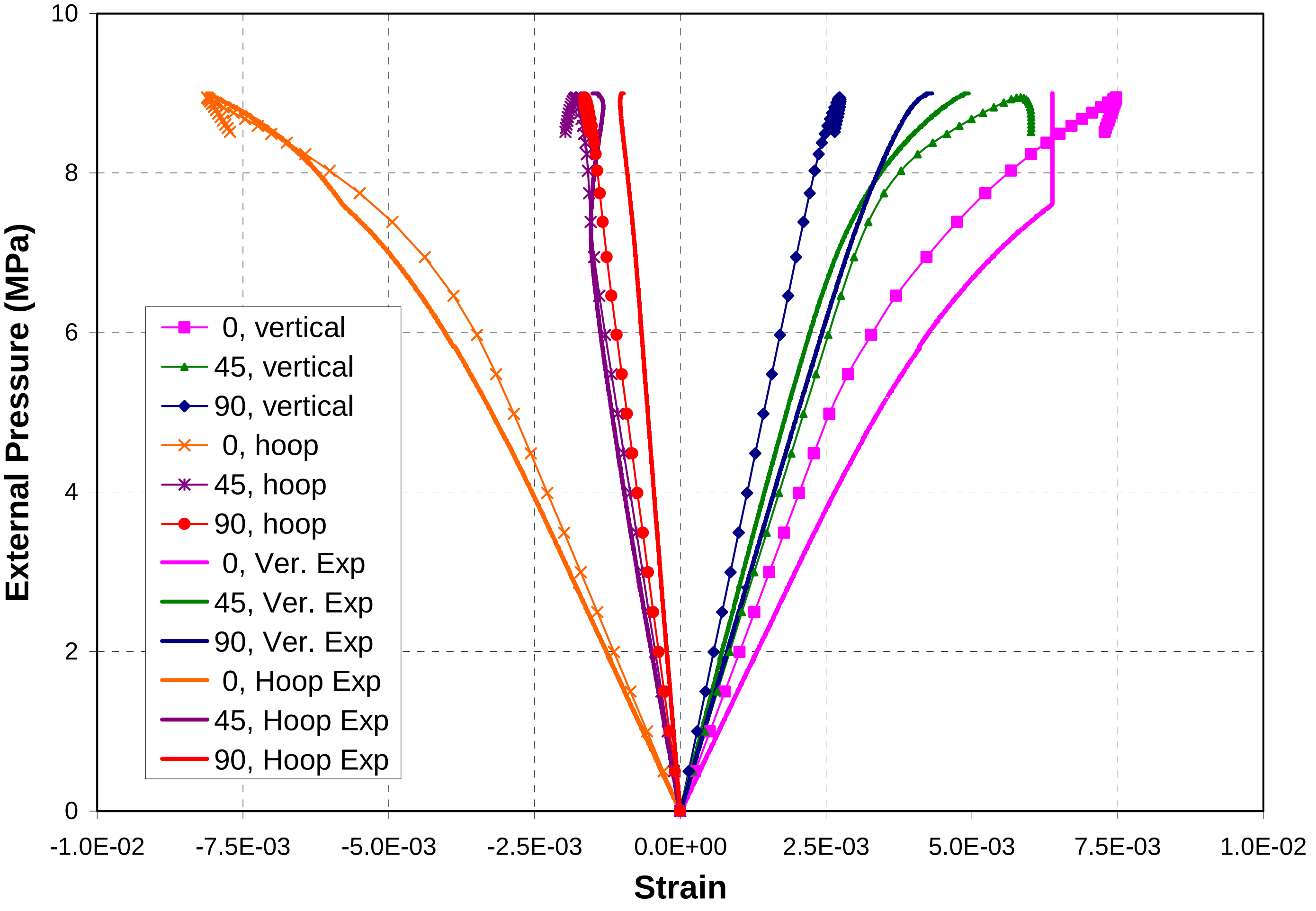




Displacements; Load Step 40 Load Parameter 0.852E+01

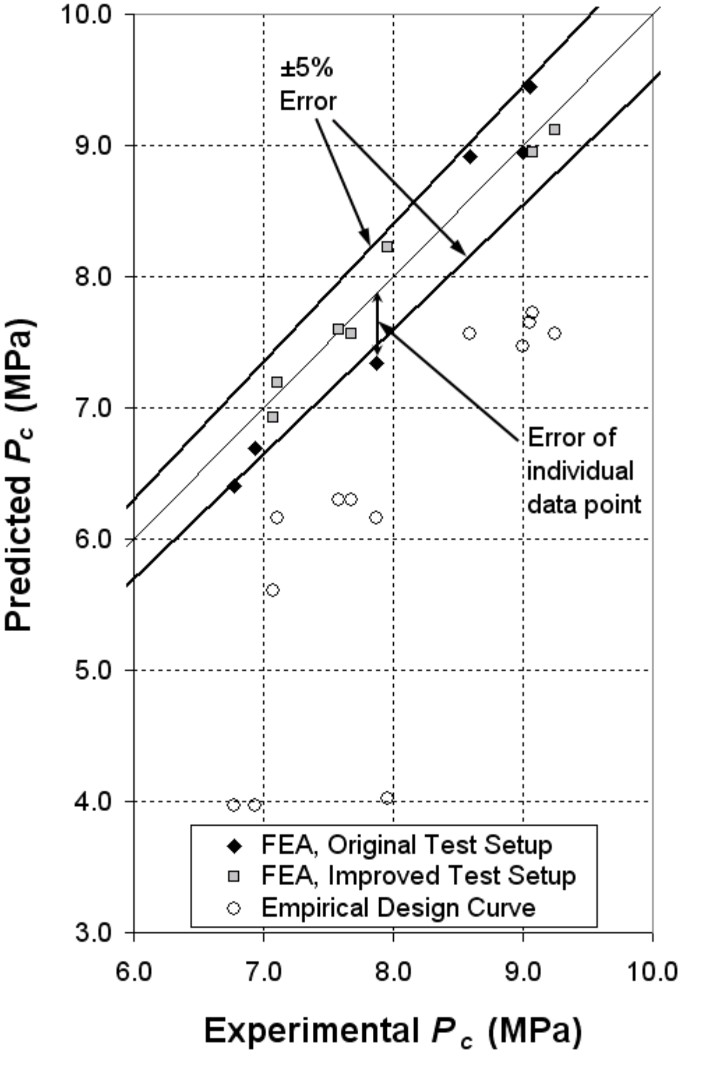
Cylinder with Penetrations





Summary of Finite Element Results

- For most test cylinders, the predicted collapse pressure is in ±5% of the experimental data
- Better agreement achieved for cylinders tested using the improved test setup
- Finite element predicted strength reduction due to corrosion also agrees with the test results
- Empirical design curve underestimates strength of test cylinders by 23%.



Conclusions and Future Work

- The FE modeling and analysis methods utilized in the present work, i.e. using SubSAS and VAST, are capable of predicting the experimental collapse pressure and failure mode accurately.
- The FE results indicated that the predicted failure modes are most sensitive to the thickness variations, whereas the pressure-displacement behavior is most significantly influenced by the material modeling parameters.
- An anisotropic plasticity model should be implemented and employed in future analyses.
- Additional FE results are required to establish partial safety factors applicable to FE predictions, which is an important step towards definition of FE modeling and analysis guidelines for pressure hull structures.

Questions?

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CONSULTANCY

Future Corrosion Signatures Modelling

AJ Keddie, S Harrison, MD Pocock

Systems and engineering technology

Overview

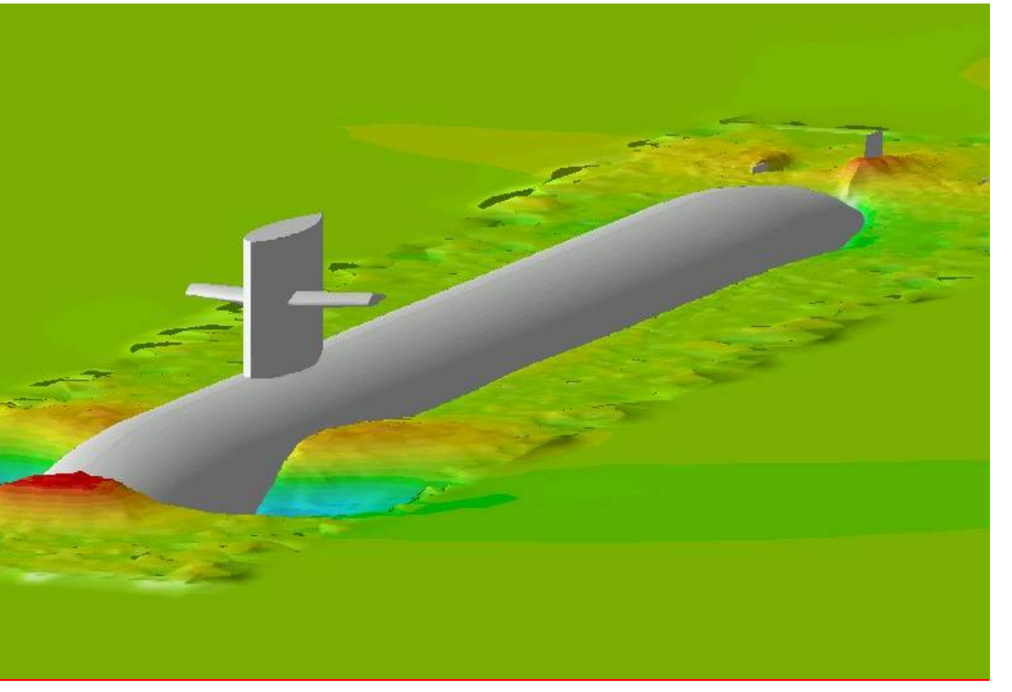
- Complex ICCP Systems
- Computational Optimisation
  - Fast Multipole Method
  - Surrogate Optimisation
- Corrosion Modelling Electrochemistry
  - Crevice Corrosion
  - Crevice Model

Introduction

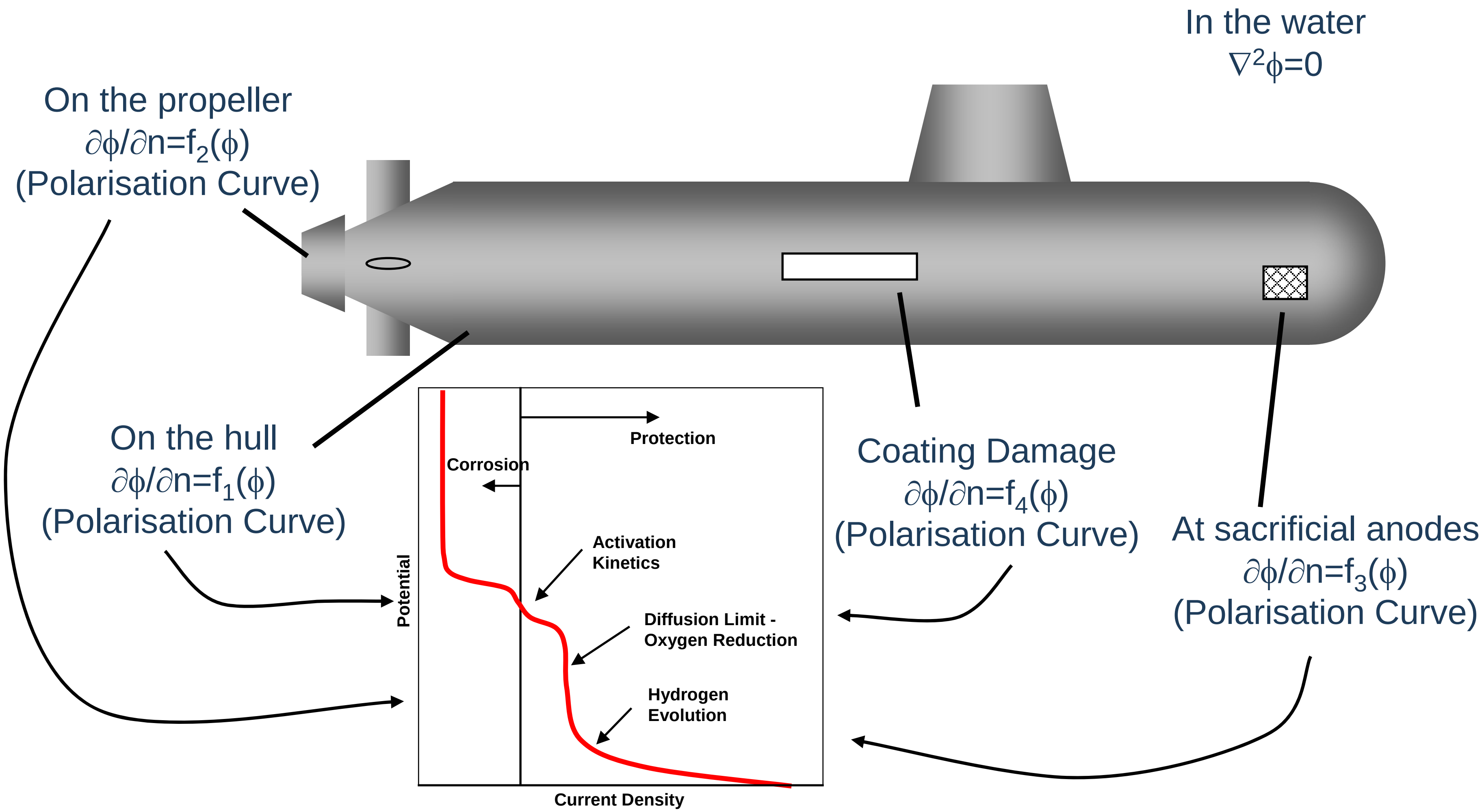
- Reducing signatures crucial
- Computational tools allow designers to predict and minimise the signature of a submarine
- Accuracy of computational tools must improve as signatures reduce
- Signatures intimately linked to corrosion

Modelling

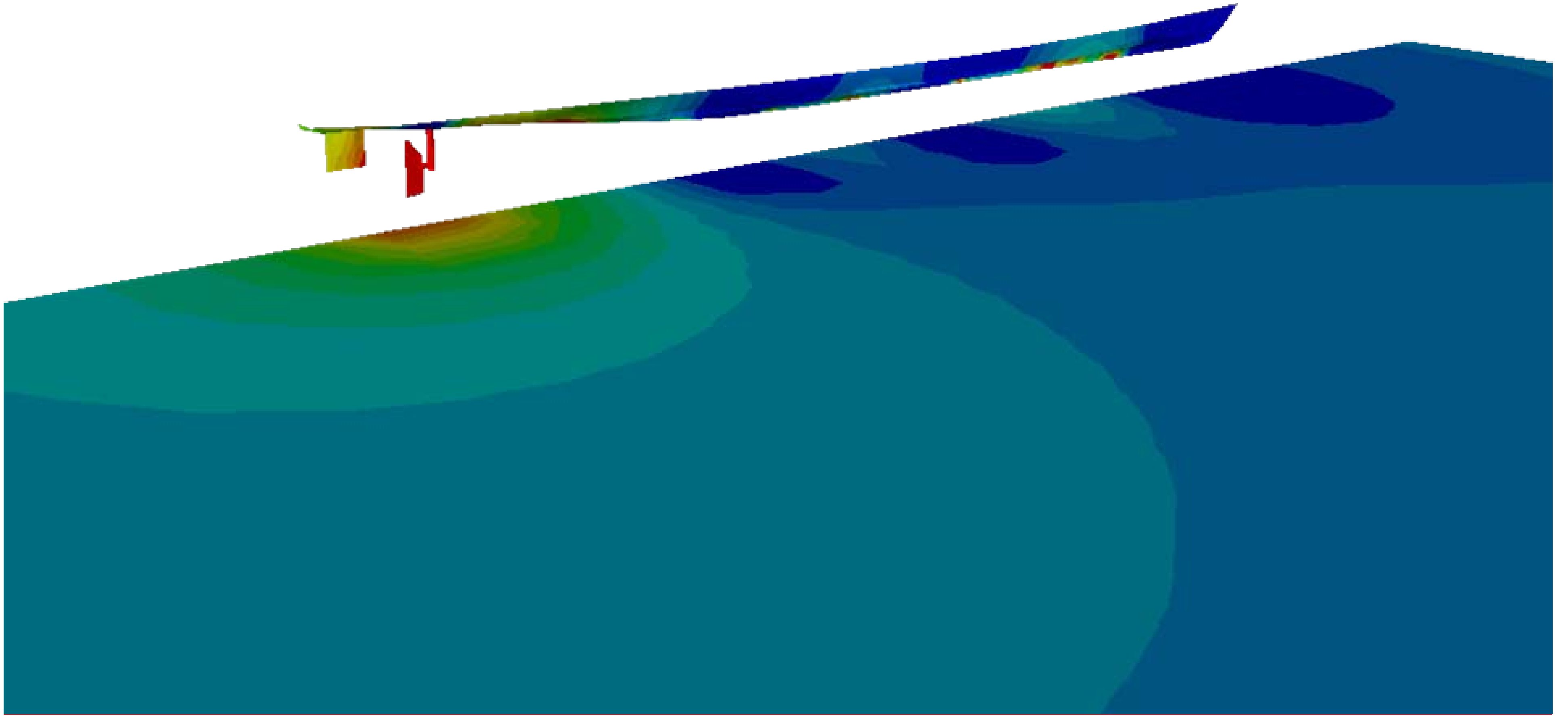
- Why model
  - Understand sensitivities
  - ‘What if …’
  - Obtain confidence in design concepts through to in-service modifications
- Model the extremes
- Need to assess model quality
  - Convergence tests
  - Experimental trials
- Best to combine numerical and physical modelling



Corrosion and Signature Modelling - Diagram



Sample Solution



ICCP Systems

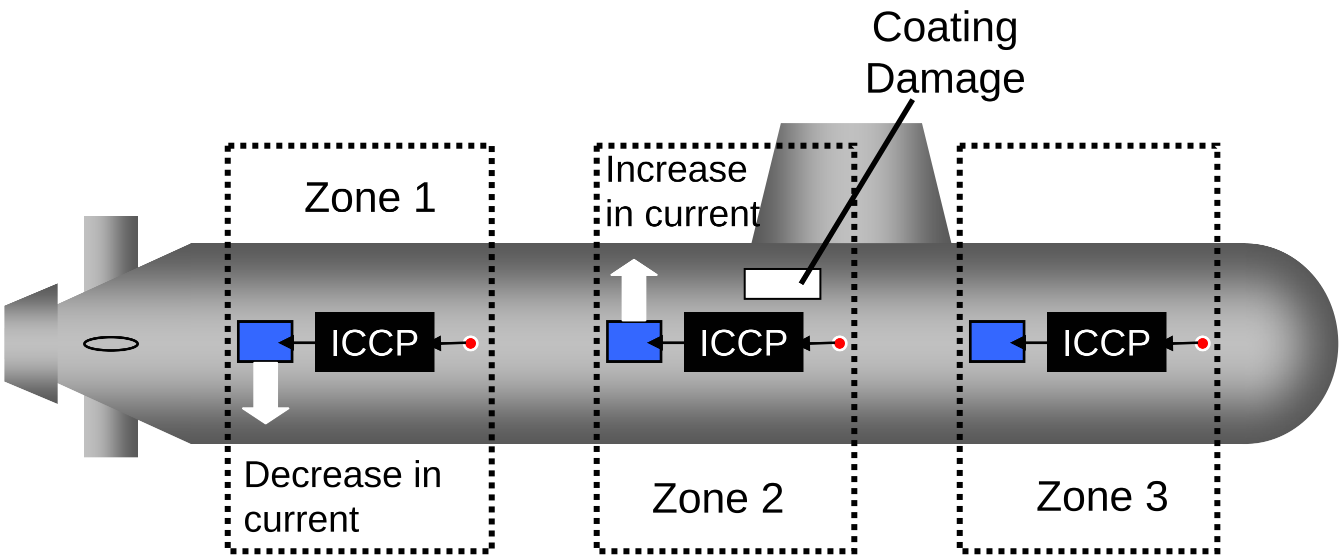
- Must react to changes to maintain cathodic protection and keep signature low
  - No point having active system if it does not react
- The ICCP must not over-react
  - The slightest change might make things much worse than a passive system
- Two types of ICCP system to consider
  - Zonal ICCP systems
  - Complex ICCP systems

Zonal ICCP Systems

- Each zone consists of:
  - Anode(s) connected to a power supply
  - Reference cell(s) to monitor the hull potential
  - A controller to adjust the current output of the anode(s)
- A control algorithm exists for each zone
- Instabilities
  - ICCP zones are not independent
  - A change in current in one zone will affect reference electrodes in other zones

Zonal ICCP Systems – Example

- 3-Zone ICCP System
- Coating damage close to one reference electrode can have an undesired effect on surrounding anodes
- Can result in poor CP or large signature

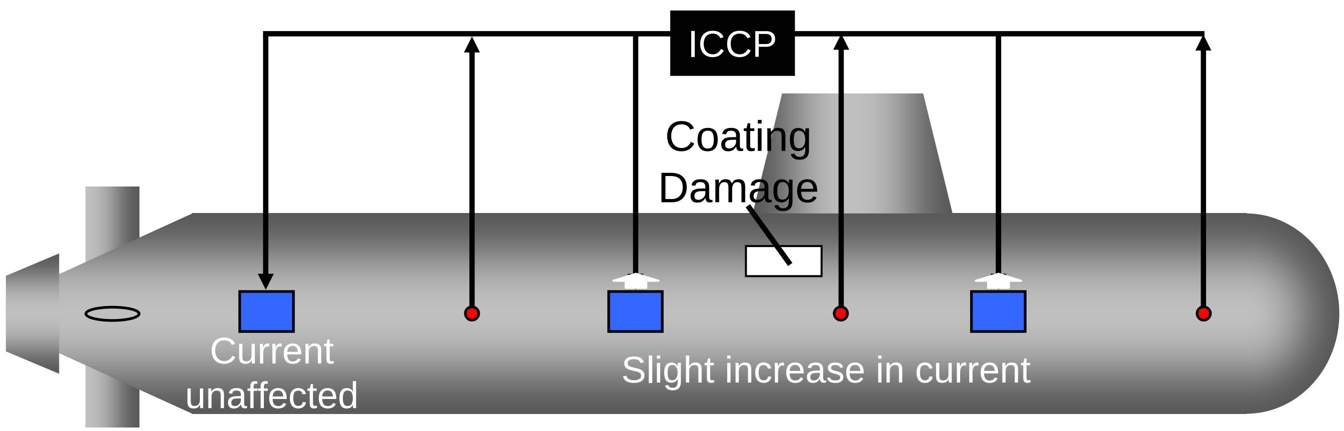


Complex ICCP Systems

- Consists of:
  - Anode(s) connected to a power supply
  - Reference cell(s) to monitor the hull potential
  - A controller to adjust the current output of the anode(s)
- All anodes are regulated by a single controller
- Single algorithm used to model complex system
- Incorporated into FN*REMUS*

Complex ICCP Systems – Example

- Complex ICCP zone
  - 3 anodes and 3 references electrodes
- Anodes ‘work together’ to reduce corrosion and/or signatures



Corrosion and Signature Modelling

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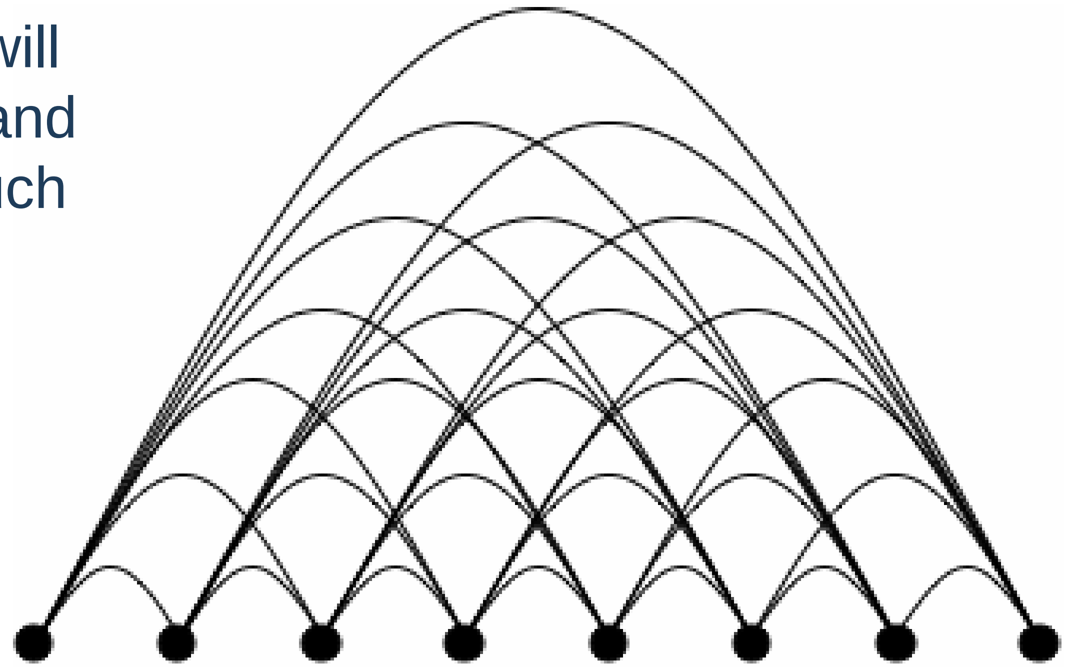
- Traditional computational methods expensive
  - Problem size must be sacrificed
  - Unable to model areas of interest
  - Accuracy of predicted corrosion and signatures compromised
- Optimised computational tools
  - Allow problems to be run quicker
  - Allow areas of interest to be modelled in desired resolution
  - Allow ‘what if...’ type scenarios to be run

Numerical Modelling

- Iterate between polarisation curves and Laplace's Equation
- Laplace's Equation
  - Calculates surface potential
  - Bottleneck!
  - FE previously used to solve Laplace's Equation
    - Seawater is an infinite domain
    - Prohibitively large models required for suitable accuracy
  - Boundary Element Method (BEM) used more recently
    - Requires modelling only the submarine surface
    - Boundary subdivided into elements and nodes (N)

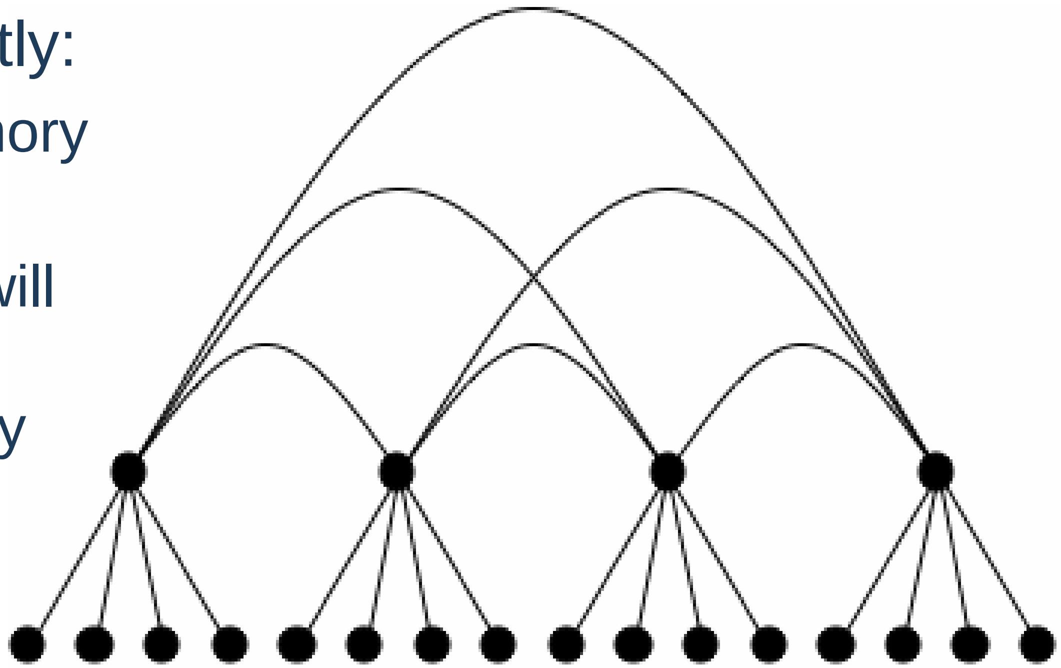
BEM Solution

- Requires solving a system of N linear algebraic equations
- All nodes interact with each other resulting in N^2 interactions
- Solving equations indirectly:
  - Computational and memory costs scale with order N^2
  - A problem twice as big will take four times as long and require four times as much memory



Fast Multipole Method

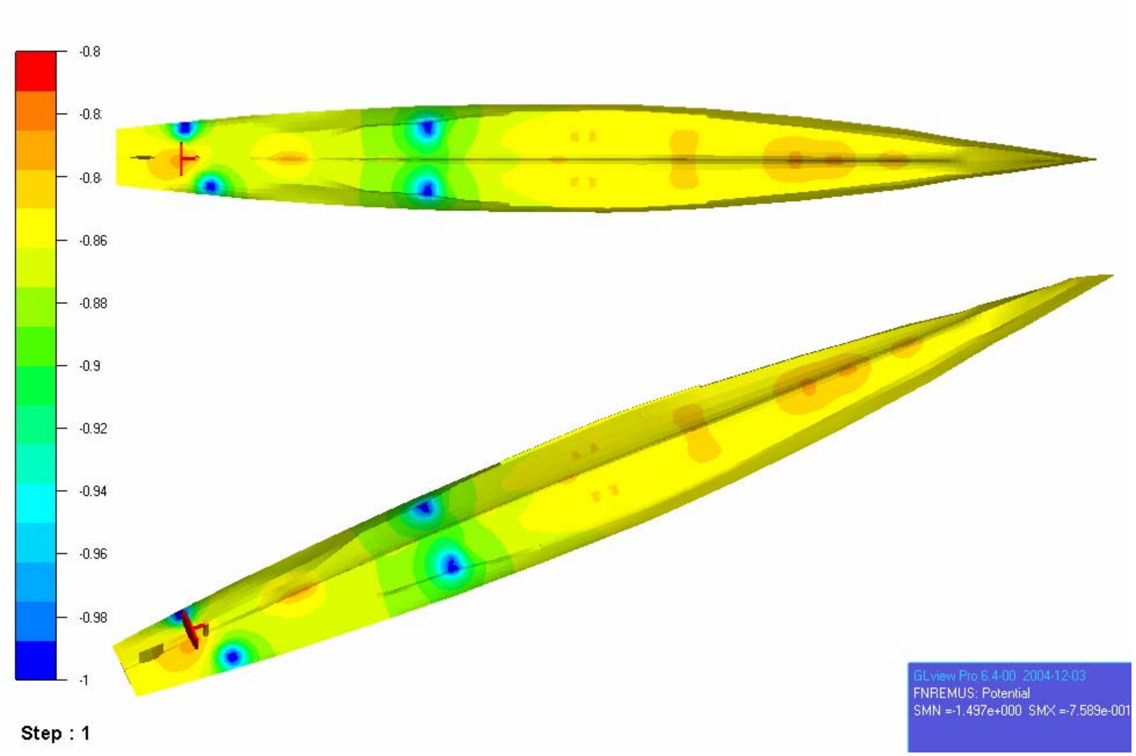
- An accelerated form of the BEM
- Nodes averaged to produce “pseudo-particles”
- Pseudo-particles interact with each other resulting in order N interactions
- Solving equations indirectly:
  - Computational and memory costs scale with order N
  - A problem twice as big will take twice as long and require twice the memory



Example

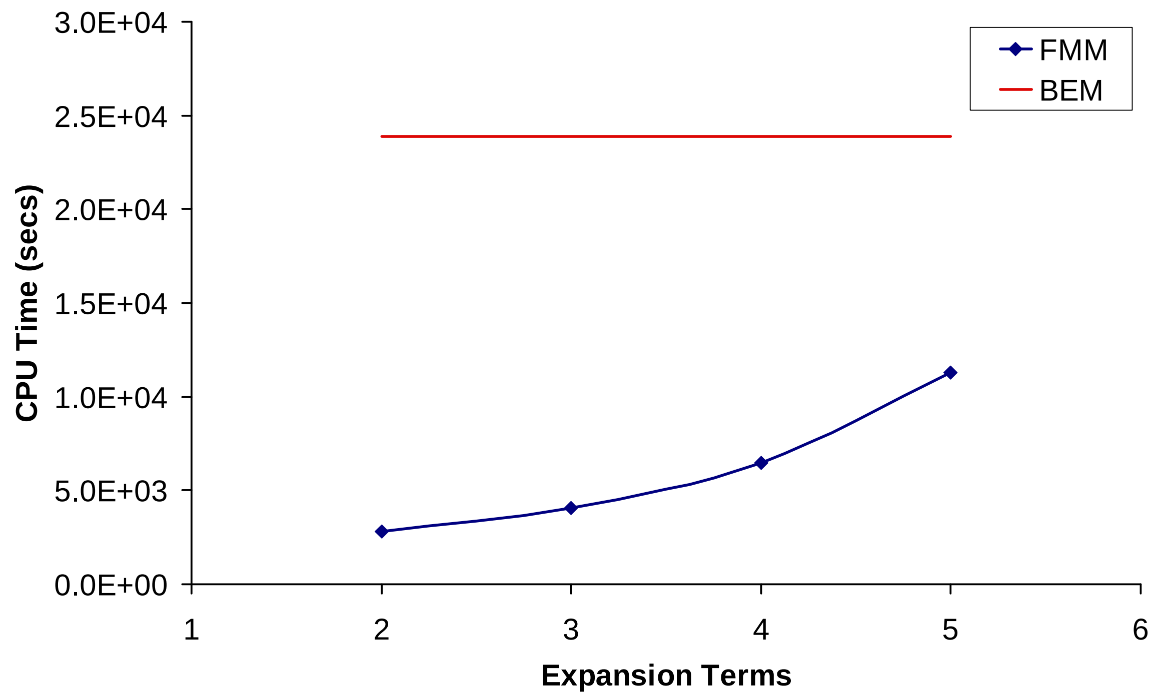
From ‘Fast Solution Techniques for Corrosion and Signatures Modelling’ A. J. Keddie et al, Electrocor 2007

- Ship hull
- ICCP System Turned On
  - Model includes controller and reference electrodes
- Approximately 3,600 elements and 15,000 Nodes
- Solved using FMM and BEM versions of FN*REMUS*
- Physical scale model results also exist



Computational Performance

- FMM up to eight times as fast as BEM
- Accuracy improved by increasing the number of expansion terms
- Allows for sensitivity analyses to be undertaken
- Cost savings more evident as problem size increases



Surrogate Optimisation

- Further speed up available using surrogate models
- Require fewer function evaluations
- Suited to iterative procedures including:
  - Solving the Laplace matrix equations
  - Iterating between Laplace solver and polarisation curves
- Successfully incorporated into other Frazer-Nash codes
- Research undertaken to employ within FN*REMUS*

Corrosion Modelling Electrochemistry

- Present platforms for corrosion modelling represent seawater, coatings and corroding steel as coupled electrical resistors
- Interactions between coupled resistors analysed using Laplace's equation
- Electrochemical corrosion reactions of metallic surfaces modelled as non-linear resistors using polarisation curves
- Reasonable for the overall effects of corrosion of a submerged structure in a large volume of electrolyte

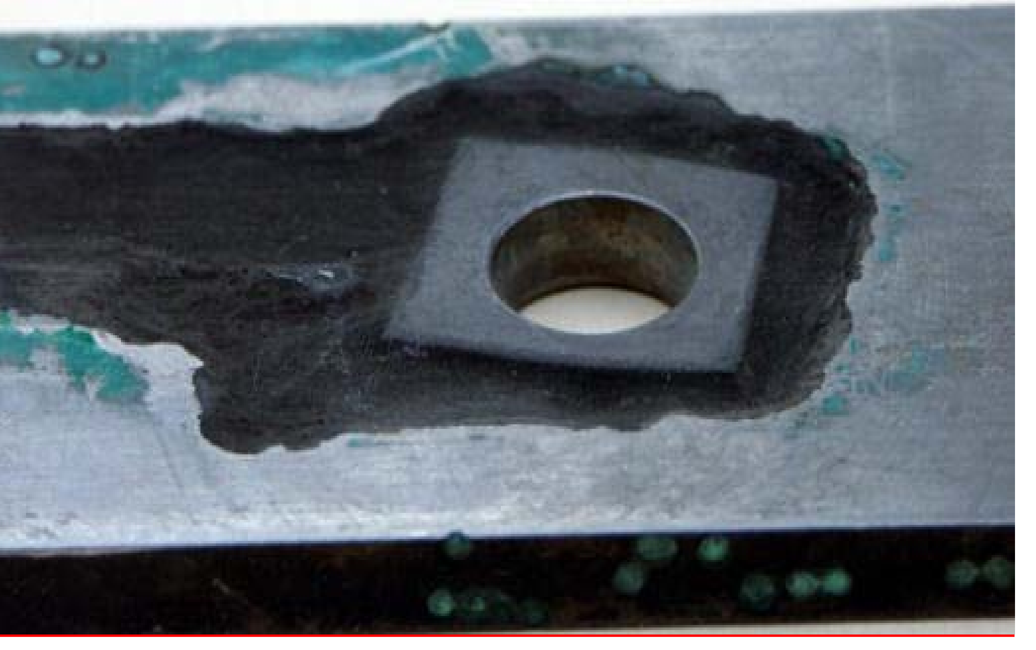
Corrosion Modelling Electrochemistry

FRAZER-NASH CONSULTANCY

- Simplified representation of electrochemistry unable to deal with issues of seawater chemistry
  - Laplace approach does not allow for the flow of ions within the seawater
- One of the most difficult areas to model are crevices

Crevice Corrosion

- Crevices develop a local chemistry
- Crevice corrosion is localized and can lead to component failure – overall material loss is minimal
- The initiation and progress of crevice corrosion can be difficult to detect
- Examples include
  - Gaps and contact areas between parts
  - Under gaskets or seals
  - Inside cracks and seams



Crevice Corrosion – Step 1

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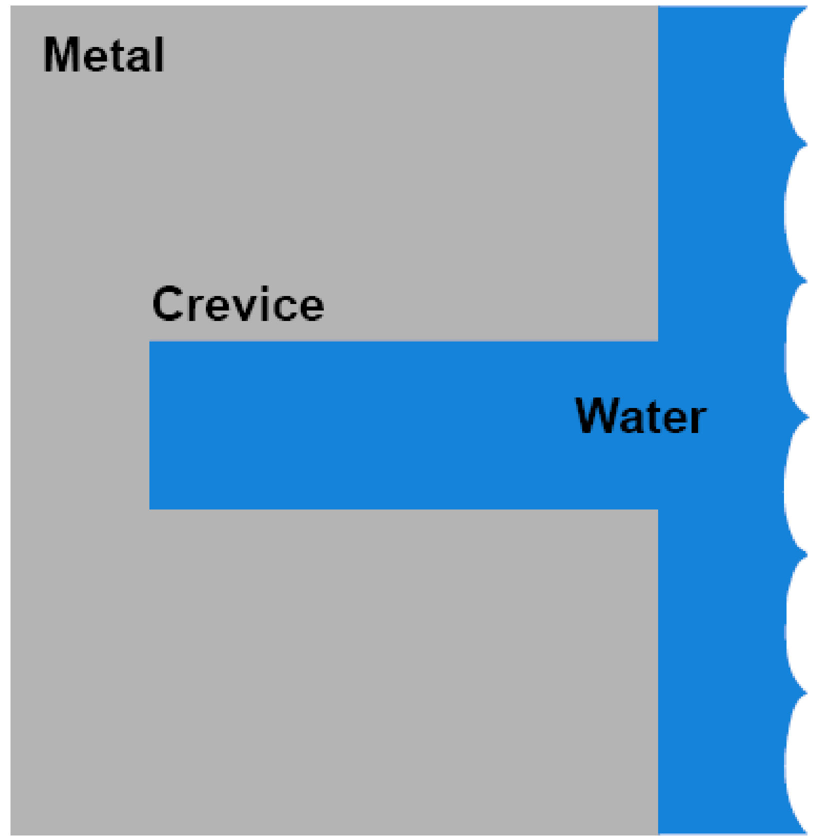
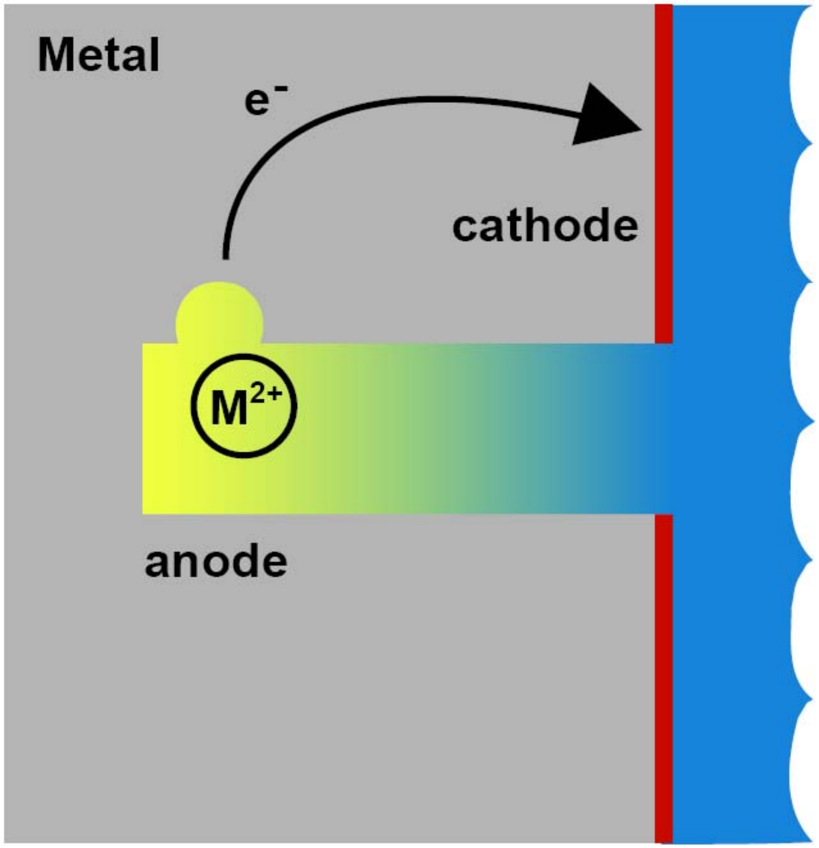
- Water contained in crevice
- Water contains a uniform level of soluble oxygen



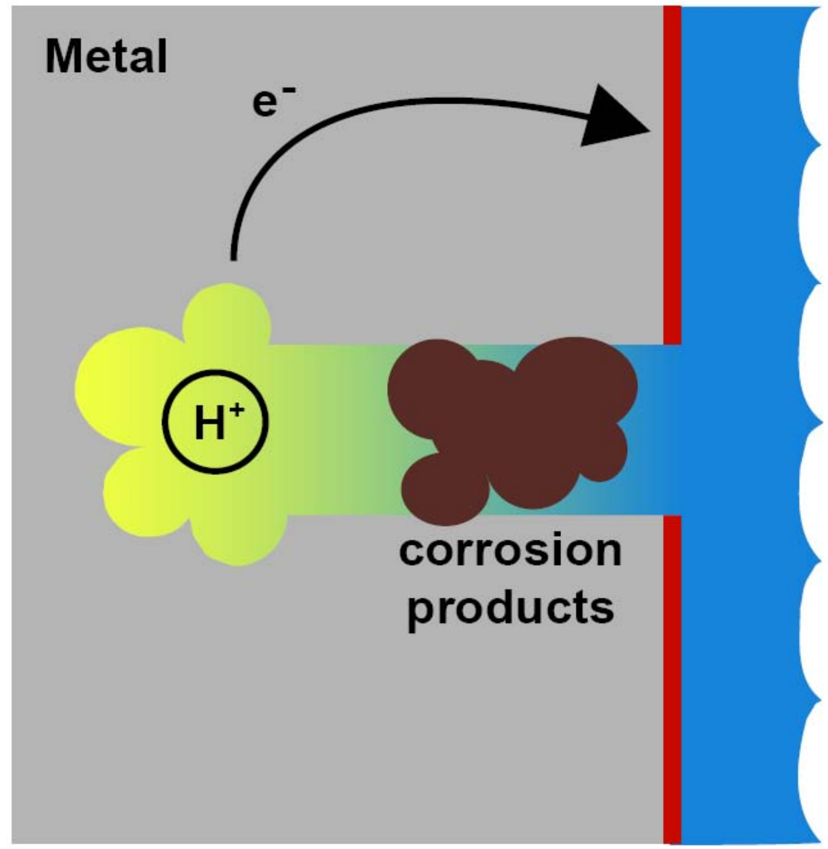
Crevice Corrosion – Step 2

- Geometry hinders ability of oxygen to be consumed within crevice
- Oxygen depleted in the crevice
- Crevice – anodic
- Open surface – cathodic
- Large ratio of cathodic to anodic surface exacerbates anodic reaction



Crevice Corrosion – Step 3

- Metal ions hydrolyse to release protons
- Forms corrosion products further sealing crevice
- Crevice pH reaches very acidic values
- Increases corrosion rate of metal
- Crevice attracts negative ions increasing corrosion



Crevice Model

FRAZER-NASH CONSULTANCY

- Quasi-one-dimensional hybrid FE/FD computational crevice model developed by Frazer-Nash
- Incorporates chemical transport
- FE allows basic crevice geometry to be represented - includes electrochemical reactions at surfaces
- FD calculates migration and diffusion of species within crevice - models chemical equilibrium and ion hydrolysis
- Iteration between FE/FD allows full transient solution to be derived

Benefits

- Signature reduction
  - Improving ICCP systems
  - Optimising computational models
  - Improving electrochemistry modelling

Questions?

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Future Submarine

Safety and Environmental Challenge

MINISTRY OF DEFENCE

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Context – Defence White paper
December 2006

- *"We have therefore decided to maintain our nuclear deterrent by building a new class of submarines"*
- *"Much has changed since 1980. Safety and regulatory standards have been raised over the last 25 years."*
- *"Safety will be a key element of the design and operation of the replacement SSBNs.*
- *Successful safety risk management is founded in a proper understanding of… technologies.*

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Safety and Environmental Goals

- Control Major Accident Hazards
- Provide a Safe Working Environment
- Protect the Environment

  and

- Prevent Programme Excursions

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BP Texas City - 2005

PANEL STATEMENT

Process safety accidents can be prevented.

On March 23, 2005, the BP Texas City refinery experienced a catastrophic process accident. It was one of the most serious U.S. workplace disasters of the past two decades, resulting in 15 deaths and more than 170 injuries.

In the aftermath of the accident, BP followed the recommendation of the U. S. Chemical Safety and Hazard Investigation Board and formed this independent panel to conduct a thorough review of the company's corporate safety culture, safety management systems, and corporate safety oversight at its U.S. refineries. We issue our findings and make specific and extensive recommendations. If implemented and sustained, these recommendations can significantly improve BP's process safety performance.

Throughout our review, we focused on being thorough and then letting the chips fall where they may. As our charter contemplates, we allowed BP to comment on our report to ensure its factual accuracy. However, we are solely responsible for our report's final content.

Although we necessarily direct our report to BP, we intend it for a broader audience. We are under no illusion that deficiencies in process safety culture, management, or corporate oversight are limited to BP. Other companies and their stakeholders can benefit from our work. We urge these companies to regularly and thoroughly evaluate their safety culture, the performance of their process safety management systems, and their corporate safety oversight for possible improvements. We also urge the same companies to review carefully our findings and recommendations for application to their situations.

Preventing process accidents requires vigilance. The passing of time without a process accident is not necessarily an indication that all is well and may contribute to a dangerous

BP Texas City –Baker Report

March 2005

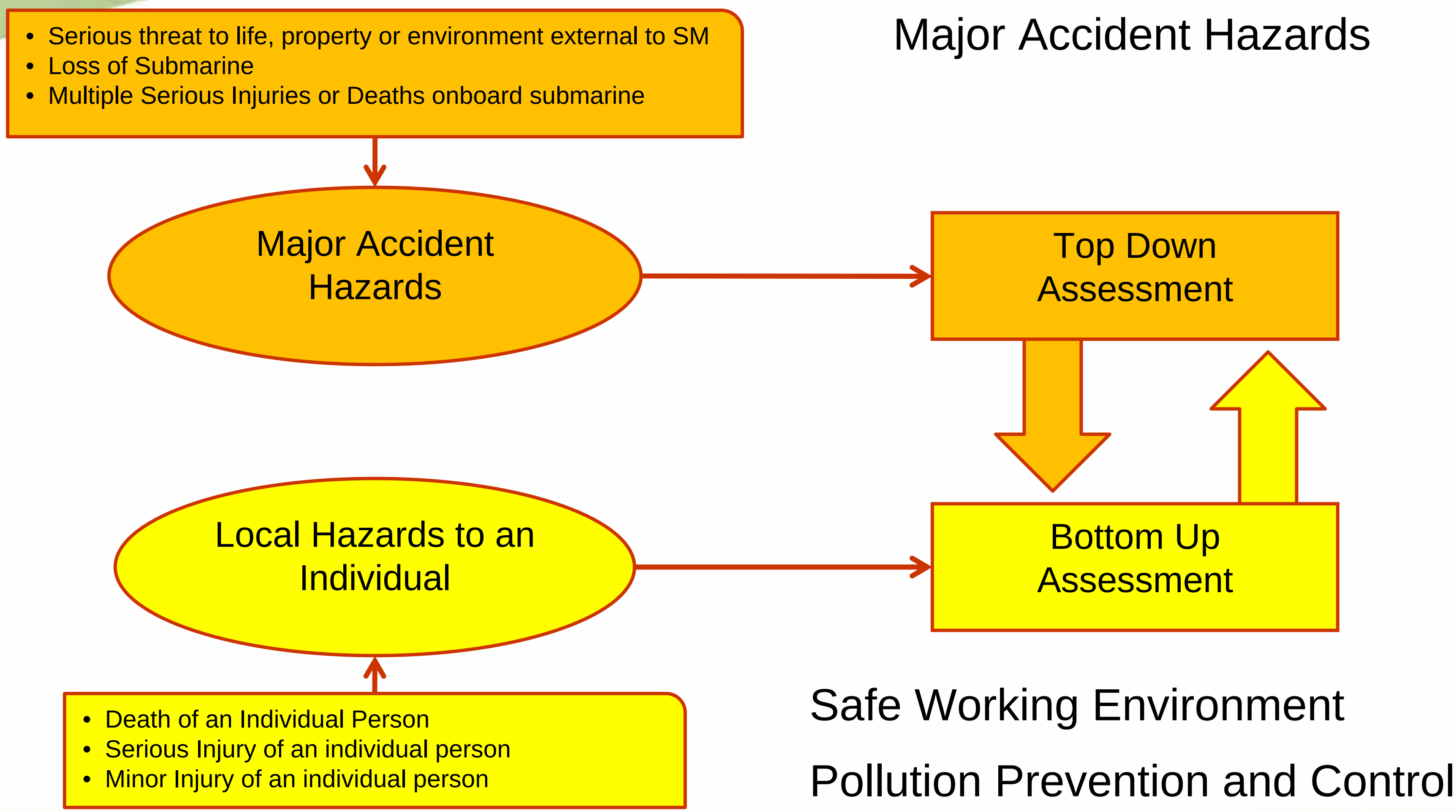
- *“BP appears to have established a relatively effective personal safety management system by embedding **personal safety** aspirations and expectations within the U.S. refining workforce.*

- *However, BP has not effectively implemented its corporate-level aspirational guidelines and expectations relating to **process risk**.*

- *Therefore, the Panel found that BP has not implemented an integrated, comprehensive, and effective process safety management system for its five U.S. refineries.”*

Major Accident Hazards and

Local Hazards to Individuals



MODERN STANDARDS SAFETY

“Goal-Based Regulation”

Prescriptive

- “You shall install a 1 metre high rail at the edge of the cliff”

Goal Based

- “People shall be prevented from falling over the edge of a cliff”

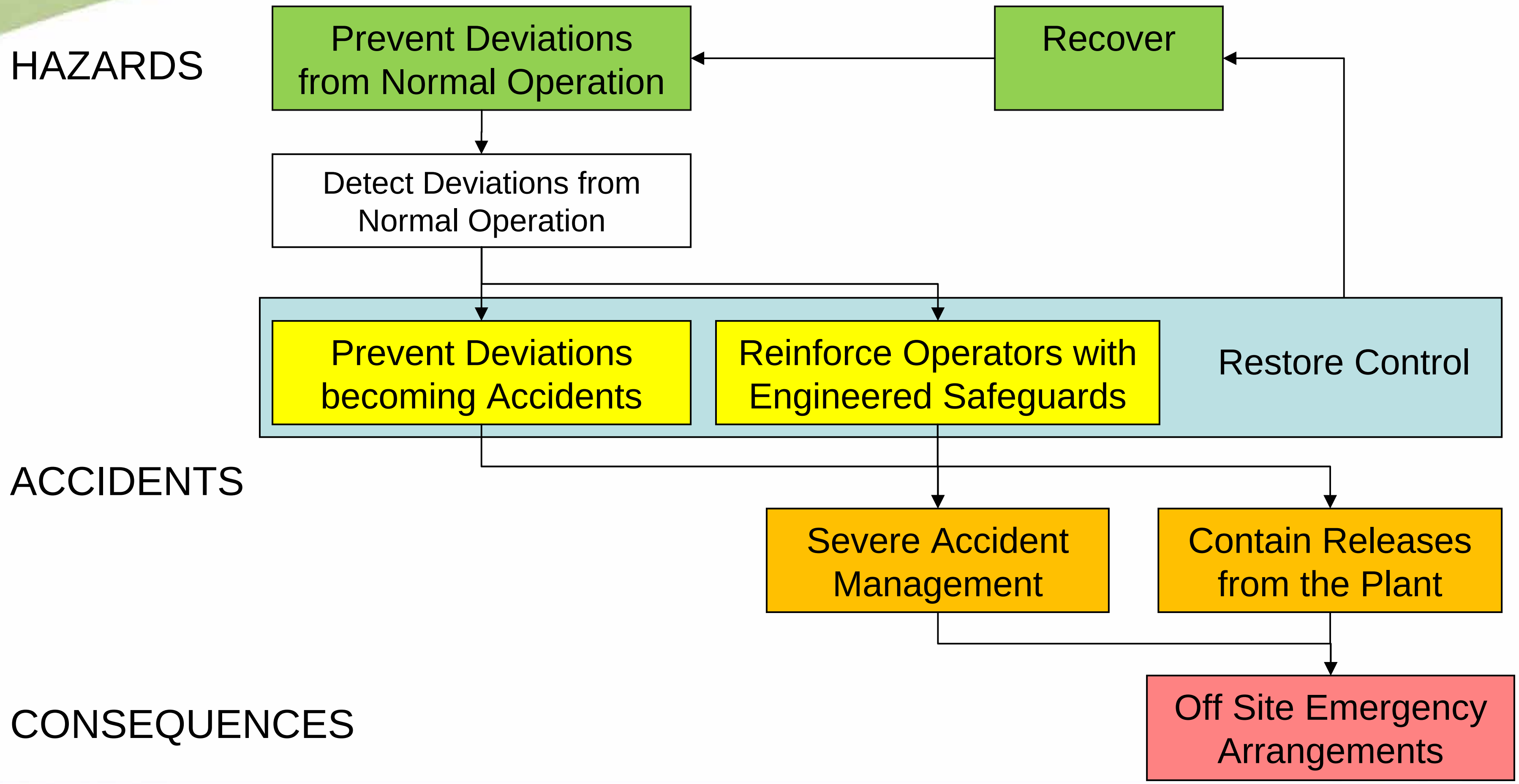
IMO – Goal Based Standards

- Tier 1
  - Goals
- Tier 2
  - Functional Requirements
- Tier 3
  - Verification of Compliance Criteria
- Tier 4
  - Technical Procedures & Guidelines; Classification Rules; and Industry Standards
- Tier 5
  - Codes of Practice; Safety & Quality Systems; Operation; Maintenance; Training; Manning

Naval Ship Codes

- Structure
- Buoyancy and Stability
- Machinery installations
- Electrical installations
- Fire Safety
- Escape, Evacuation and Rescue
- Radiocommunications
- Safety of Navigation
- Carriage of Dangerous Cargoes

Defence in Depth



Case Studies

MAJOR ACCIDENTS

Goal: Prevent Navigation and Manoeuvring Accidents

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Goal: Prevent WTI Accidents

Upper rudder of the sunken USS Thresher, photographed by USNS Mizar, 1964

Mosaic of sail and other debris of sunken USS Th

Goal: Prevent Major Fires

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Goal: Prevent Reactor Accidents

Goal: Prevent TWS Accidents

Photo # NH 97221-KN Stern section of sunken USS Scorpion, 1986

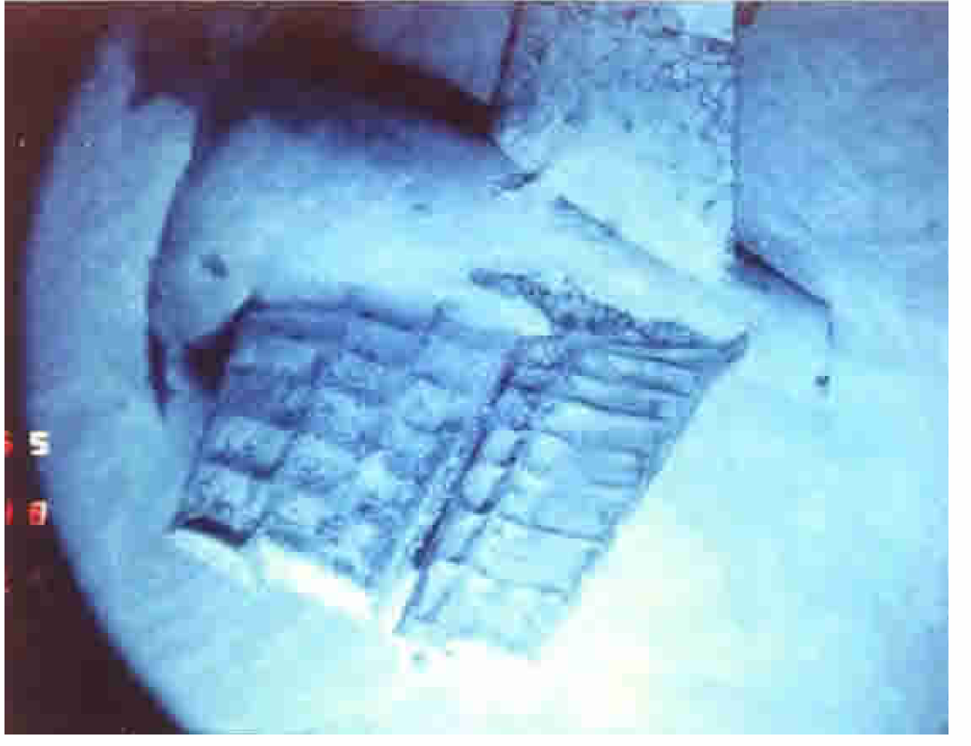
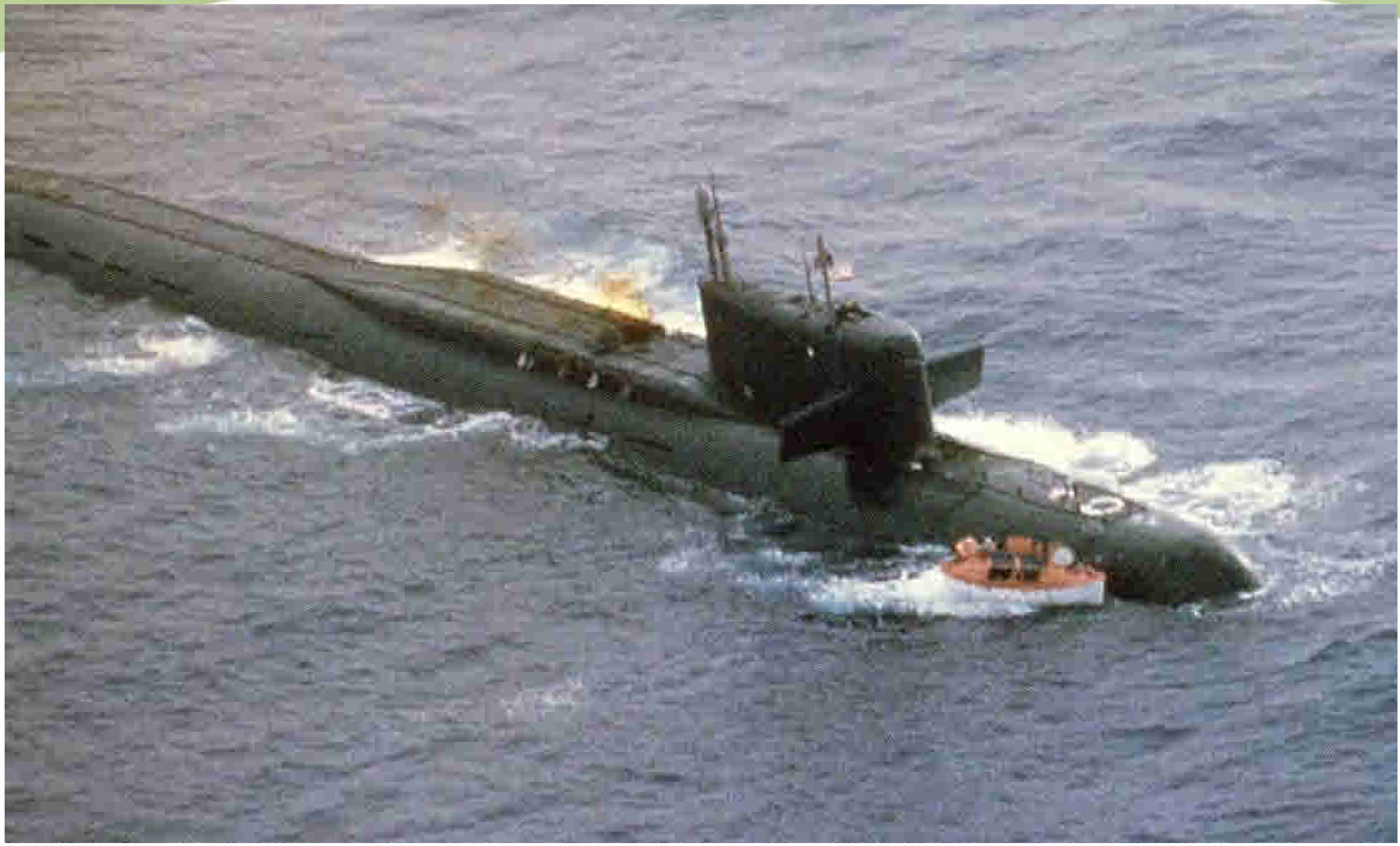


Photo # NH 97223-KN Sail of sunken USS Scorpion, 1986

Goal: Prevent SWS Accidents



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Goal: Prevent SWS Accidents

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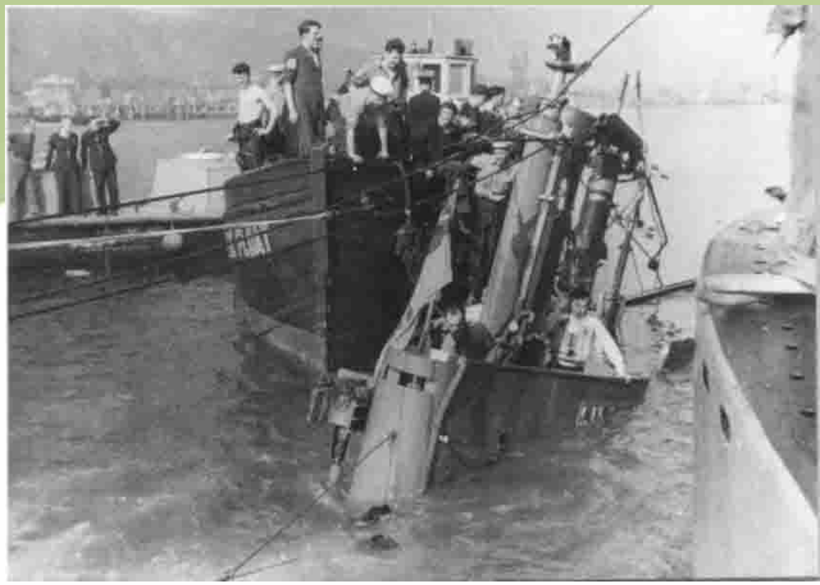
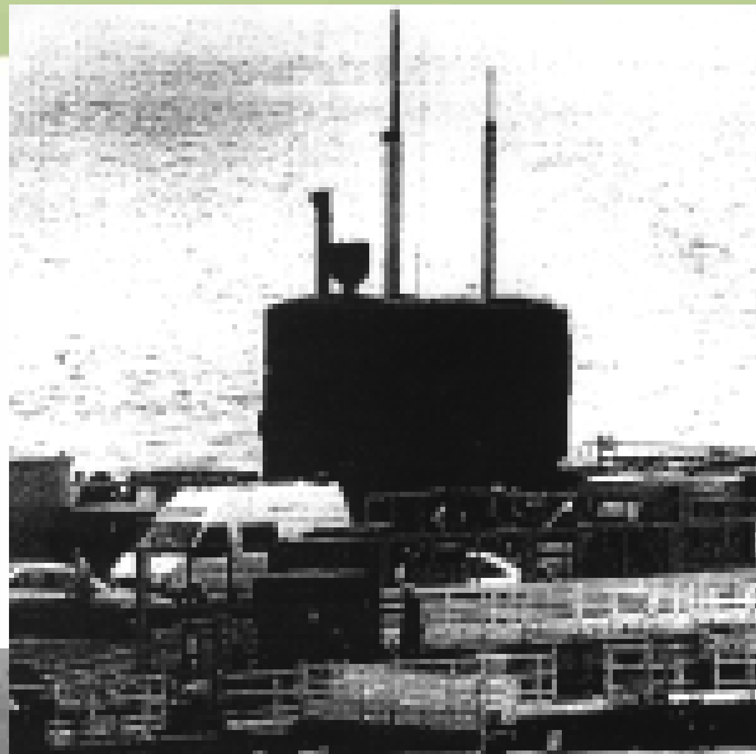
Goal: Prevent Accidents in Harbour





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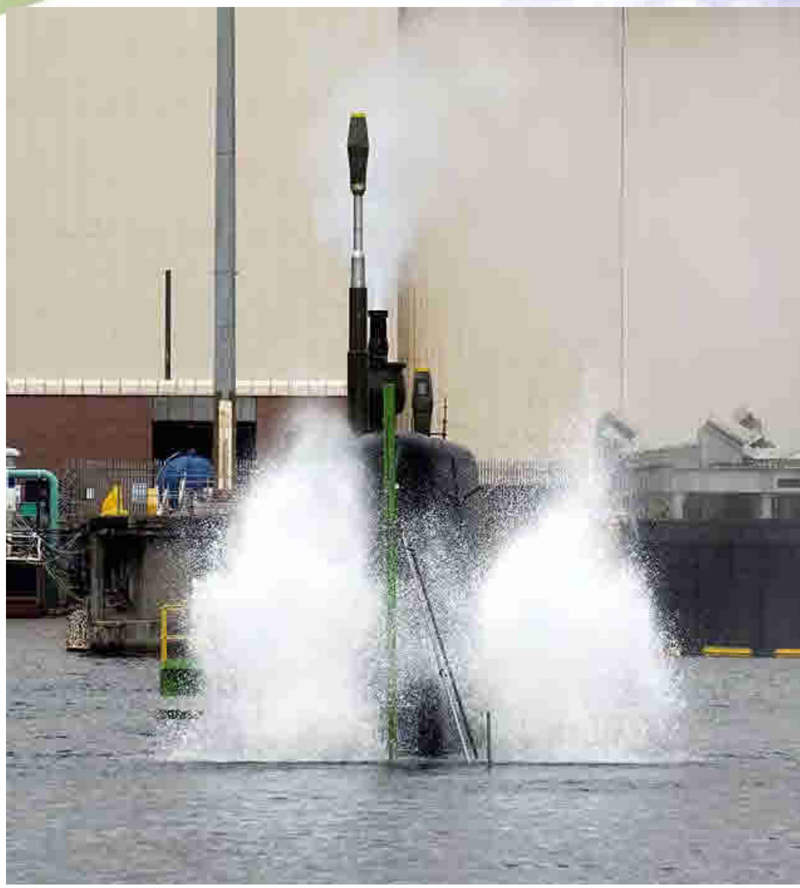
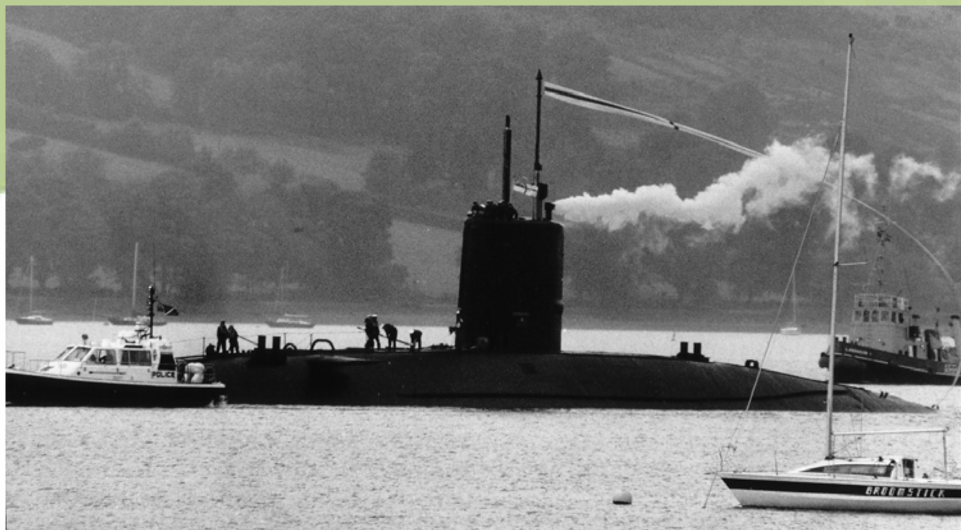
Goal: Control Pressure in Habitable Areas



Goal: Enable Towing



Police chase Greenpeace crews in nuclear sub protest

Goal: Enable Disposal

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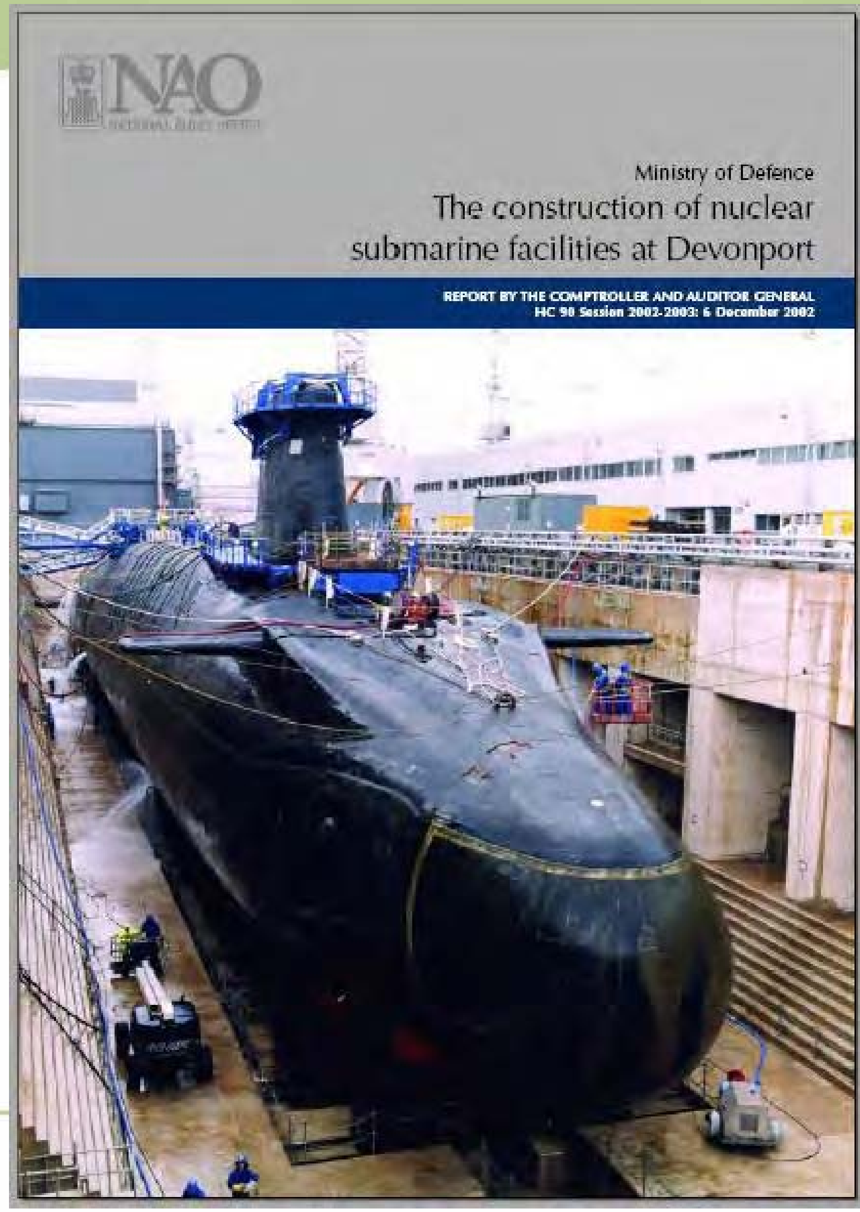
Goal: Prevent Programme Excursions



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Future Submarine

Strategy

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Logical Derivation of Functional Goals

Goal Structuring Notation

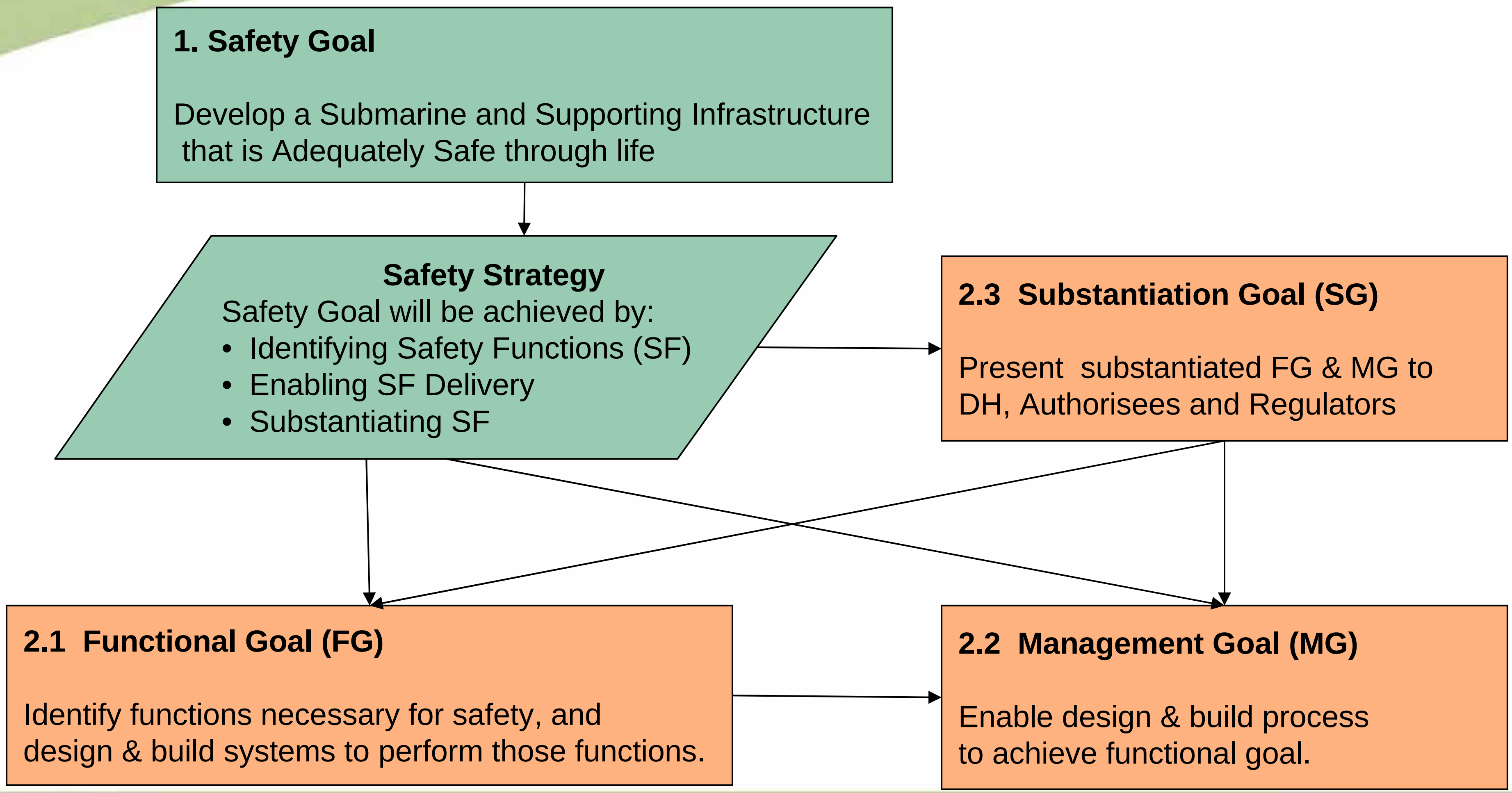
- Tier 1 – Safety Case Goals
- Tier 2 – Key Safety Functions
- Tier 3 – Fundamental Safety Functions
- Tier 4 – System Functions
- Tier 5 – Sub-System & Support System Functions

Tier 1

SAFETY STRATEGY

SAFETY GOALS

Tier 1 Goals



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Tier 2.1

SAFETY STRATEGY

KEY SAFETY FUNCTIONS

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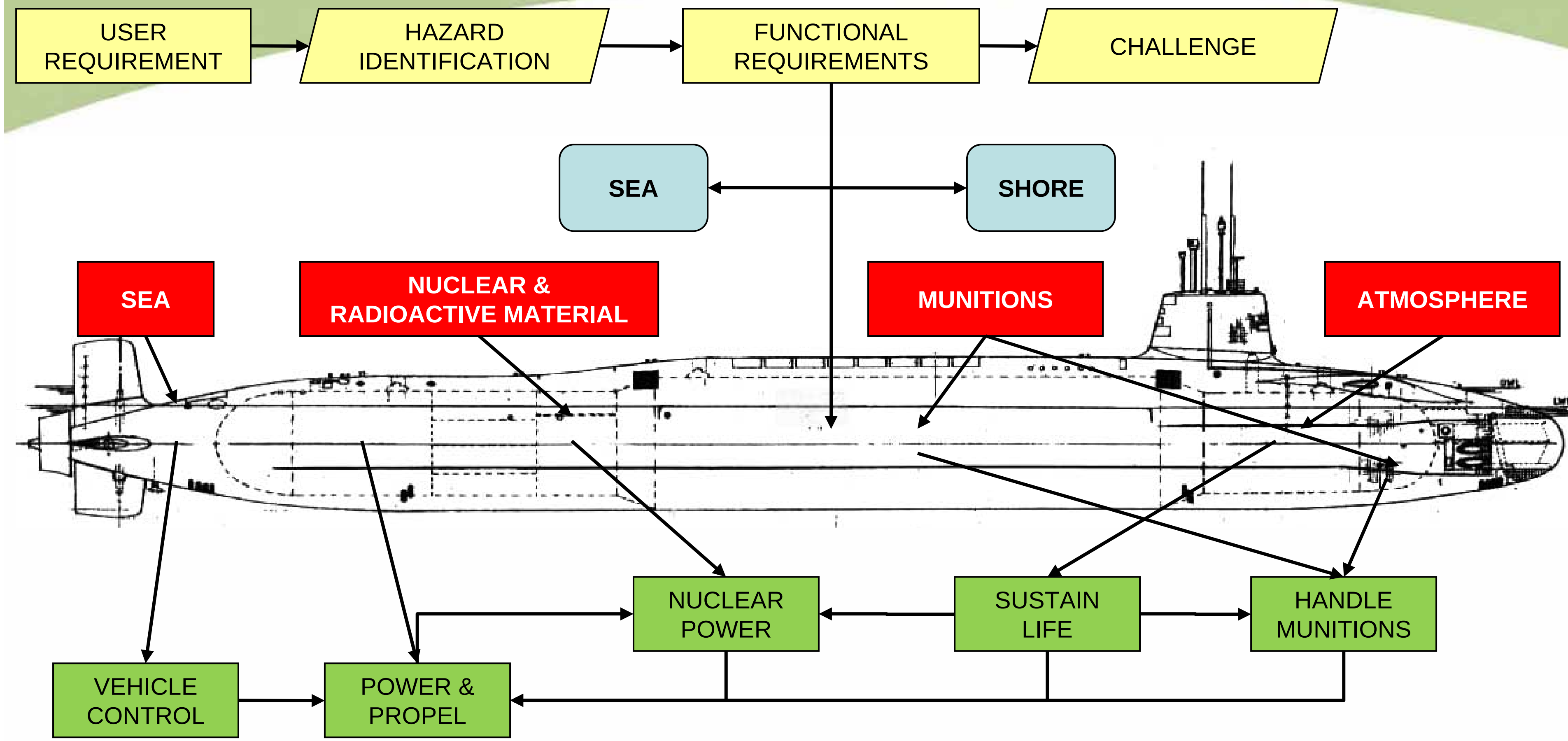
Safety Functions



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Tier 2.2

SAFETY STRATEGY

MANAGEMENT

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Safety Management Tactics

- *Integrated* Safety *and* Engineering

Good Practice

- Safety Group *generated* Safety Functional Requirements *provided to* Designers

Workable, but

- *Retrospective* Safety Analysis *of* Engineering Design

To be avoided

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Tier 2.3

SAFETY STRATEGY

SUBSTANTIATION

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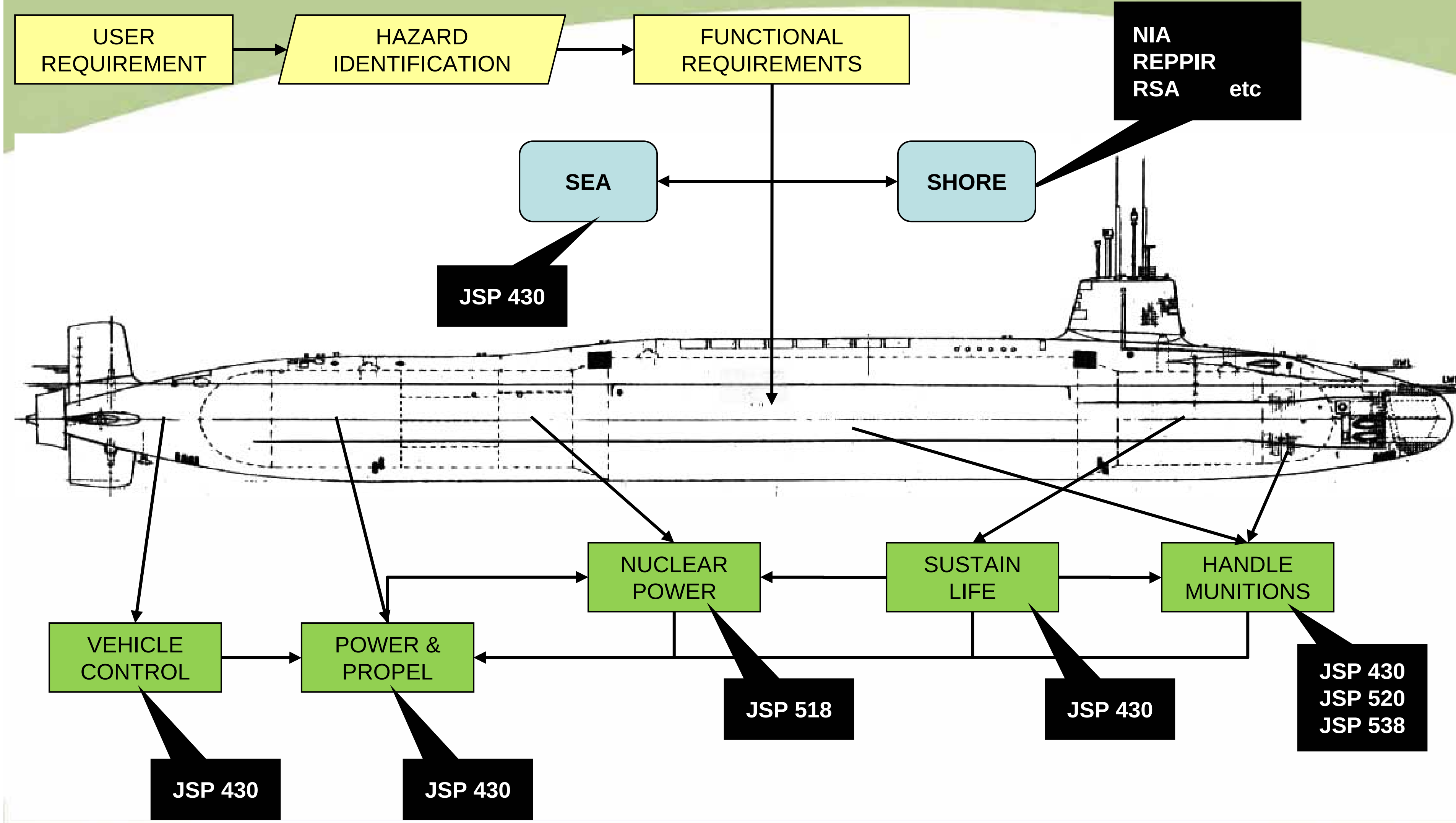
Safety Regulation



Tier 3

SAFETY STRATEGY

FUNDAMENTAL SAFETY FUNCTIONS

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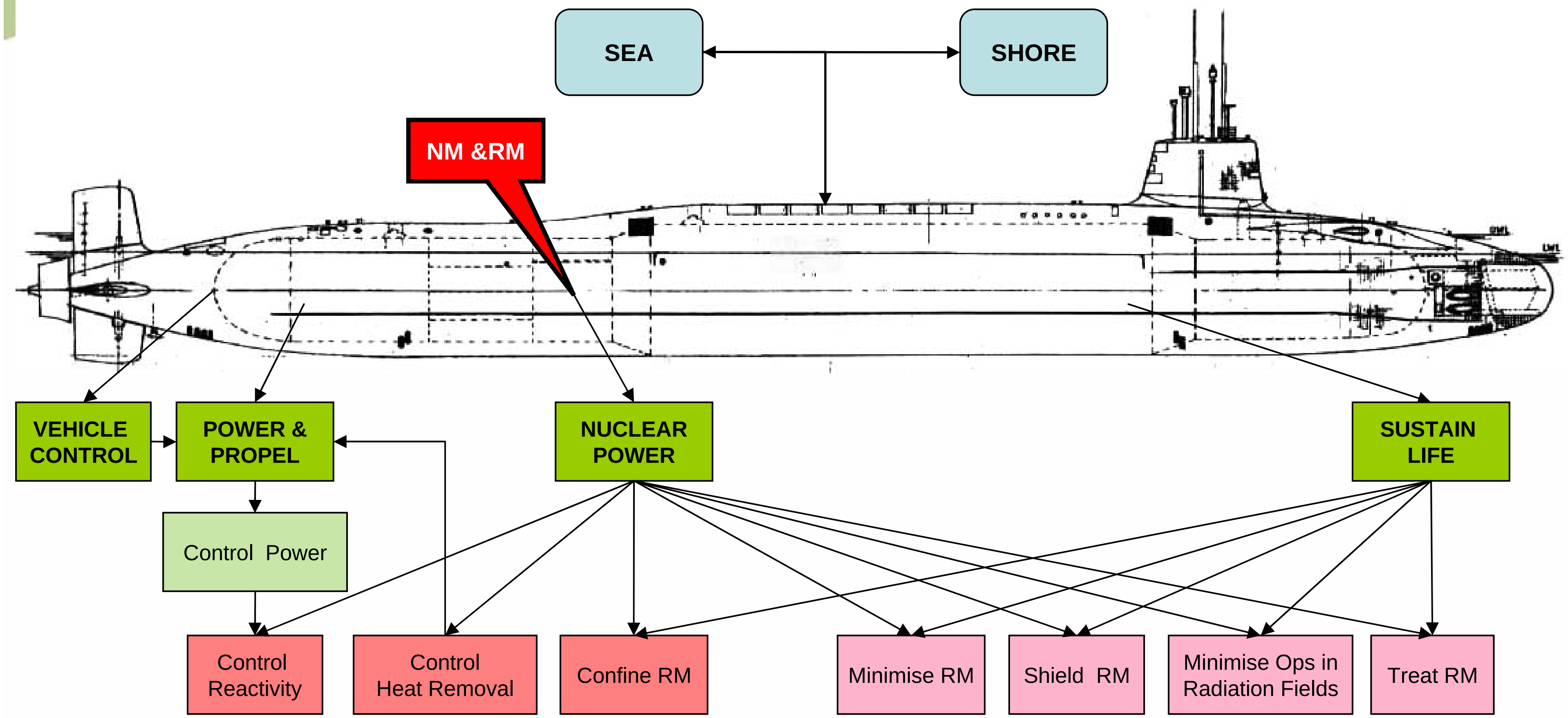
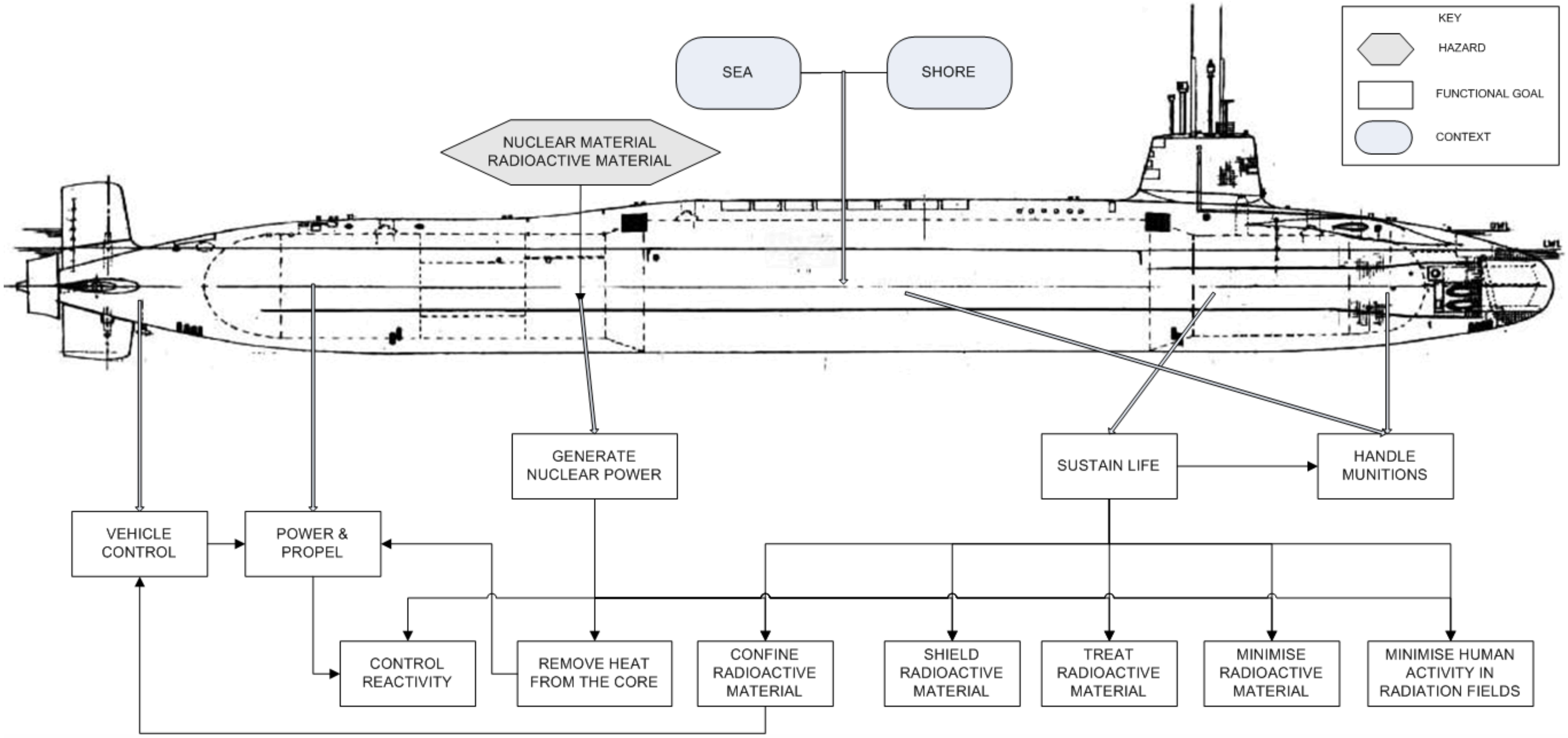
Fundamental Safety Functions

Nuclear Power Generation



Fundamental Safety Functions – Nuclear Power Generation



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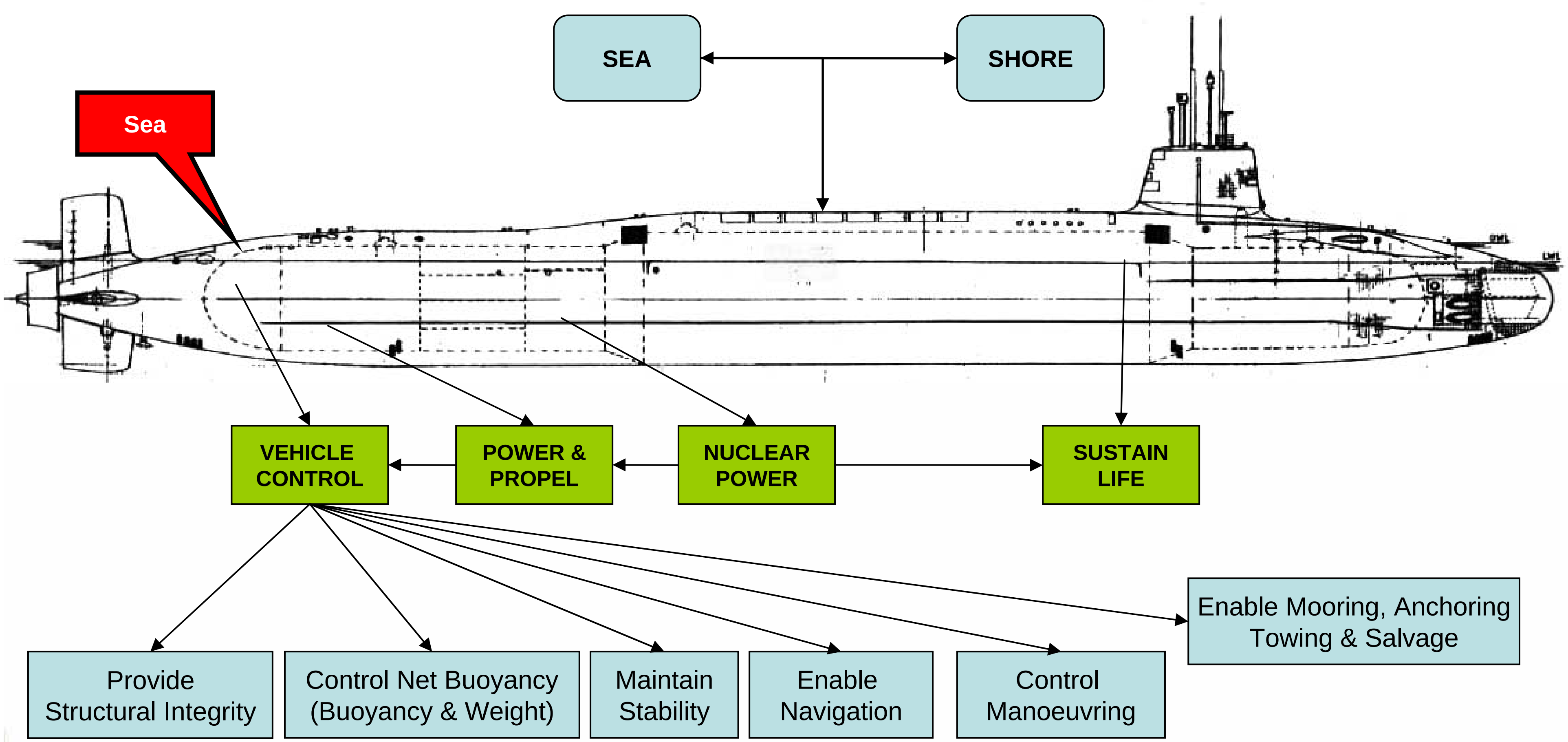
Tier 3 Safety Case Goals

Fundamental Safety Functions – Vehicle Control



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JSP430 - Key Hazard Areas:

Stability; Structural Strength; Manoeuvring & Control; Watertight Integrity

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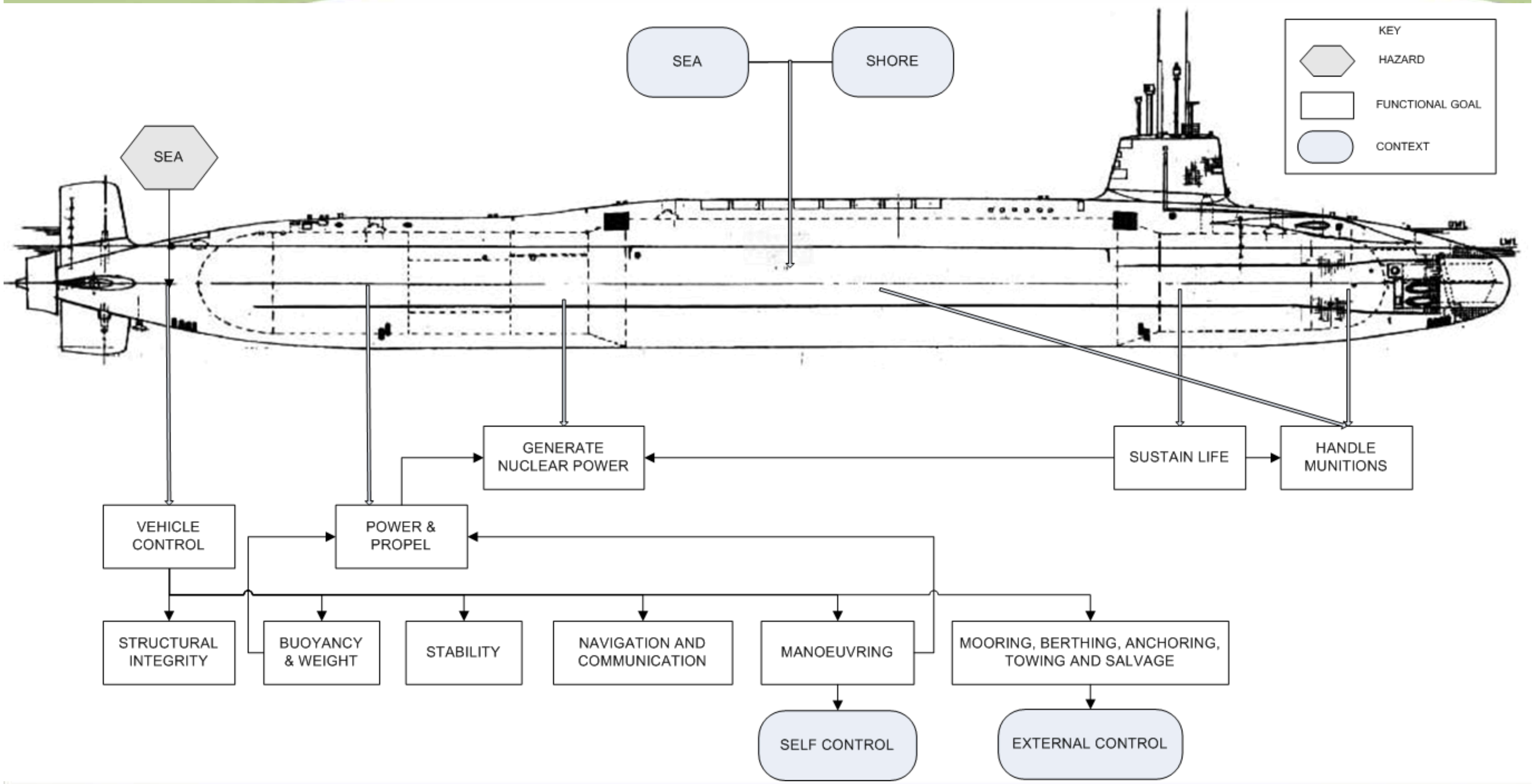
Tier 3 Safety Case Goals

Fundamental Safety Functions – Vehicle Control



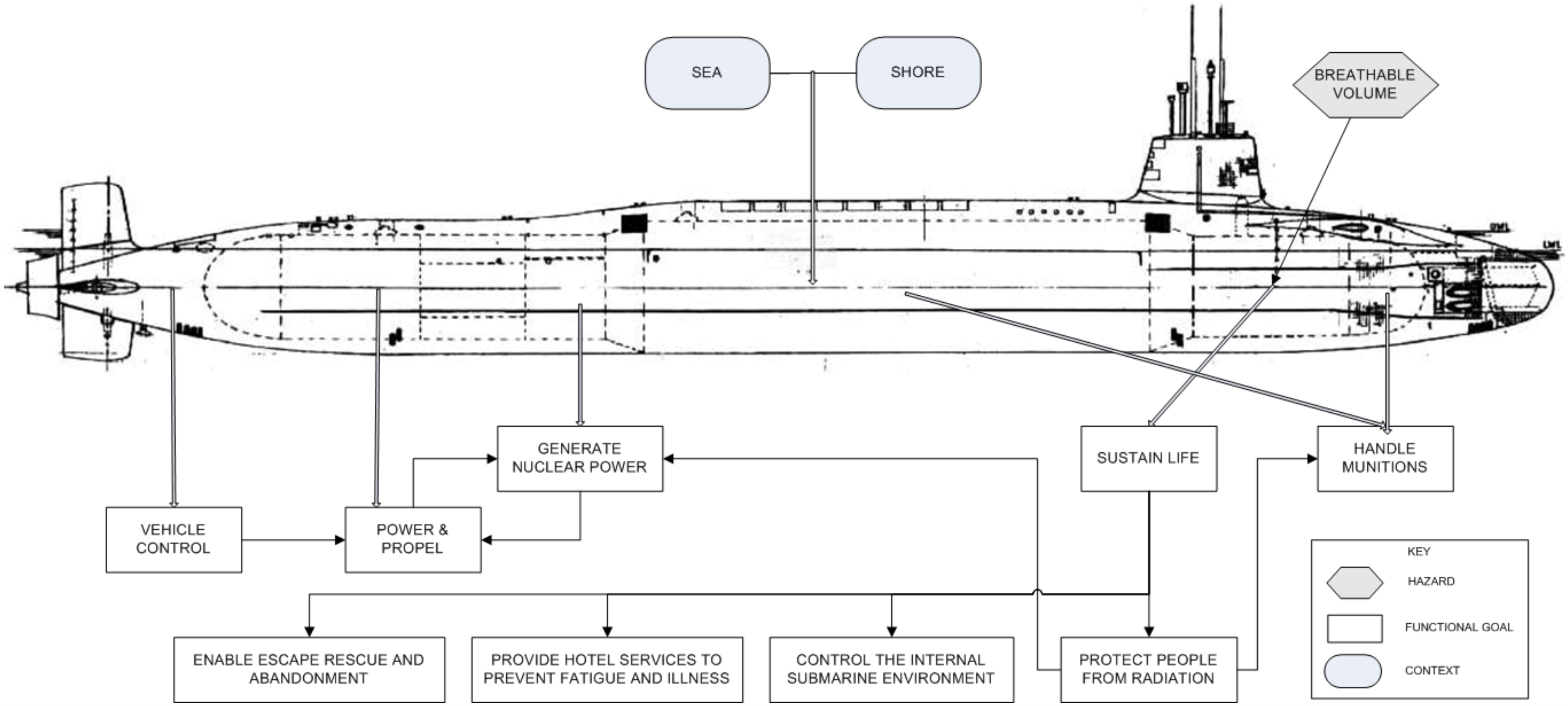
MINISTRY OF DEFENCE

JSP430 - Key Hazard Areas:

Stability; Structural Strength; Manoeuvring & Control; Watertight Integrity

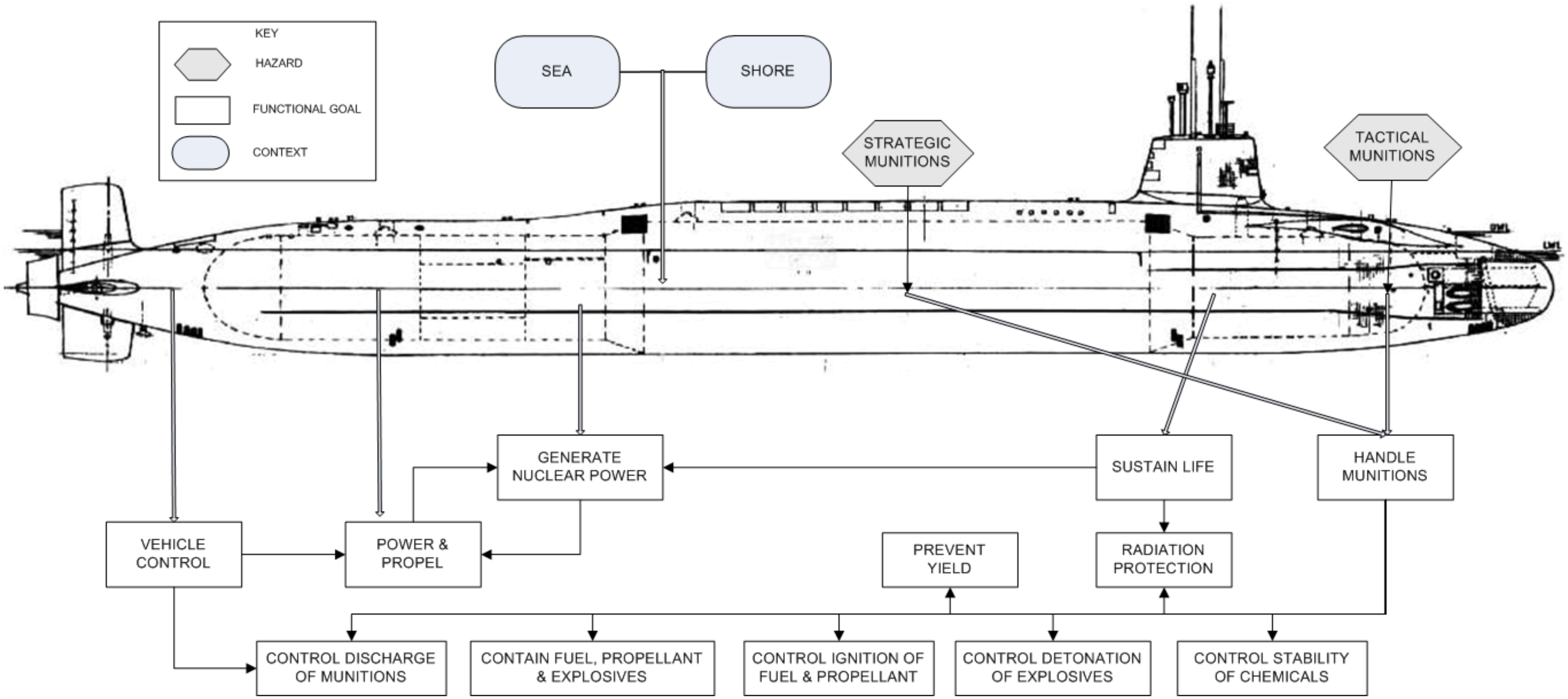
Tier 3 Safety Case Goals

Fundamental Safety Functions – Sustain Life



Tier 3 Safety Case Goals

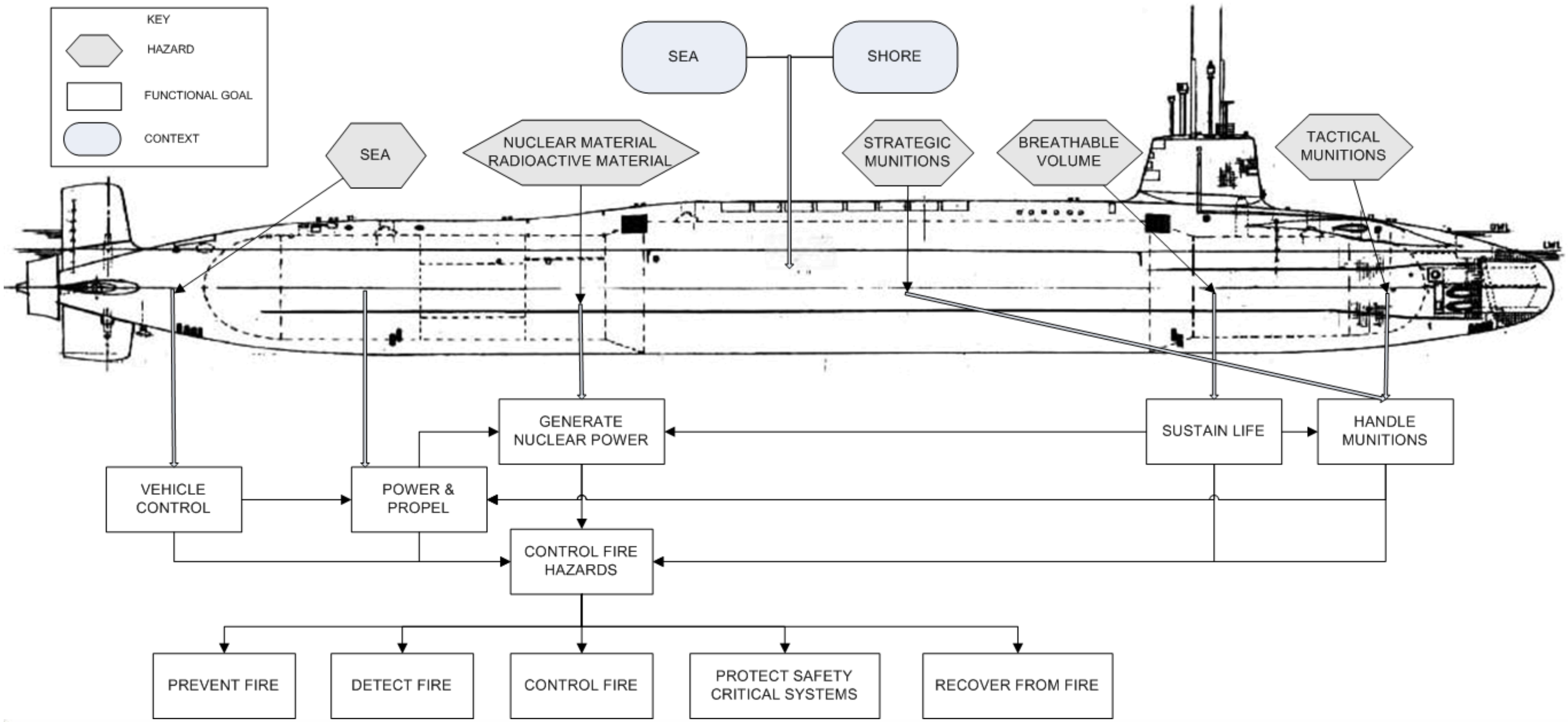
Fundamental Safety Functions – Handle Munitions



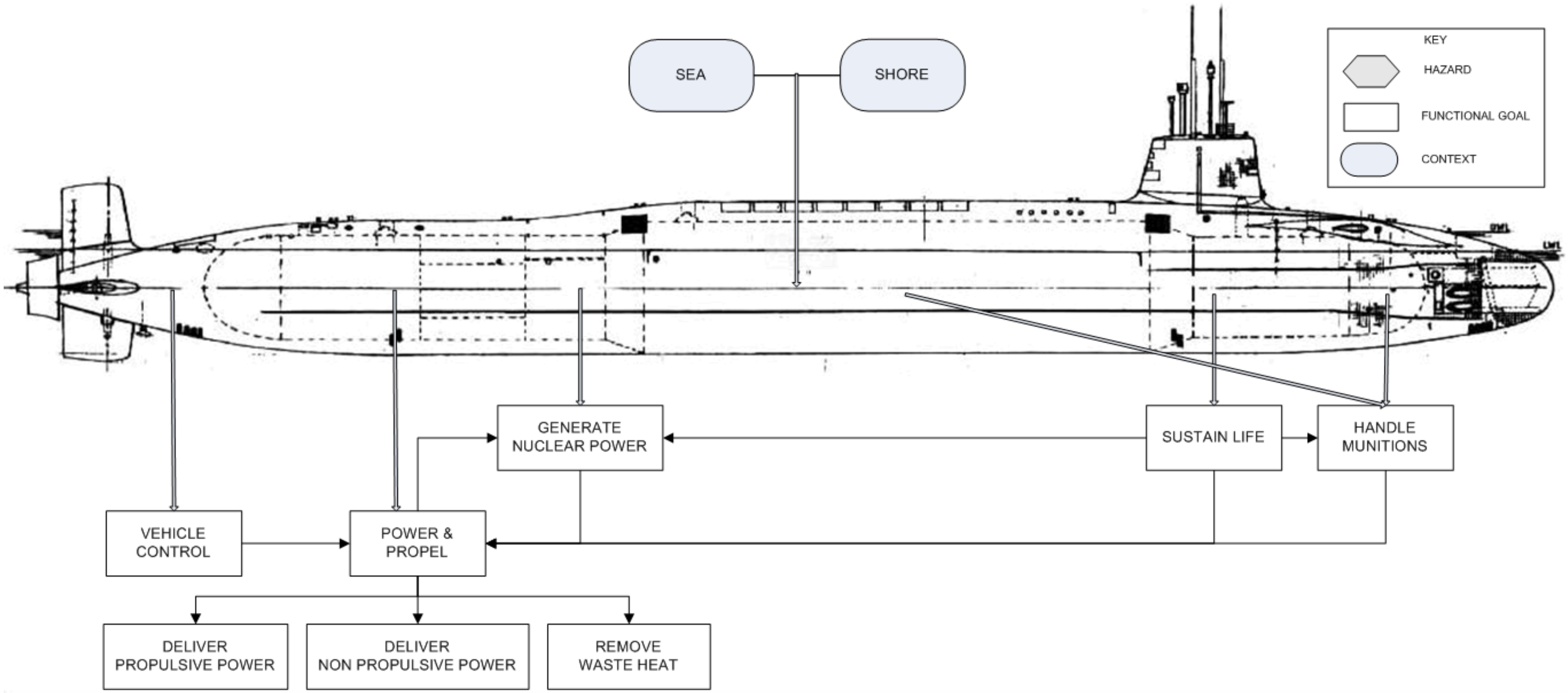
JSP 430 - Key Hazard Areas: *Explosives*
JSP 538 - Fundamental Nuclear Weapons Safety Aims

Tier 3 Safety Case Goals

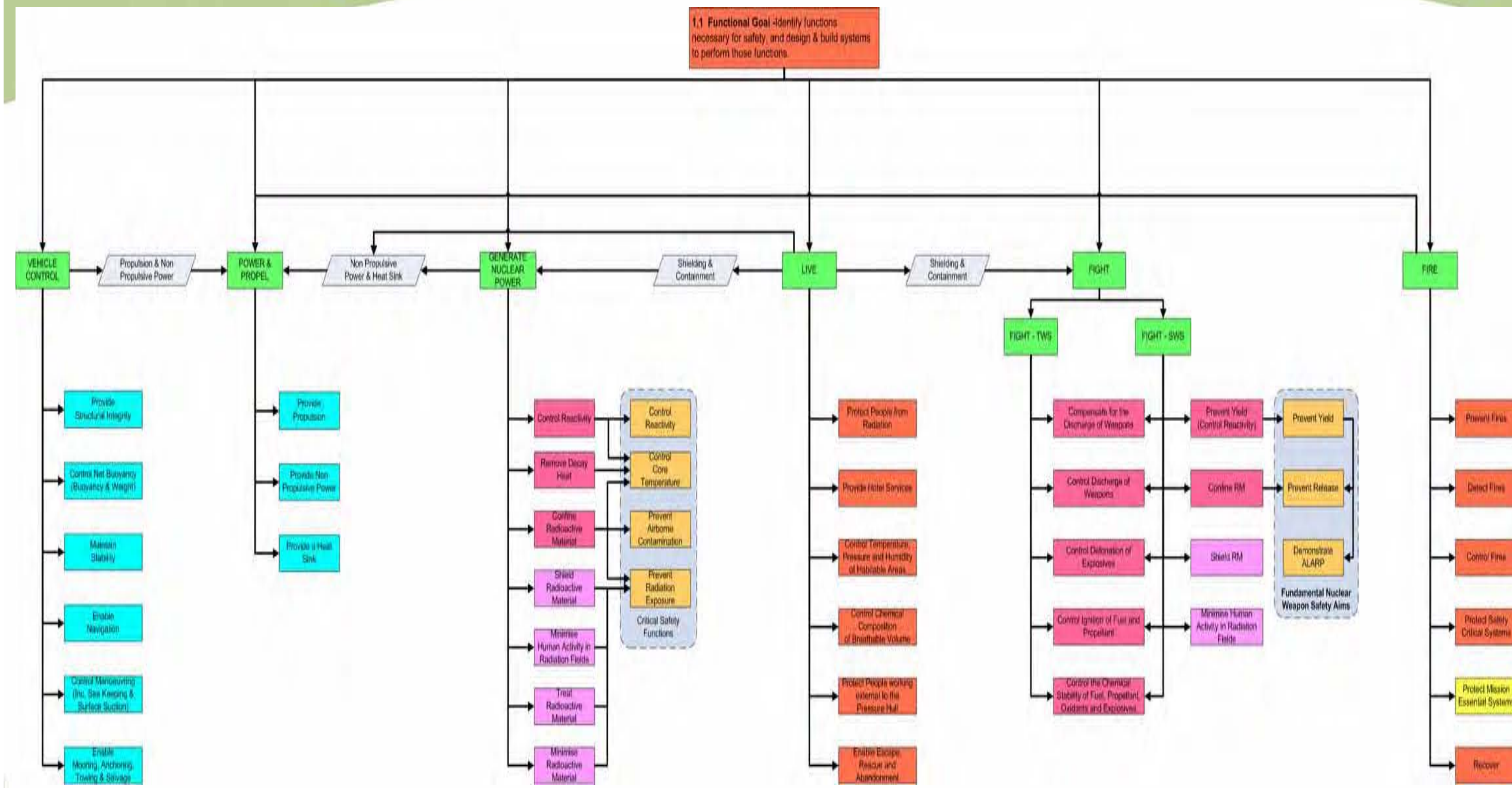
Fundamental Safety Functions – Control Fire Hazards



Fundamental Safety Functions – Power & Propel



Fundamental Safety Functions



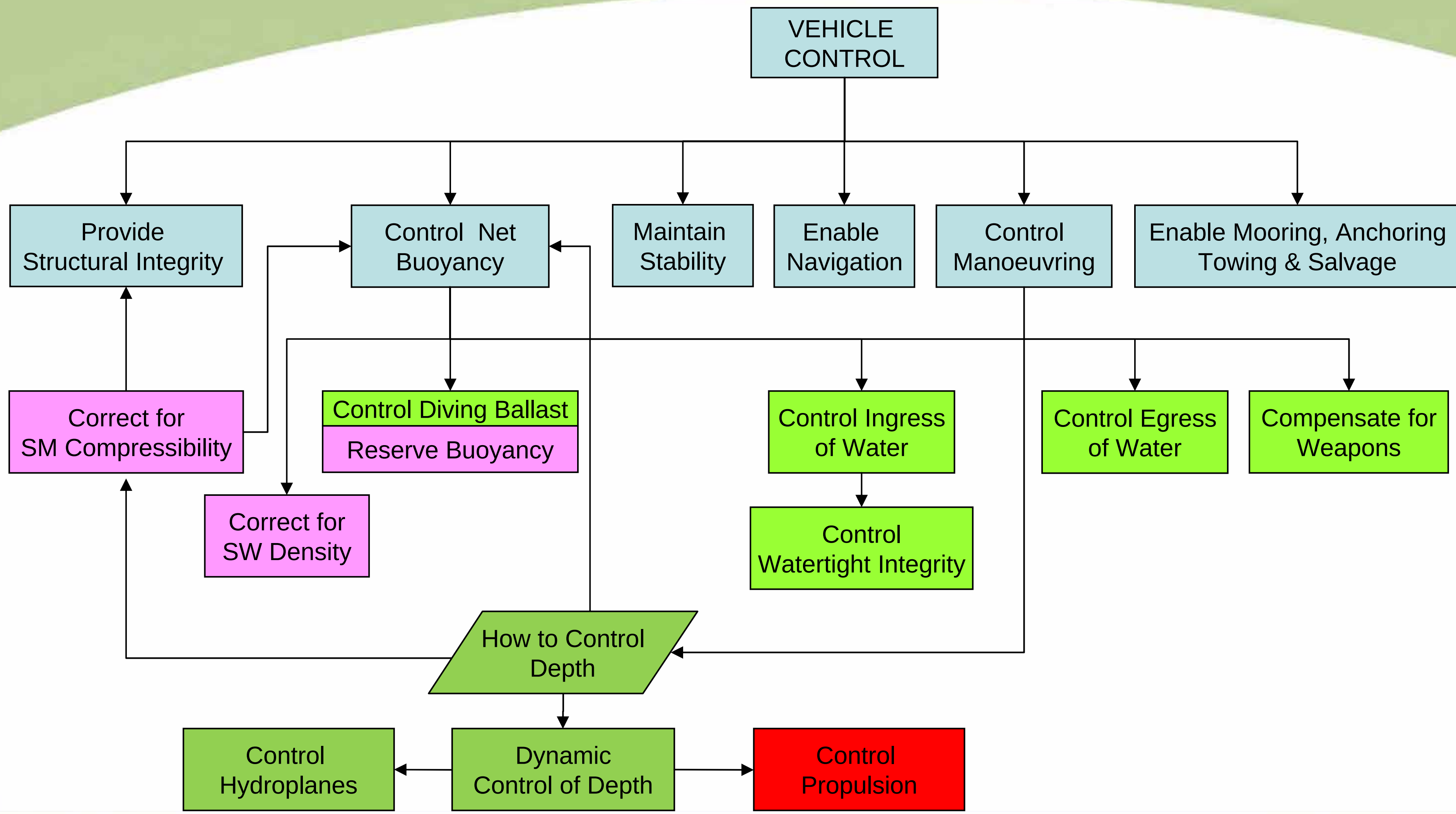
Tier 4

SAFETY STRATEGY

SYSTEM SAFETY FUNCTIONS

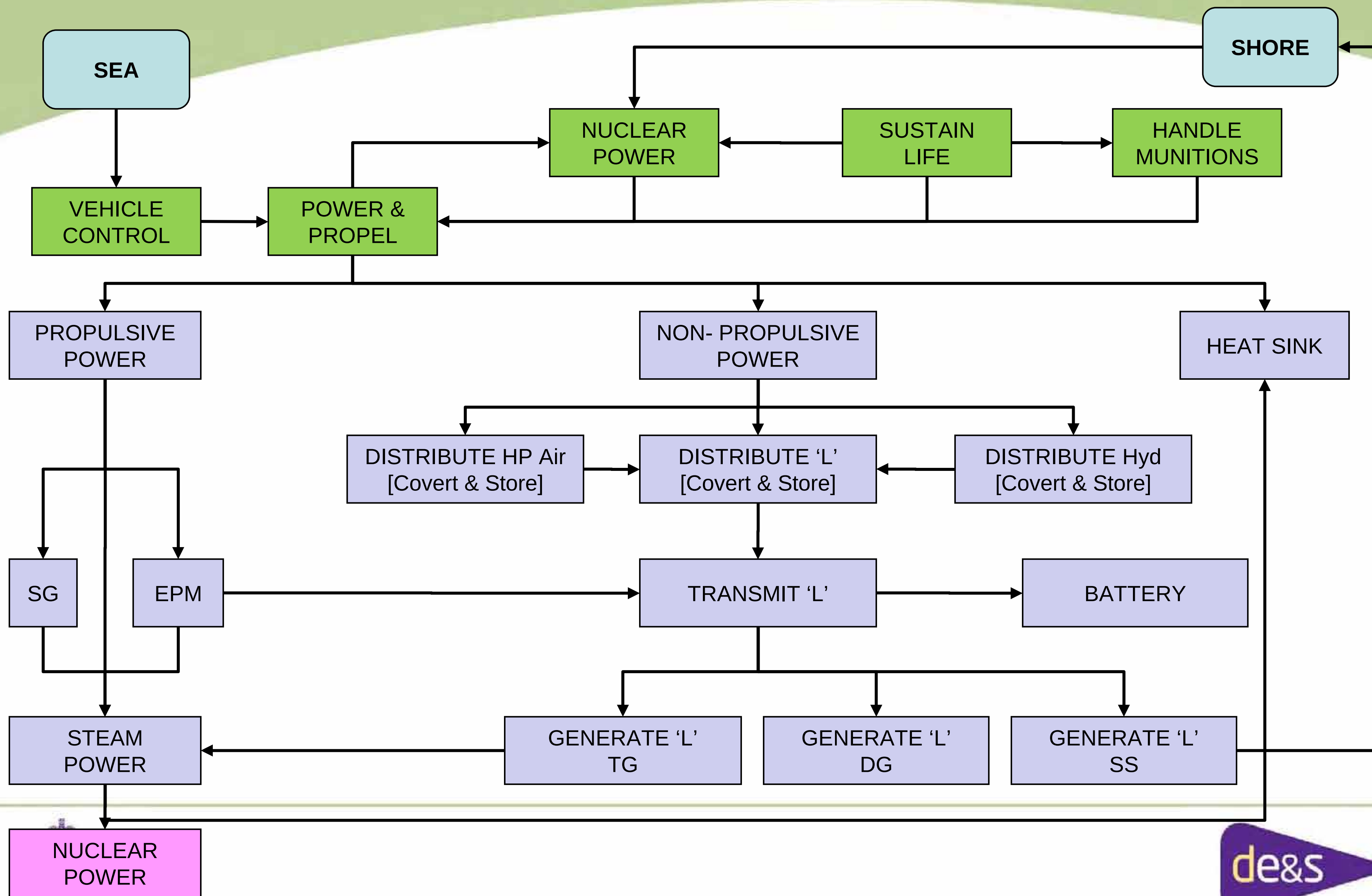
Tier 4

Vehicle Control – System Goals



Tier 4

Power & Propel – System Goals



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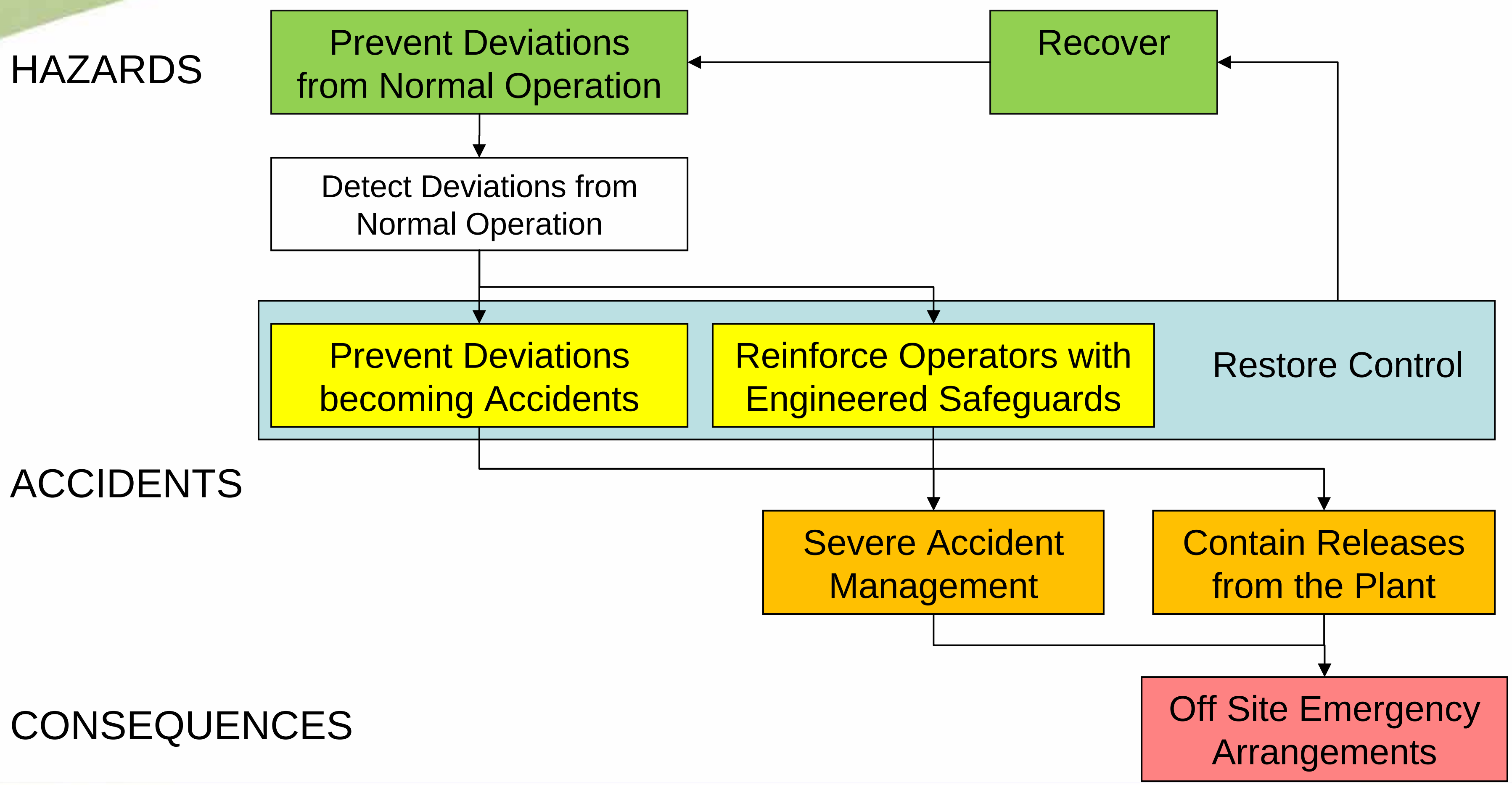
Tier 5

SUB-SYSTEM GOALS

SUPPORT SYSTEMS & DEFENCE IN DEPTH

Defence in Depth



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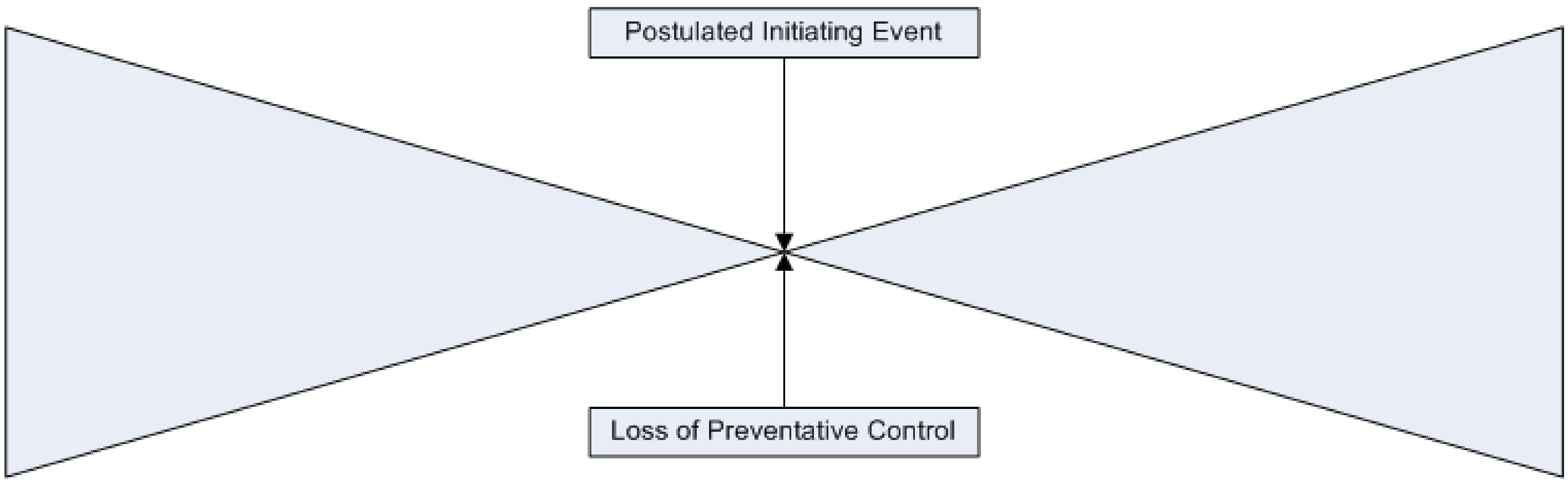
Tier 5 Safety Case Goals

Sub-System Goals

Postulated Initiating Events

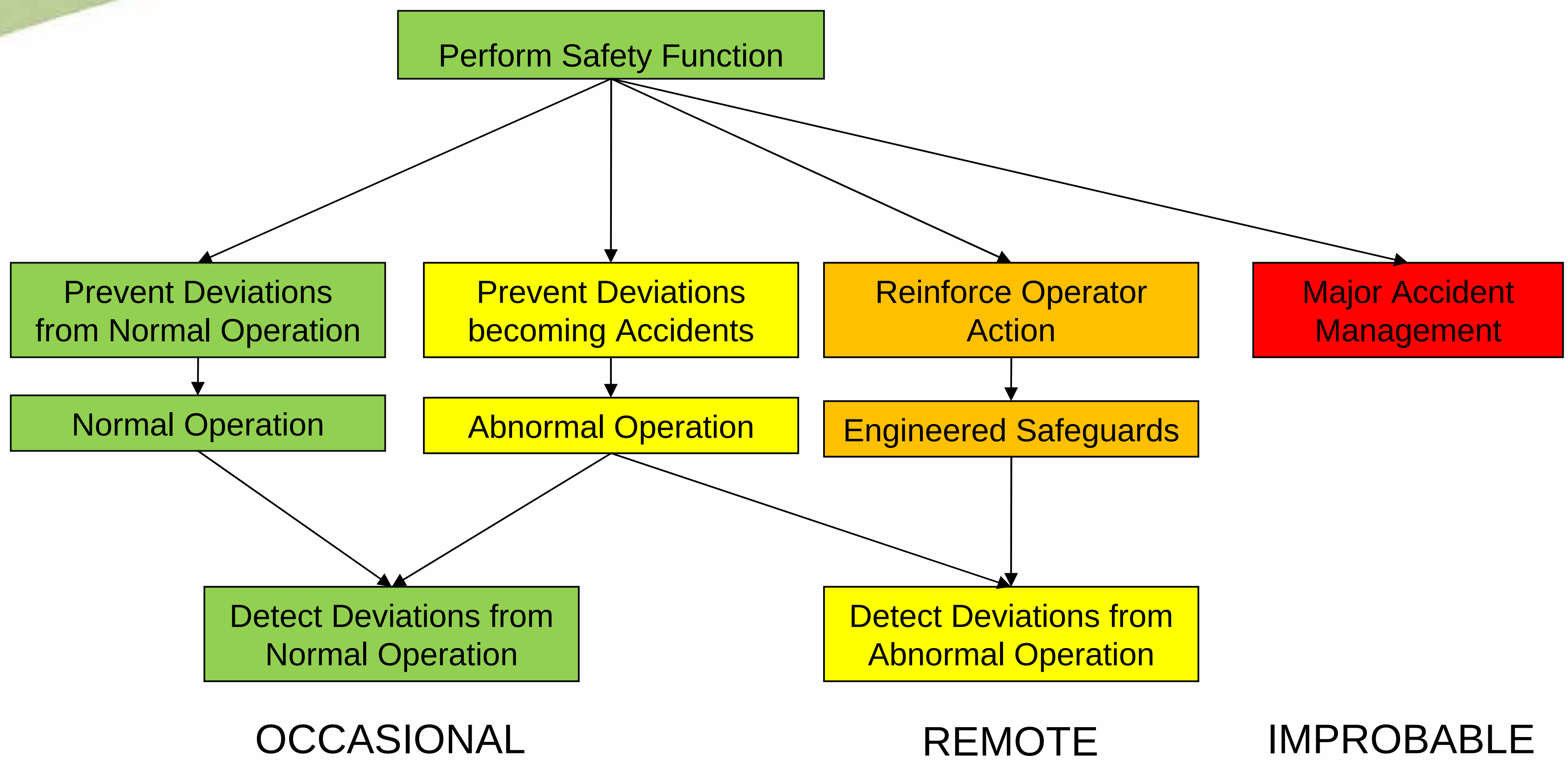


Level 4 KSF Duty System	Level 4 KSF Standby System	Level 4 KSF Emergency System	Level 4 KSF Severe Accident
Preventative Control		Protective Measures	

Likelihood

Likelihood Category	Frequency per Annum	Numerical Expression	Meaningful Equivalent
Frequent	>1	Greater than once per operating year	Likely to occur every patrol
Probable	10-1 to 1	Once every 1 to 10 operating years	Likely to occur every commission
Occasional	10-2 to 10-1	Once every 10 to 100 operating years	May occur once per submarine lifetime
Remote	10-3 to 10-2	Once every 100 to 1,000 operating years	May occur once per Flotilla lifetime
Improbable	10-4 to 10-3	Once every 1,000 to 10,000 operating years	Unlikely to occur in Flotilla lifetime
Highly Improbable	10-5 to 10-4	Once every 10,000 to 100,000 operating years	Not known to have occurred in operating history
Incredible	<10-5	Less than once every 100,000 operating years	Not credible considering known submarine history

Defence in Depth



Way Ahead

- Claim
- Argument
- Evidence

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Drake’s Prayer

- O Lord, when thou givest to thy servants to endeavour in any great matter, grant us to know that;
- It is not in the beginning but the continuing of the same until it be thoroughly finished that yieldeth the true glory;

to be continued…

RINA Warship 2008: Naval Submarines
SECC Glasgow

10 June 2008

Hybrid Nuclear/Fuel-Cell Submarine

Lt R H Goodenough BEng MSc RN
Dr A Greig CEng FIMarEST

INTRODUCTION

www.brittany-ferries.co.uk

G.C.Slawson / www.horning.org.uk

www.naval-technology.com

CONCEPT - ADVANTAGES

- Operational patrols with reactor shutdown (noise)
- Air independent auxiliary power source
  - Extended scrams
  - Under ice operations
  - High sea states
- Reduced battery size (short term only)
- No DG exhaust mast required
- SN mast smaller
- Dieso fuel removed
- Nil emissions therefore IMO proof
- Easier build/maintenance (removable components)

CONCEPT - DISADVANTAGES

- Poor energy storage density (mass and volumetric) therefore range less than diesel
- Hydrogen and oxygen safety risk
- Cost
- Added complexity
- Increased standards in build/maintenance and operation (= more time and cost)

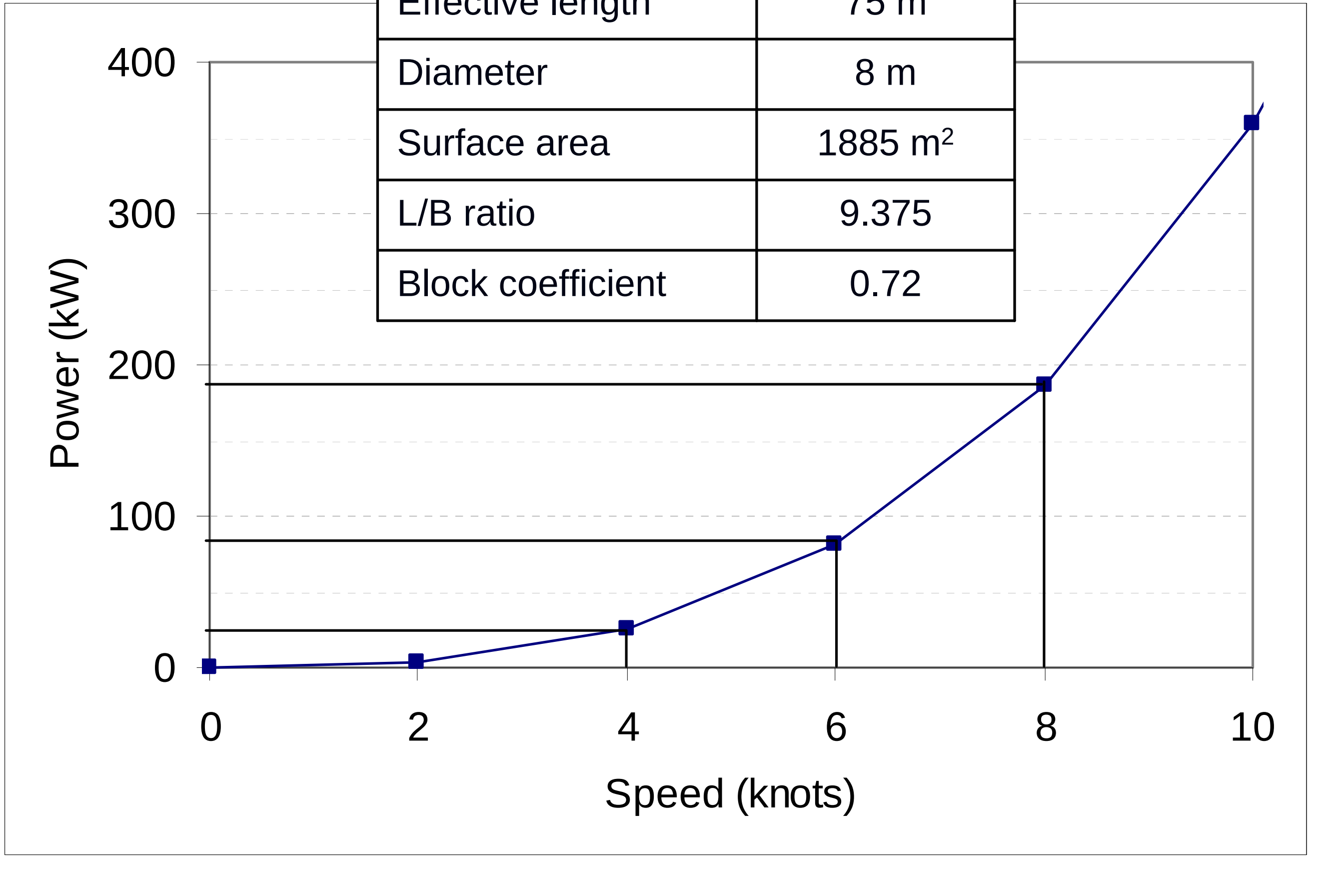
INTRODUCTION
CONCEPT
CHARACTERISTICS
PLANT SELECTION
REACTOR SAFETY
FUEL CELL SYSTEM
SAFETY RISKS
CONCLUSION

CHARACTERISTICS - ARCHITECTURE

- RUBIS/COLLINS Size
- “Appropriate sized reactor”
- 2-3,000 tonnes
  - Length: 75m
  - Diameter: 8m
  - Surface area: 1885m^2
  - L/B ratio: 9.375
  - Block coefficient 0.72

CHARACTERISTICS - POWERING

Characteristics	
Effective length	75 m
Diameter	8 m
Surface area	1885 m^2
L/B ratio	9.375
Block coefficient	0.72



CHARACTERISTICS - POWER PLANT

Propulsion Efficiencies	
Prop	75%
Propulsion Motor	95%
Power Electronics	95%
Total	**68%**

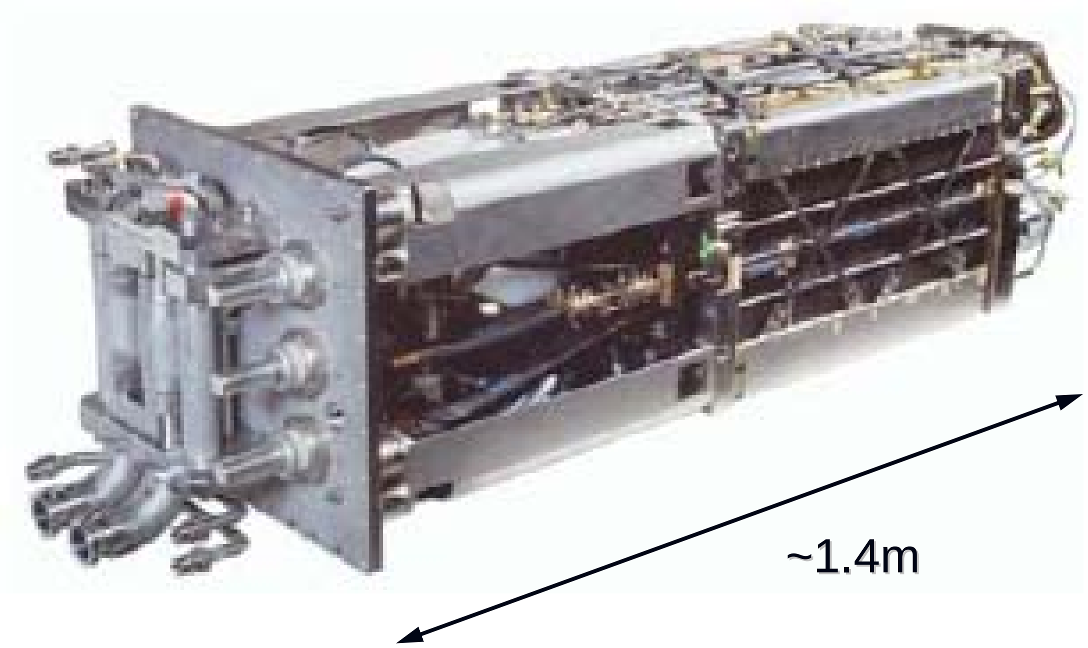
Loads	
Propulsion	187kW
Reactor Safety	100kW
Ship Service	100kW
Total	**477kW**

→

- 1 x PWR
- 2 x TGs (DC)
- DC distribution system
- 4 x 120kW fuel cells
- DC propulsion motor

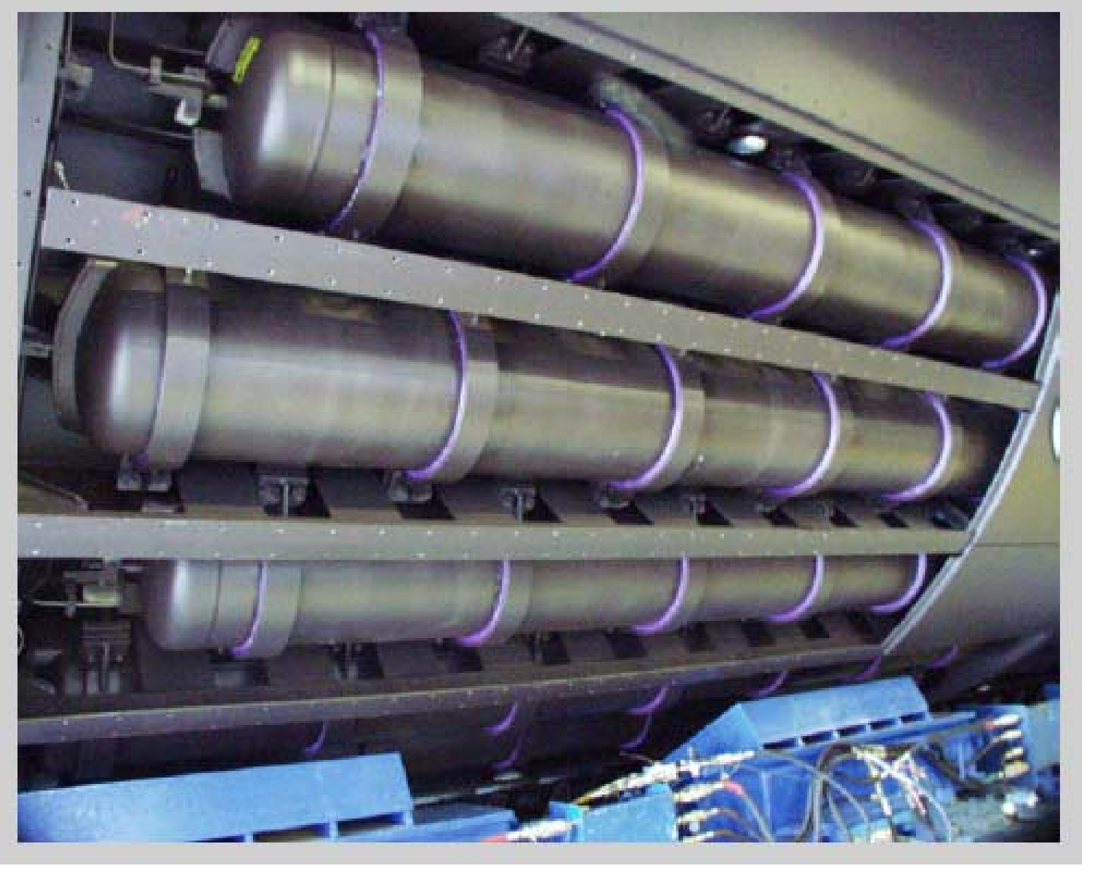
PLANT SELECTION - FUEL CELL

- Siemens BZM120 as fitted to U214 Class



Ref:
Dr. A.E. Hammerschmidt, Siemens AG, *Fuel Cell Propulsion of Submarines,* Advanced Naval Propulsion Symposium, Arlington 2006.

PLANT SELECTION - FUEL STORAGE



Ref:
Dr A.E.Hammerschmidt, Siemens AG, *Fuel-cell propulsion of submarines*, Intl. Conf. on Hydrogen and Fuel-Cell Technologies, Munich, 2006.

PLANT SELECTION - OXYGEN STORAGE

- LOX
  - Volumetric compression ratio: 860:1
  - Compatible with HTS motor?
- Compressed gas
  - Volumetric compression ratio: 200– 300:1
  - Can be produced onboard
- Alternatives
  - Chemical
  - Variants of the above

REACTOR SAFETY

- Battery required for immediate power following scram
- Fuel cell allows battery size reduction
- Hydrogen/oxygen storage sufficient for 7 days at 137kW:
  - Reactor safety load: 50kW (50% normal)
  - Ship safety load: 50kW (50% normal)
  - 4 knot propulsion: 37kW
- Onboard recharge required

INTRODUCTION

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FUEL CELL SYSTEM

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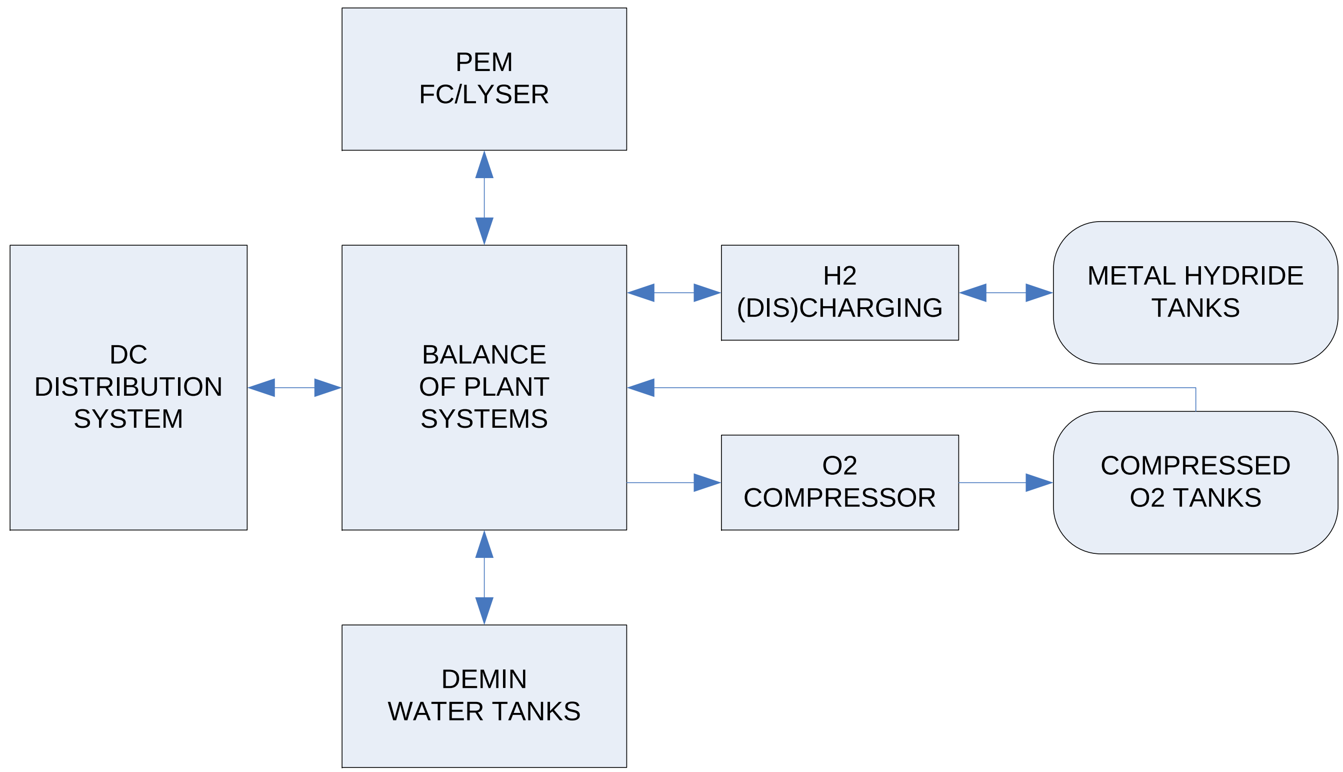
CONCLUSION

FUEL CELL SYSTEM - SCHEMATIC

- Reversible fuel-cells save electrolyser volume
- Heating/cooling required for H_2 (dis)charging
- Demin water tanks can be shared with reactor

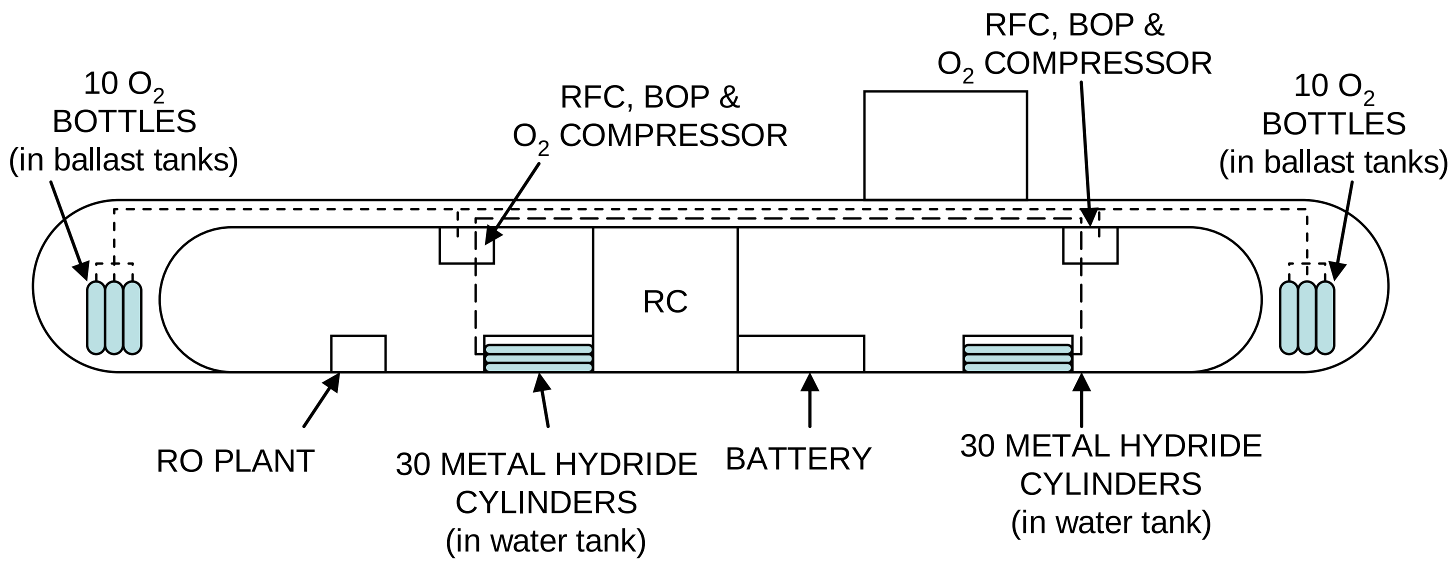


FUEL CELL SYSTEM - SIZING

Scenario	**Metal Hydride Cylinders**	**O_2 Bottles**	**Water Production**	
	620m³ H_2 each	960 m³ O_2 each	Tonnes/day	Litres/man/day
Operations	42	14	3	43
Emergencies	18	6	1.3	18
Total	**60**	**20**	**/**	**/**

- Operations: 7 days at 6kts
- Emergency: 7 days at 4kts
- Recharge: 55 hours

FUEL CELL SYSTEM - LAYOUT



- Total volume (includes 100% access envelope): 285m^3 (5.6m hull plug)
- Total mass: 313 tonnes
- ~ ½ vol & 3x mass of existing DG system

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SAFETY ANALYSIS

- Hydrogen explosion
  - Hydride cylinders – max 0.1m^3 (trivial)
  - RFC compartment – 2 l/s: 30 air changes/hour sufficient
  - Hydrogen pipework – double walled, no fittings
- Hydrogen fire
  - RFC only credible location
  - 2.3^{o}C/sec – detectable!
- Hydrogen asphyxiation – incredible event
- Oxygen reactivity
  - RFCs & ballast tanks only
  - RFCs maintained as “clean” spaces
- Increased AIP redundancy

CONCLUSION

- Concept revolutionary
- Outstanding questions
  - Reactor type and size?
  - Separate or reversible fuel cell/electrolysers?
  - Liquid or compressed oxygen storage?
  - Sea temp. effect on hydride charging?
  - H_2/O_2 storage .v. weight/space trade off?

QUESTIONS

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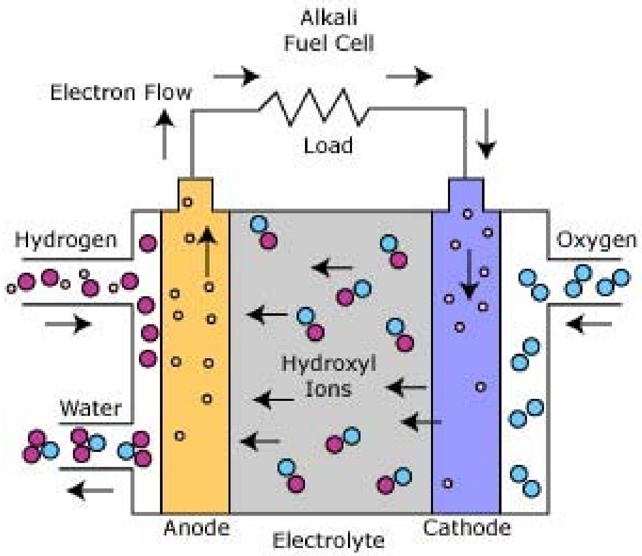
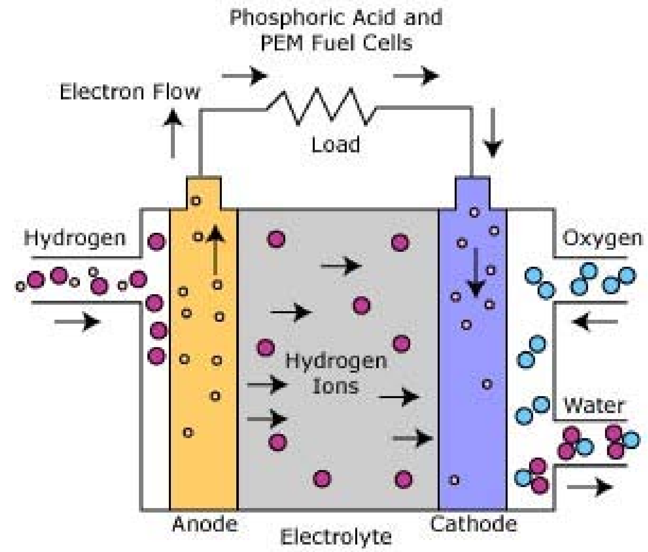
QUESTIONS

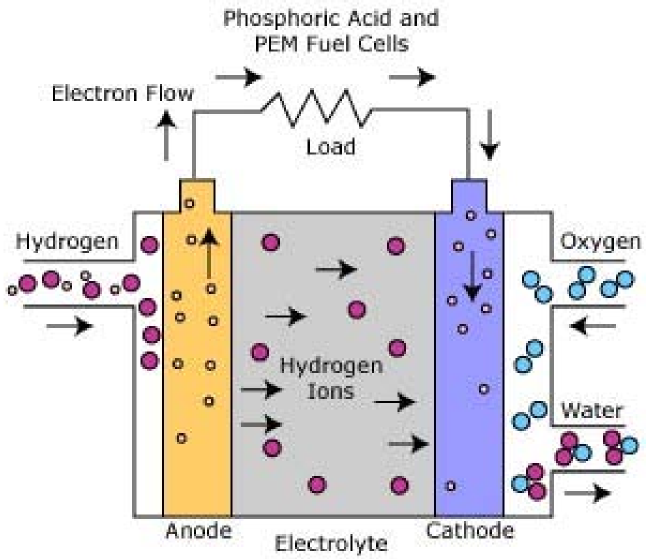
FUEL CELLS
U212/4
RFC
METAL HYDRIDE
LOX TANK
FUEL CELL η'S
SSN/FC CALCS
SSN/FC POWERING



AFC

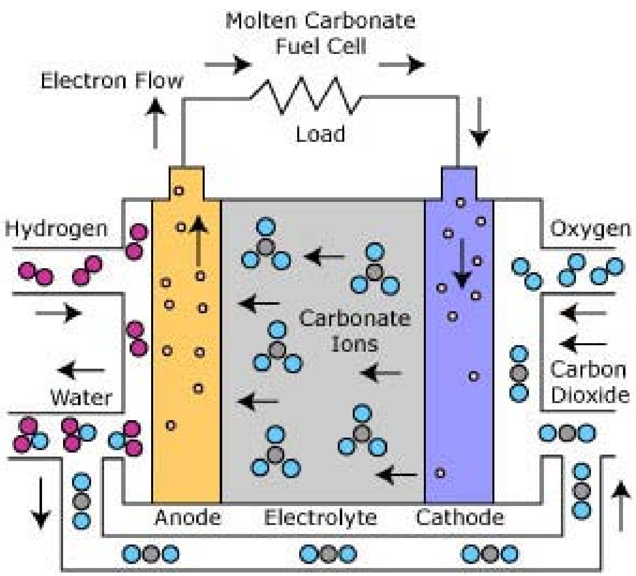


PAFC

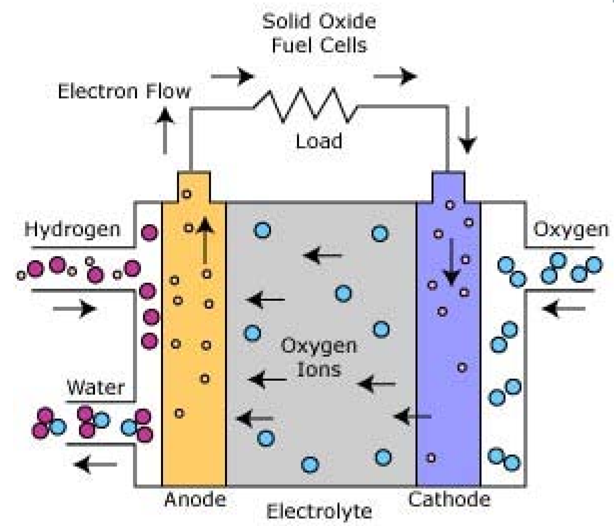


PEMFC

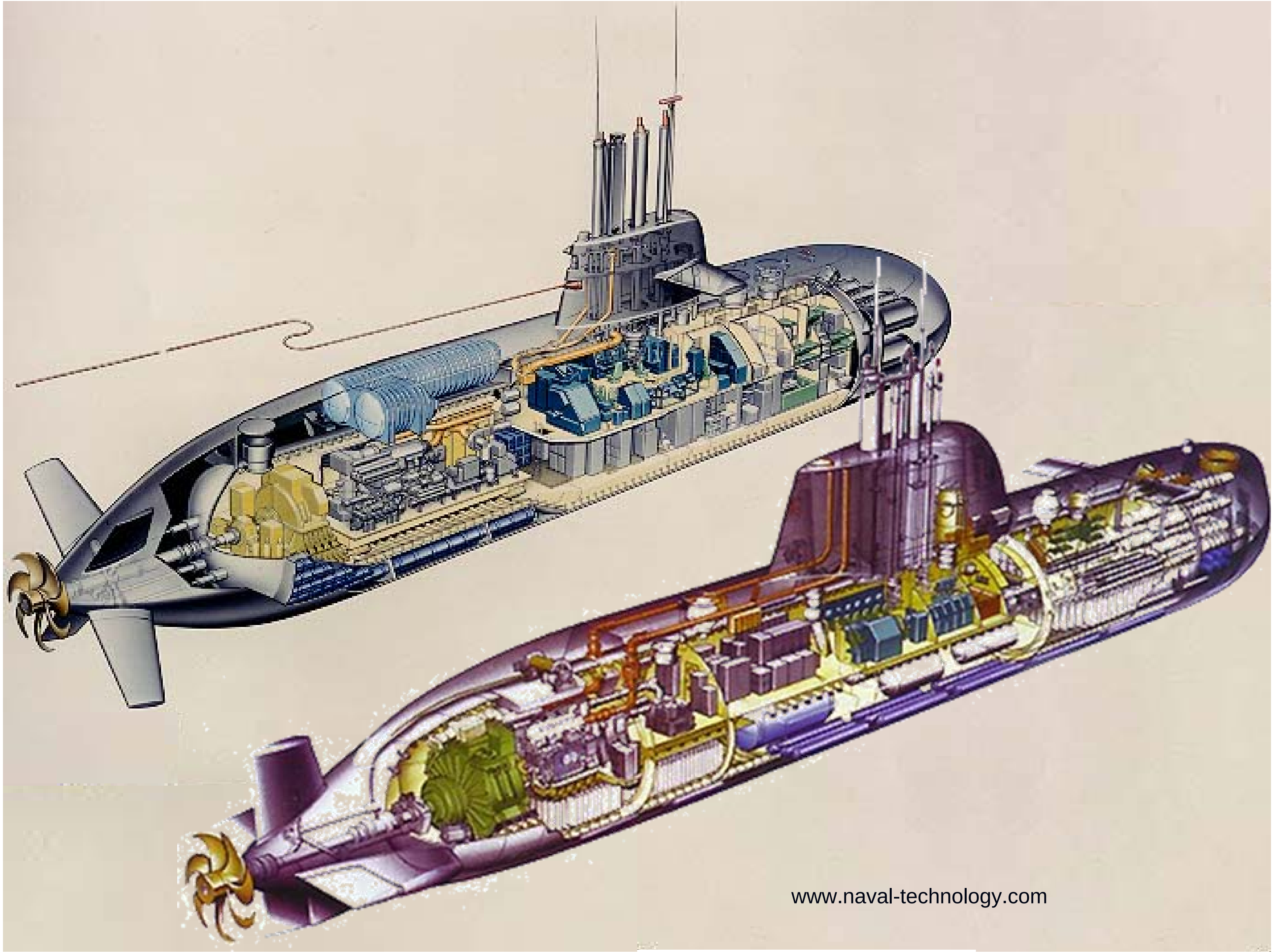
MCFC



SOFC



www.fctec.com

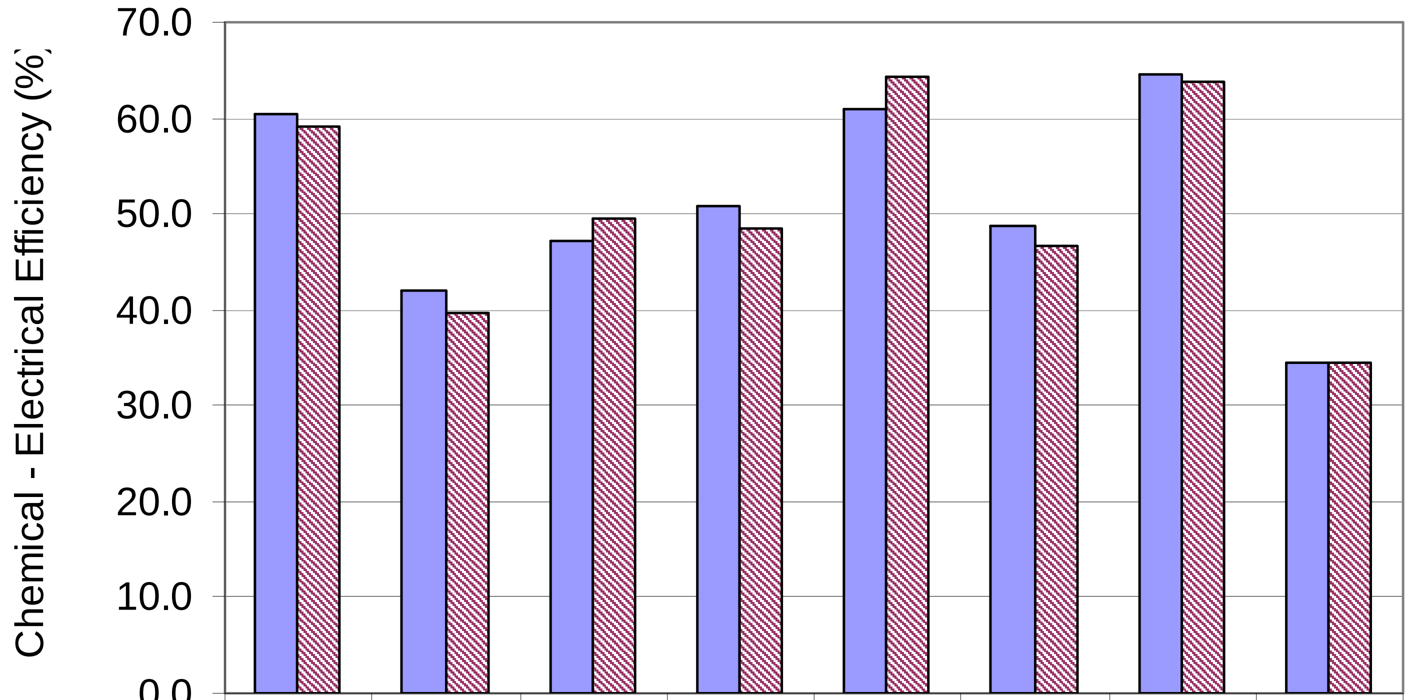

www.naval-technology.com

Dr A.E.Hammerschmidt, Siemens AG, *Fuel-cell propulsion of submarines* Intl. Conf. on Hydrogen and Fuel-Cell Technologies, Munich, 2006.

www.thehydrogencompany.com

www.rixindustries.com

Dr. A.E. Hammerschmidt, Siemens AG, *Fuel Cell Propulsion of Submarines,* Advanced Naval Propulsion Symposium, Arlington 2006.



	AFC	PAFC	PEMFC	MCFC	MCFC-GT	SOFC	SOFC-GT	DMFC
η (%)	60.5	42.1	47.2	50.8	60.9	48.6	64.5	34.5
Corr.η	59.2	39.5	49.4	48.5	64.4	46.7	63.7	34.5

Innovative solutions for pressure hull ends using optimisation methods

Crerar Christie

RINA, Warship 2009: Submarines 9
Glasgow

June 2008

QinetiQ

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www.QinetiQ.com

Contents

01
Objectives

01 Objectives

- Aims of the programme of work for Flat End Closures:
  - To establish a maximum of two suitable design alternatives.
  - To demonstrate the impact of optimisation based design methods.
  - Establish prescribed methods of design.

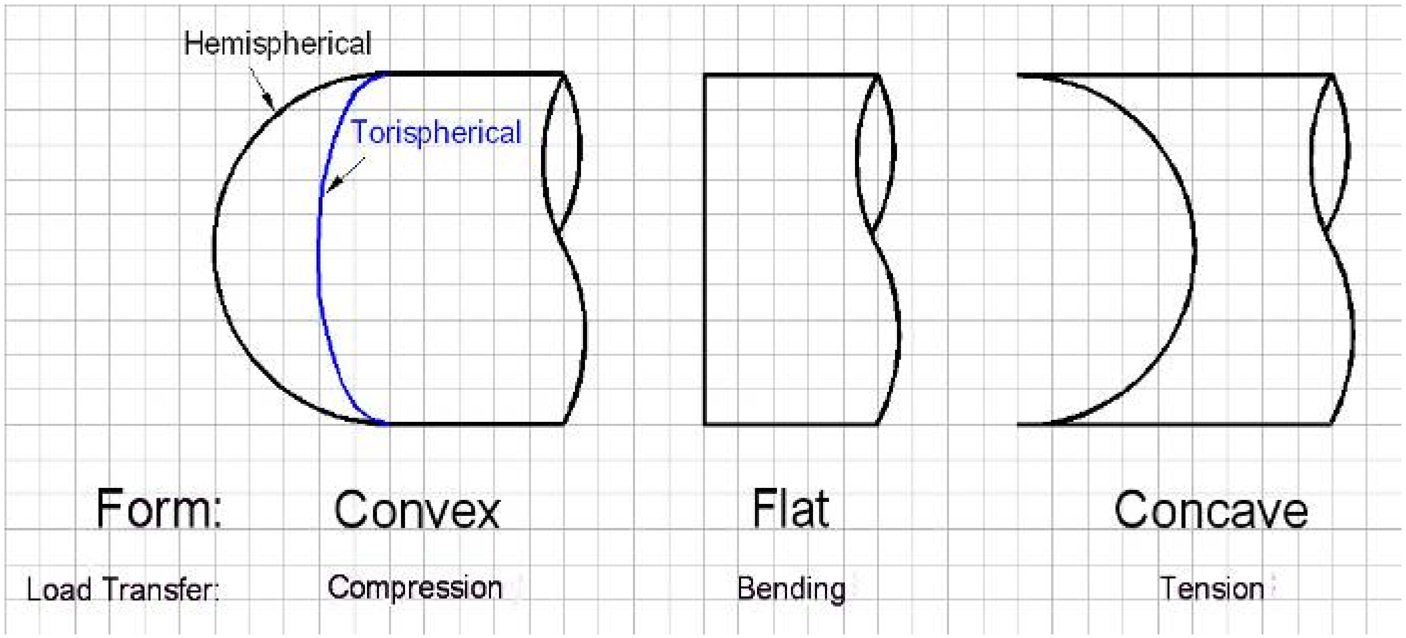
02
Conceptual Considerations

02 Conceptual Considerations

- Though relatively unchanged for post-war classes of UK nuclear submarines, the design of pressure hull end closures has remained a design issue for decades.
- QinetiQ last visited end closure design in 1997. Work was done on flat ended design solutions incorporating GRP materials ("Submarine flat main bulkheads", Creswell and Hobson)
- With the development of analytical and optimisation methods two questions arise: can flat end solutions be designed economically, and, can optimisation methods be effectively integrated into the design method?

02 Conceptual Considerations

- Conceptually, there are three ways of closing the ends of a pressure vessel



- Most efficient structural solution is a convex end closure
- Best solution for space utilisation, ease of construction, and modular construction is a flat end closure
- Traditionally Torispherical domes are used on UK Navy submarines

02 Conceptual Considerations

- Astute bow dome under assembly

02 Conceptual Considerations

- So what's wrong with torispherical domes?
  - Structurally, "nothing", however, there are other issues…
  - Manufacture
    - Torispherical domes are manufactured by cold pressed steel plate into doubly curved petals. Dome has to be thick to prevent snap through collapse.
    - Large presses and specialist knowledge are required, and method is relatively time consuming.
    - BAE acquired 2,500T press from Motherwell bridge and is developing in-house skill in pressing out the required shapes
    - Net consequence is that construction of dome ends is time consuming and costly. Furthermore, it requires specialist equipment and skills which are rare, to the point of extinct, in the UK.

02 Conceptual Considerations

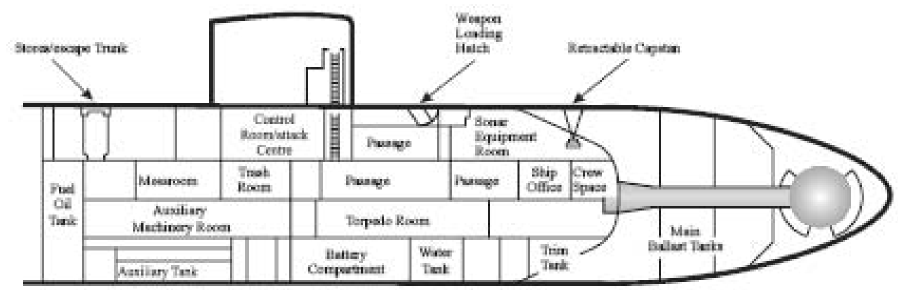
- So what's wrong with torispherical domes, cont.?
  - Best use of space?
    - Extra work is required to make best use of the available space within a dome, compared to a flat surface.
    - Flat surface would more readily facilitate modular construction.
  - Construction
    - Curved surface means that additional manufacturing effort is required to construct adjacent structure, primarily the external casing, at both bow and aft ends.

02 Conceptual Considerations

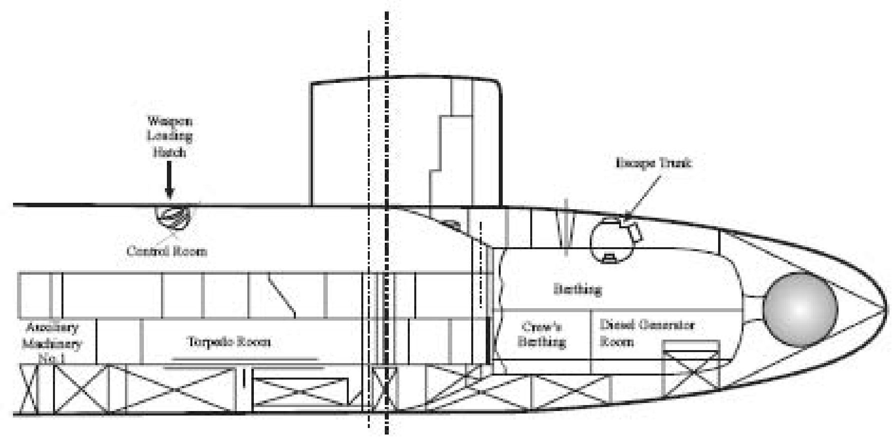
- Construction of Astute bow and stern sections

02 Conceptual Considerations

- A brief look at how others do it…
  - US SSNs
  - Los Angeles Class



  - Sturgeon Class



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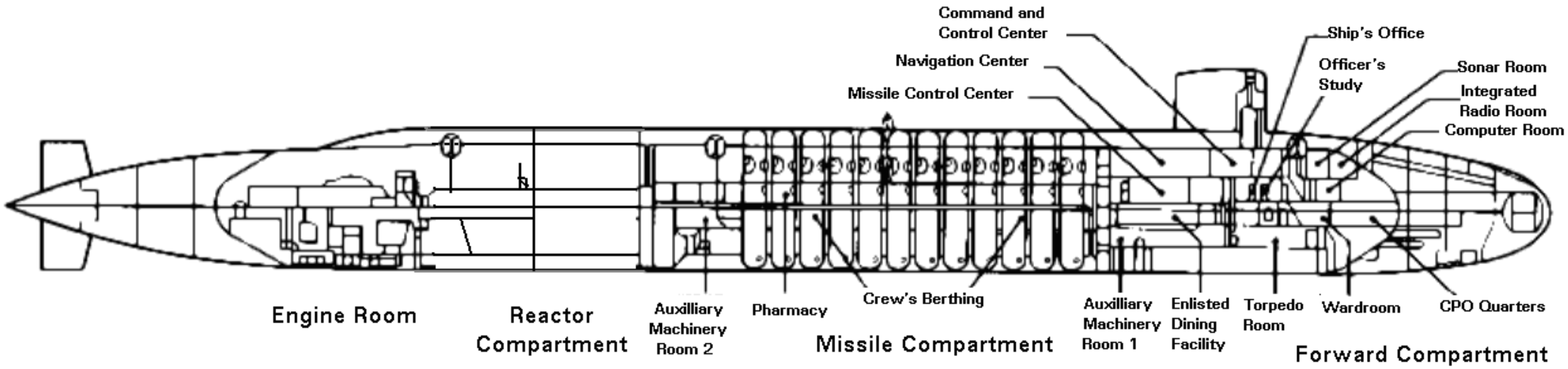
02 Conceptual Considerations

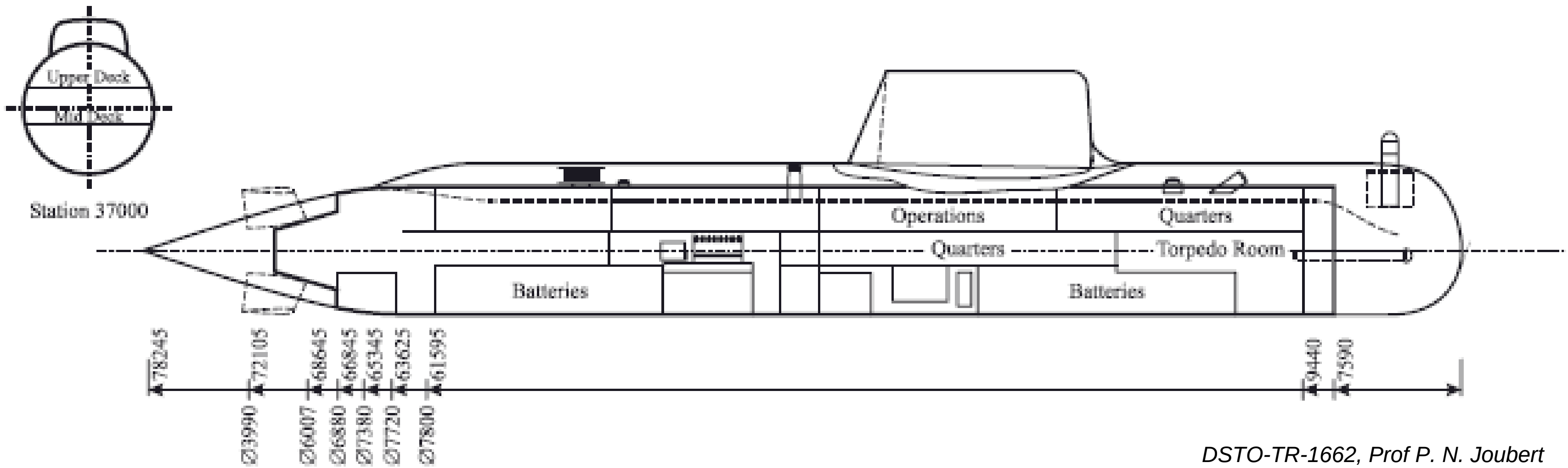
- A brief look at how others do it…
  - US SSBN Ohio class (Class also re-configured as SSGN)



SSBN-726 Ohio Class FBM Submarine

02 Conceptual Considerations

- A brief look at how others do it…



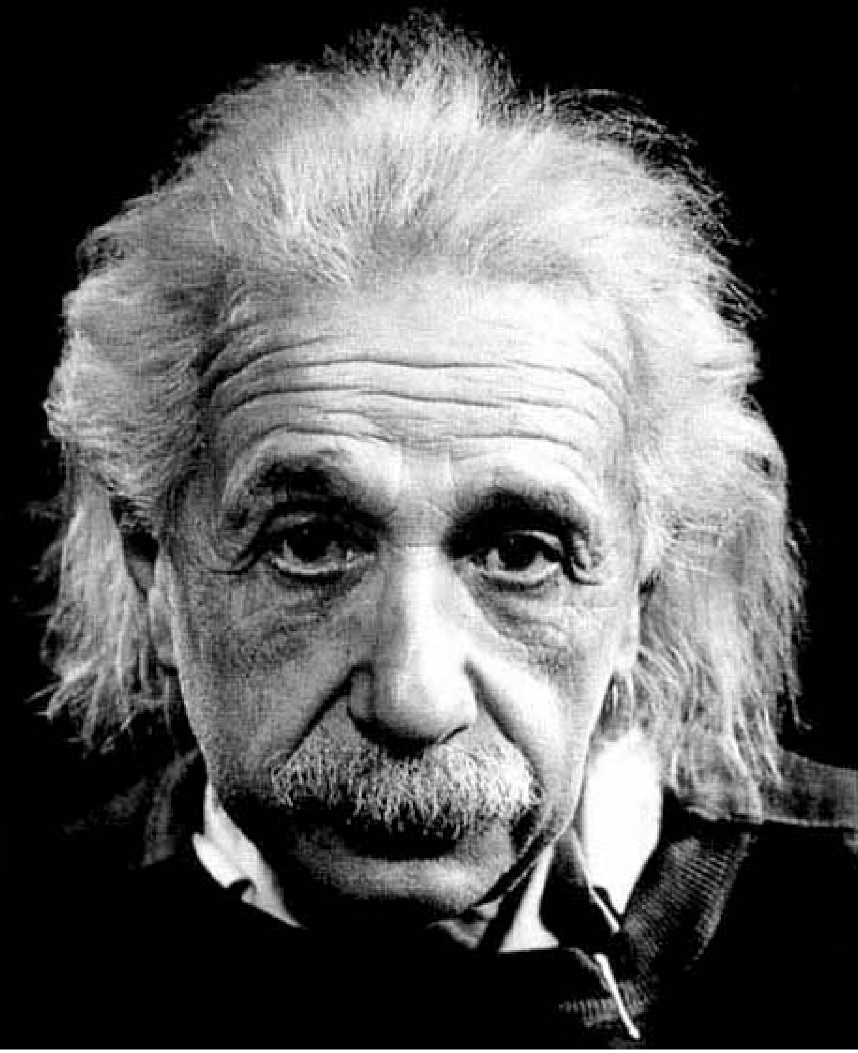
DSTO-TR-1662, Prof P. N. Joubert

– Royal Australian Navy, Collins Class – Construction: Kochums, type 471, 1993
  - L=77m, Beam = 8m, Disp. = 3,500 tonnes
  - *Astute Comparison: L=97m, Beam = 11m, Disp. = 7,800 tonnes*
  - *Vanguard Comparison: L=150m, Beam = 13m, Disp. = 15,680 tonnes*

02
Approach

"Everything should be made as simple as possible, but not simpler."

Albert Einstein



02 Approach

1. Baseline design
   - Follow stipulated guidance in BS 5500/ SSP74 for dome ends
2. Grillage design
   - Abstract design guidance in relevant standards and guides of practice, e.g., PD 5500, and particularly SSP74 to develop structural forms, e.g., recommendations for safety bulkheads used to design end closures
   - Assume more severe load conditions and service requirements
   - May need to use grillage design methods for flat end closures
   - Can also use sizing optimisation

02 Approach

3. Conceptual Design

   Can be approached by either…

   – Brainstorming, story boarding, etc.
     - Time consuming and no guarantee of best solution
     - Too random to be effective
   – Applying a rational method, i.e., optimisation software
     - Quick, providing a rationally optimal solution
     - Need to be careful in both phrasing problem and in interpreting the solution to assure a practicable design.

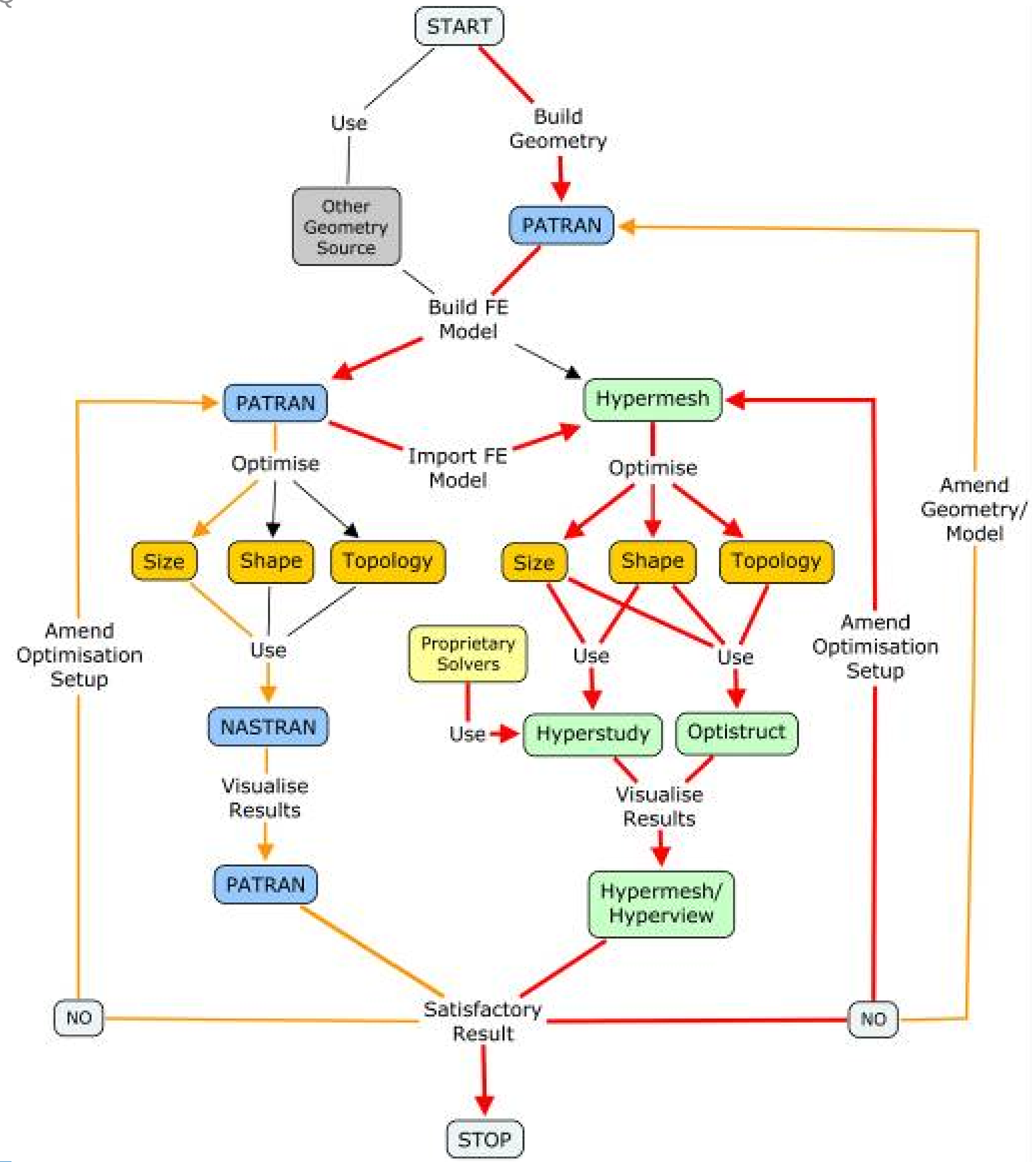
02 Approach

- Software configuration to develop conceptual solutions

Primary route

Secondary route

Other possible routes



02 Approach

- Difference between size shape and topology optimisation

- SiZe – Changes member and section sizes
- Shape - Changes existing boundary profiles (including stiffener spacing)
- T op ol o gy – Changes overall structural forms

02 Approach

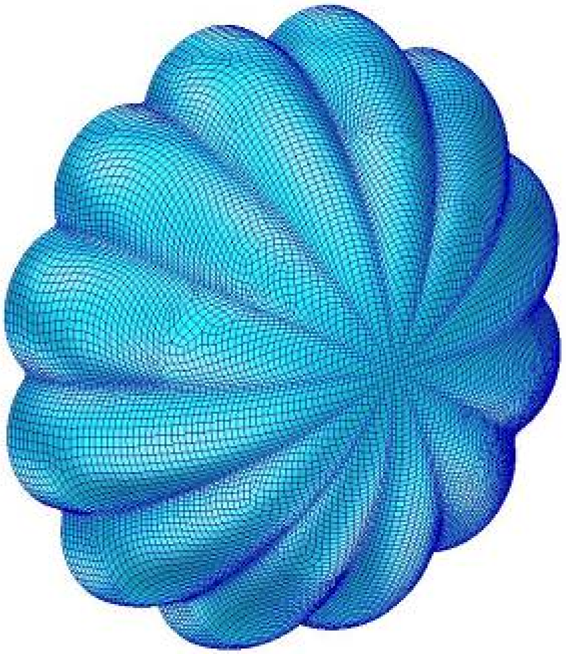
The optimisation problem…

Minimise $f(x)$, subject to:	Objective function
$g_j(x) \leq 0,\ j = 1,\ldots,\ n_g$	Inequality constraints
$h_k(x) = 0,\ k = 1,\ldots,\ n_h$	Equality constraints
$x_{iL} \leq x_i \leq x_{iU}$	Side constraints
for, $x = \{x_1, x_2,\ldots,x_n)$	Design variables

03
Design

03 Design

- Need to develop a baseline comparisons: - a perfect and imperfect 10m torisphere
- Imperfect torisphere - N=12 out of sphericity



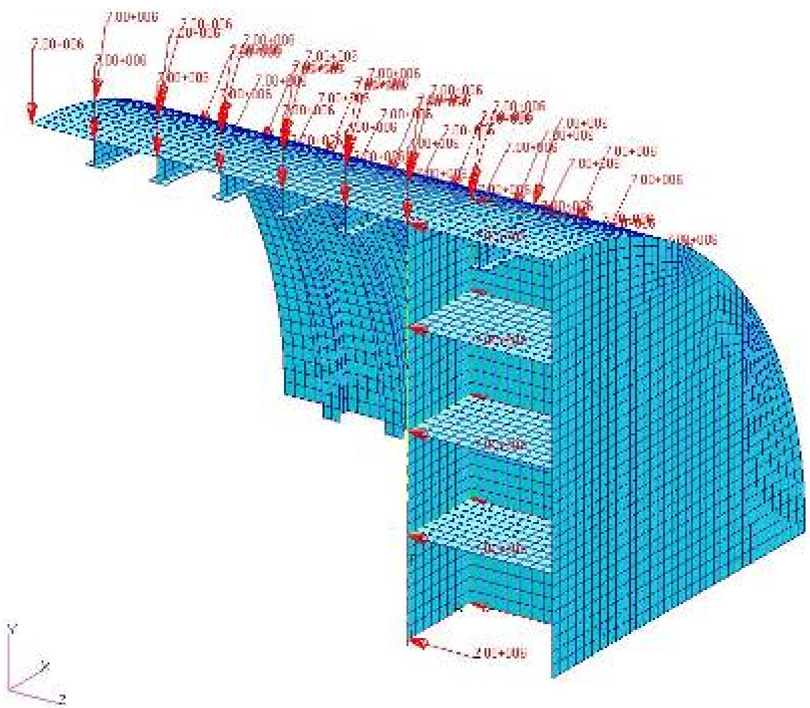
Non-linear collapse analysis of the perfect torispherical dome shape indicates a collapse pressure of 8.66 MPa. Inclusion of the N=12 petal shape reduces the collapse pressure by 0.57MPa or 6.6%.

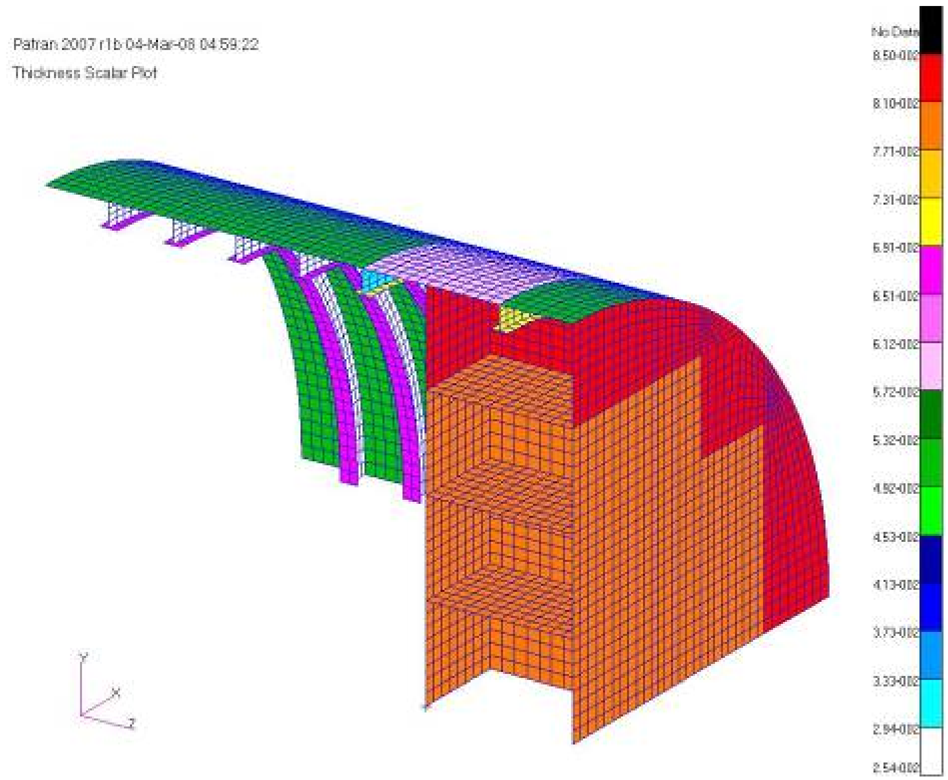
03 Design

- Developing design requirements…
  - End closure should, preferably, be unsupported by decks
  - End closure and transition designs should collapse at greater depths than pressure hull (keep structure elastic up to design collapse pressure - should ensure collapse pressures are near those of dome)…
    - A maximum design pressure of 90% of the dome collapse pressure was adopted (empirical collapse pressure)
    - A maximum yield stress constraint of 3/4s yield was imposed (This is a stringent requirement, but such a conservative approach was thought suitable for exploring novel design solutions)

03 Design

Externally Framed model – loads and property sets (design variables)

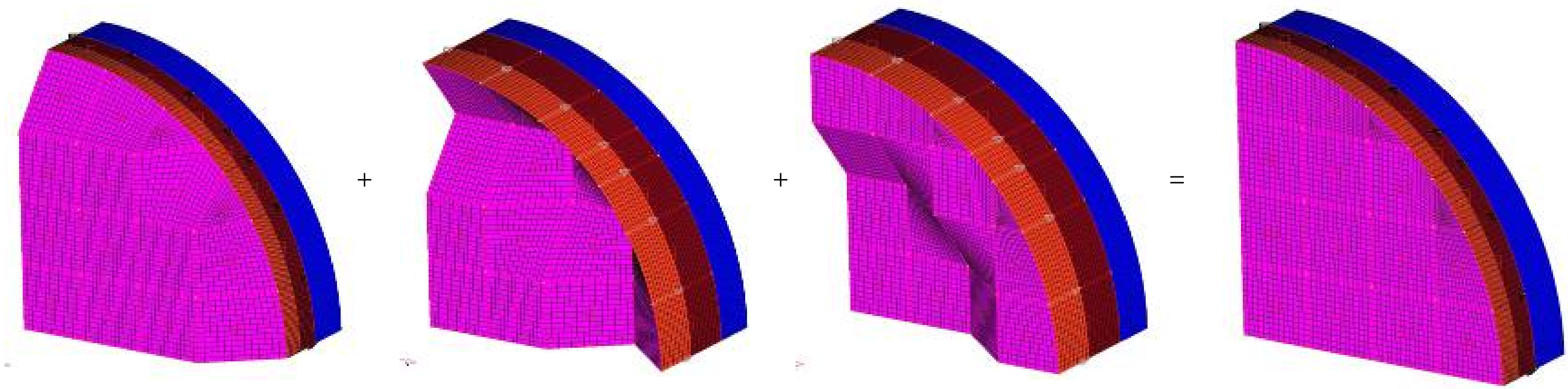




Initially sized using bulkhead design guidance

03 Design

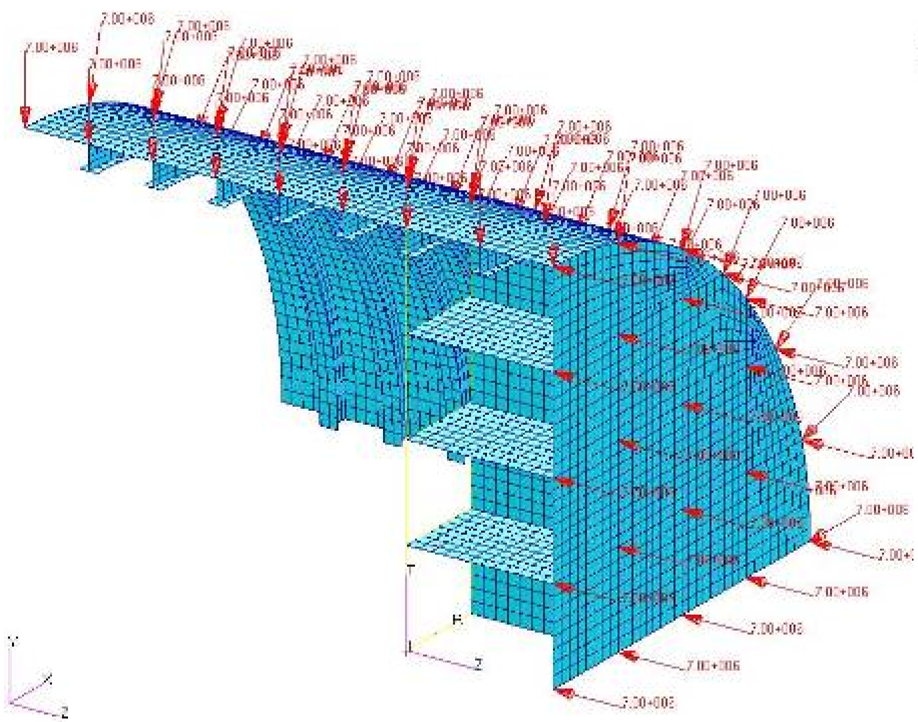
Shape variables for externally framed design

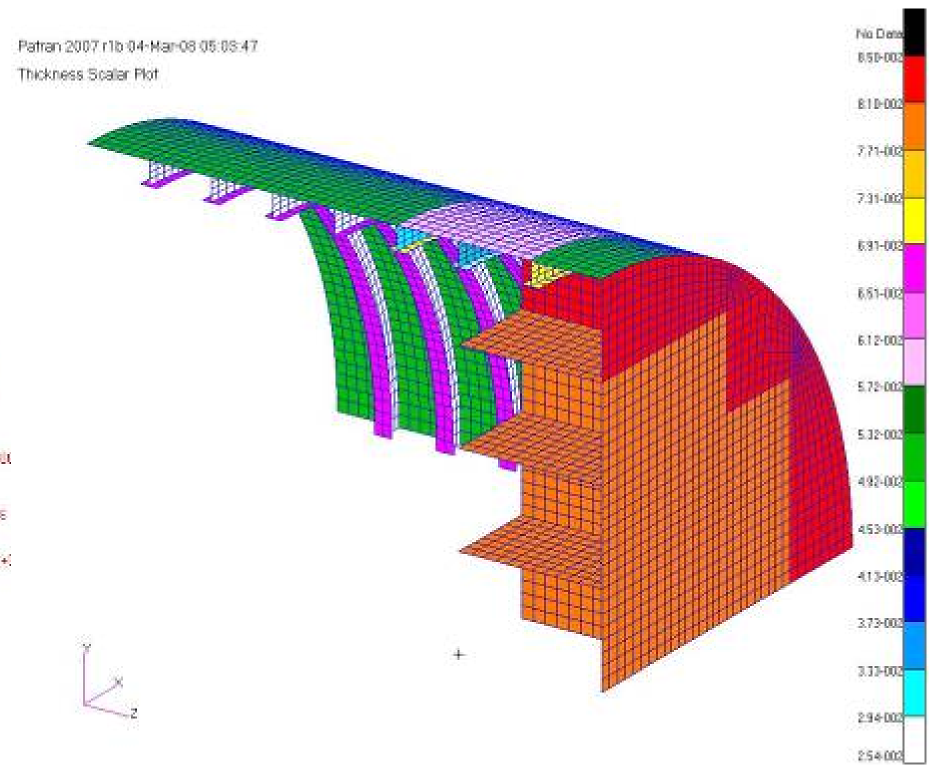


Mode 1 Mode 2 Mode 3 Combined

03 Design

Internally Framed model – loads and property sets (design variables)





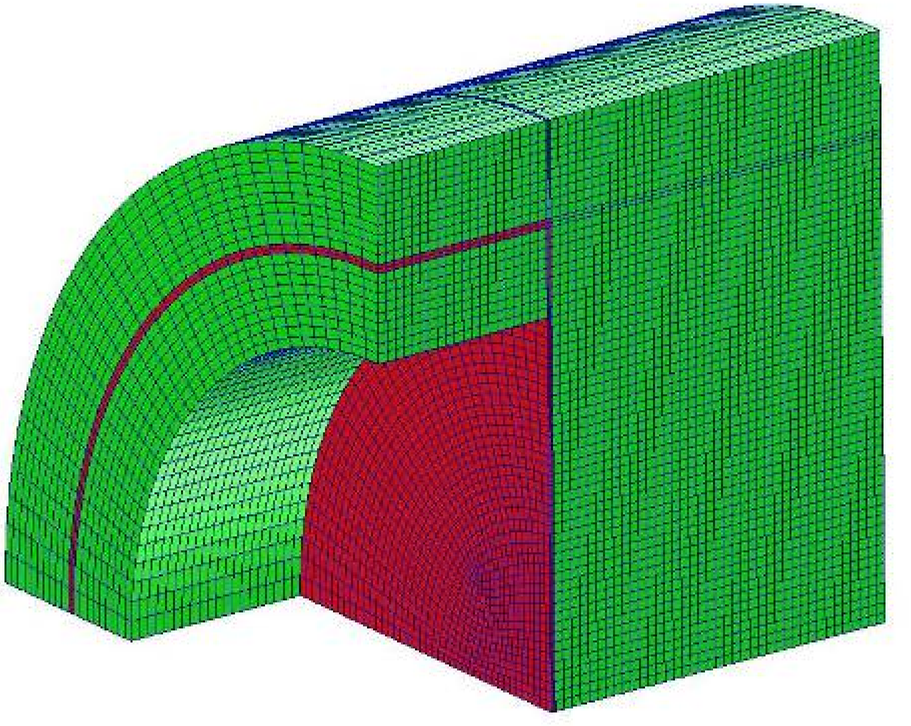
Initially sized using bulkhead design guidance

03 Design

Conceptual Design

Initial step:

Develop overlarge non-design and design domains, with loads and appropriate boundary conditions



Second step:

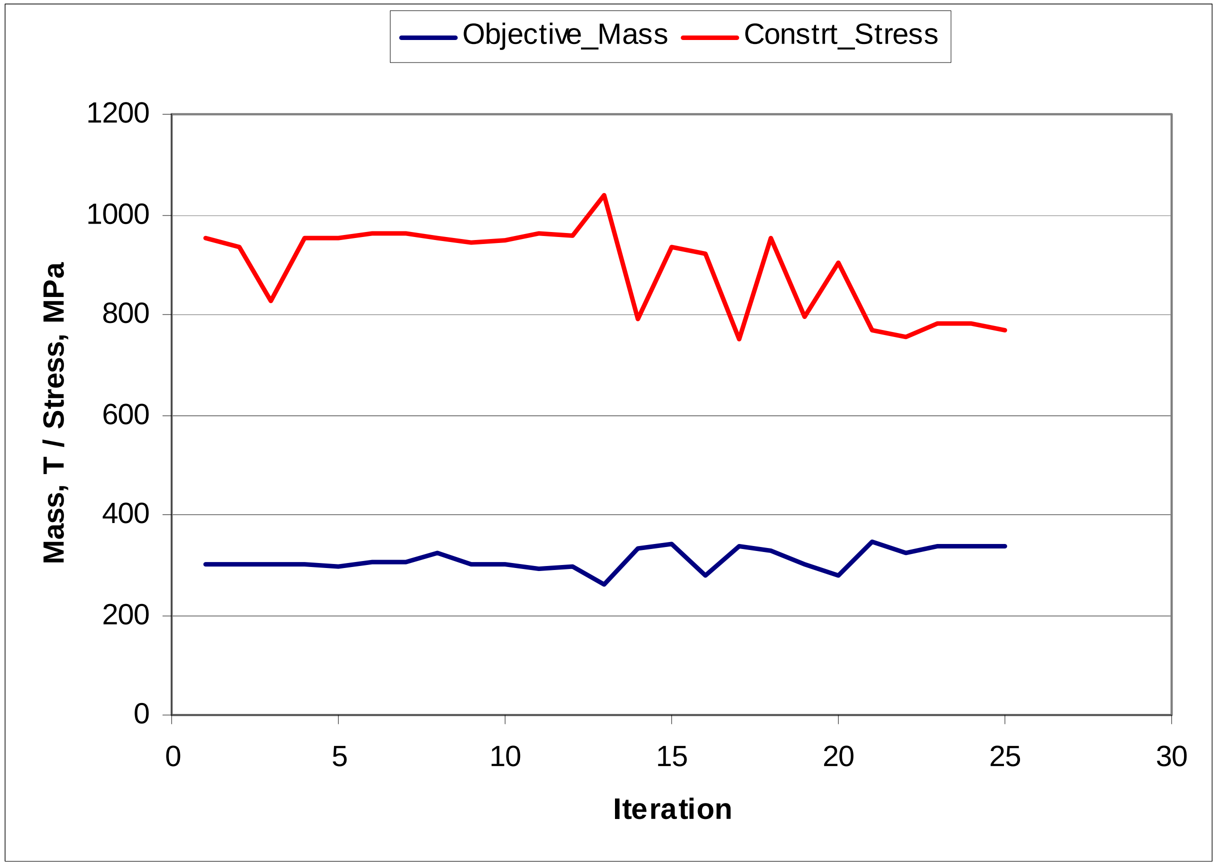
Specify design variables, objectives and constraints for optimisation problem.

Example shown: 10m diameter

04
Results

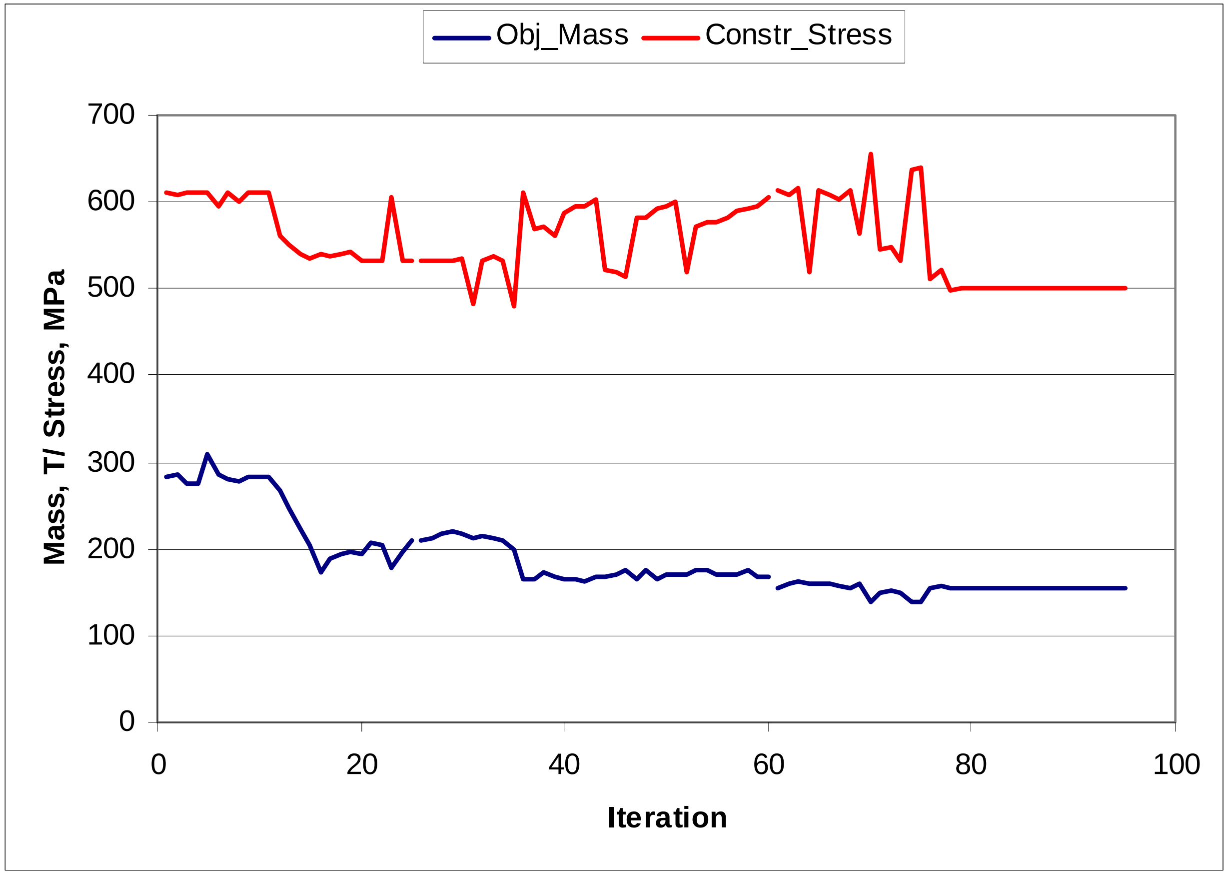
04 Results

Externally framed design variant



04 Results

Externally framed design variant – modified, 4 MPa design pressure



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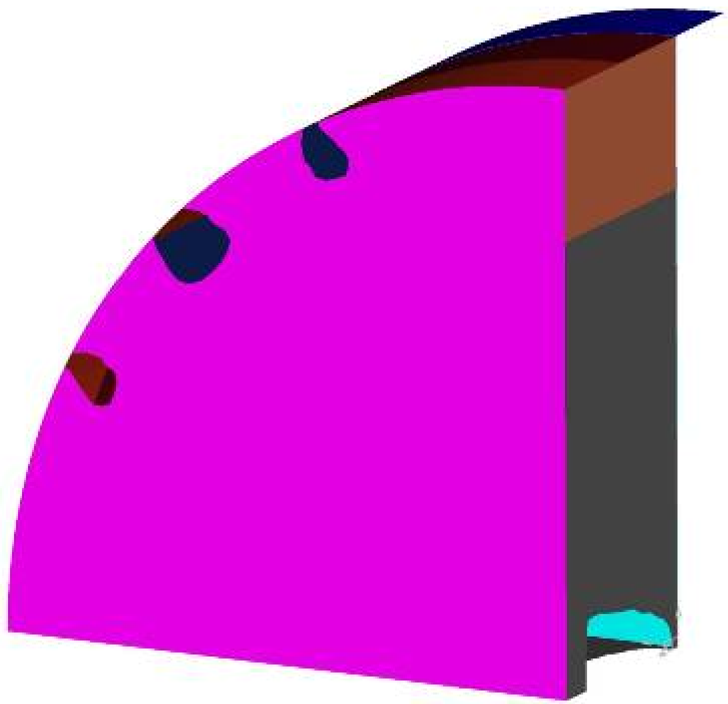
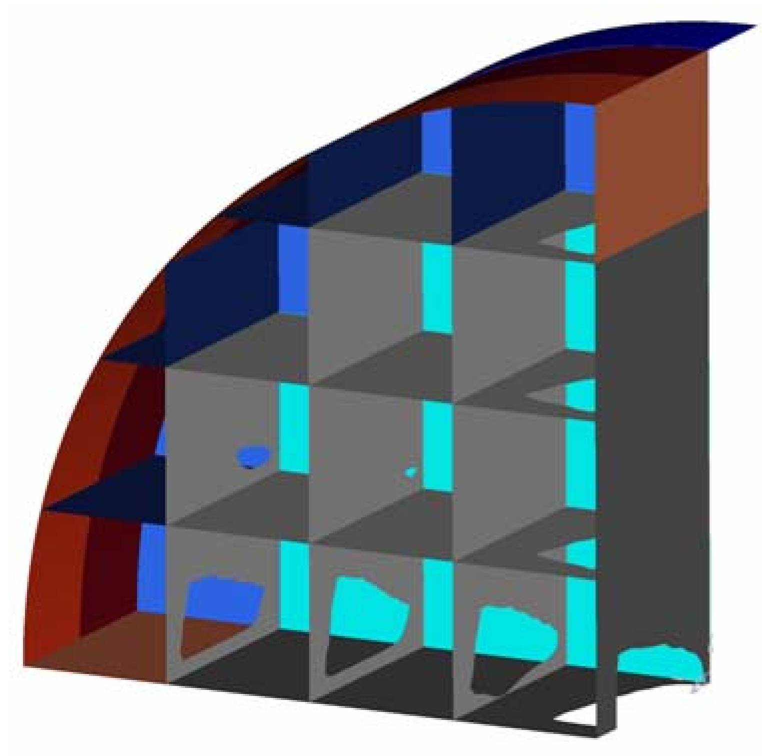
04 Results

Topology optimisation results for modified external frame, 4 MPa design pressure



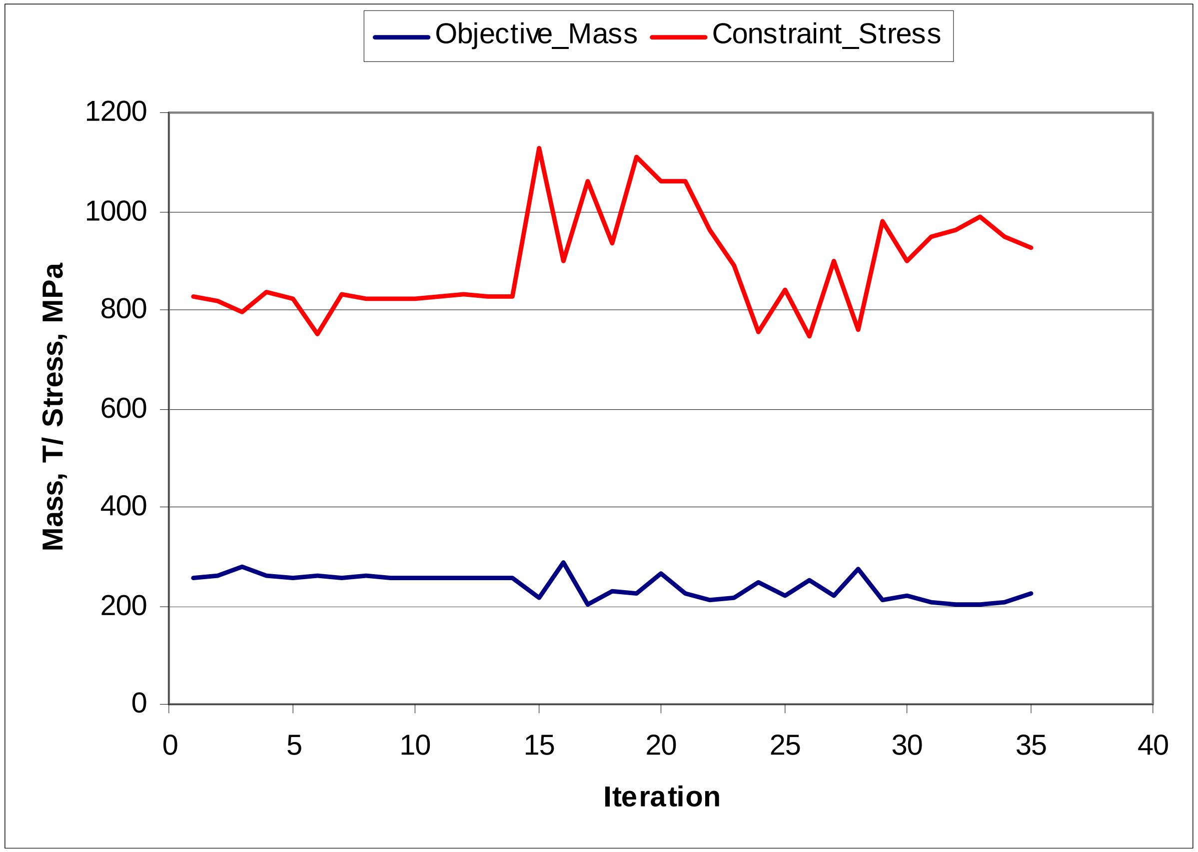
With cover plate



Cover plate removed

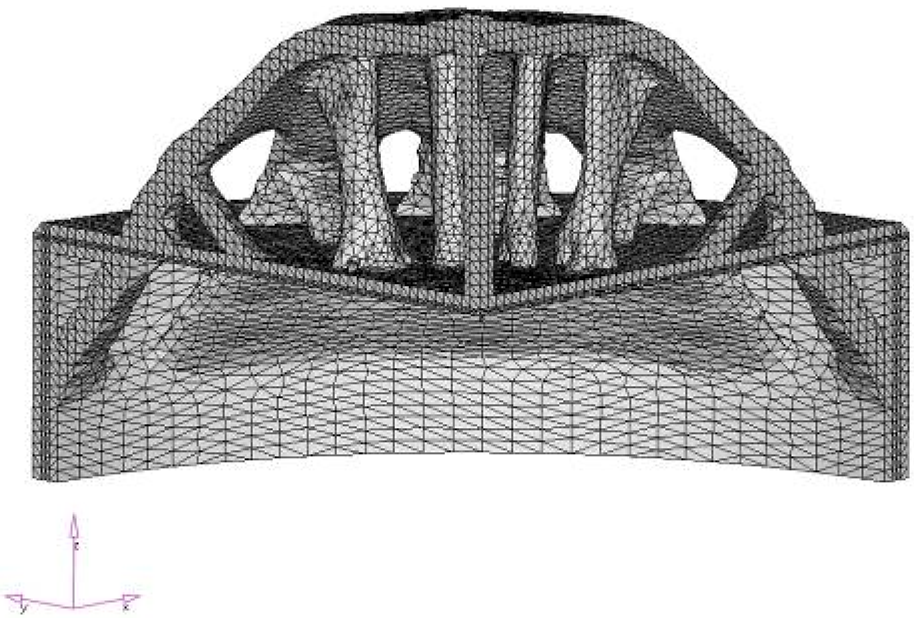
04 Results

Internally framed design variant

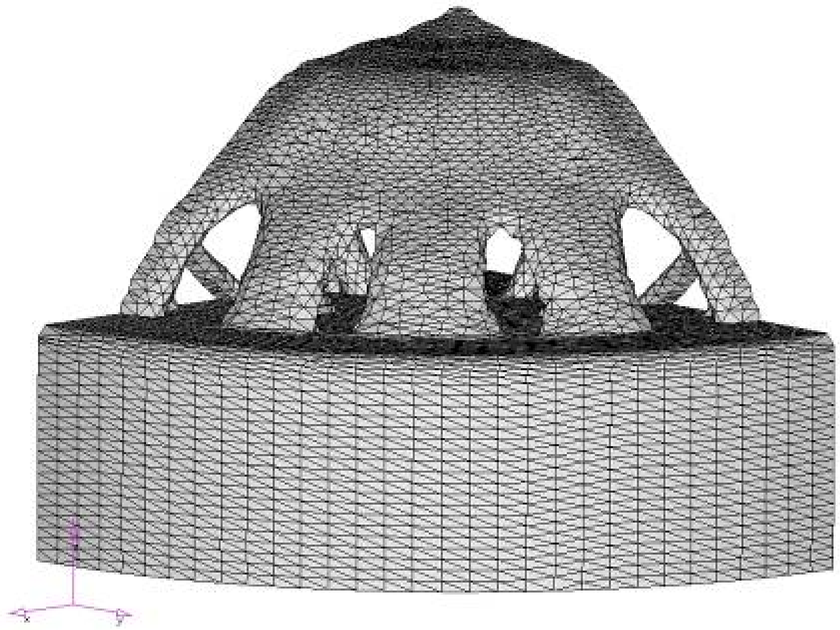


04 Results

Conceptual designs after topology optimisation of solid model



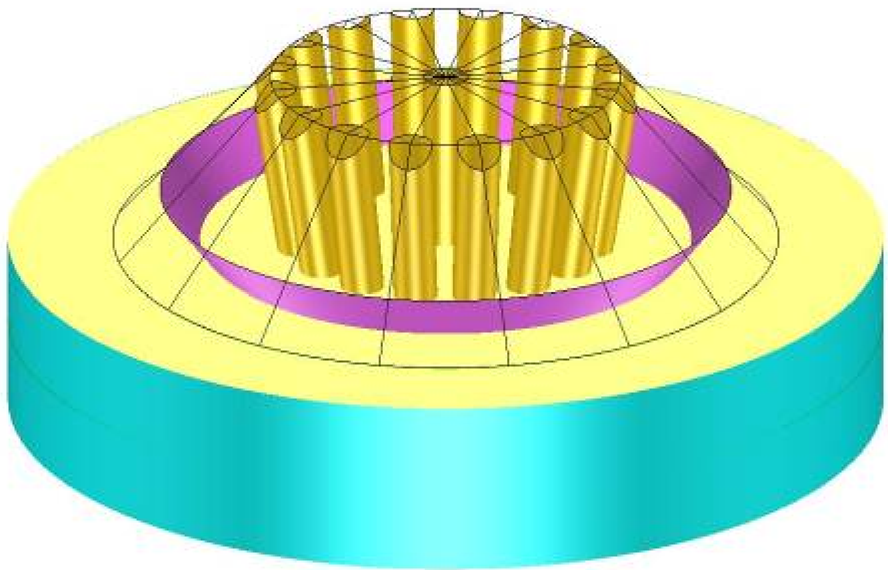
Internal view



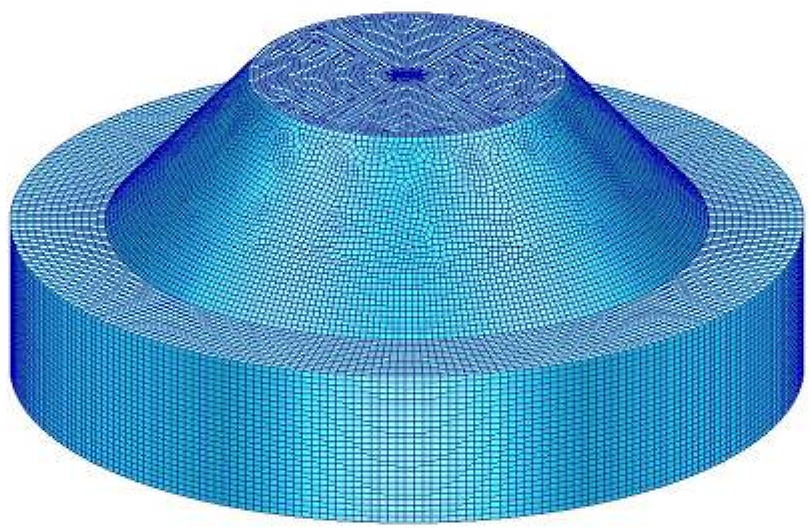
External view

04 Results

Shell idealisation of optimised solid mesh

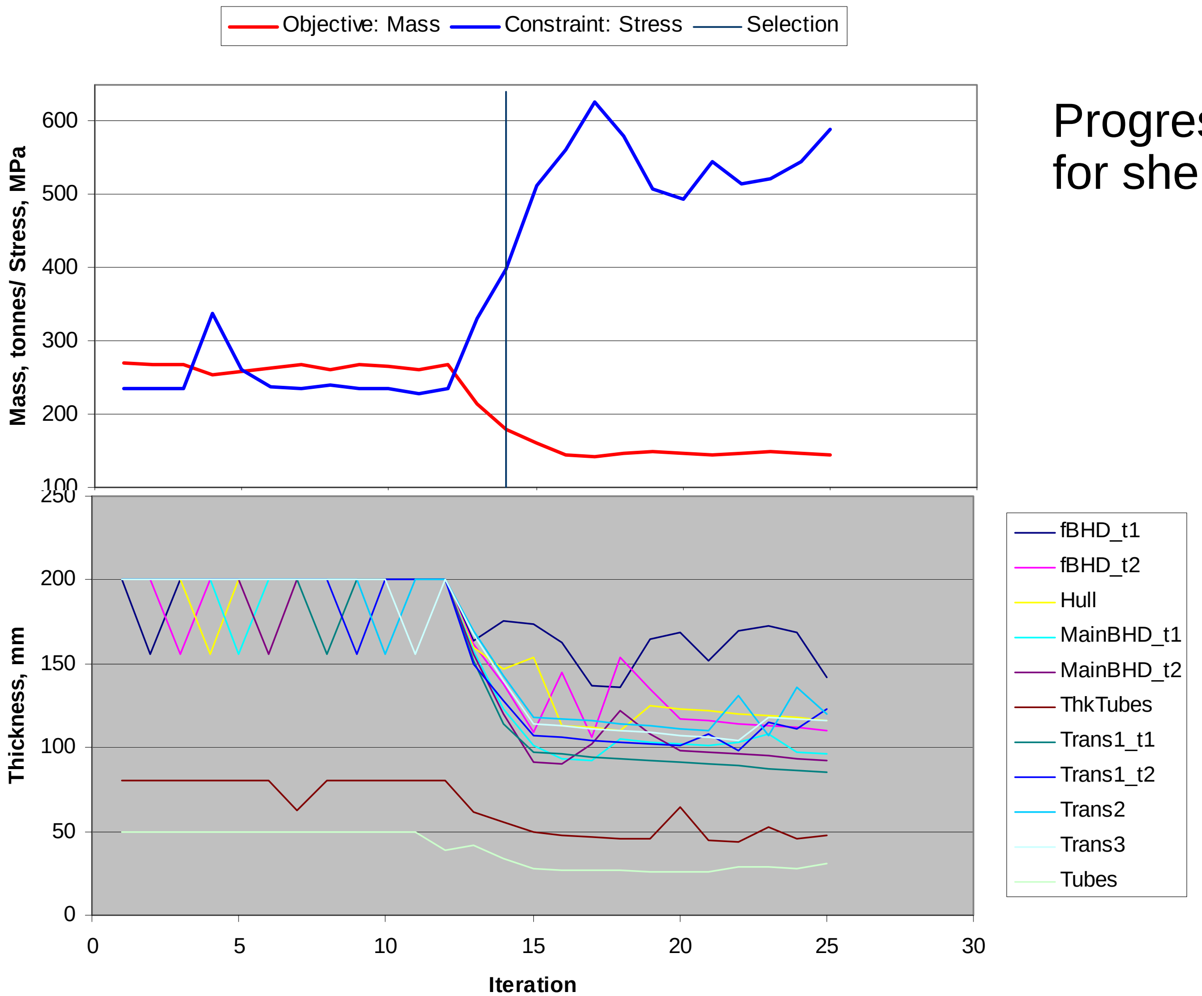


Geometry



Mesh

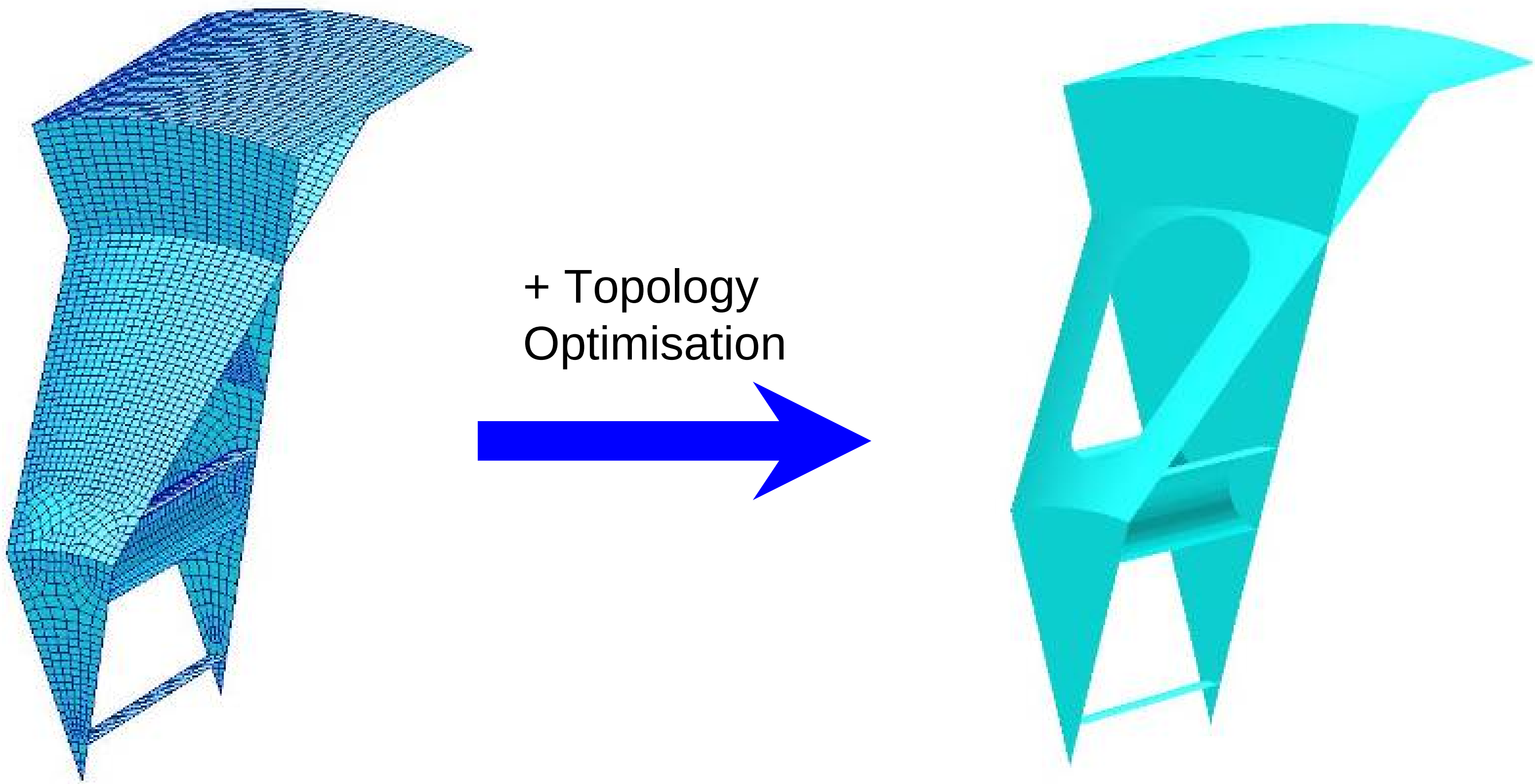
04 Results



Progression of size optimisation for shell idealised structure

04 Results

Can reduce mass further using topology optimisation of shell solution, but depends upon robustness of solution



04 Results

Preliminary results for Conceptual Design solutions

Model	Design	Load, MPa	Peak σ_{vm}, as a fraction of yeild	Mass, as a proportion of Dome mass	P_c, As a proportion of dome
Dome	-	-	-	1.00	1.00
Ext. Frame	SSP74	7	1.74	4.93	-
	Size Opt.	7	1.37	5.29	0.97
Int. Frame	SSP74	7	1.50	4.19	-
	Size Opt.	7	1.38	4.07	0.97
Modified Ext. Frame	SSP74	4	1.11	4.66	-
	Size Opt.	4	0.91	2.55	-
	Top. Opt.	4	0.97	2.23	0.66
Conceptual	Top. Opt, Size Opt.	7	0.88	5.98	2.61

05
Summary

05 Summary

- In relation to objectives…
  - Three design alternatives developed using both traditional methods and a combination of size, shape, and topology optimisation methods.
  - Optimisation based design methods, though unable to achieve all target criteria in this instance due to over onerous loading condition, provide a more effective and economical means of design than traditional methods.
  - No bespoke method for optimised design of end closures: best approach would be to the configure optimisation problem within an EN 13445, design by analysis, interpretation of the design guidance.
- Specifically…
  - More economical designs could be achieved by using a non-linear collapse constraint and by incorporating more refined zones of plate thickness and stiffener spacing within the optimisation problem.

05 Summary

- Making changes to end closures and transitions has other design implications…
  - Buoyancy
  - Placement of torpedo tubes and bow array
  - FBT/ ABT placement
  - Signatures
  - Shock response

06
Questions?


QinetiQ

The Global Defence and Security Experts

Low Signature Propeller Capability

RINA Conference
Warship 2008: Naval Submarines

N Ireland and G J Cooper

11th June 2008

QinetiQ

LSPC - Introduction

Naval vessels, both surface ships and submarines, are, in most cases, subject to meeting requirements for Cavitation Inception Speed (CIS). This is normally measured at model scale and then predictions made for the vessel at full scale, the actual performance then being established during noise trials when the platform enters service. This process carries both risk and associated cost through the overall procurement programme.

The LSPC is designed to reduce both risk and cost by the introduction of a process which allows a more accurate prediction of CIS earlier in the procurement programme. Many elements of the LSPC are directly applicable to both surface ships, which its is currently developed around, and for future submarine designs which have CIS requirements.

LSPC - Background

- Warship propellers designed by iterative model tests to meet specification
- Ship trials are too late in procurement process to establish whether specified inception speed has been met

LSPC - Objective

- To provide a process by which low signature propellers can be incorporated in new surface ship procurement whilst avoiding prohibitive costs and high risks to both MOD and contractor
- Output from the LSPC programme will be used in the procurement of future warships with ASW capability, including FSC

LSPC – New ship procurement process

- QinetiQ to develop a model test process and correlation methodology acceptable to MOD and industry that will enable cavitation performance of the ship to be reliably predicted
- MOD will then accept the risk that the ship will not meet the specified inception speed

Industry Forum

Designed to involve the propeller and naval shipbuilding industry for whom the LSPC is directed.

- Forum meetings twice each year
- Useful involvement of industry
  - Benefit of their experience and “Buy-in” to solution
- Industry Forum receive progress reports and invited to view cavitation tests at Haslar
- Industry presentations - Diverse
  - Stone Manganese Marine report on a portable propeller blade measuring device.
  - Lloyds Register on the feasibility study into the viewing of cavitation inception at full scale
  - Wartsila Lips Defence on a Low Noise Design Strategy for Propellers

Cavitation Inception Test Methodology

Hull model

– Accurate propeller finished to high standard
– Accurate representation of shaft brackets
– Ship hull shortened to obtain large size, typically 5m long

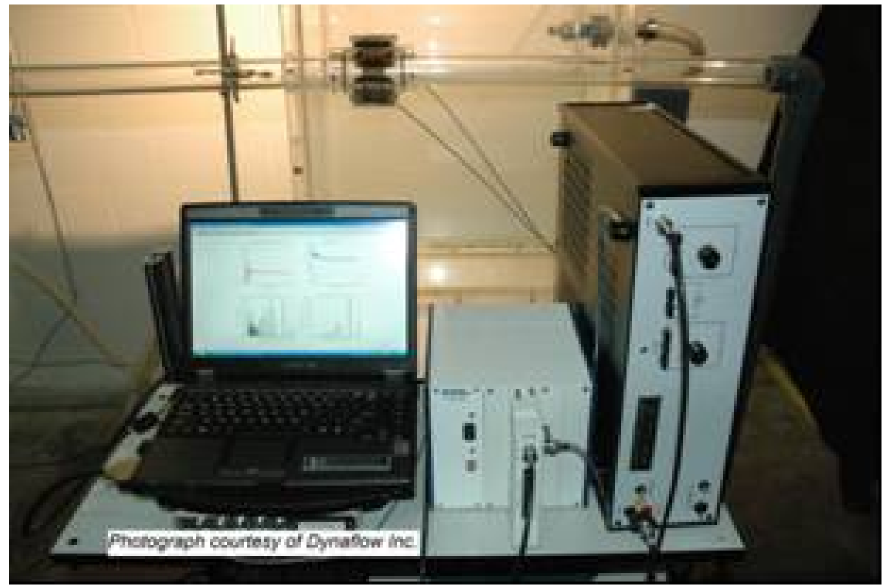
Cavitation Inception

– Visual determination
– De-aerated water
– Constant water speed
– Change propeller shaft speed to generate different forms of cavitation
– Various static pressures

Water Quality Instrumentation

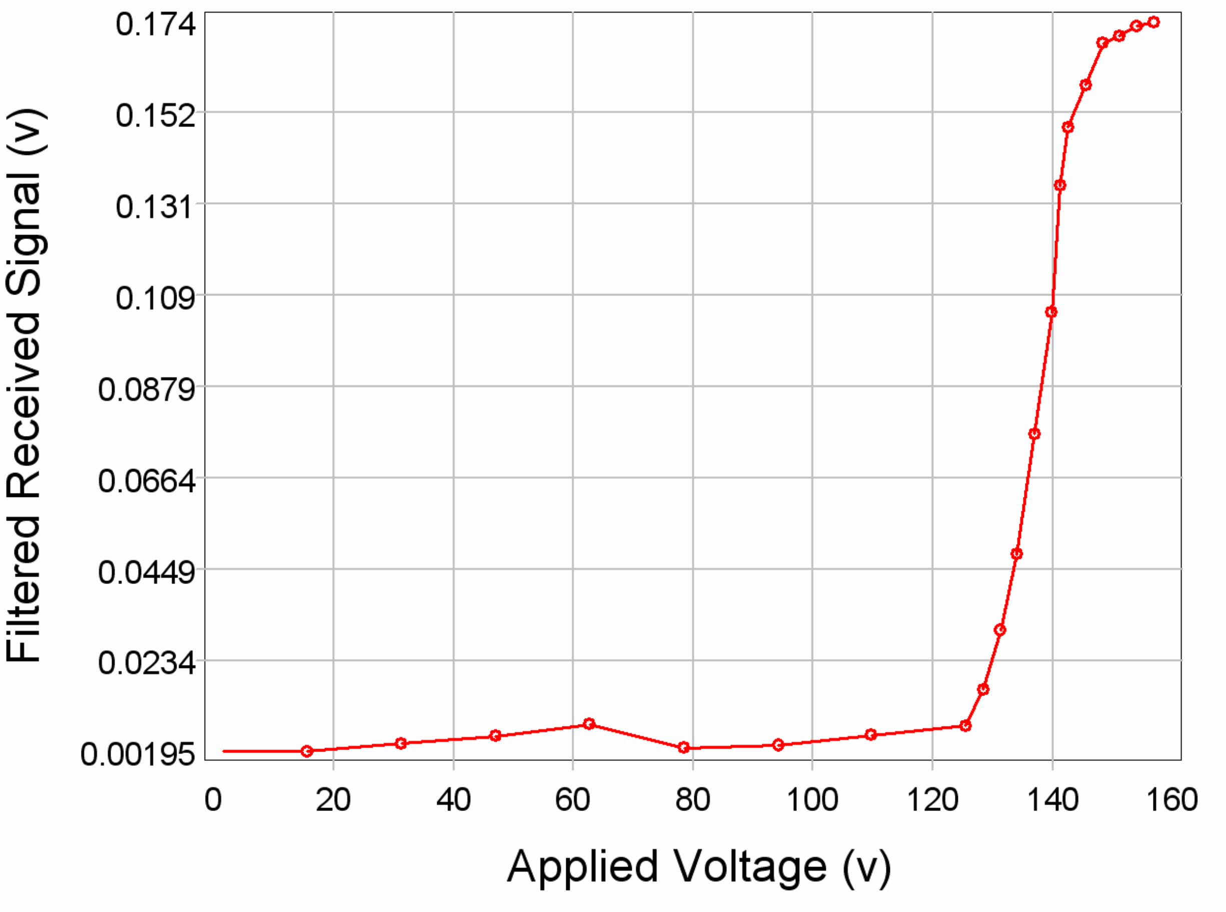
Nuclei concentration

Dissolved gas content
Temperature
Salinity



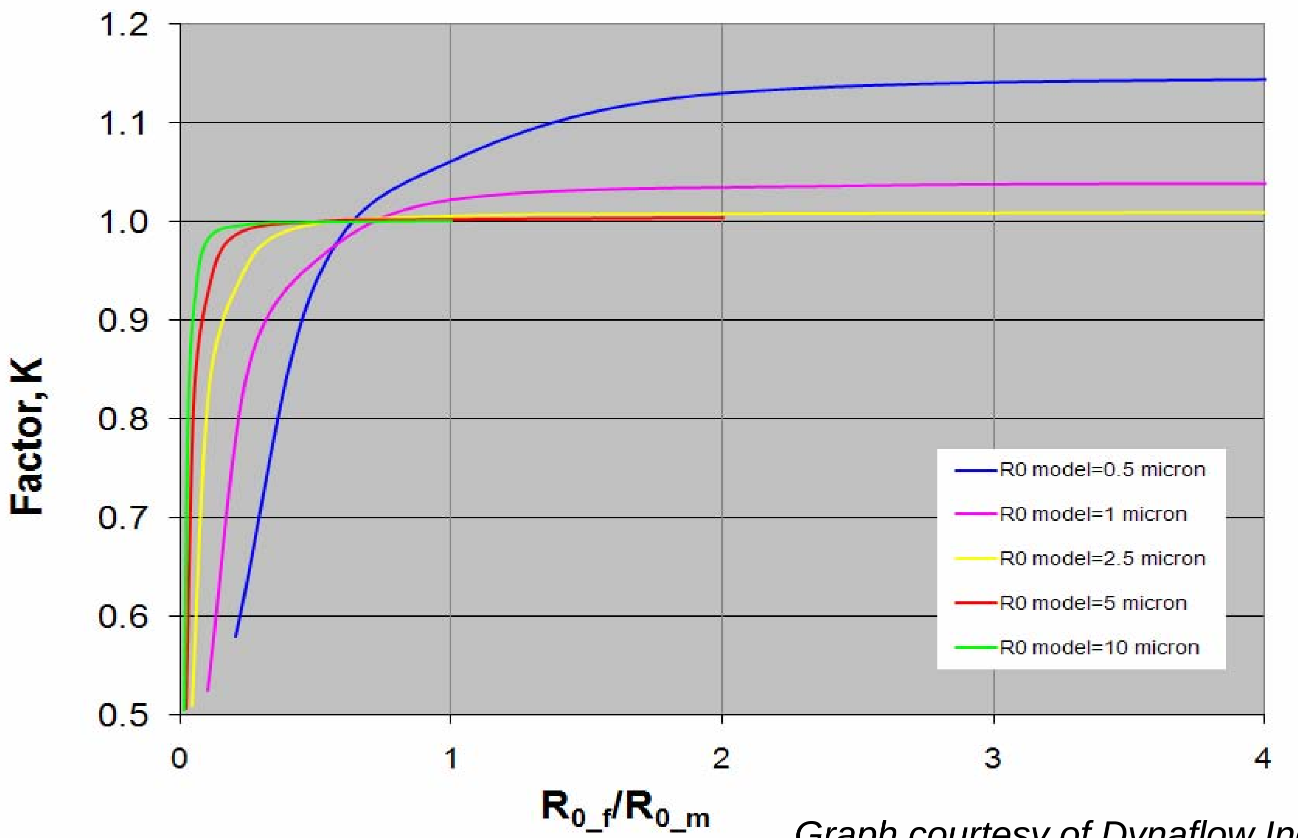
Bubble concentration
Cavitation susceptibility

Cavitation Susceptibility



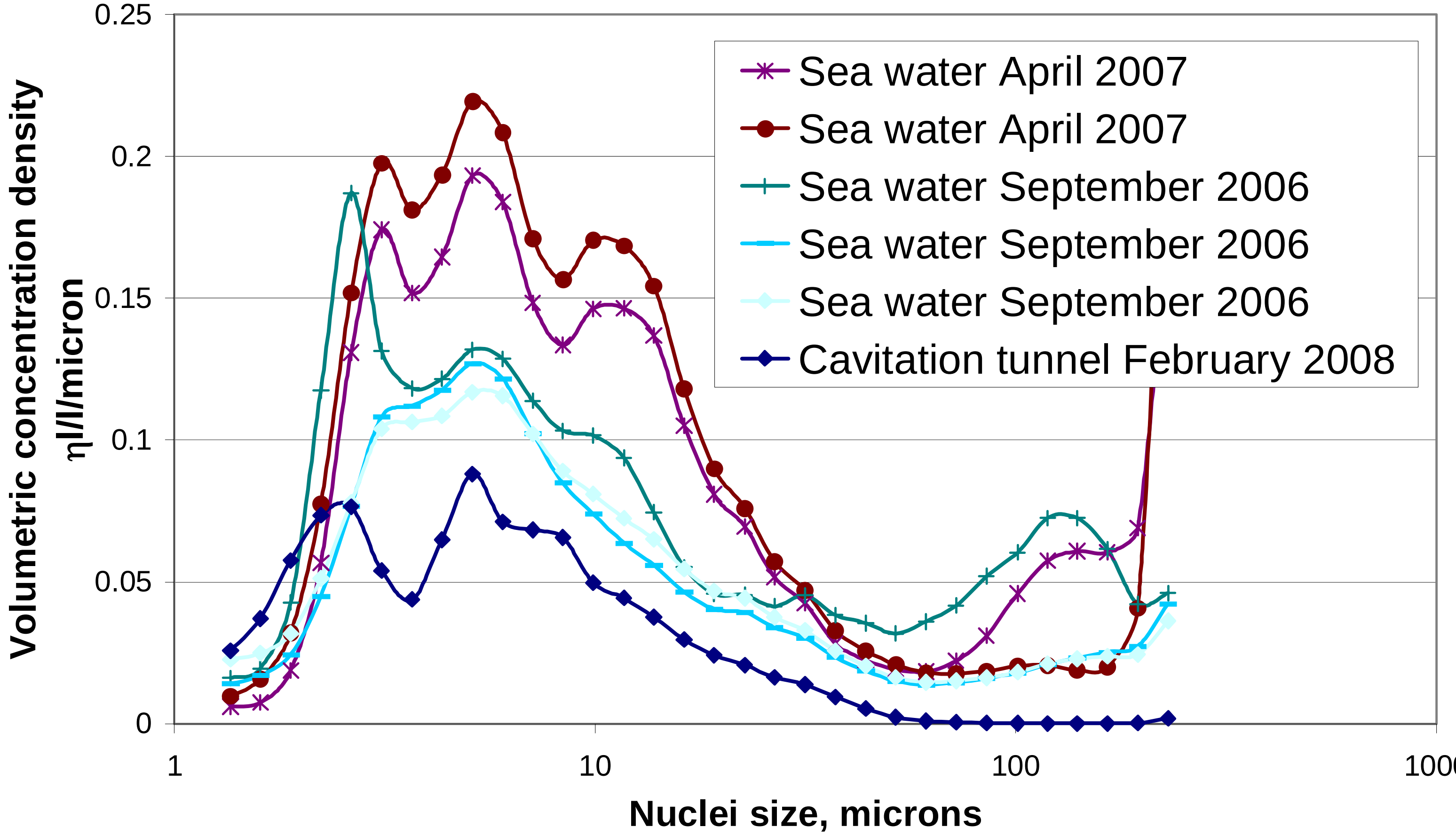
Graph courtesy of Dynaflow Inc.

Scaling of Model Data to Ship Conditions

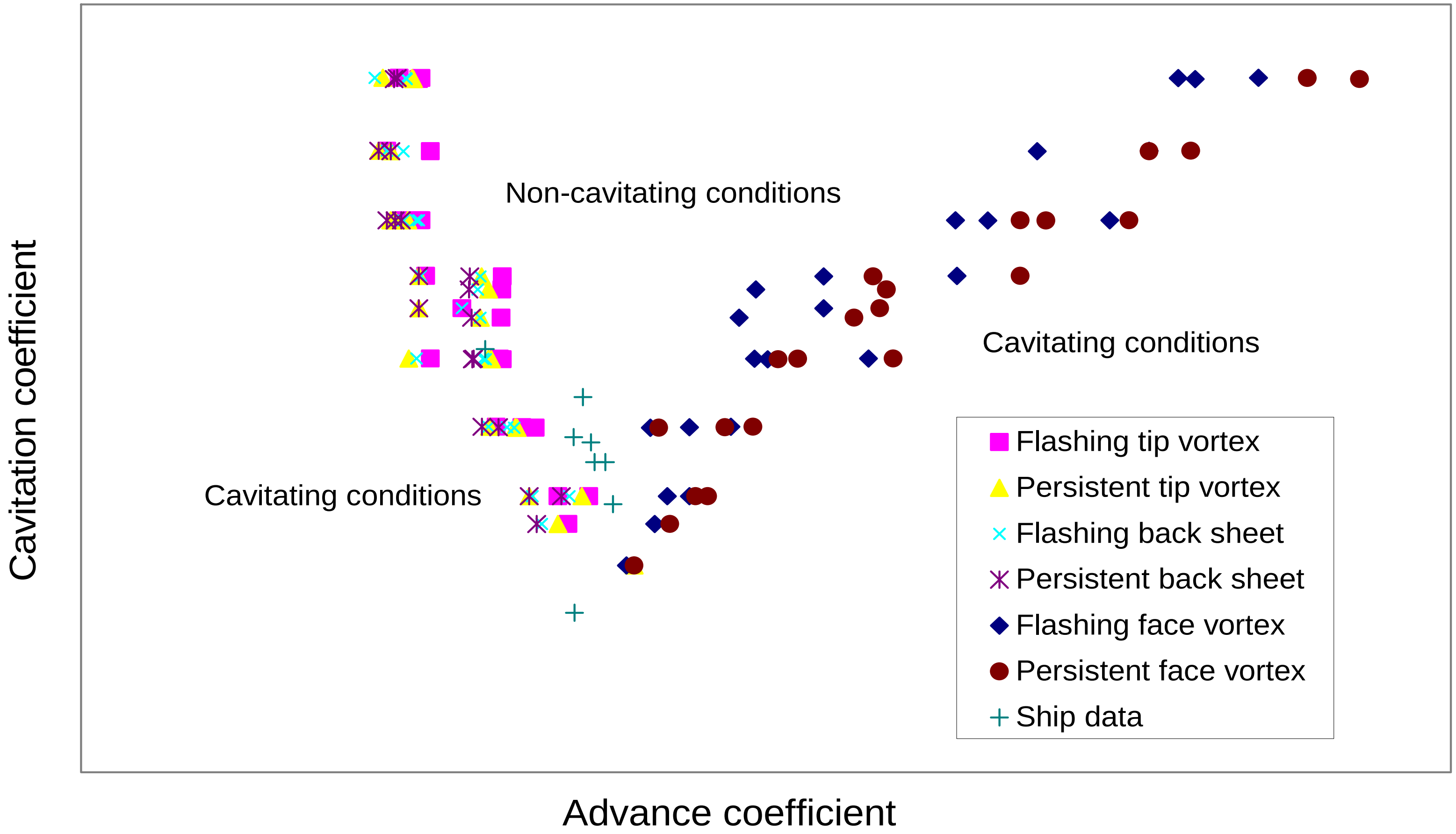


Graph courtesy of Dynaflow Inc.

Scaling of model data to ship conditions



Scaling of Model Data to Ship Conditions



Scaling of Model Data to Ship Conditions

- Scaling based on propeller blade Reynolds number and bubble/nuclei concentrations in tunnel water and sea water
- Ship data obtained from Radiated Acoustic Noise (RAN) rangings
  - Inadequate resolution of inception speed; lack of water quality data and ship data
- Development of correlation process requires knowledge of
  - Accurate determination of inception speed
  - Knowledge of type of cavitation
  - Water quality data
  - Details of ship operating conditions
- Dedicated viewing trial is essential
  - Traditional viewing ports in the hull
  - Fitting of boroscopes and underwater cameras

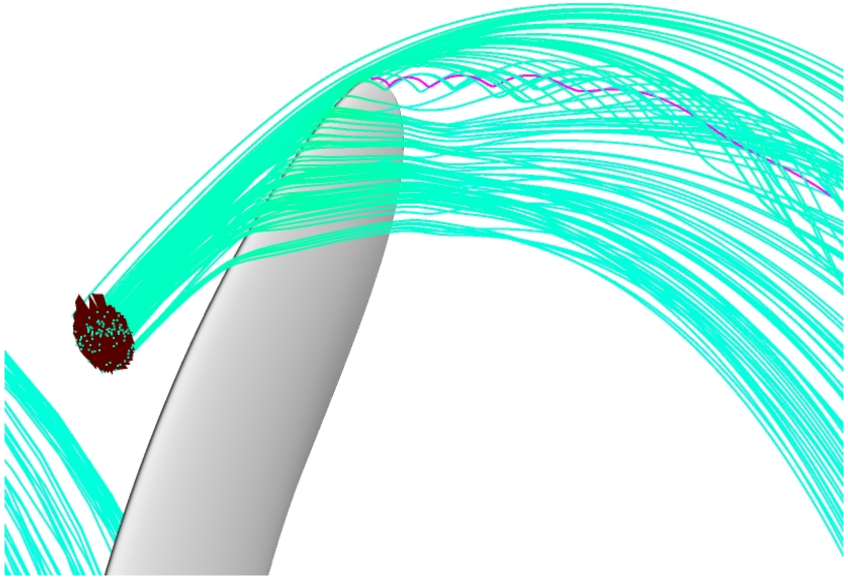
Aims of Proposed CIS Ship Trial

- View propeller to obtain inception speeds for different types of cavitation
  - Long runs in clear water
- Obtain water quality data from ship system drawing sea water from outside
  - Bubble and nuclei concentrations, temperature, dissolved gas content, salinity
- Obtain accurate data on ship condition
  - Shaft speed, ship speed through water & over ground, thrust/torque, draught, trim
  - Small speed increments, minimum helm movement, paired runs in opposite directions
- Obtain data on the environmental conditions
  - Wind speed and direction, tide/current conditions, sea state and direction and swell conditions, atmospheric pressure
- Assess cavitation inception from other sources
  - Radiated noise
  - Hull surface pressures
  - Hull accelerations

Computational Tool

Computational tool developed within commercial CFD code to use in the process of developing cavitation scaling methodology and for use as a preliminary design assessment tool

- Nuclei trajectories simulation
  - Use single phase flow data / one-way influence
  - Nuclei sources
  - Preparation of representative sample
  - Trajectory calculation
- Simulations for propeller in open water
  - Various advance ratios
  - Propeller sizes from model to ship
  - Two turbulence models



Propeller Specification for Manufacture

Propeller Industry working within the LSPC to provide experience on the key aspects of manufacture required to achieve low signature/ CIS requirements.

- Ensure that only applicable tolerances should be applied
- Takes account of current modern design, manufacturing and measurement methods
- Reduces the possibility of both over and under specification of an appropriate standard.
- Allows possible cost/performance trade off in terms of manufacture to be established.
- Gives early visibility of likely requirements to Industry, 'No Surprises'.

Requirements for Ship Acceptance Trial

- CIS predicted from model tests must be confirmed by full scale trials requiring definition of limits on some parameters
- Obtain water quality data from ship system drawing sea water from outside
  - Bubble and nuclei concentrations, temperature, dissolved gas content, salinity
- Vessel operating condition
  - Shaft speed, ship speed through water and over ground, thrust/torque, draught, trim
  - Small speed increments, minimum rudder movement, paired runs in opposite directions
- Obtain data on the environmental conditions
  - Wind speed and direction, tide/current conditions, sea state and direction and swell conditions, atmospheric pressure

LSPC Summary

- Process applicable to propellers which have signature, particularly CIS requirements, irrespective of platform.
- LSPC programme has the involvement of Industry to draw on wider base of knowledge and ensure procurement process holds ‘no surprises’.
- Model to Full scale prediction process using correlation process developed during the LSPC reduces the design risk for CIS at earlier stage than previously in UK warship procurement.
- Co-operation with Industry should provide for a realistic appropriate manufacturing standard to be specified and achieved based on current manufacturing processes.
- The specification and agreement of the future conduct of sea trials for the measurement of CIS should lead to better consistency of such measurements, important as the correlation is improved and populated.

Questions?

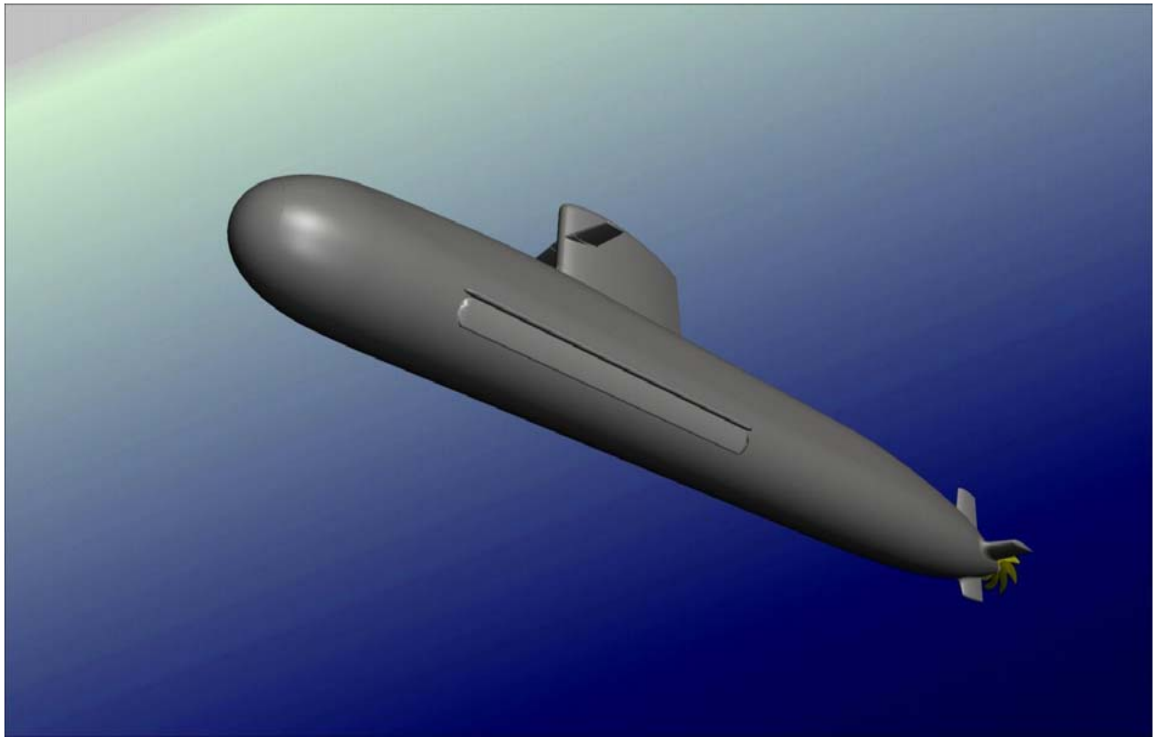
MANOEUVRABILITY OPTIMIZATION OF THE NAVANTIA S-80 SUBMARINE

June, 10th, 2008

SUMMARY

• CONTROL SURFACES DESIGN DECISIONS ('SIMUSUB' CODE)

• IMPROVING 'SIMUSUB', LQ vs CONTROLLABILITY THEORY

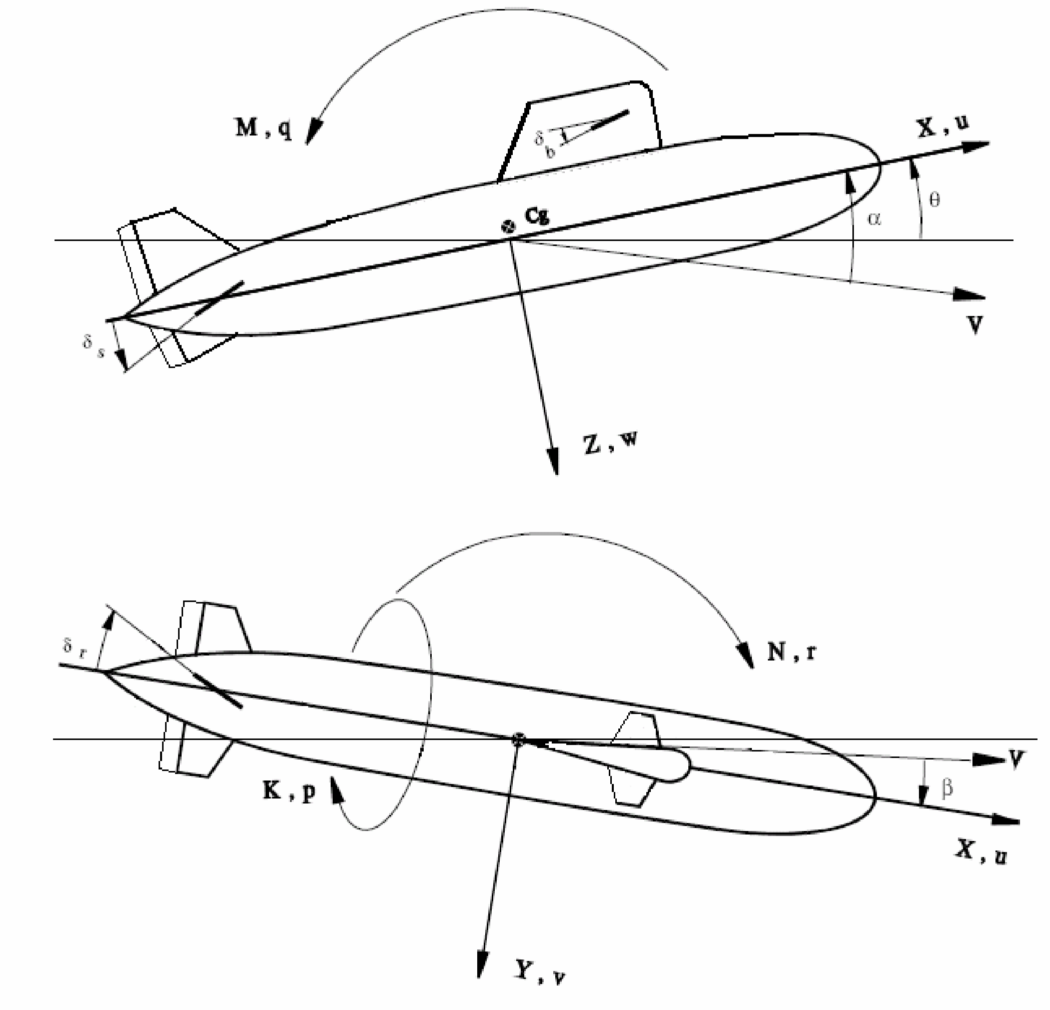


MISSIONS & MANOEUVRABILITY

- Surface Ships Warfare Sub to Surface Missiles
- Anti-Submarine Warfare, Torpedo Striking
- Land Attack, Tactical Missiles
- Intelligence Gathering
- Special Forces Insertion
- Civil Personnel Rescue

Ocean going and littoral Water Operations

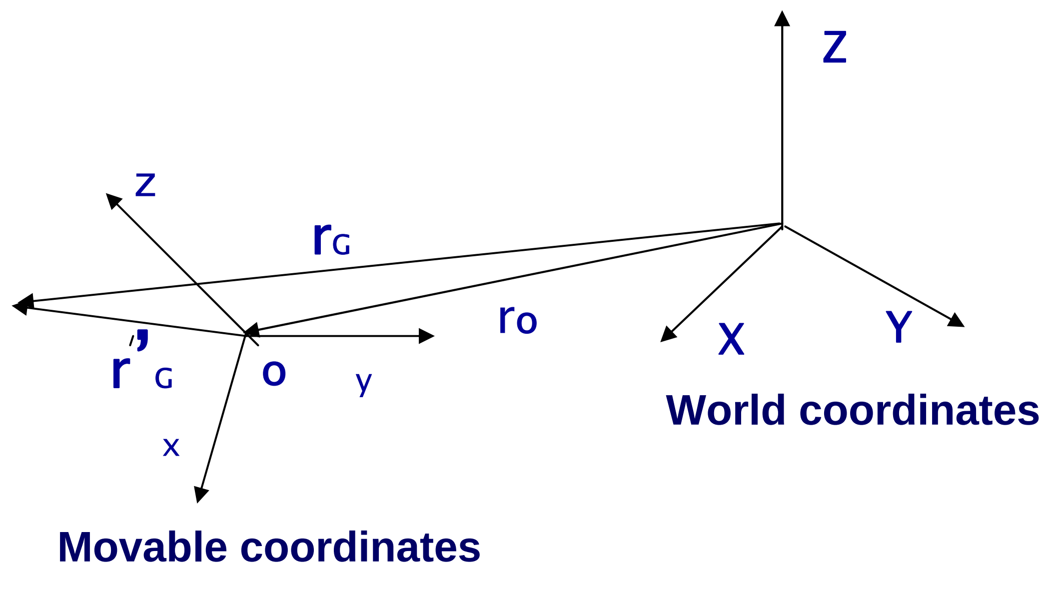
SUBMARINE MOTIONS (DEFINITIONS)



SUBMARINE EQUATIONS OF MOTION

$$\sum \overline{F}_{ext} = M.\overline{a}_G,$$

$$\frac{d\overline{H}_G}{dt} = \overline{N}_{Fext},$$



$$\overline{a}_G = \overline{a}_O + \overline{\Omega} \wedge \overline{V}_O + \overline{\alpha} \wedge \overline{r}_{OG} + \overline{\Omega} \wedge \left(\overline{\Omega} \wedge \overline{r}_{OG}\right)$$

Linear approach

$$\overline{a}_G = \overline{a}_O + \overline{\Omega} \wedge \overline{V}_O$$

SUBMARINE EQUATIONS OF MOTION

$$m\,\dot{u} = \sum X$$

$$m\left(\dot{v} + ru\right) = \sum Y$$

$$m\left(\dot{w} - qu\right) = \sum Z$$

$$I_{xx}\,\dot{p} = \sum K$$

$$I_{yy}\,\dot{q} = \sum M$$

$$I_{zz}\,\dot{r} = \sum N$$

– Horizontal Motion:

$$\left(m' - Y'_{\dot{v}}\right)\dot{v}' - Y'_{v}\,v' + \left(m' - Y'_{r}\right)r' = 0$$

$$\left(I'_{zz} - N'_{\dot{r}}\right)\dot{r}' - N'_{v}\,v' - N'_{r}\,r' = 0$$

– Vertical Motion:

$$\left(m' - Z'_{\dot{w}}\right) - Z'_{w}\,w' - \left(m' + Z'_{q}\right)q' = 0$$

$$\left(I'_{yy} - M'_{\dot{q}}\right)\dot{q}' - M'_{w}\,w' - M'_{q}\,q' + \frac{\overline{GB}\,\theta\,g}{u^{2}} = 0$$

CHARACTERISTIC EQUATIONS, STABILITY

$as^2 + b\,s + c = 0$ Horizontal

$As^3 + Bs^2 + Cs + D = 0$ Vertical

For horizontal plane stability:

- Negative real roots : $c>0$ (ROUTH HURWITZ)

For vertical plane stability:

- Complex roots with negative real part at low speed
- Negative real roots at high speeds :
  $B > 0$, $C > 0$, $BC > AD$ (ROUTH HURWITZ)

But for the appropriate judgment of the stability and also of the controllability, it is necessary to refer to a set of representative parameters

DESIGN DECISIONS

- Rudders and aft planes in cross configuration

- Fwd planes in the fin

- Sufficient inherent stability which could guarantee successful depth keeping and course keeping with minimum actuation of the planes, and so less generated noise, but in such way that the Submarine responses will not be too stiff

- Critical speed enough below the patrol speed

- Robust horizontal control movements

- Moderate vertical control movements, especially to avoid high depth overshoots in case of the aft diving planes jam

DESIGN DECISIONS

X ARRANGEMENT

Advantages:

- **Higher aspect ratio possibility**
- **Implies better surface manoeuvrability**
- **Less complication for a towed array arrangement**

Drawbacks:

- **Forces symmetry**
- **No independent selection of stability & controllability characteristics in design**
- **Arrangement difficulties, longitudinal position different for each pair**
- **Control complexity, stalling with angles out of plane?**

DESIGN DECISIONS

FWD DIVING PLANES ARRANGEMENT

Advantages when located in the fin:

- **Located near neutral point**
- **Higher aspect ratios**
- **No interferences with aft planes and propeller**
- **No noise in the fwd areas near the sonar**
- **Not necessary to be retractable**

OK!

Drawbacks:

- **No collaboration in fast immersion from surface**
- **Drag originates a pitching moment**

DESIGN DECISIONS
STABILITY & CONTROLLABILITY COEFFICIENTS

Denomination	Definition	Typical SSK figures	S-80 Design Decisions	Comment *[Ref (2)]*
Horizontal Index	$G_H = 1 + \frac{(m' - Y'_r) N'_v}{Y'_v N'_r}$	< 0,1	> 0,3	Near to upper limit
Vertical Index	$G_V = 1 - \frac{M'_w (m' + Z'_q)}{M'_q Z'_w}$	< 0,3	> 0,3	Above upper limit
Heave coefficient (Stern planes)	$\frac{Z'_{\delta s}}{\frac{L}{10^3}(Z'_{\dot{w}} - m')}$	~ 2,5	> 3,0	Nearer upper limit

DESIGN DECISIONS
STABILITY & CONTROLLABILITY COEFFICIENTS

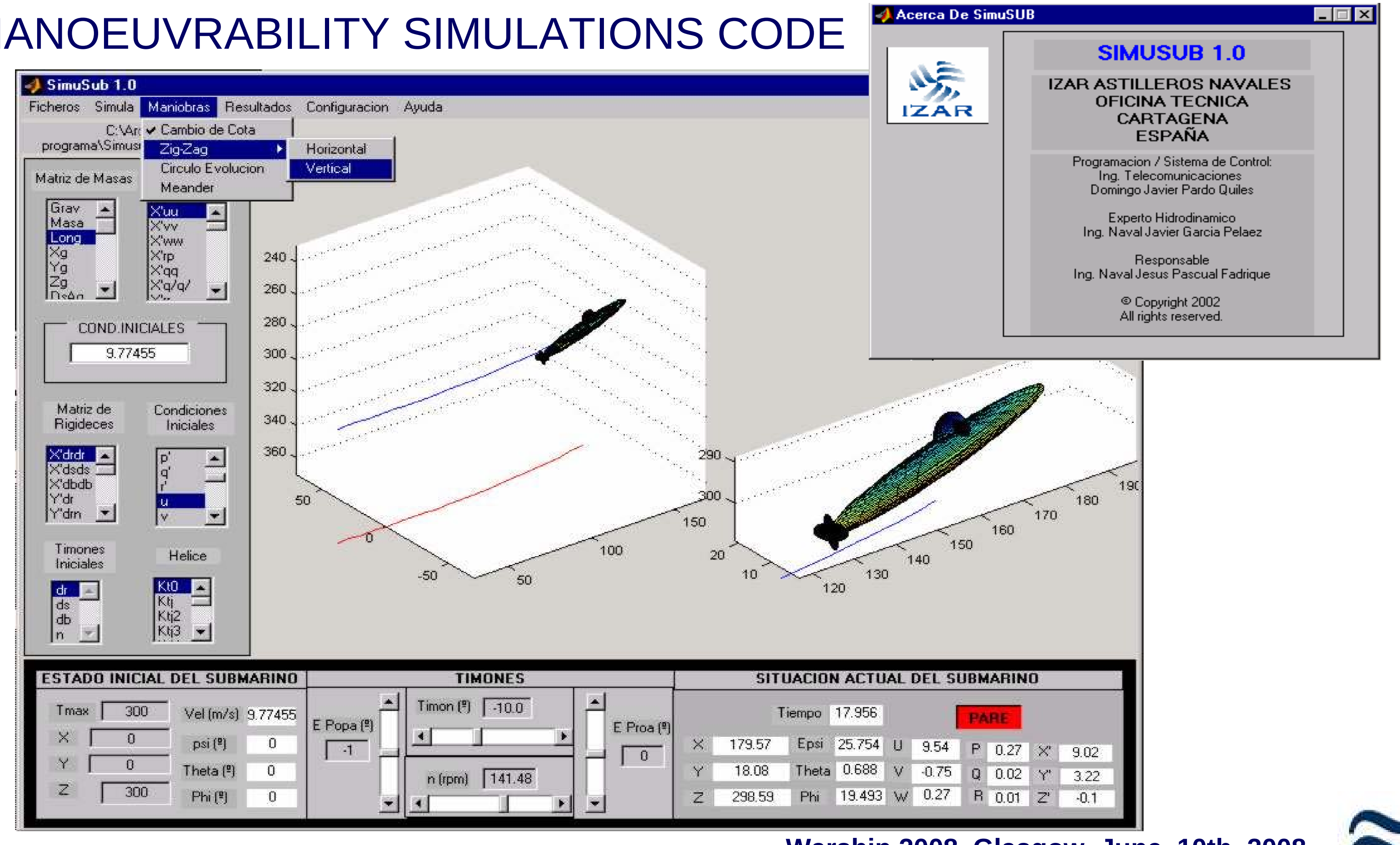
Pitch coefficient (Aft diving planes)	$\dfrac{M'_{\delta s}}{\frac{L}{10^3}\left(M'_{\dot q} - I'_{yy}\right)}$	~ 0,3	> 0,4	Above upper limit
Heave coefficient (Fwd diving planes)	$\dfrac{Z'_{\delta b}}{\frac{L}{10^3}\left(Z'_{\dot w} - m'\right)}$	~ 3,0	> 3,0	Typical increment
Pitch coefficient (Fwd diving planes)	$\dfrac{M'_{\delta b}}{\frac{L}{10^3}\left(M'_{\dot q} - I'_{yy}\right)}$	> - 0,2	> - 0,2	Intermediate
Sway coefficient (Steering rudders)	$\dfrac{Y'_{\delta r}}{\frac{L}{10^3}\left(m' - Y'_{\dot v}\right)}$	~ 4,0	> 4,0	Near to upper limit
Yaw coefficient (Steering rudders)	$\dfrac{N'_{\delta r}}{\frac{L}{10^3}\left(N'_{\dot r} - I'_{zz}\right)}$	~ 0,5	> 0,5	Nearer upper limit

MANOEUVRABILITY CHARACTERISTICS & SIMULATIONS

PLANE	SIMULATED MANOEUVRES	STUDY	RESULTS
Horizontal	Zig-zag 10° / 10° @ 10 and 15 knots	Horizontal plane stability	Good horizontal stability, acceptable overshoot angles.
	Turning circle with depth control @ 10, 15 knots and max speed	Evolution capability	Fulfillment of the evolution requirements (Staff Requirements)
Vertical	Meander manoeuvre @ 5, 10, 15 knots and maximum speed	Oscillation damping	Excellent damping of the oscillation in the vertical plane
	Zig-zag 10°/10° @ 15 and max speed	Stability in vertical plane	Submarine with high stability. Low overshoot angles
	Depth changes at different speeds from snort depth, using automatic pilot	Depth changes efficiency	Fulfillment of depth changes (Staff Requirements)
Both	Emergency recovery against aft diving planes jam and flooding in different locations	Analysis of the SOE	Wide SOE obtained

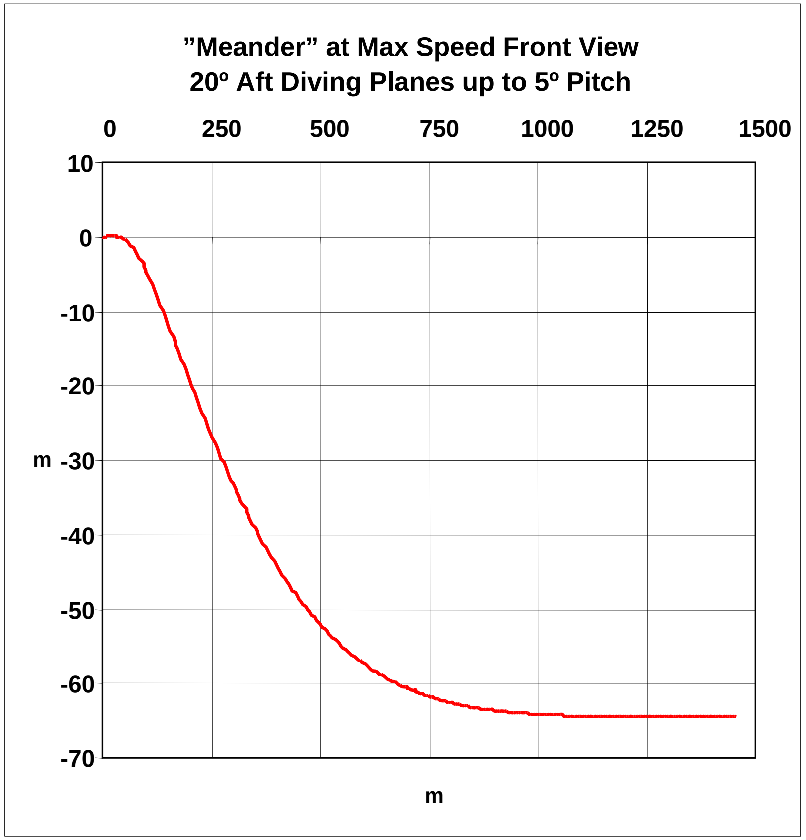
SIMULATIONS

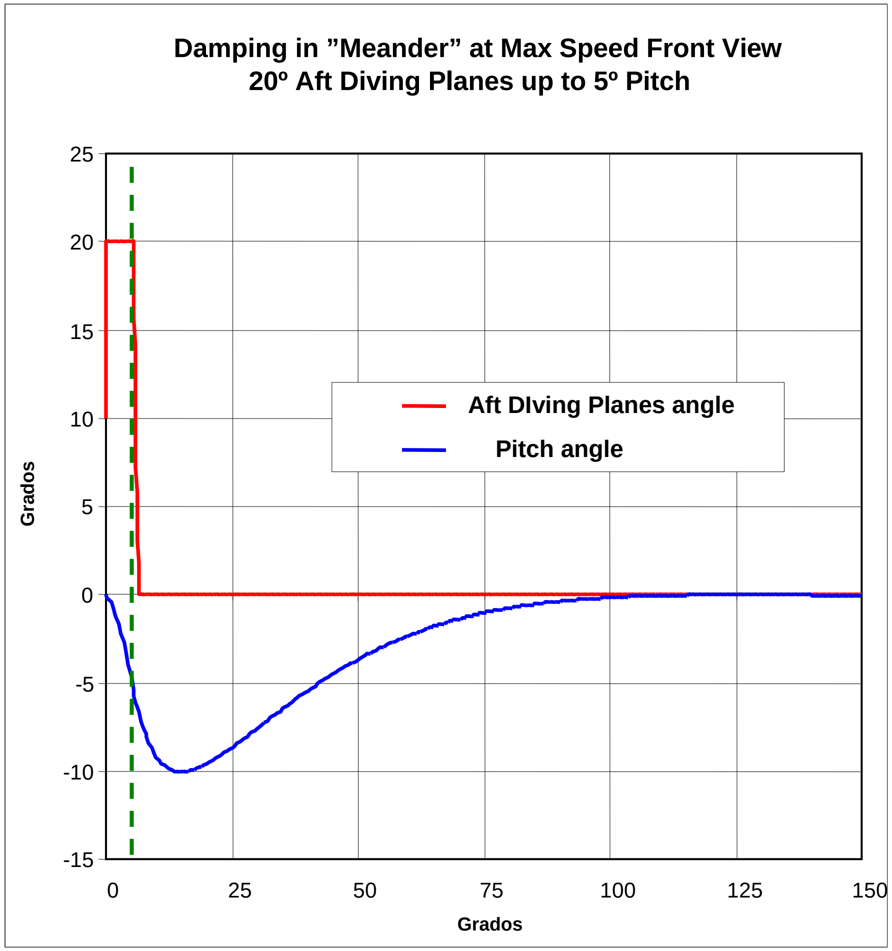
NAVANTIA 'SIMUSUB'
MANOEUVRABILITY SIMULATIONS CODE



SIMULATIONS

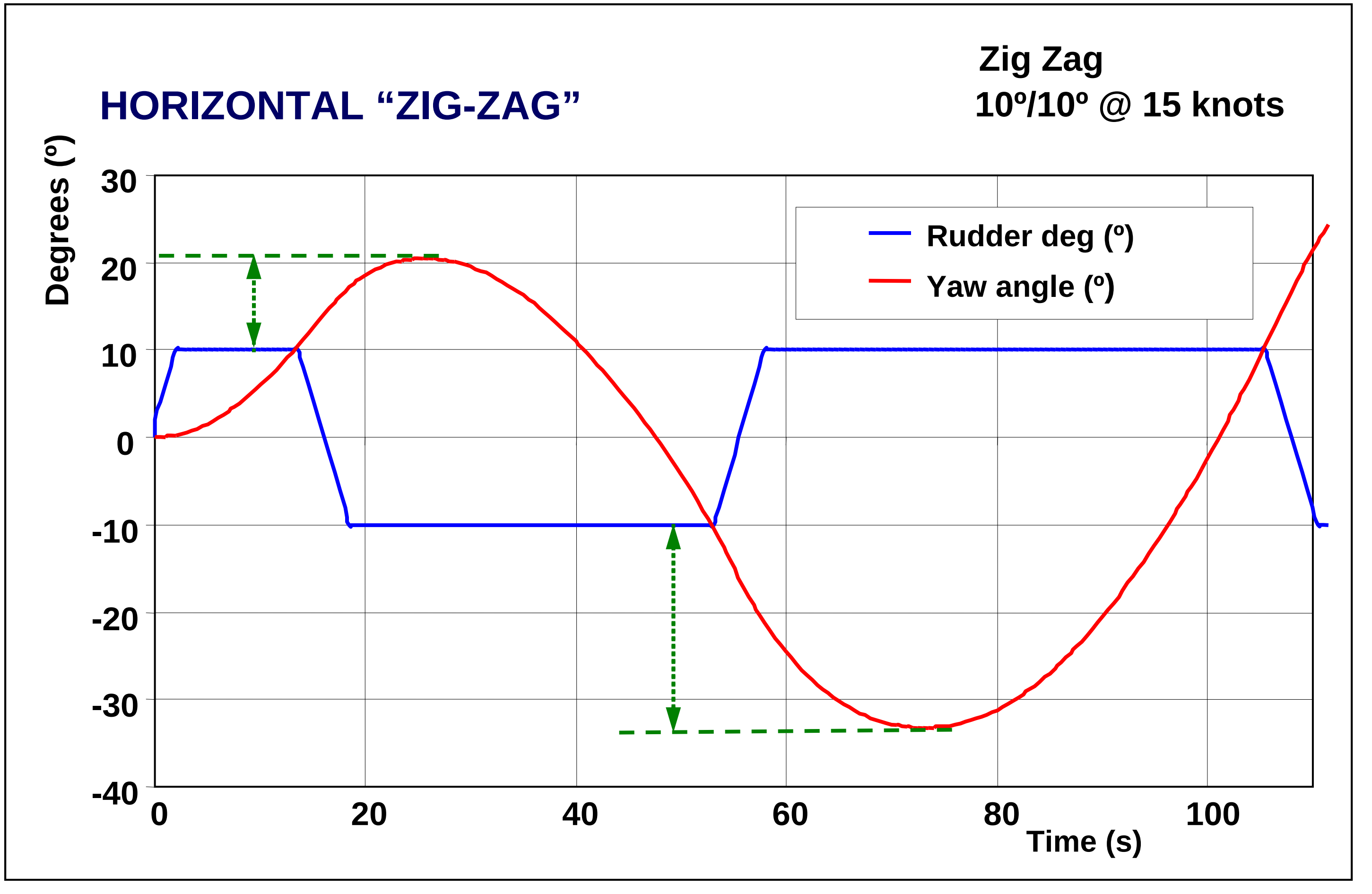
"MEANDER"





Good oscillation damping. Excellent vertical stability

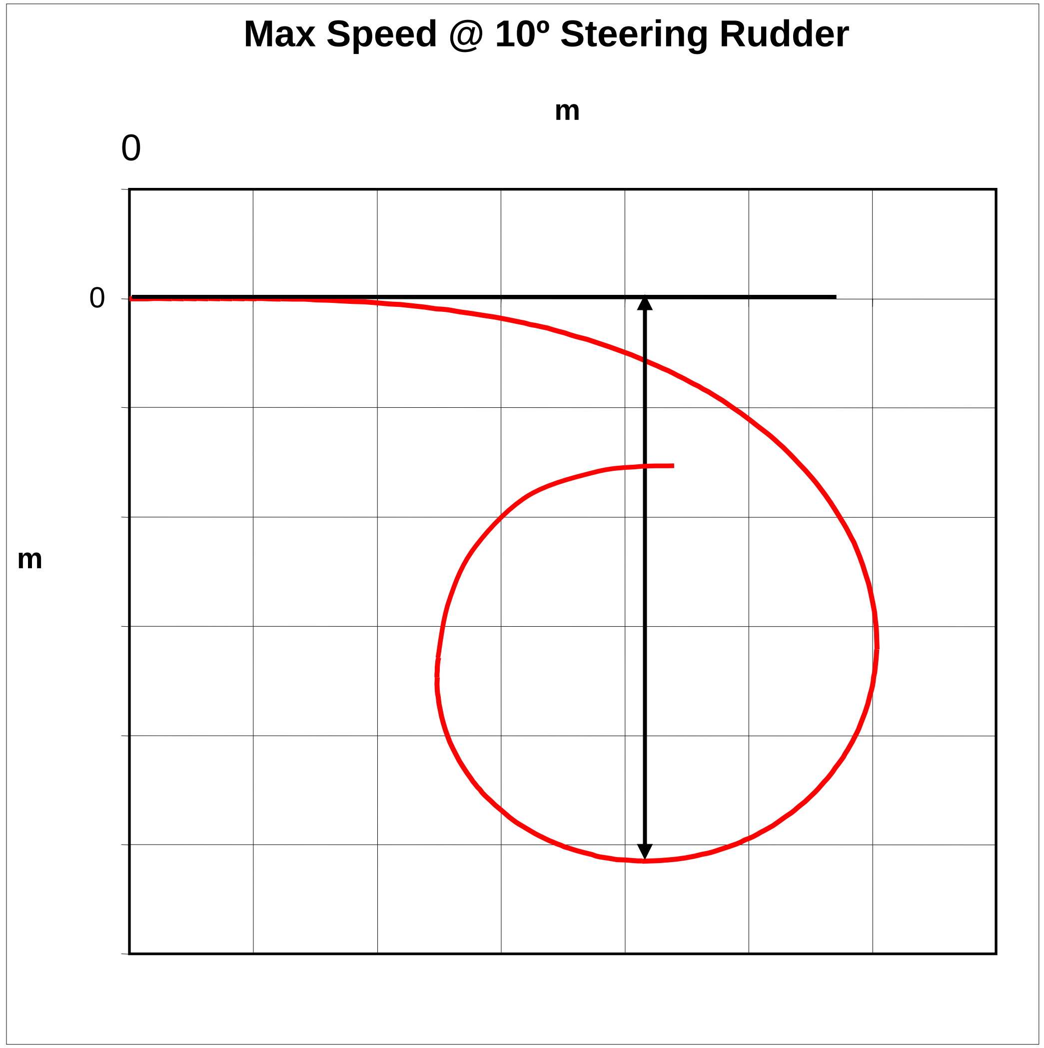
SIMULATIONS



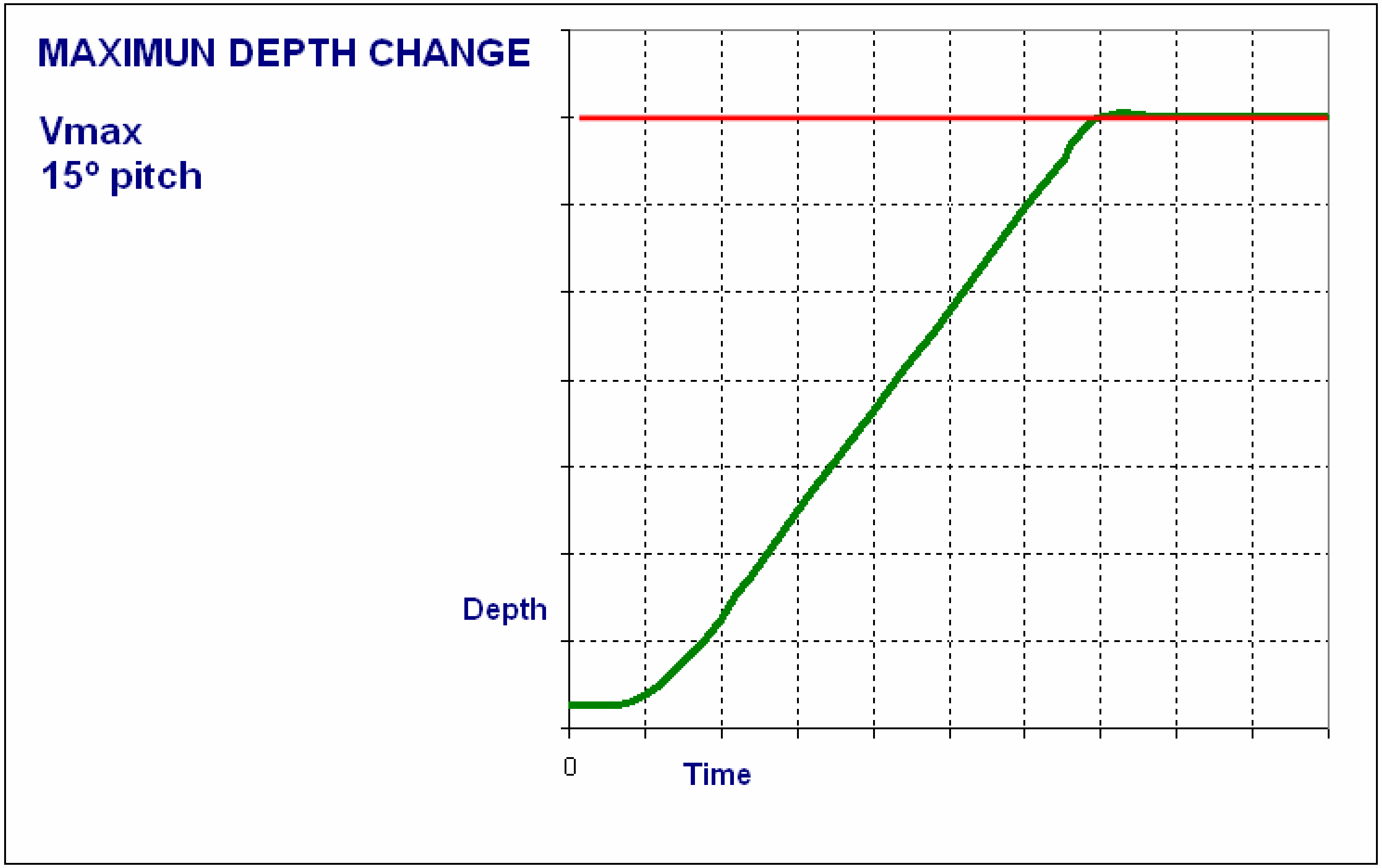
Low overshoot angles. Excellent horizontal stability

SIMULATIONS

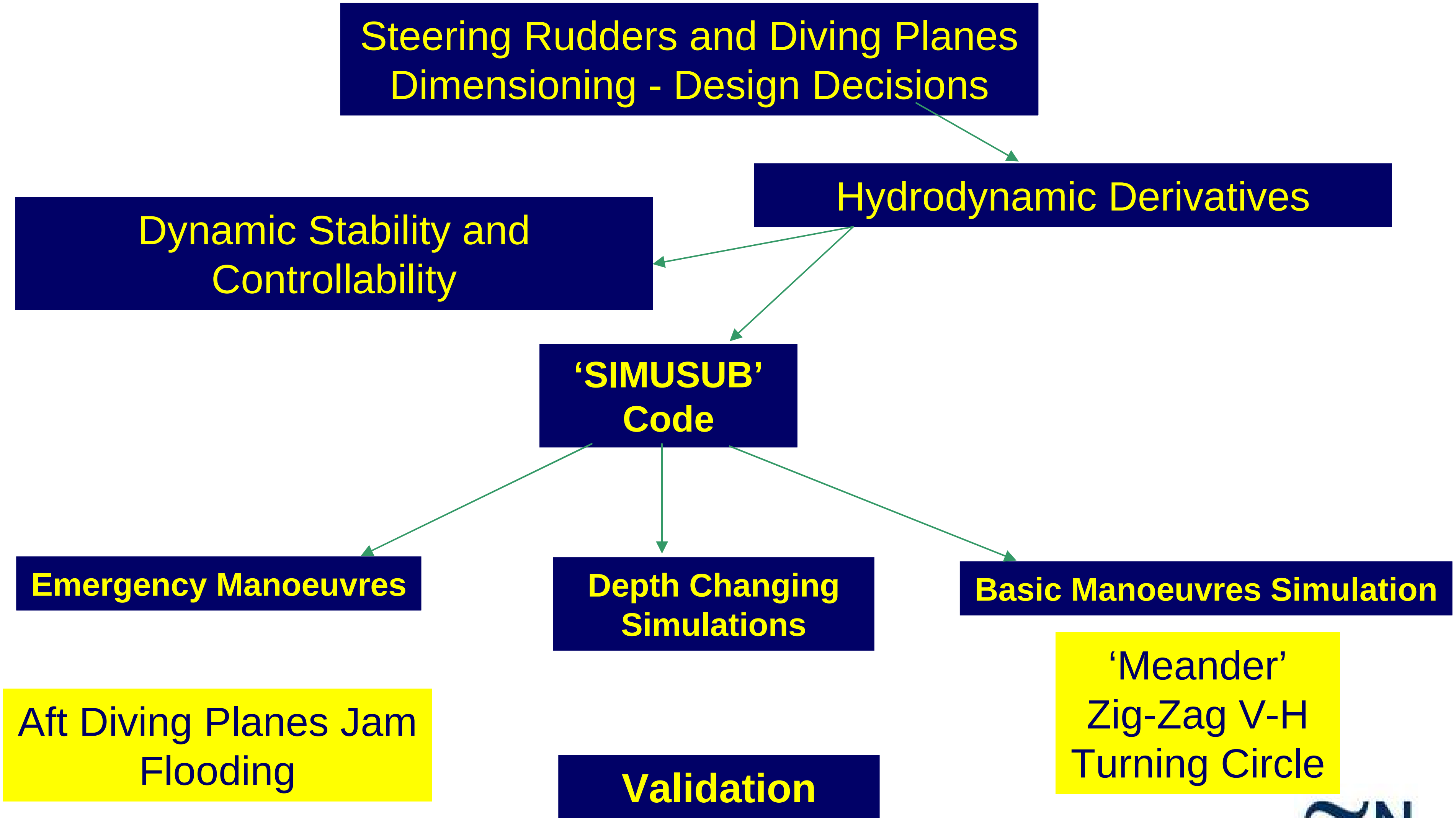
TURNING CIRCLE



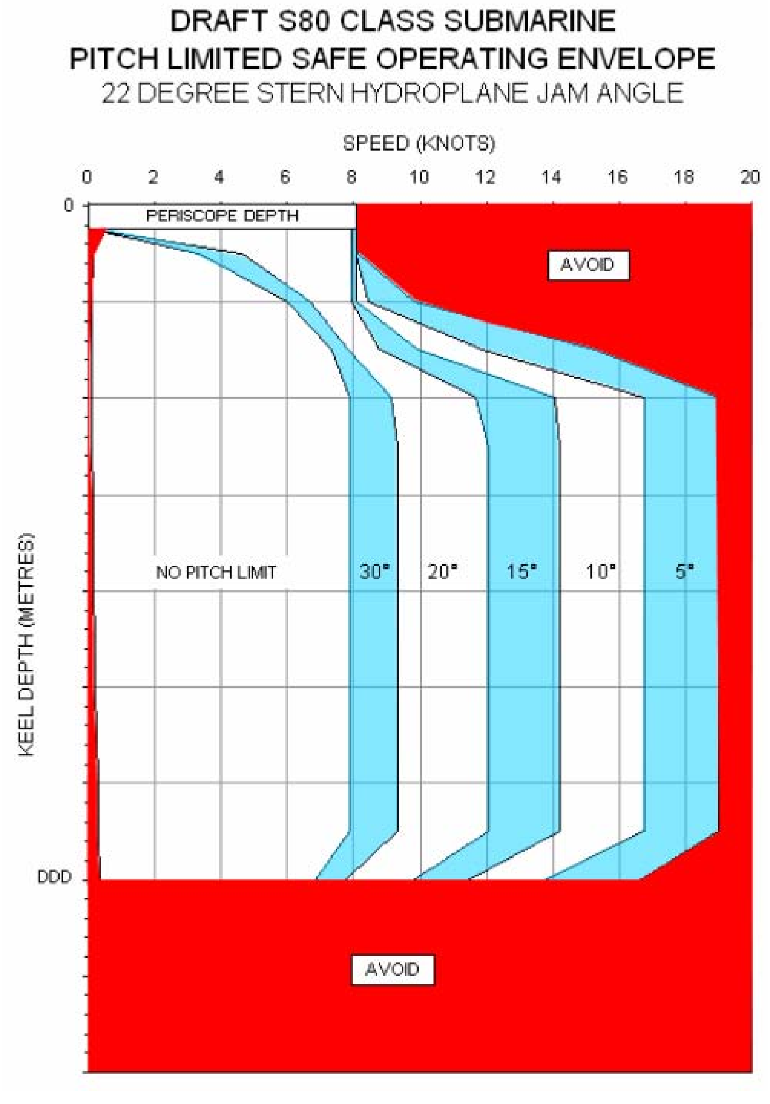
SIMULATIONS



PROCESS SUMMARY



VALIDATION



Towing Tank Manoeuvrability Test and Simulations (P650 and S-80)

Trajectory Modeling Simulation for SOE

CONCLUSIONS

The design and optimization of a set of Control Surfaces implies:

- **Carefull analysis of the Requirements and Missions**
- **Selection of an appropriate set of Stability and Controllability Parameters**
- **Complete simulation study of ship Manoeuvrability, including Emergency Manoeuvres**
- **Validation**

IMPROVING 'SIMUSUB'
LQ vs CONTROLLABILITY THEORY

June, 10th, 2008

IMPROVING 'SIMUSUB'
LQ vs CONTROLLABILITY THEORY

I. SSK SIMULATION MODEL

SSK submarine with the following characteristics (similar manoeuvrability performance to S-80):

- Length: 60 m
- Beam : 6.4 m
- Form Displacement : 2,000 m^3
- Max Speed: 20 knots @ 180 rpm

II. CONTROLLABILITY

II.1. STATE CONCEPT

- **Differential dynamic system:**

$$x'(t) = A\ x(t) + B\ u(t)$$

$$\begin{cases} \dot{x}(t) = f(t, x(t), u(t)) & \textbf{STATE EQUATION} \\ y(t) = \Phi(t, x(t), u(t)) & \textbf{OUTPUT EQUATION} \end{cases}$$

$$\begin{aligned} x &= (v, r, \psi, y_0, w, q, \theta, z_0) \\ u &= (\delta_r, \delta_s, \delta_b) \end{aligned}$$

In the model: $y(t) = x(t)$

Objective

$$\dot{x}(t) = f(t, x(t), u(t))$$

$$\Downarrow$$

$$\dot{x}(t) = A\ x(t) + B\ u(t)$$

II. CONTROLLABILITY

II.2. CONTROLLABILITY THEORY

$$\dot{x}(t) = A\,x(t) + B\,u(t) \qquad \text{(II.2)}$$

$$\begin{cases} x(t) \in \mathbb{R}^n & \text{STATE VECTOR} \\ A \in \mathbb{R}^{nxn} & \\ B \in \mathbb{R}^{nxr} & \\ u(t) \in \mathbb{R}^r & \text{CONTROL} \end{cases}$$

Definition II.2.1 *Fixed T > 0, it is said the linear system (II.2) is exactly controllable at time T if for all* x_0, x_f *belonging* R^n *exists u(t) belonging* R^r *such that the solution x(t) of the linear system (II.2) satisfies* $x(0) = x_0$ *and* $x(T) = x_f$.

II. CONTROLLABILITY
II.2. CONTROLLABILITY THEORY

Definition II.2.2 *The controllability matrix associated to (II.2) is:*

$$Q = [B \; AB \; A^2B \; \ldots \; A^{n-1}B]$$

where, n is the number of state variables

Proposition II.2.1 *(II.2) is exactly controllable at time T if and only if:*

$$r(Q) = n$$

the controllability matrix has maximal range

If the system is exactly controllable, then it will be able to reach the desired final state, starting from the initial state, applying a specific control u(t) that will be calculated next

II. CONTROLLABILITY

II.2. CONTROLLABILITY THEORY

Definition II.2.3 *With T > 0 and the matrices A and B, Gramiam matrix is obtained as follows:*

$$P(T) = \int_0^T e^{At} B B^* e^{A^* t} dt$$

Theorem II.2.1 *If (II.2) is exactly controllable at time T, then P(T) can be inverted. Moreover, control u(t) is:*

$$u(t) = B^* e^{A^*(T-t)} P(T)^{-1} (x_f - e^{AT} x_0)$$

And the state vector is given by:

$$x(t) = e^{At} x_0 + \int_0^t e^{A(t-\tau)} B u(\tau) d\tau$$

III. NUMERICAL SIMULATIONS

Application of the Controllability Theory to the Lineal

Mathematical Model of the Submarine:

$$A = \begin{pmatrix} -0{,}0440 & -0{,}0679 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1{,}7776 & -0{,}0036 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0{,}1396 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0{,}0057 & 0{,}0760 & 0 & 0 \\ 0 & 0 & 0 & 0 & -0{,}0429 & -0{,}0054 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & -0{,}1396 & 0 \end{pmatrix}$$

$$B = \begin{pmatrix} 0{,}0049 & 0 & 0 \\ -0{,}0056 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -0{,}0034 & -0{,}0020 \\ 0 & -0{,}0021 & 0{,}0007 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

III. NUMERICAL SIMULATIONS

- **The number of state variables is eight. So, it is checked the controllability condition calculating the range of the following matrix:**

$$Q = [B \ AB \ A^2B \ A^3B \ A^4B \ A^5B \ A^6B \ A^7B]$$

$$r(Q) = 8$$

The system is exactly controllable at any time T > 0.

- **For the calculation of P(T), it is integrated using Simpson's method:**

$$P(T) = \int_0^T e^{At} B B^* e^{A^* t} dt$$

III. NUMERICAL SIMULATIONS

- **For the calculation of the control, it is necessary to establish the position where the Submarine is (x_0) and where it is desired to take it (x_f) at time T. With this information and the matrix P(T), the control u(t) is explicitly given by:**

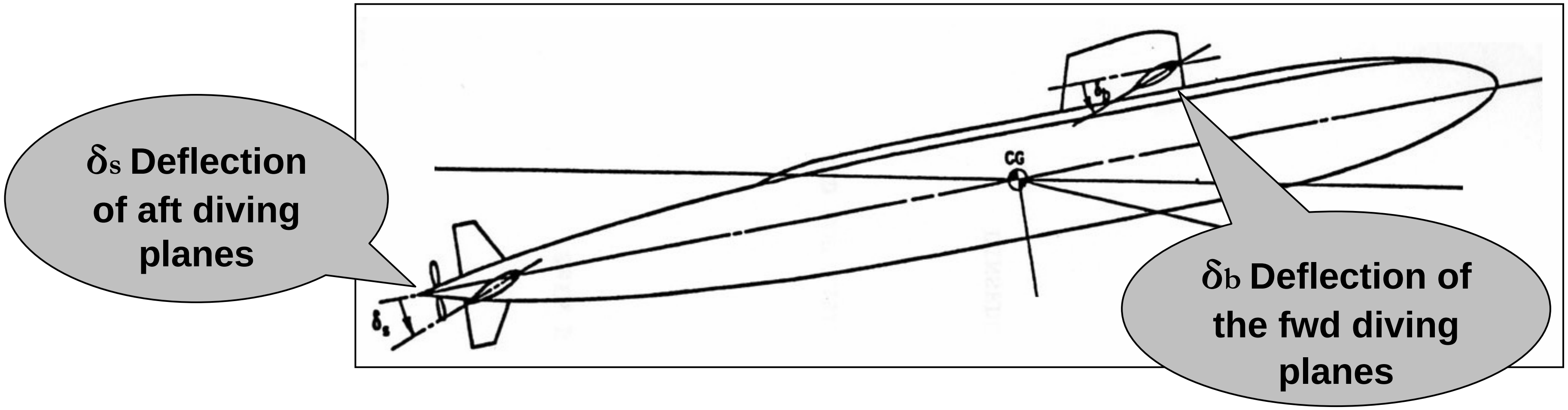
$$u(t) = B^* e^{A^*(T-t)} P(T)^{-1} (x_f - e^{AT} x_0)$$

- **The last step is to calculate the evolution that the state vector has suffered during the time of simulation (T), to check if the proposed final state has been reached at this time:**

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ x(0) = x_0 \end{cases}$$

III. NUMERICAL SIMULATIONS

III.1. DEPTH CHANGE



- **δ_s & δ_b are both the control variables that carry out the vertical action:**

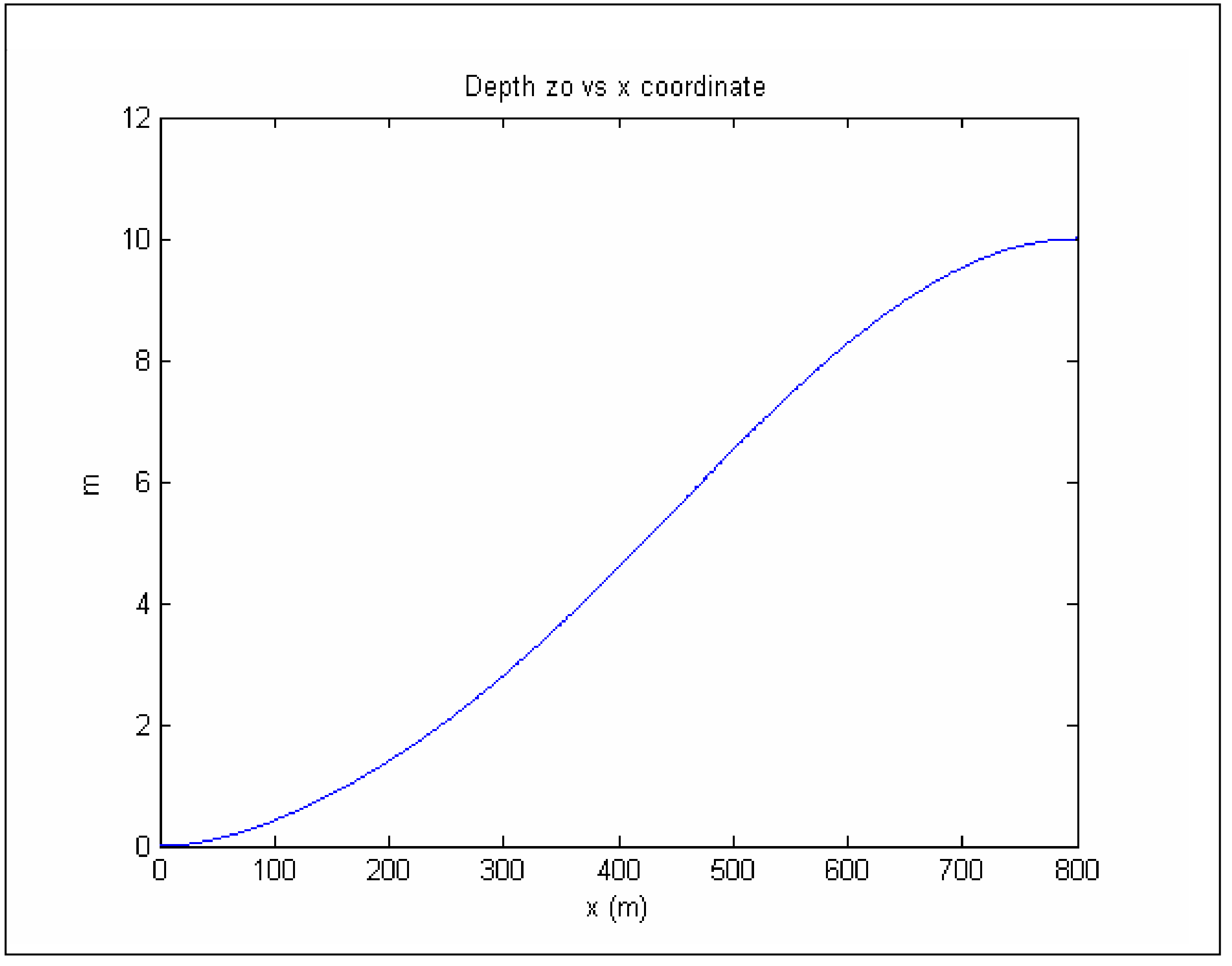
$$x = (0, 0, 0, 0, w(t), q(t), \theta(t), z_0(t))$$

The rest of the state variables (v, r, ψ, y_0) are zero during the time of simulation, because they do not appear in the control of the depth change manoeuvrability

III. NUMERICAL SIMULATIONS

III.1. DEPTH CHANGE

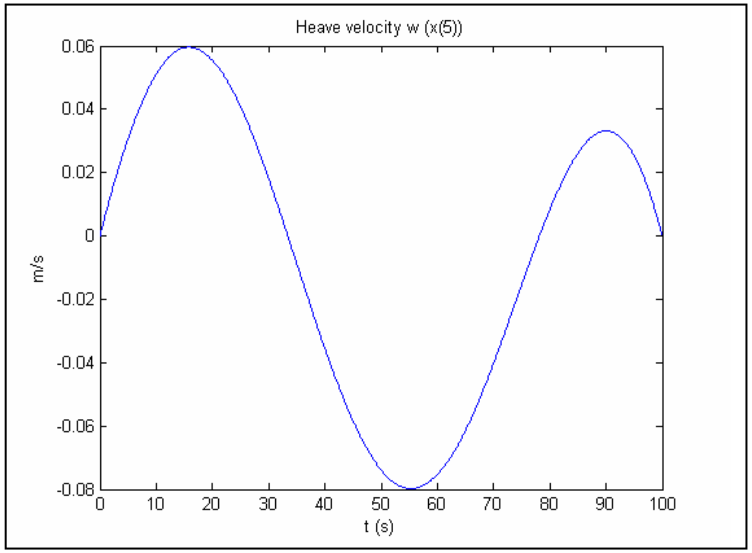
- **Depth change of 10 m in 100 s**

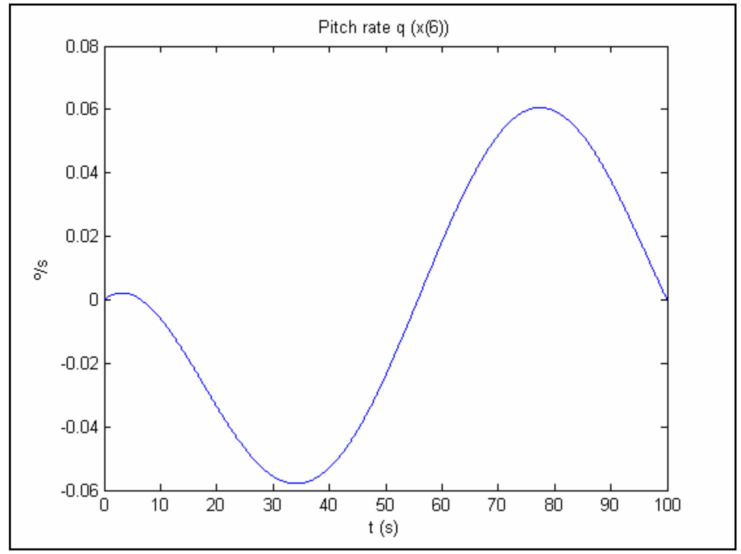


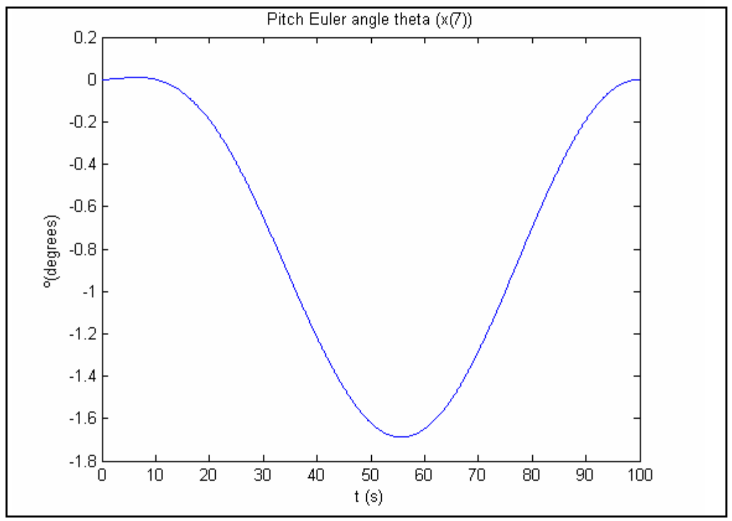
$$x_0 = (0,0,0,0,0,0,0,0)$$
$$x_f = (0,0,0,0,0,0,0,10)$$

III. NUMERICAL SIMULATIONS

III.1. DEPTH CHANGE

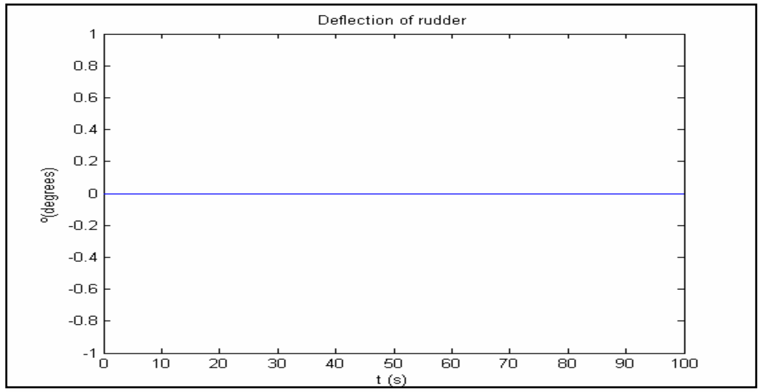


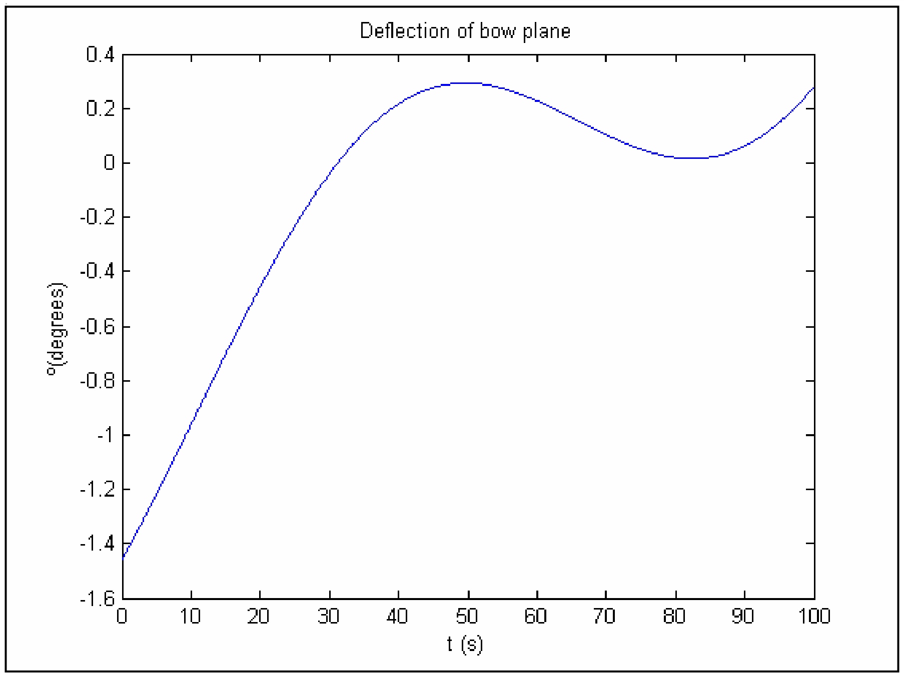


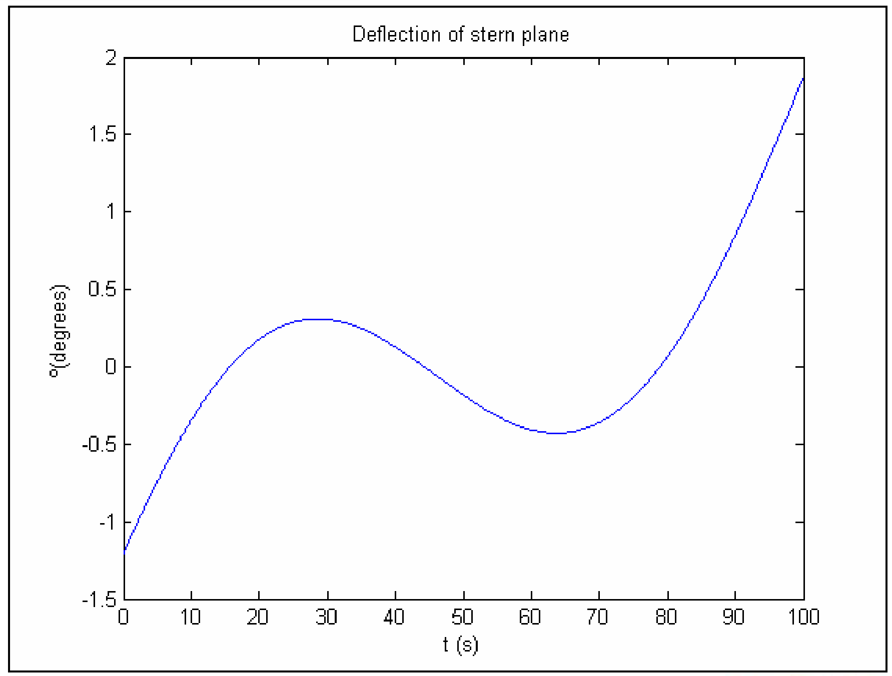


III. NUMERICAL SIMULATIONS
III.1. DEPTH CHANGE

Control (diving planes):

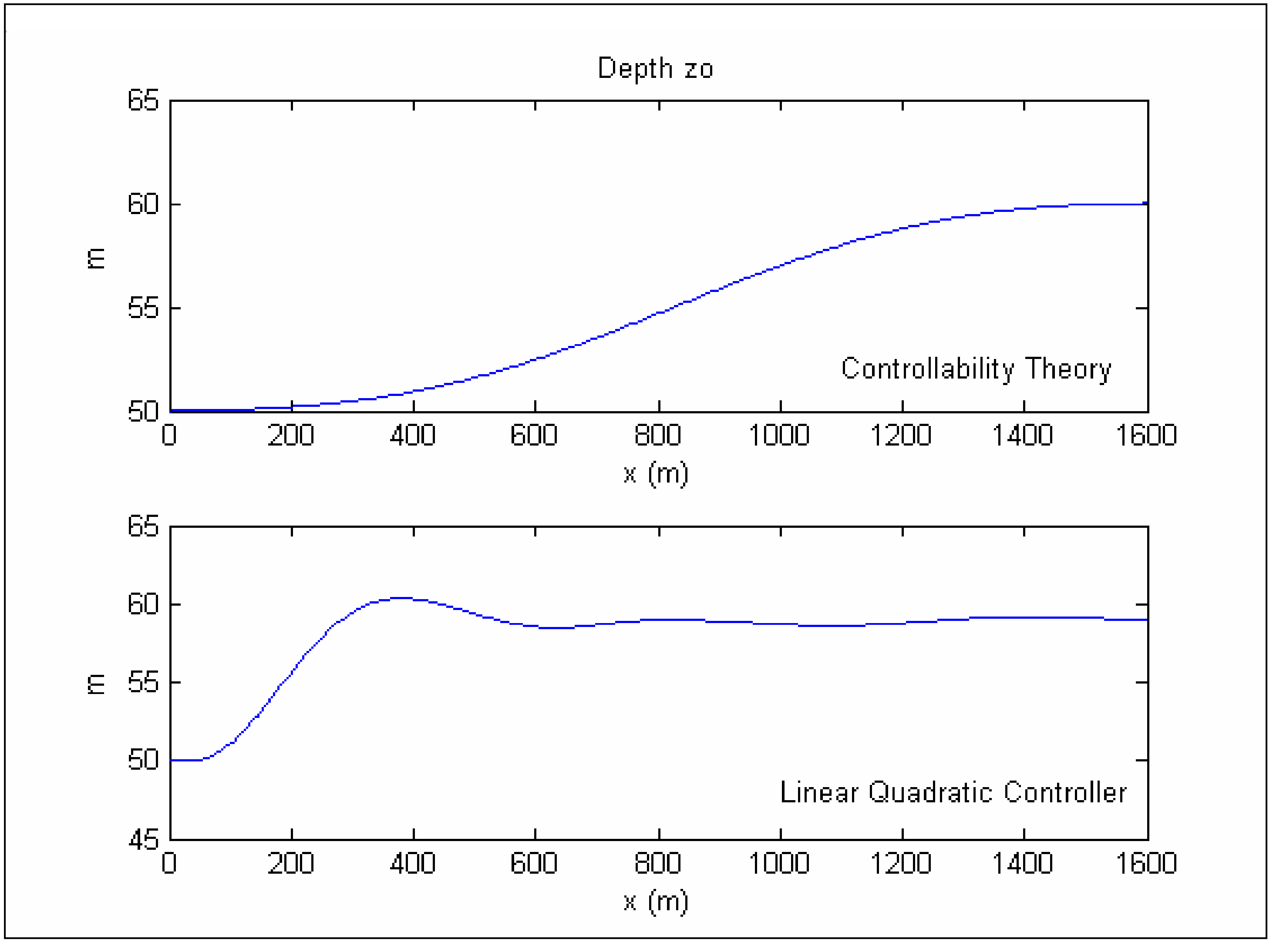






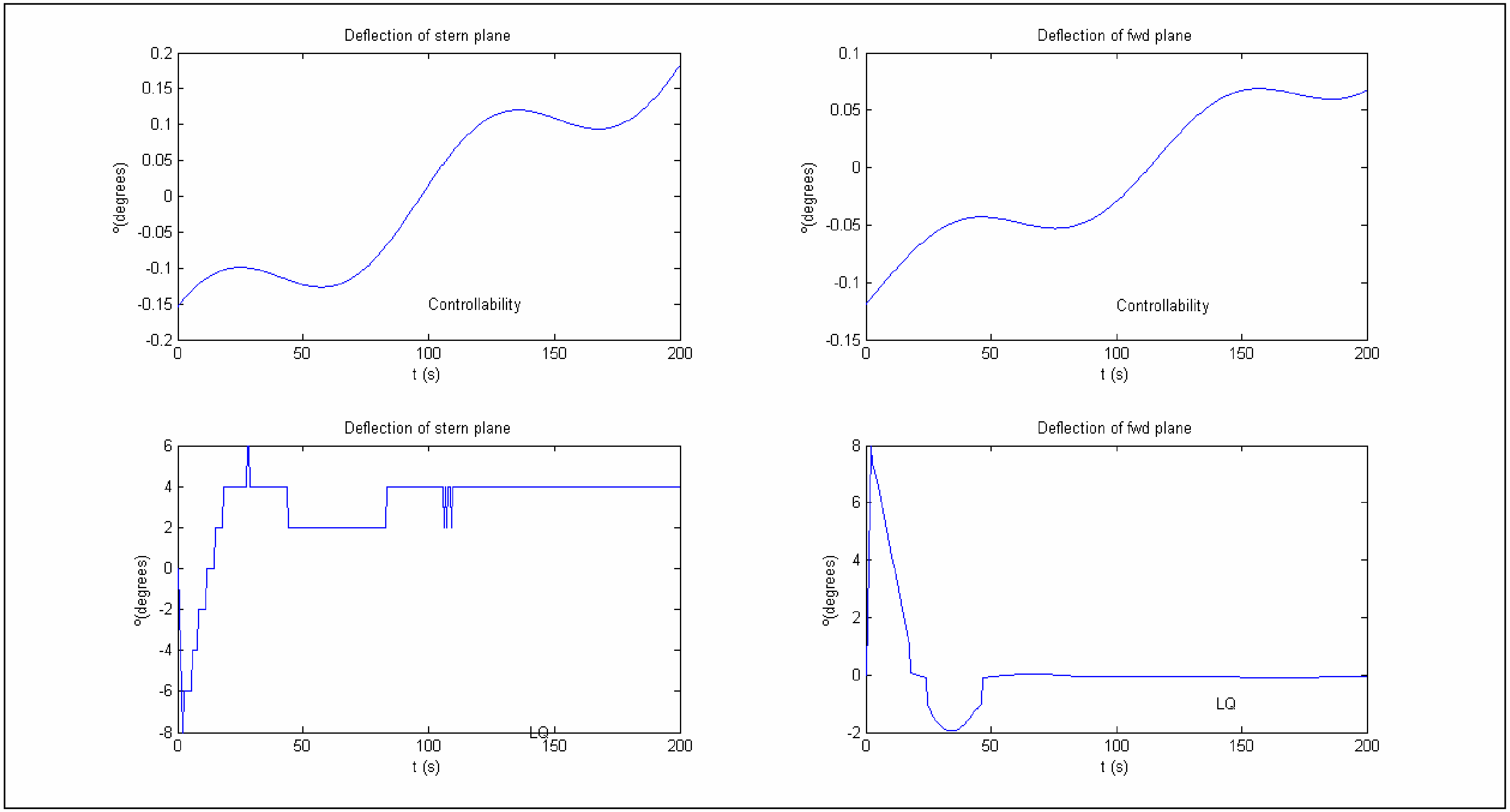
III. NUMERICAL SIMULATIONS

III.2. LQ vs CONTROLLABILITY



III. NUMERICAL SIMULATIONS

III.2. LQ vs CONTROLLABILITY



IV. CONCLUSIONS (LQ vs CONTROLLABILITY)

- **Can we reach the desired final state starting from the initial state in which is the entity to control?**

Characteristics of the Controllability Theory

• No constraints on the controls are imposed in the controllability strategy

• Only real feedback (perturbation register) is necessary for complete control calculation

• The manoeuvre can be selected to be as soft as decided by Commanders

•The required hydraulic power is the minimum possible respect to the tactical decisions. So, it is expected a minimum acoustic impact

THANK YOU FOR YOUR ATTENTION

BMT Defence Services

"Where will our knowledge take you?"

'Meeting the Current Challenge of Designing High Capability SSKs'

Simon Binns, BMT Defence Services

1.0 The Military Need

- There is a predicted large increase in future submarine procurement and operations
- The Submarine's key advantages are its inherent clandestine and persistent nature
- **Potentially wide and varied roles include:**
  - Traditional sea-denial, or Anti Submarine Warfare (ASW) and Anti-Surface Warfare (ASuW)
  - Force protection in support of a task force
  - Land attack/strike
  - Special forces insertion and recovery
  - Intelligence, Surveillance and Reconnaissance (ISR)
  - Coastguard roles as part of anti-smuggling and anti piracy duties

2.1 Challenges and Requirements

Range & Endurance

- Allows sustained presence in distant areas of operation
- Responsible in part for the relatively high displacement of the Australian Collins Class
- not quite as simple as placing a SSN type combat fit in a SSK design
- Challenge is to retain to inherent SSK advantages

Communications

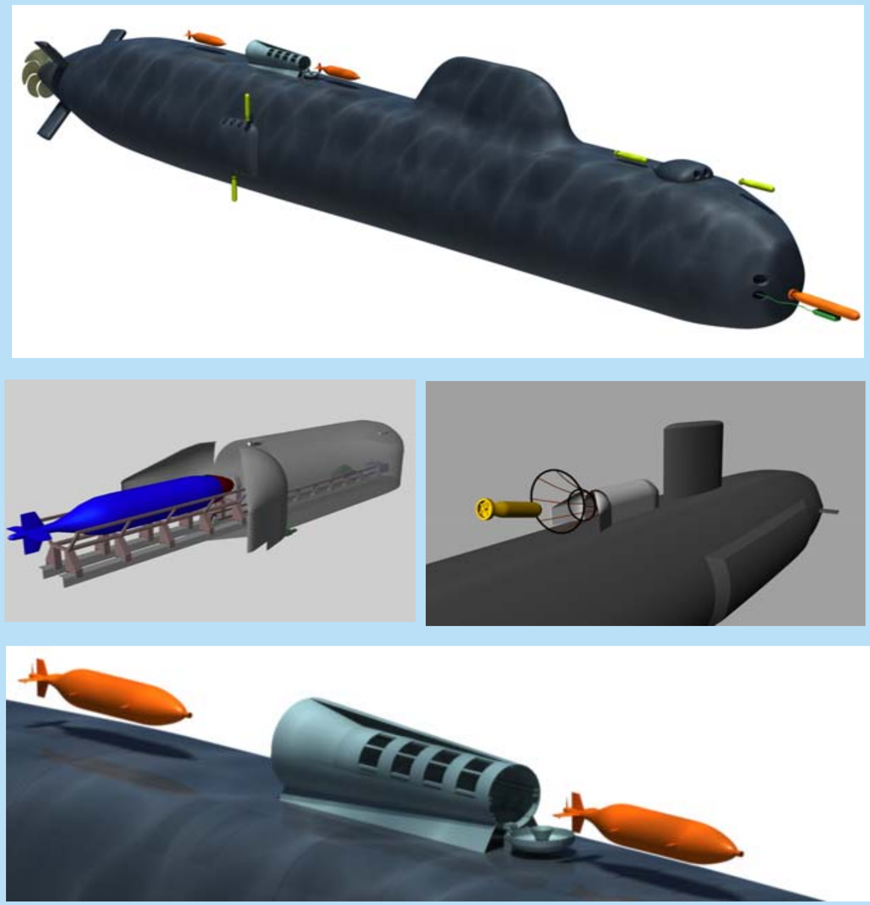
- Submarines are now required to operate within a network of assets
- Increased importance of maintaining communications with other platforms
- Reelable buoy systems such as RTOF enable SATComms whilst manoeuvring at depth
- Adds to competition for valuable external 'real-estate' with a range of other systems

2.2 Challenges and Requirements

Brown & Blue Water Operations

- The focus of current operations has moved from the blue water environment to the littoral
- A platform will face increased and varied threats
- Mitigating measures:
  - Reduced platform vulnerability such as incorporation of double hulls and increased Reserve Of Buoyancy
  - Operation of unmanned offboard vehicles
  - Increased manoeuvrability facilitated by hover tanks, increased trim and compensation capacity and increased appendage sizes
  - Minimum size
- Requirement for compatible with blue water operations remains
- Could emphasis return to blue water operations?

2.3 Challenges and Requirements



Example UUV launch and recovery system concepts

Offboard Systems

- Growing interest in the operation of unmanned vehicles from marine platforms
- UUVs and UAVs have been deployed from submarines in the US
- UUVs in particular can range in size and shape
- The major challenge is compatibility with a range of vehicles through life and simple and effective recovery
- Aft facing targets that the vehicle can drive itself into could offer simple un-complicated solutions

2.4 Challenges and Requirements

Crew Habitability

- Navies now must consider habitability to retain and ensure the development of personnel
- … As a result there is a general need to increase habitability standards on board submarines
- May be facilitated by simple provision of deck area, and also access to the internet, more regular communications with family

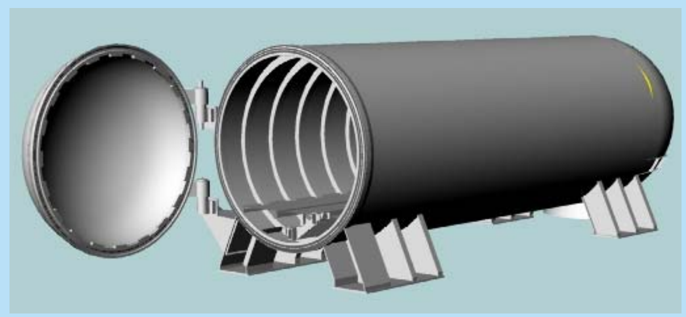
Under-Ice Operations

- Emphasis on the safety and reliability of key systems
- Mitigating measures:
  - High endurance AIP systems
  - Offboard systems may allow the platform to remain in relatively safety
  - Ice strengthened fin and casing structure
  - Fin mounted hydroplanes must rotate to a vertical position to penetrate substantial ice
- Difficulties of maintaining communications and escape and evacuation

2.5 Challenges and Requirements

Embarked Military Force

- In the current climate there has been an increase in the importance of special operations
- Special Forces (SF) requirements:
  - Bunk space
  - Munitions and explosives requiring suitable storage facilities
  - Route in and out of the submarine whilst submerged
  - Inflatables and outboards
- Biggest challenge is the SDV
- Range in size and capability:
  - Personnel vehicles that will fit in a 21” tube
  - Mk 8 Mod 1
  - Advanced SEAL Delivery System (ASDS)
- A Dry Deck Hanger (DDH) is required to house large vehicles that are not resistant to deep diving depth
- Also places increased demands on platform systems



2.6 Requirements Space Upper & Lower Bounds

Characteristic	Minimum	Maximum
Transit range	2000nm ROO	3500nm ROO
Range (direct snort)	8000nm	15000nm
Endurance	40 days	80 days
AIP Endurance	14 days	28 days
Transit speed	8 knots	18 knots
Sprint speed	20 knots	30 knots
Weapons rounds	12	36 plus 12 VLS
DDD	200m	400m
Sonar fit	(Thales S-Cube system)	Plus enhanced flank array,
	Bow array,	fully reelable TA.
	Flank array,	
	Intercept array,	
	Clip on TA.	
Communications	2x mast systems	Plus RTOF or equivalent
		1x Mast system
		Buoyant Wire Aerial
SF Payloads	Team 4,	Team 10,
	Inflatables & Outboards	Inflatables & Outboards,
		SDV (Mk8 Mod1)
UXVs*	21” tube UUV,	Oversized UUVs,
	‘micro’ UAVs	‘large’ UAVs

ROO: Radius Of Operation

3.0 Design Options and Drivers

	SINGLE HULL CONFIGURATIONS		
	BASELINE	TRADED	ADVANCED
			
Submerged Displacement (te)	3060.9	3600.4	4415.5
PH Diameter (m)	8.1	8.4	8.4
Length overall (m)	70.5	79.0	94.0
ROB	0.14	0.14	0.11
Performance			
Transit speed (kts)	10.0	10.0	10.0
Range (nm)	8000.0	9000.0	10000.0
Patrol speed (kts)	5.0	5.0	5.0
AIP speed (kts)	NA	5.0	5.0
AIP range (nm)	0.0	2250.0	2250.0
AIP Endurance (days)	0.0	18.8	18.8
Combat Fit Summary	Cylindrical bow array	Baseline plus: Partially reelable towed array	Bseline plus: Fully reelable towed array (thin)
	Flank array	2x Optronic mast	2x Optronic mast
	HF intercept array	Radar	Radar
	Active sonar	ESM	ESM
	2x Optronic mast	SatComms	SatComms
	Radar	Integrated comms	Integrated comms
	ESM	EHF/SHF	EHF/SHF
	SatComms	Mast growth bay	Mast growth bay
	Integrated comms	UAV (micro)	UAV (micro)
		6x 21" tubes	6x 21" tubes
	6x 21" tubes	18x 21" rounds	36x 21" rounds
	18x 21" rounds	5 man LILO	5 man LILO
		10 man LILO	10 man LILO
	Buoyant Wire Aerial	Buoyant Wire Aerial	Buoyant Wire Aerial
		2x Countermeasures (x3 standard)	Countermeasures (x3 standard)
		External Payload Space	Countermeasures (x3 enhanced)
		2x 4 man team	SF mission package
			SDV (inc DDH)
			Reelable buoy comms system
			2x 4 man team

3.1 Design Options and Drivers

	DOUBLE HULL CONFIGURATIONS		
	BASELINE	TRADED (Partial DH)	ADVANCED
			
Submerged Displacement (te)	3218.2	3692.5	4808.4
PH Diameter (m)	varies	varies	varies
Length overall (m)	68.0	83.0	85.0
ROB	0.30	0.15	0.30
Performance			
Transit speed (kts)	10.0	10.0	10.0
Range (nm)	11000 0	10000.0	14000.0
Patrol speed (kts)	5.0	5.0	5.0
AIP speed (kts)	5.0	5.0	10.0
AIP range (nm)	0.0	2250.0	2250.0
AIP Endurance (days)	0.0	18.8	18.8
Combat Fit	Cylindrical bow array	Baseline plus Par ially reelable towed array	Baseline plus Fully reelable towed array (thin)
	Flank array	2x Optronic mast	2x Optronic mast
	HF intercept array	Radar	Radar
	Active sonar	ESM	ESM
	Underwater telephone	SatComms	SatComms
	2x Optronic mast	Integrated comms	Integrated comms
	Radar	EHF/SHF	EHF/SHF
	ESM	Mast growth bay	Mast growth bay
	SatComms	UAV (micro)	UAV (micro)
	Integrated comms	18x 21" rounds	36x 21" rounds
	EHF/SHF	2x External weapon stowage (x2)	2x External weapon stowage (x2)
	6x 21" tubes	5 man LILO	5 man LILO
	18x 21" rounds	10 man LILO	10 man LILO
	5 man LILO	Buoyant Wire Aerial	Buoyant Wire Aerial
	Buoyant Wire Aerial	2x Countermeasures (x3 standard)	Countermeasures (x3 standard)
	4 man team	External Payload	Countermeasures (x3 enhanced)
		2x 4 man team	SF mission package
			SDV (inc DDH)
			Reelable buoy comms system
			2x 4 man team

3.2 Design Options and Drivers

Propulsion System Options

Power Generation (Air Breathing) Options:

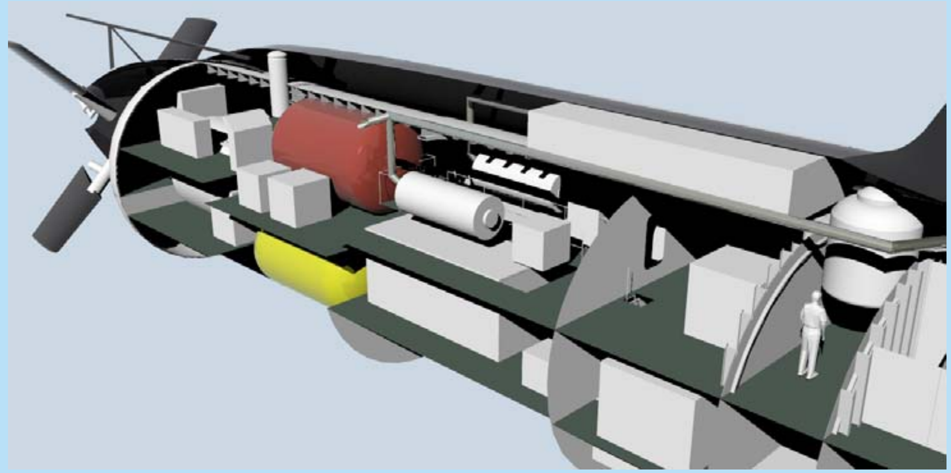
- Diesel Generators
- (Solid Oxide Fuel Cells)

Power Generation (Submerged) Options:

- Proton Exchange Membrane (PEM) Fuel Cells
- Closed Cycle Diesel
- Stirling engine
- MESMA (Module d'Energie Sous-marine Autonome)

Energy Storage Options:

- Lead Acid Batteries
- VR Lead Acid Batteries
- Zebra Batteries
- Lithium Ion Titanate Batteries



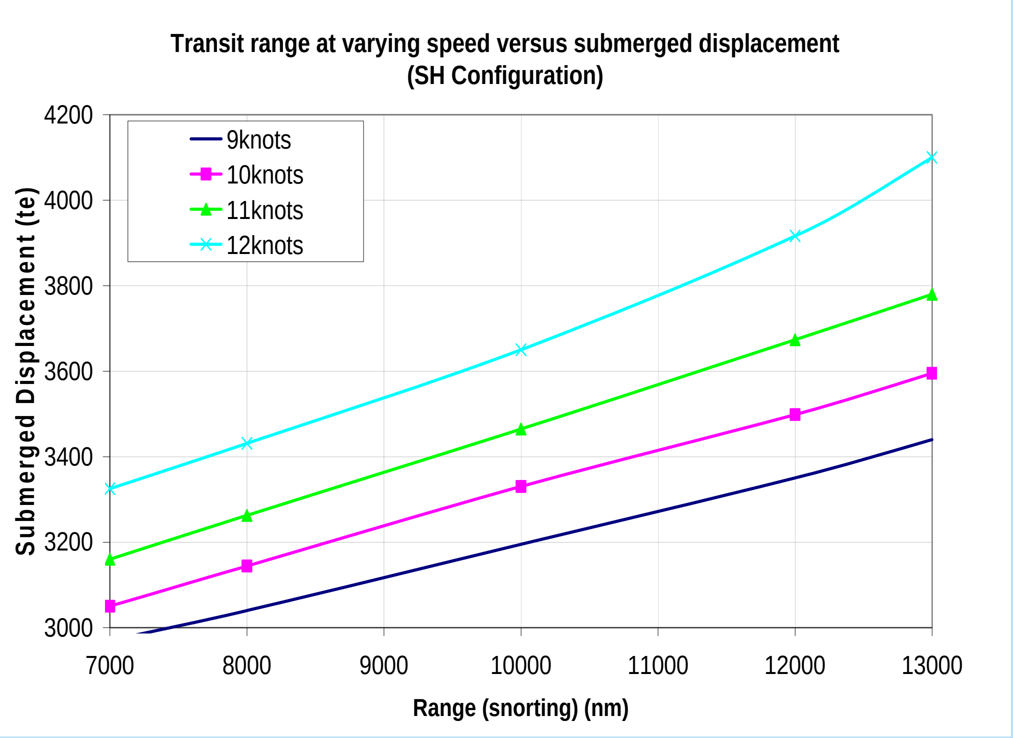
Battery type	Hrs @20knots	Hrs @10knots	Weight	Vol'
Lead acid	1.80	18.80	1.00	1.00
Zebra	3.35	48.70	0.72	1.00
Lithium Ion	4.93	51.26	1.00	0.91

3.3 Design Options and Drivers

Range and Endurance

Transit Range

- Considered direct snort at varying speed for SH configuration
- Illustrates the impact of extended range and speed combined
- i.e. 2knots increase in speed increases displacement by 150te for 10,000nm direct transit
  - hence the size of the Collins class

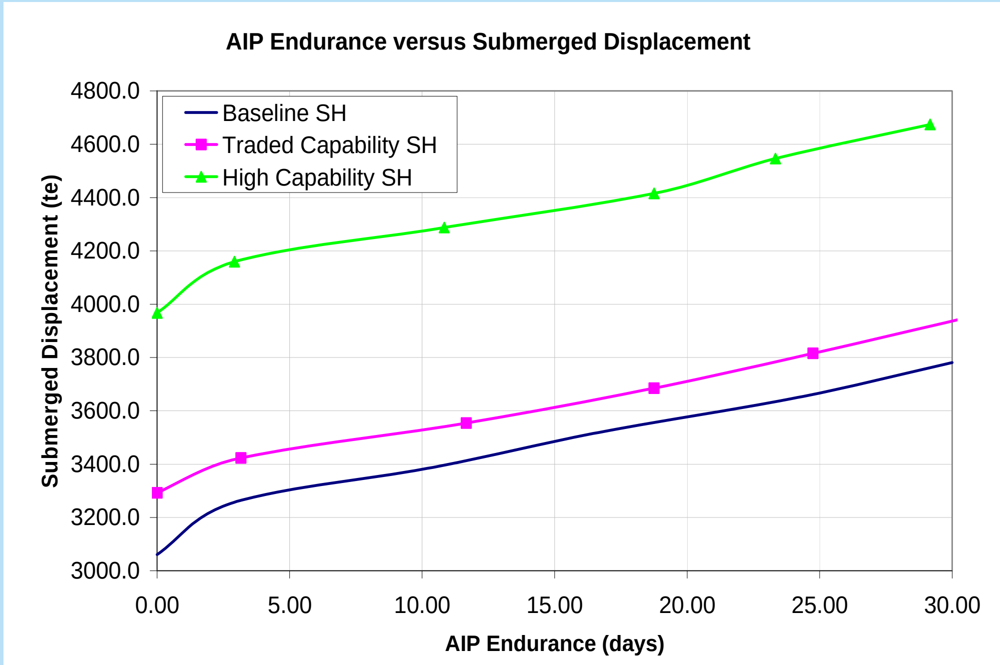


3.4 Design Options and Drivers

Range & Endurance

AIP Endurance (shown right)

- Assumes an AIP fit comprising PEM fuel cells fuelled by LOX and reformed Methanol
- Hotel Loading dominates power requirements and ultimately limits submerged endurance.
- A significant increase in displacement is required to facilitate a thirty days on AIP
- A large amount of space is also required to compensate for variations in weight due to consumables



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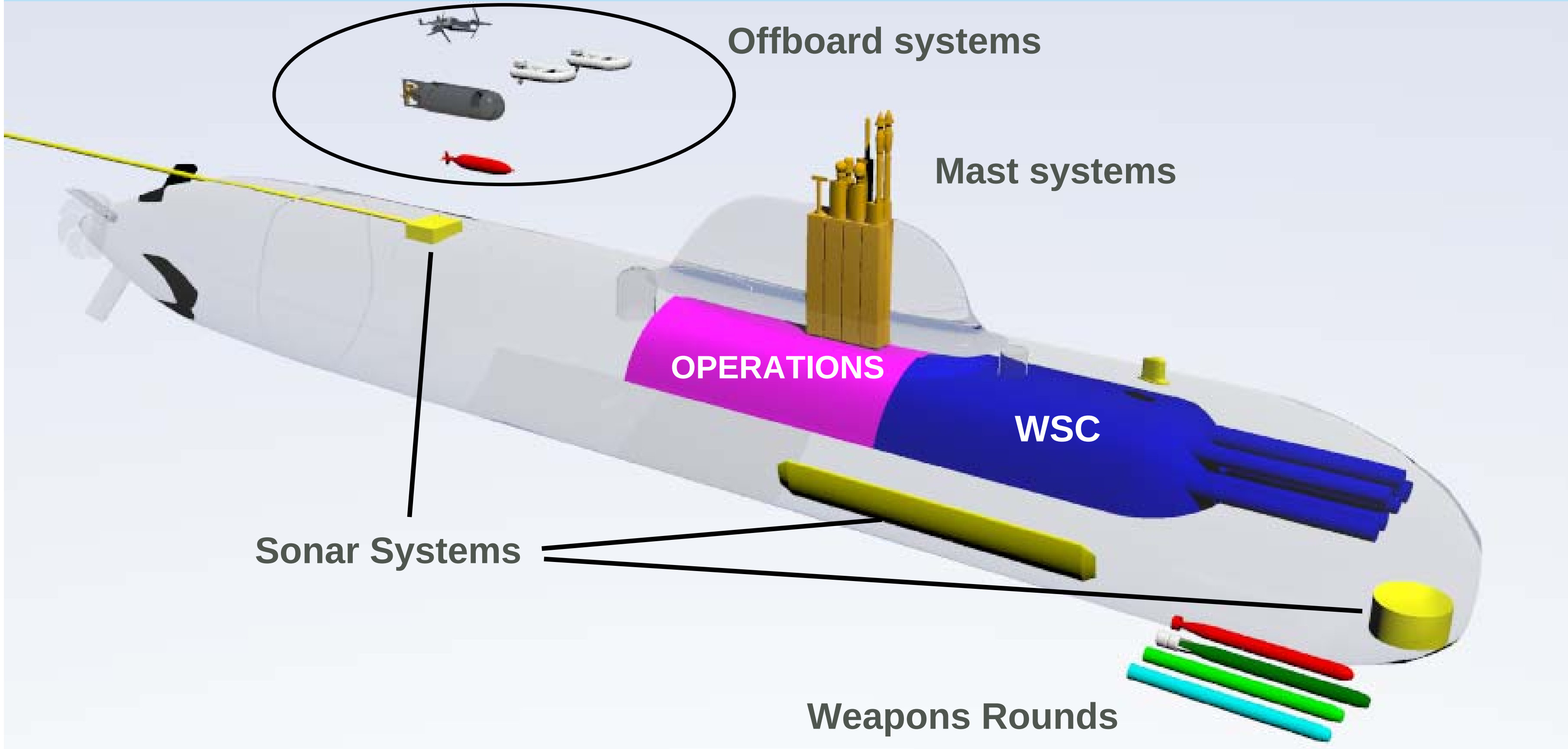
3.5 Design Options and Drivers

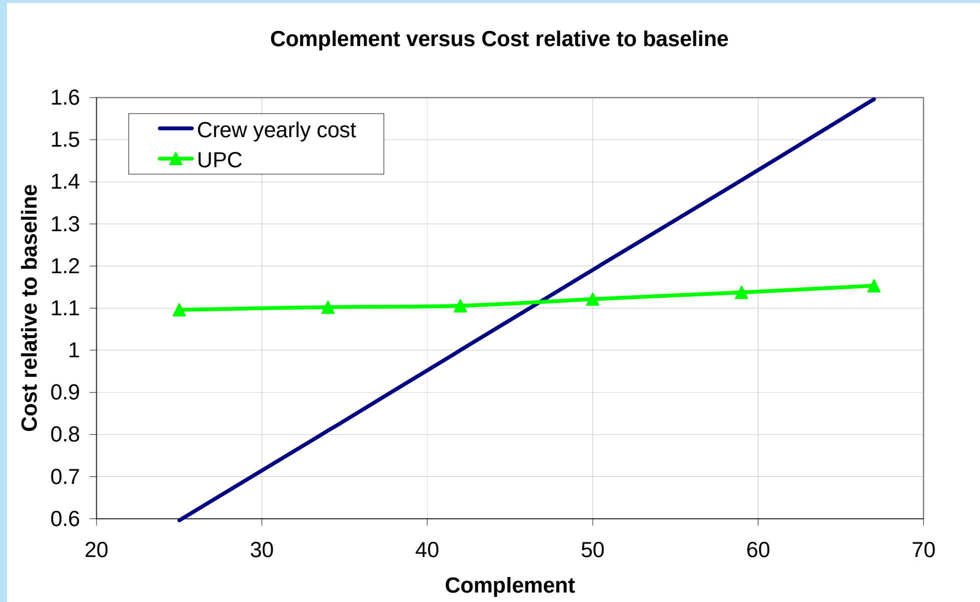
Combat Fit (Major Payload Items)



3.6 Design Options and Drivers

Crew Complement

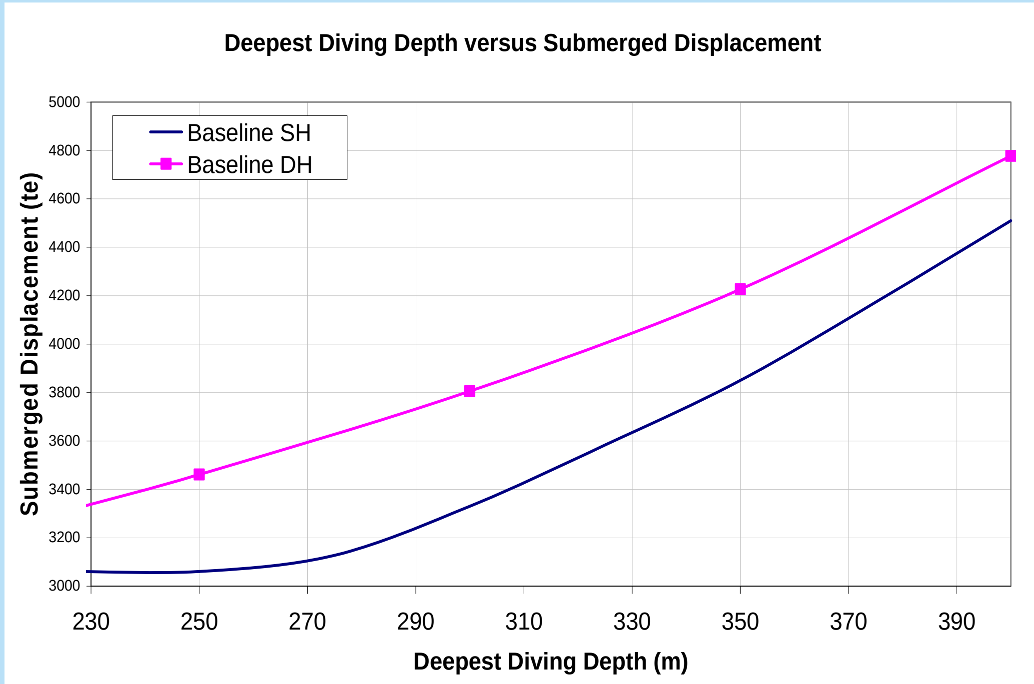
- Impacts overall size and UPC and TLC
- Crew numbers are driven by:
  - Watch station requirements
  - Damage control requirements
  - The need to sustain skills
  - Patrol duration
  - Maintenance
- Potential areas of reduction
  - Sharing of skills
  - Integrated combat systems
  - Increased automation
- Ultimately crew numbers and breakdowns will be decided by operator requirements and preference



3.7 Design Options and Drivers

Deep Diving Depth

- Current operations are envisaged to be in the littoral
- given the associated weight and cost penalties the requirement for a DDD over approximately 250m can be questioned
- Design for depths above 260m creates space may be used for storage of density items
- DDD for a submarine designed to operate in the littoral and blue water environments would be seem to be 240-260m

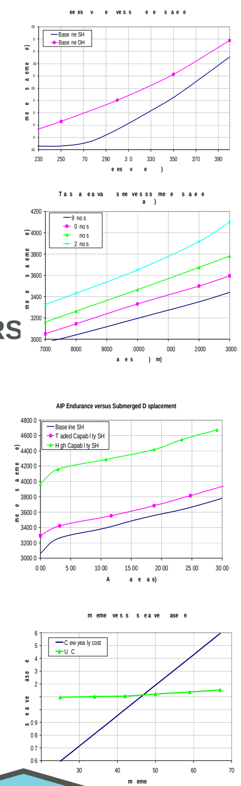


3.7 Design Options & Drivers – Process Overview

REQUIREMENTS SPACE DEFINITION

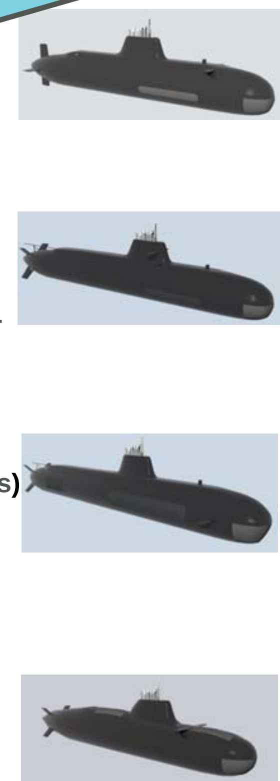
UNDERSTAND EARLY STAGE DESIGN DRIVERS

ie Range & Endurance
Combat fit
Deep Diving Depth
Complement
Cost



DEVELOP CONCEPT OPTIONS

(Capturing major configuration options)



CONCEPT DOWN-SELECTION

Key discriminators:

Cost

Performance

Programme

Understanding the high capability SSK solution space

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3.8 Concept Option Down Selection

Key Discriminators

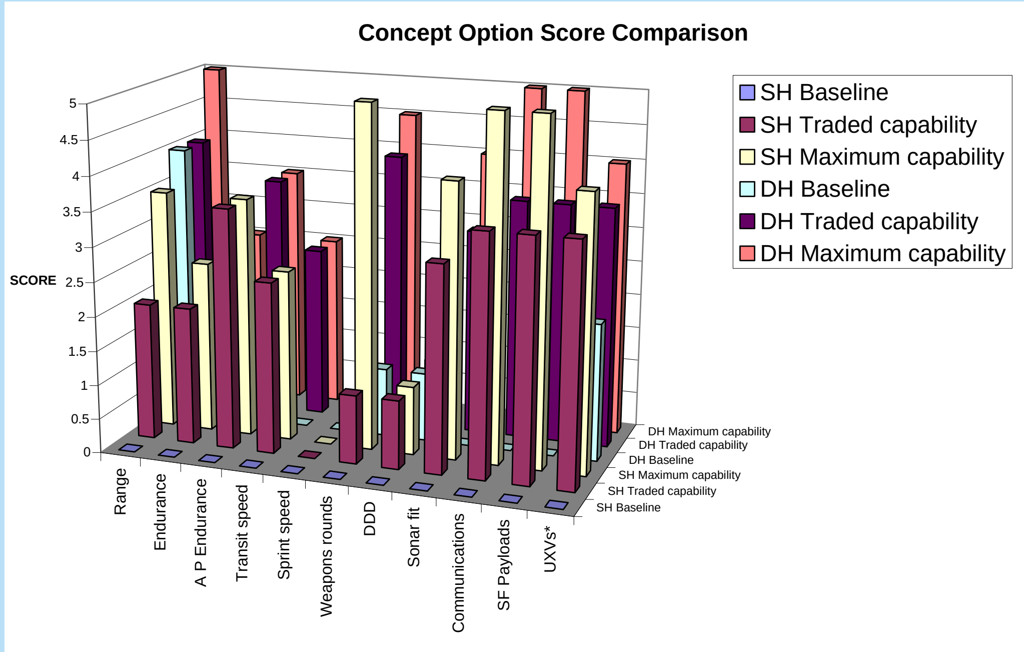
- Weighted score within requirements space upper and lower bounds
- Cost including UPC and TLCs
- Programme

Assumed weightings

- Developed to meet current emphasis on:
  - Reduced UPC and TLC
  - High TRLs
  - Range & Endurance
  - Communications capability
  - SF capability
  - Littoral compatibility

Results

- Advanced capability options penalised for increase in size and UPC
- DH options score poorly due to increase in beam/depth and TLC



4.0 Vidar-36 Submarine Design

Basic Configuration

Principal Particulars

Surface Displacement: 3237.2 te

Submerged Displacement: 3600te

Max submerged speed: 20 knots

Range @10knots (snort): 9,000nm

- Extended range option: over 10,000nm

Length: 79m overall

Max beam: 8.4m

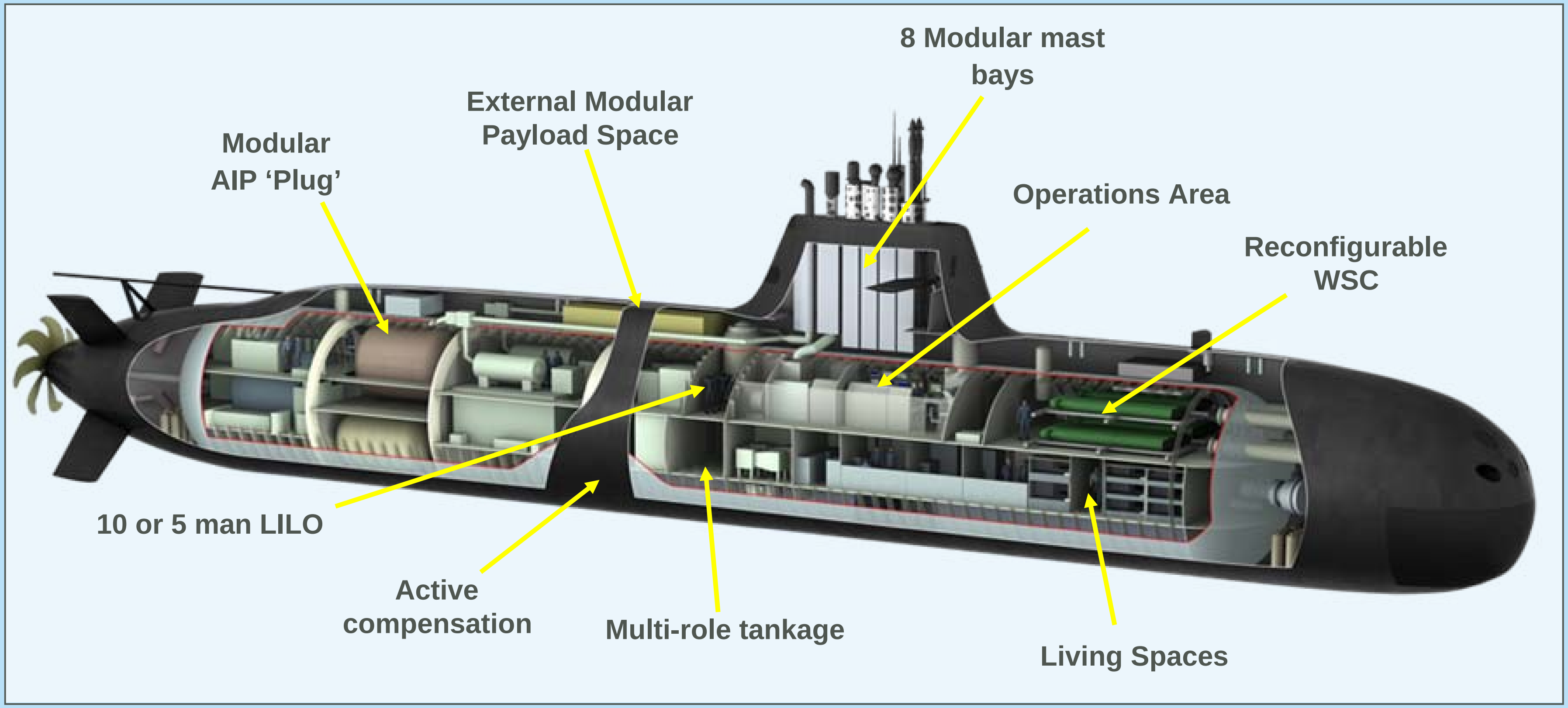
DDD: 250m

ROB (standard config):15%

Sonar Fit: Thales S-Cube System

Propulsion System: Conventional Diesel-Electric with AIP options

4.1 Vidar-36 Design Overview

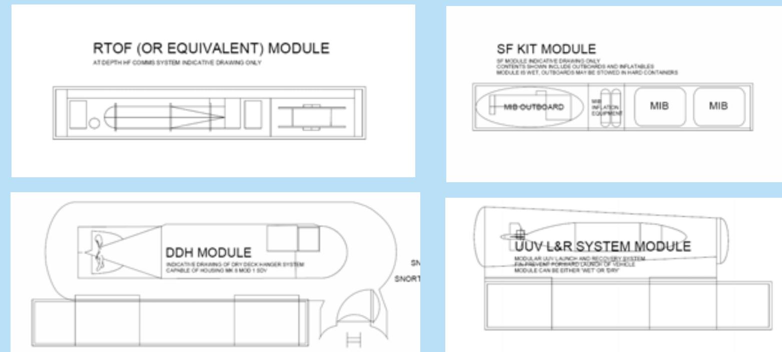


Affordable, Available and Adaptable Submarine Design

4.2 Vidar-36 Design Overview

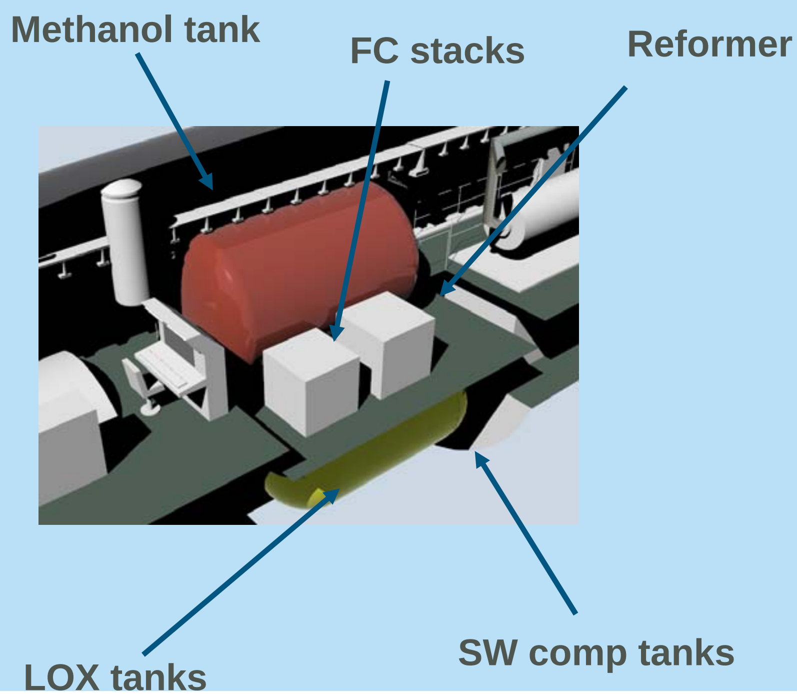
Payload bay module options:

- Dry Deck Hanger Mission Module
- RTOF/Equivalent Mission Module
- SF Kit Mission Module
- UUV L&R System Mission Module (CMH)
- Towed Array Mission Module



AIP Plug

- Baseline plug length 7.5m
- Designed to cause minimum disruption to overall platform (structure/hydrostatics)
- Baseline Power generation via PEMFC
- LOX fuel storage
- Hydrogen produced from reformed methanol
- 21 Day submerged AIP endurance



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4.2 Vidar-36 Design Overview

8 modular mast bays

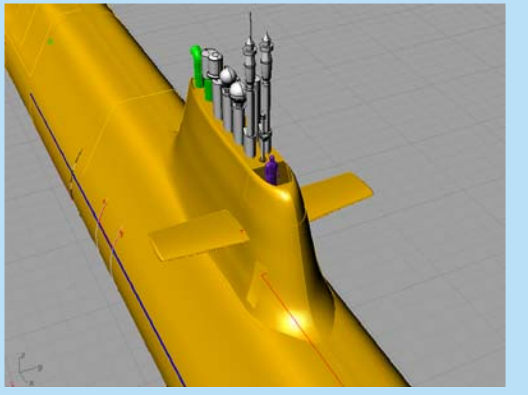
- Baseline fit:
  - 2 Optronic masts
  - SHF/EHF
  - Satcom
  - Integrated Comms
  - ESM
  - Radar
  - Growth
- Advanced mast options
  - SAM system
  - Other self protection systems

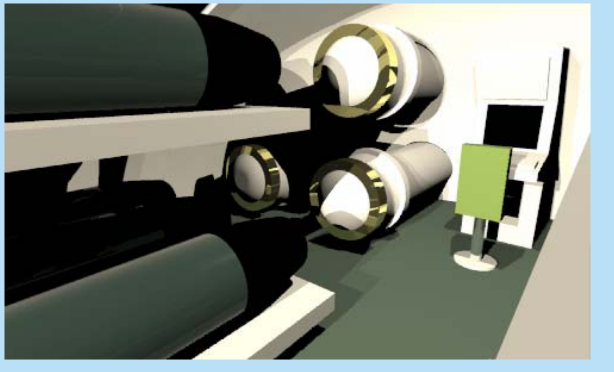
Weapon Stowage Compartment

- WSC Capacity 18 21” rounds
- or 36 mines
- SF munitions/explosives
- WSC weight capacity 30 te
- Potential muzzle reload

- Countermeasures

  - 6 cartridge located in casing

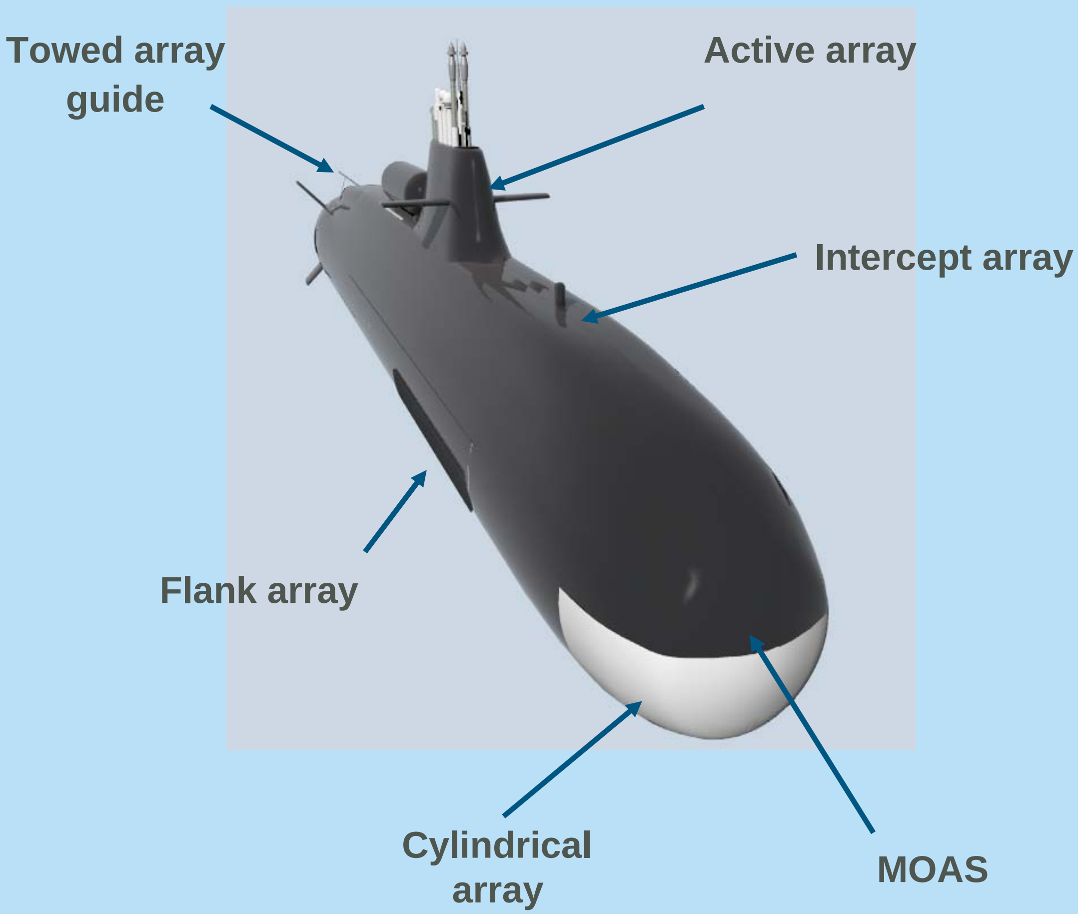




4.5 Vidar-36 Design Overview

Baseline Sonar Fit:

- Thales S-Cube System
  - Cylindrical array
  - Flank array
  - Active array
  - Partially reelable TA
  - Intercept array
  - Mine & Obstacle Avoidance Sonar (MOAS)
  - Under-water telephone
- Weight and Power margins allocated for alternative fits
- Fully reelable Towed Array mission module option



Summary & Conclusions

- It has only been possible to provide a brief highlight of the major aspects, drivers and options identified and considered
- The activity has achieved an understanding of the high capability submarine solution space….
  - The impact of capability upper and lower bounds has been assessed
  - ….this is essential in the development of realistic platform requirements
- The rigorous process has identified that the current wide and varied high capability requirements combine to drive submarine size to over 3,500te
  - This results in the need for a high degree of flexibility and adaptability
  - One indicative solution to these requirements, Vidar-36, has been proposed
  - This design takes advantage of modularity and incorporation of open architectures to facilitate a reduction in overall size

Thank you for your attention – Questions?

Acknowledgements

Images sourced from www.navy.gov.au, www.navy.mil, www.ultra-scs.com

Other images copyright BMT Defence Services.

Image credit www.DefenceImaging.com and Criterion.

A Vidar-36 datasheet can be downloaded from http://www.bmtdsl.com

BMT Defence Services

Pressure Hull Collapse Prediction Using FEA.

Dr. Derek Graham, QinetiQ Rosyth.
WARSHIP 2008: NAVAL SUBMARINES 9

10 June 2008

QinetiQ

www.QinetiQ.com

Contents slide

01 History of submarine structural research at Rosyth

Research into all aspects of submarine structures has been carried out continuously since the 1940s. Notable contributions include:

- Approximately fifty years of testing of large-scale models.
  - Ring stiffened cylinders designed to isolate interframe, overall and interactive collapse modes.
  - Cones, domes and other specialised structures.
- Bill Kendrick (1950 to 1986).
  - Largely responsible for the UK submarine pressure hull design rules.
- David Creswell (1973 to 2006).
  - Major contributions to the application on non-linear analysis to submarine structures.
  - Much work on novel structures (e.g. composite rudder).
- Experts in other areas have influenced past and present team members e.g.
  - John Sumpter (fatigue and fracture).
  - Bob Haxton (UNDEX).

02
Validation Exercise

02 Aim of validation exercise

To show that non-linear Finite Element analysis can be used reliably to predict the inelastic collapse pressures of submarine hulls.

- Structural modelling is sufficiently realistic and inclusive.
- Use the submarine legacy collapse model test data to validate FE analysis.

Provide guidance on the application of NLFE analysis, including the development and application of partial safety factors.

02 Problem!

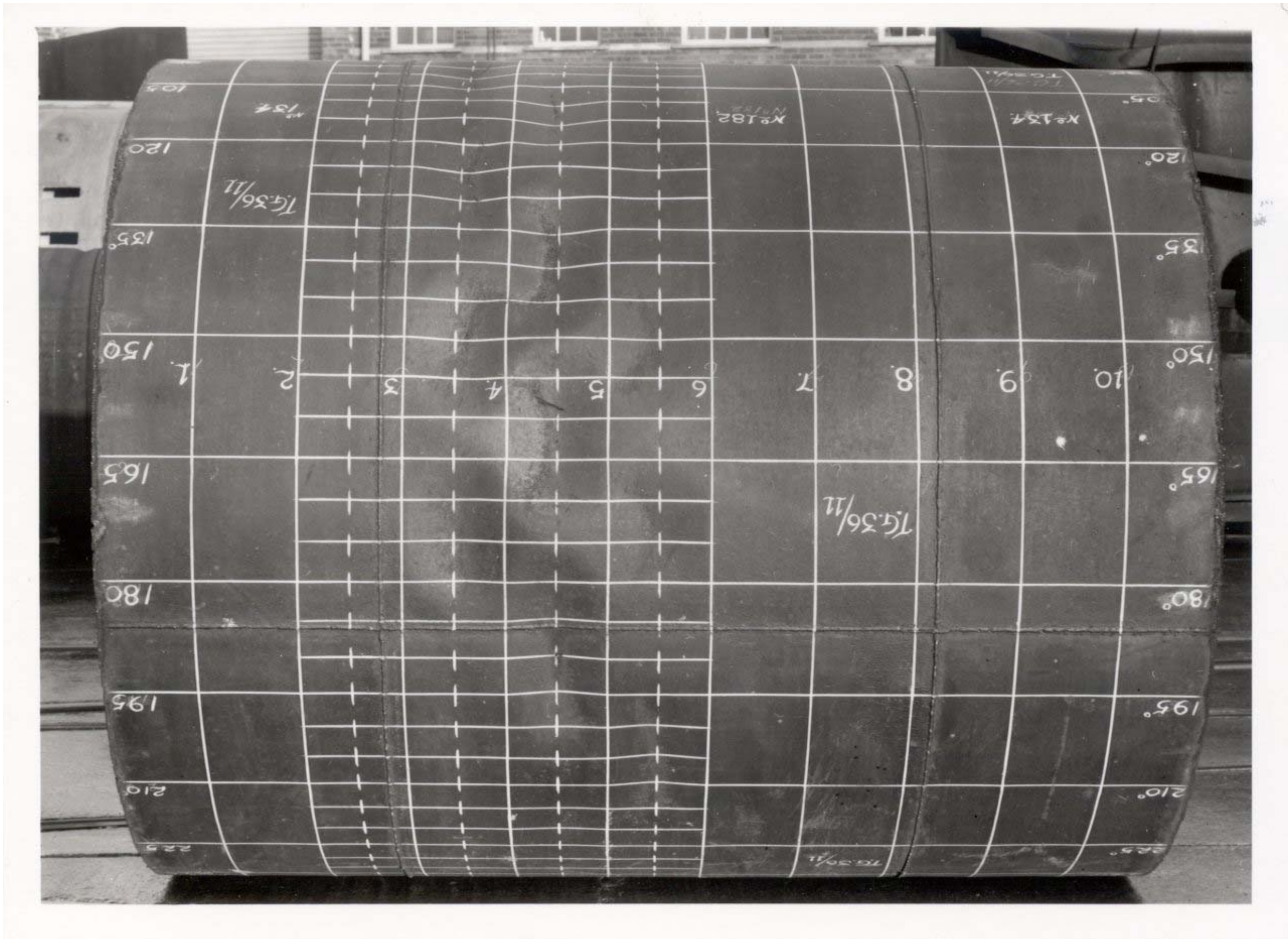
Non-linear, elasto-plastic collapse.

- Geometric and material non-linearities.
- Loss of stability.
- Shape sensitivity

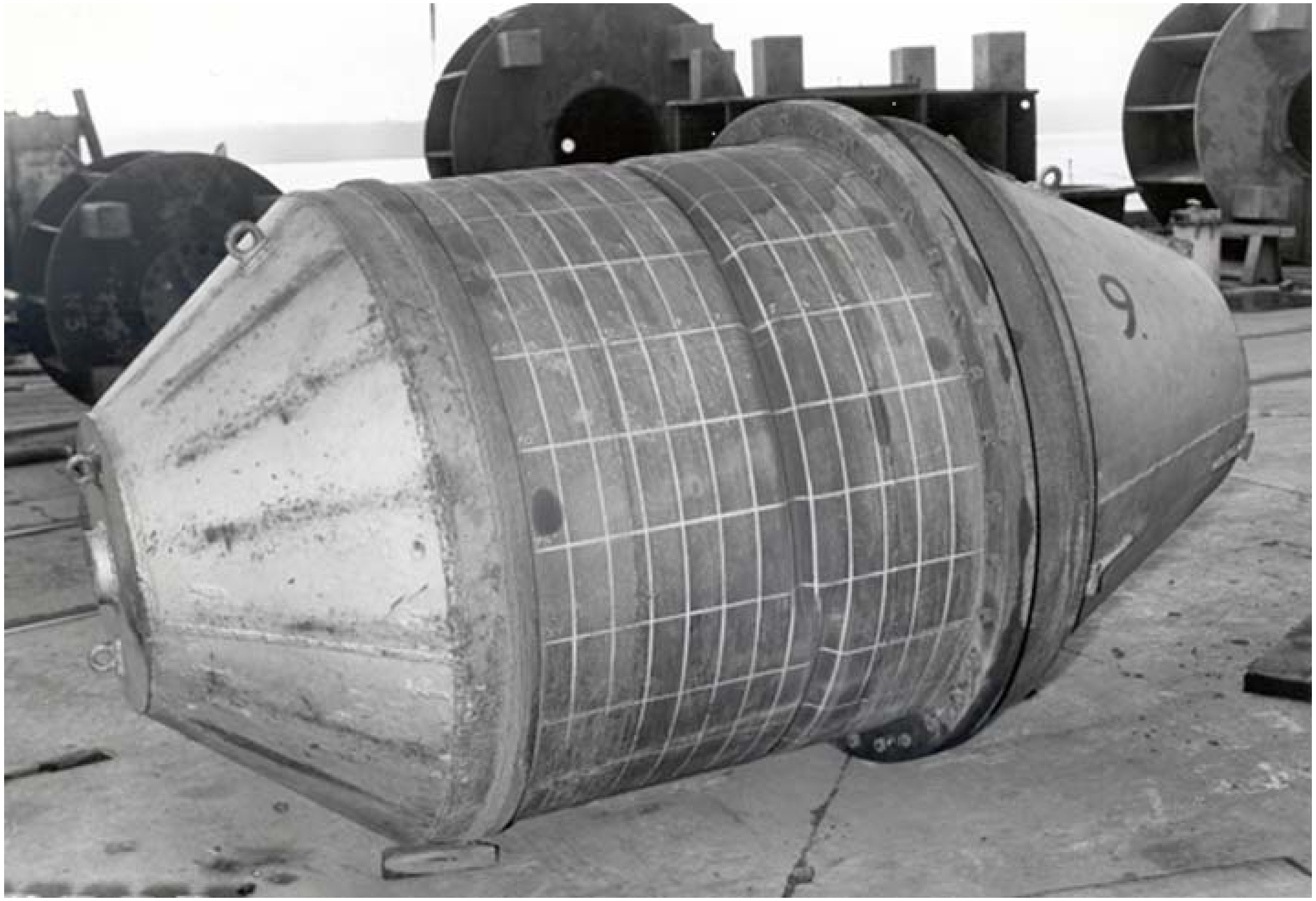
Several modes of failure.

- Interframe buckling/yielding.
- Overall collapse.
- Interactive collapse.

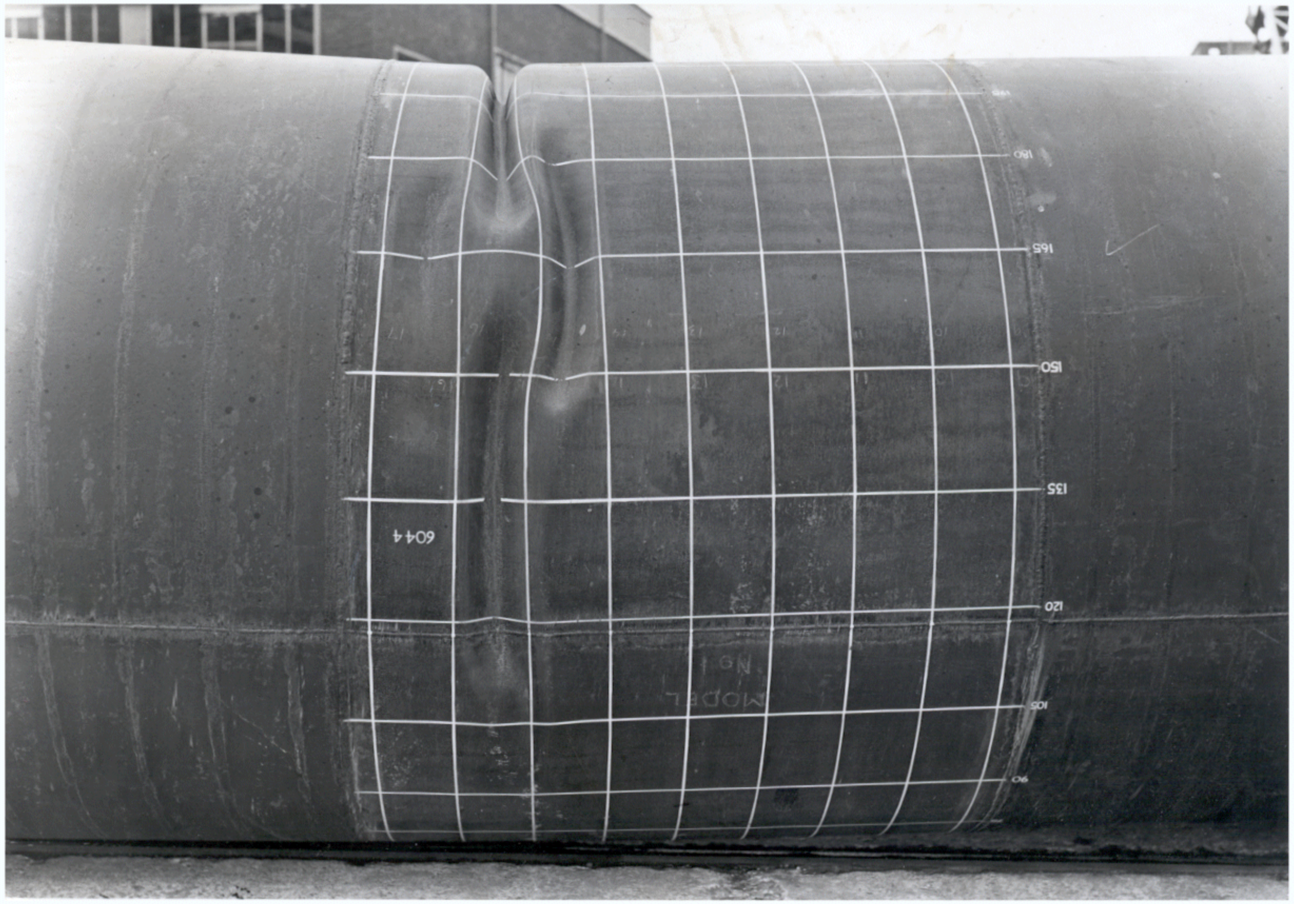
02 Interframe buckling



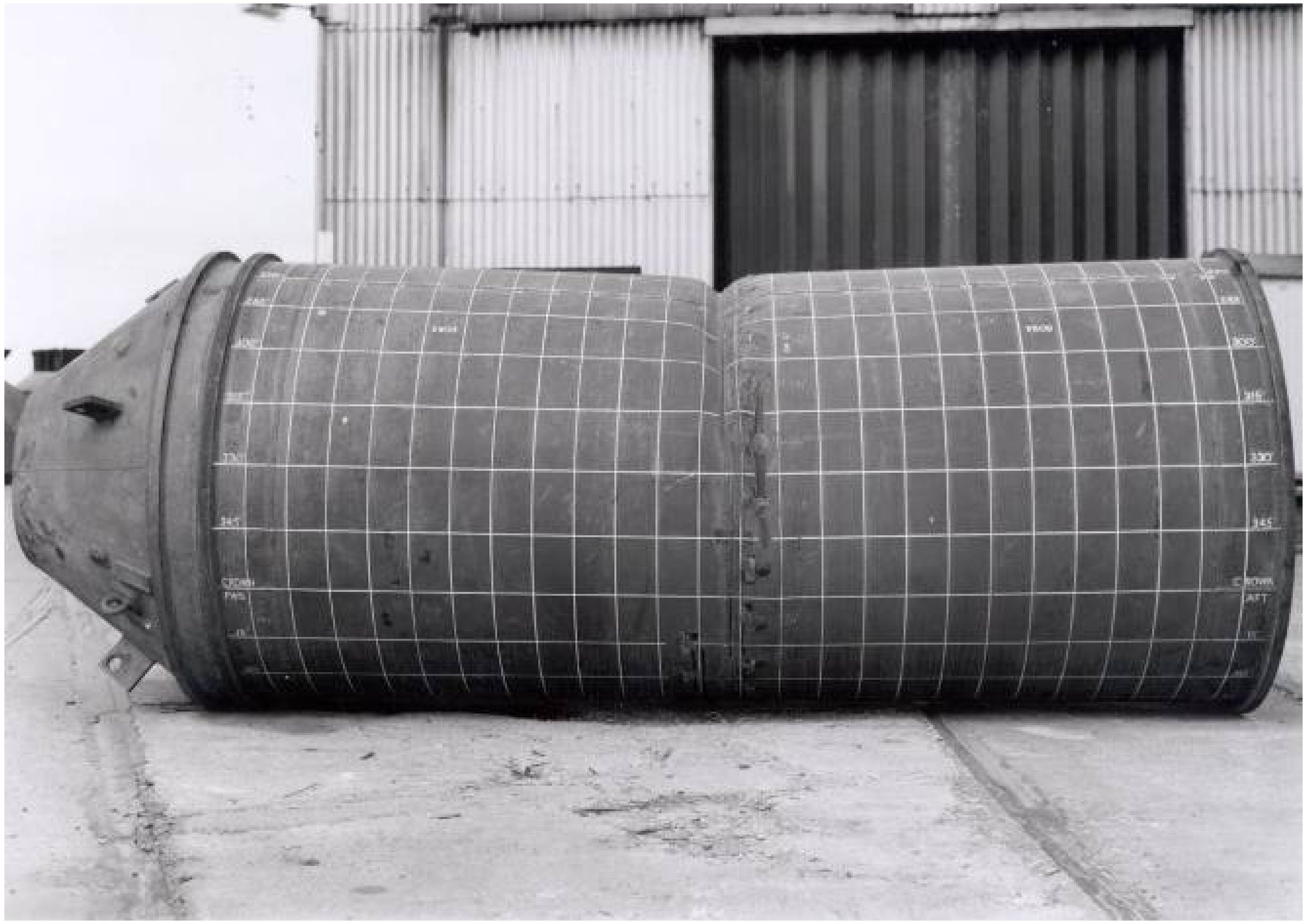
02 Interframe yielding



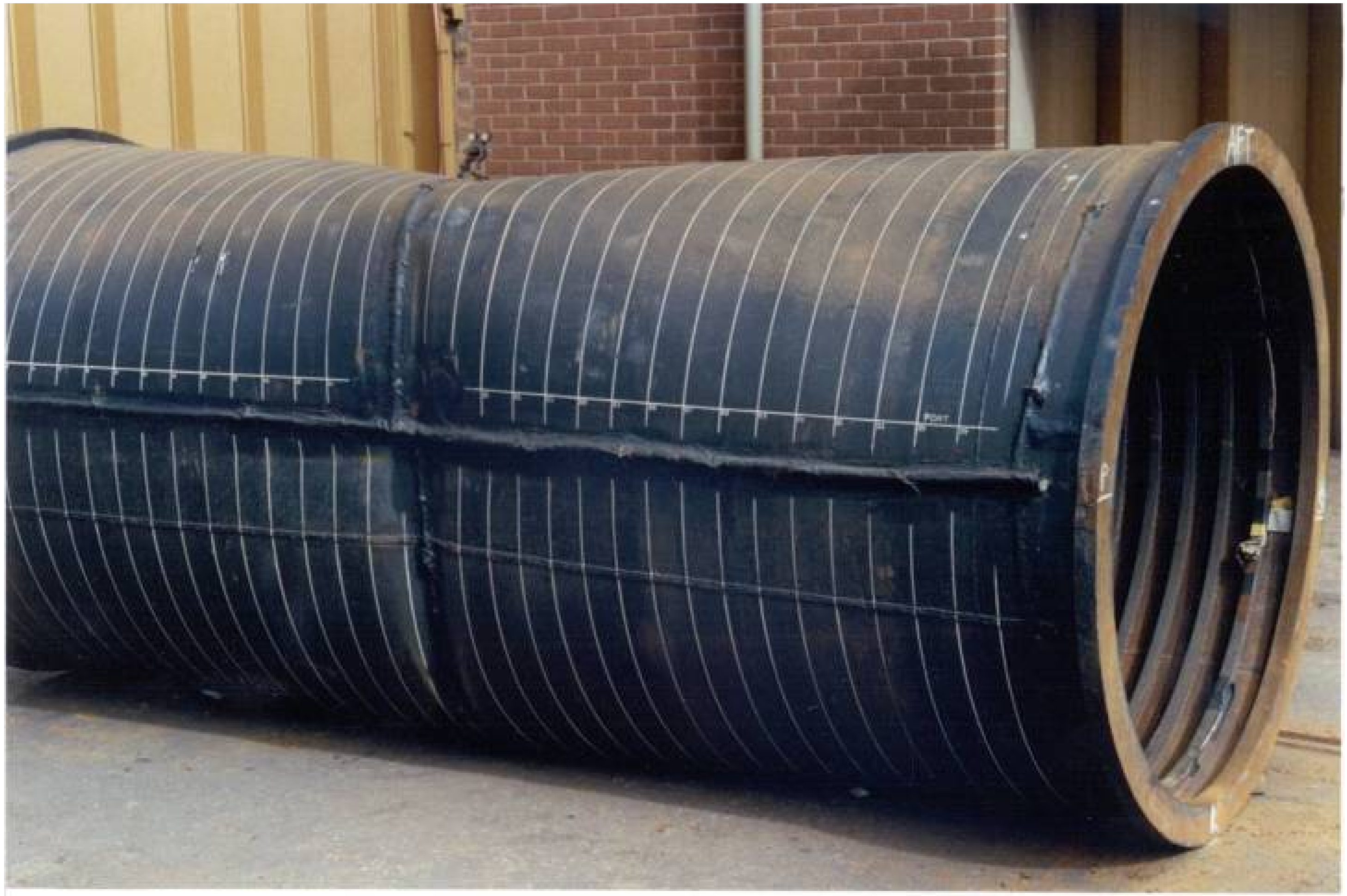
02 Interframe collapse



02 Interactive collapse



02 Overall collapse



02 Key features of the analysis

Shape modelling.

- Overall OOC, interframe shape imperfection, frame alignment, scantlings.

Material behaviour.

- Available properties and models.

Representation of residual stresses.

- Residual stresses due to cold bending of plate and frames was modelled explicitly.

02 Available plasticity models

Elastic/Perfectly Plastic.

- Relatively simple, requires only one yield stress.

Isotropic hardening.

- Detailed representation of non-linear stress-strain curves.

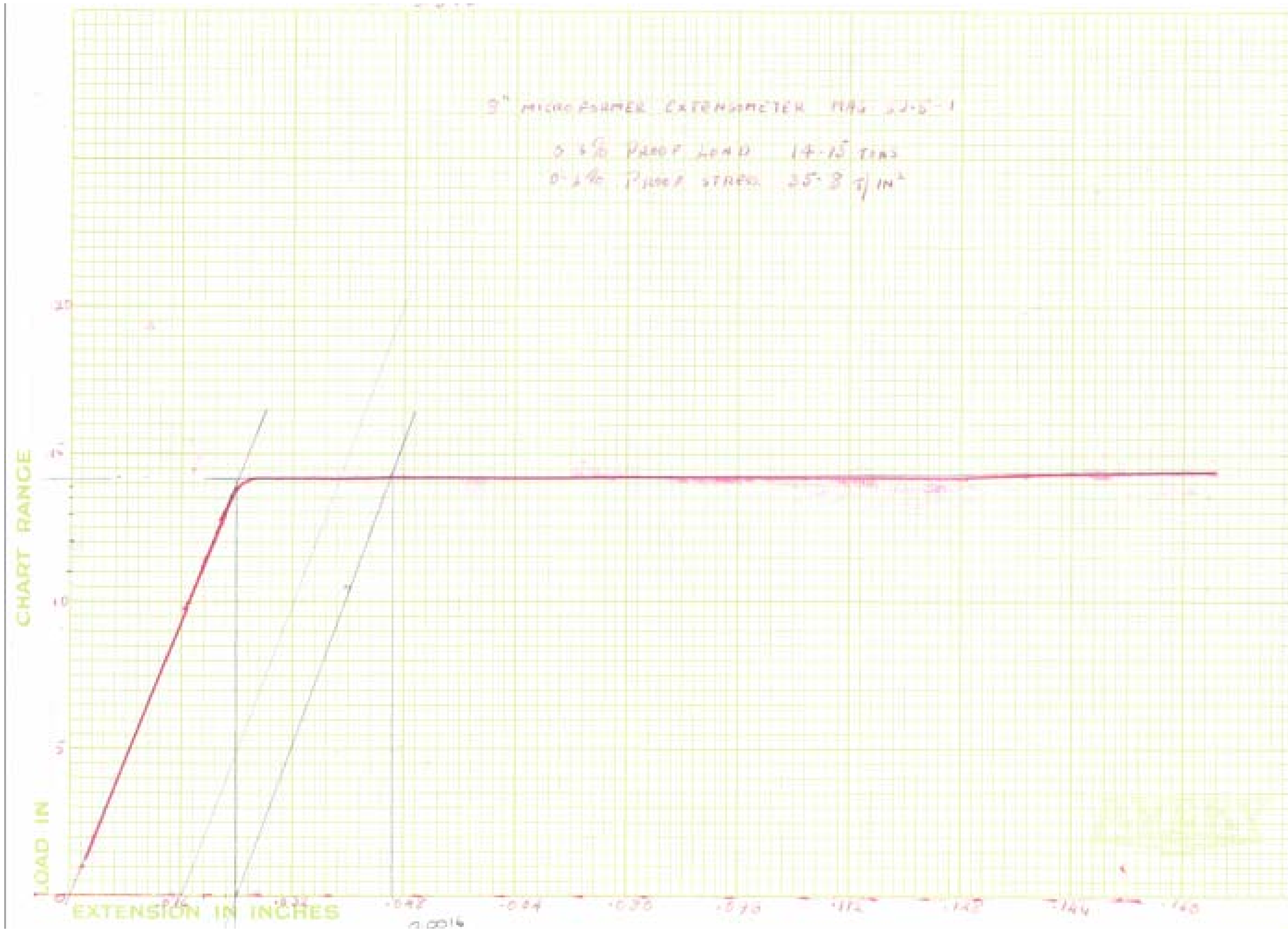
Linear kinematic hardening.

- Bi-linear representation of stress-strain curve only but models Bauschinger effect and plastic shakedown.

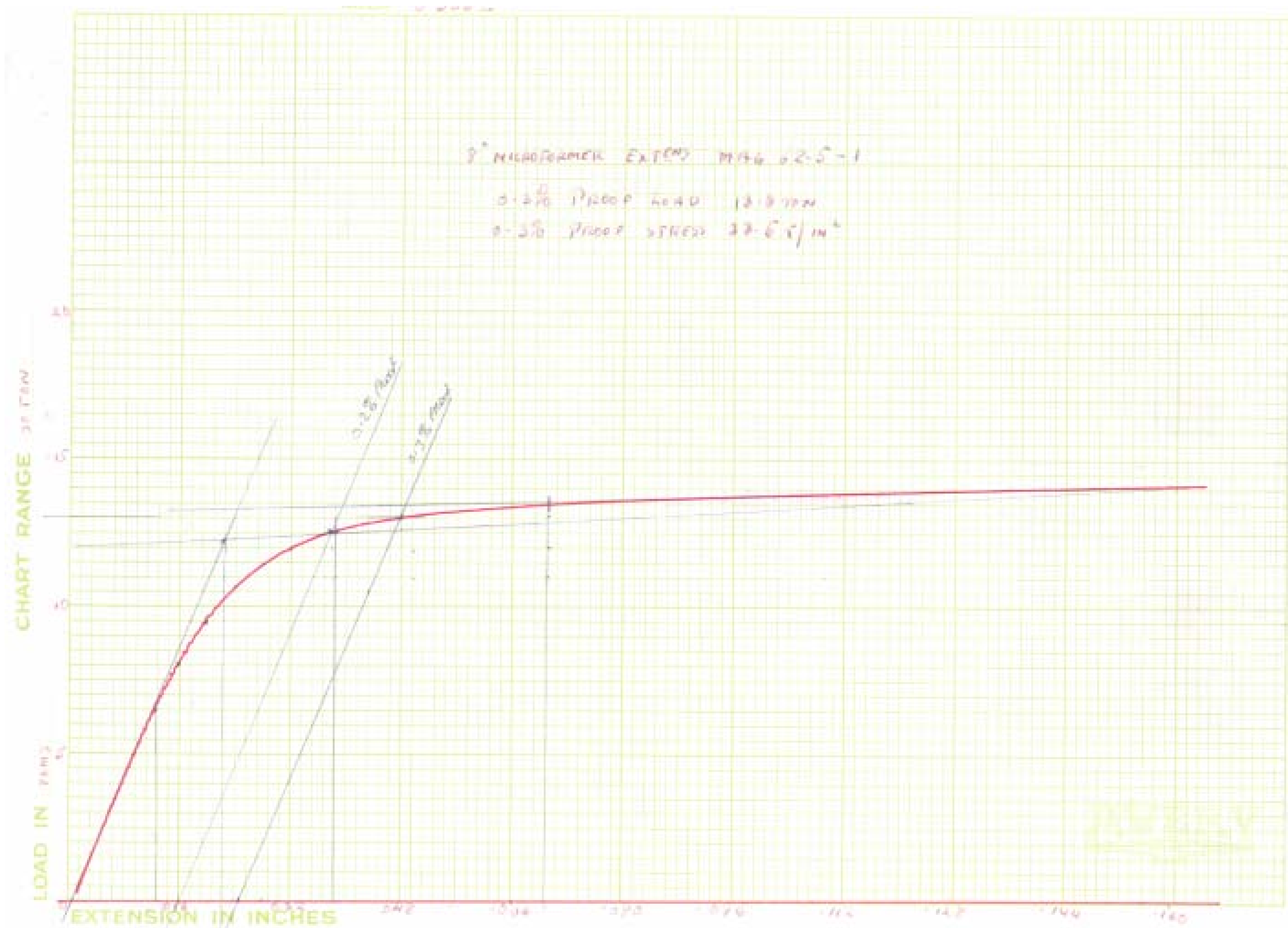
Non-linear isotropic/kinematic hardening.

- Can be more accurate but requires more input data.

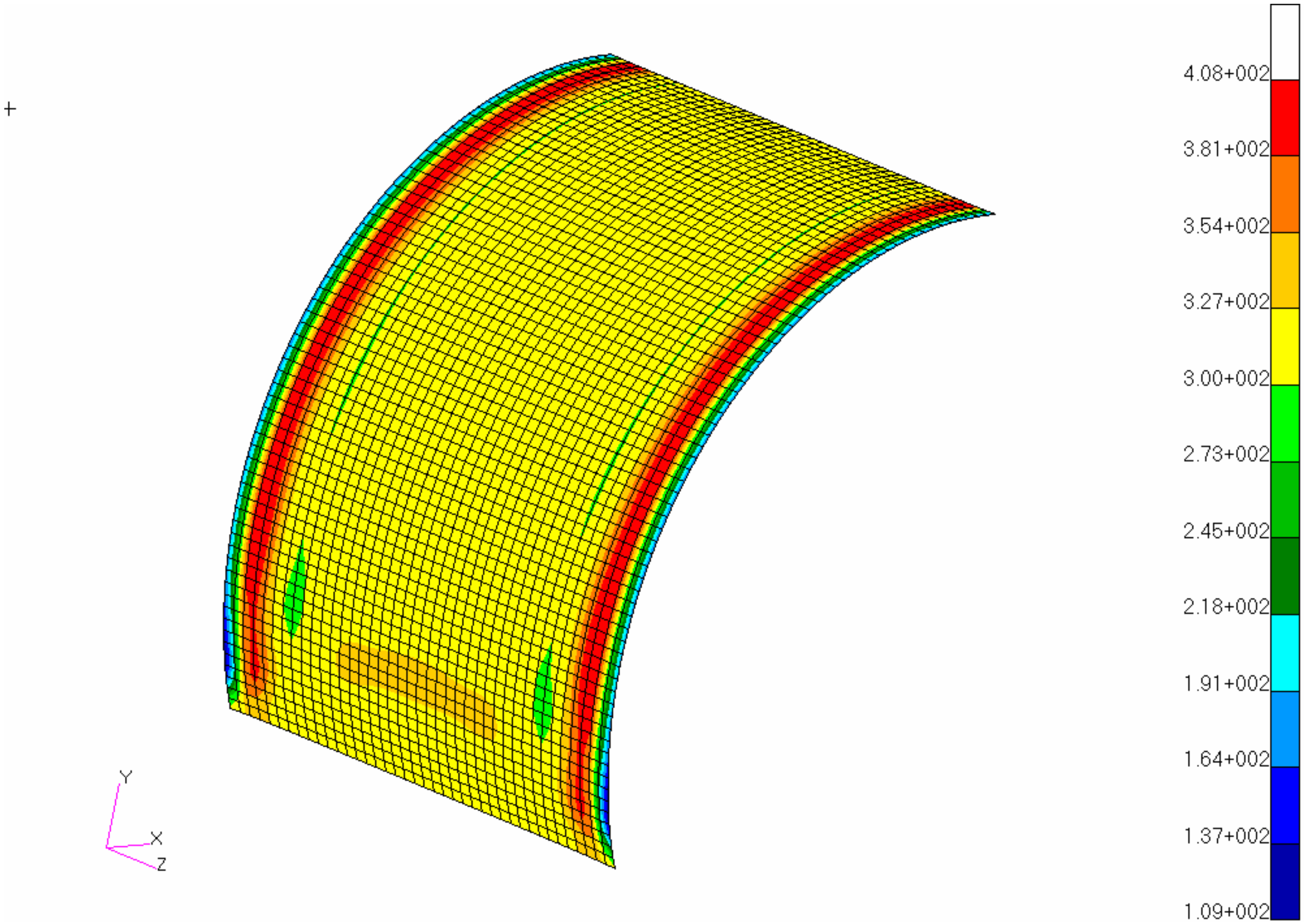
02 Stress-strain curve against roll



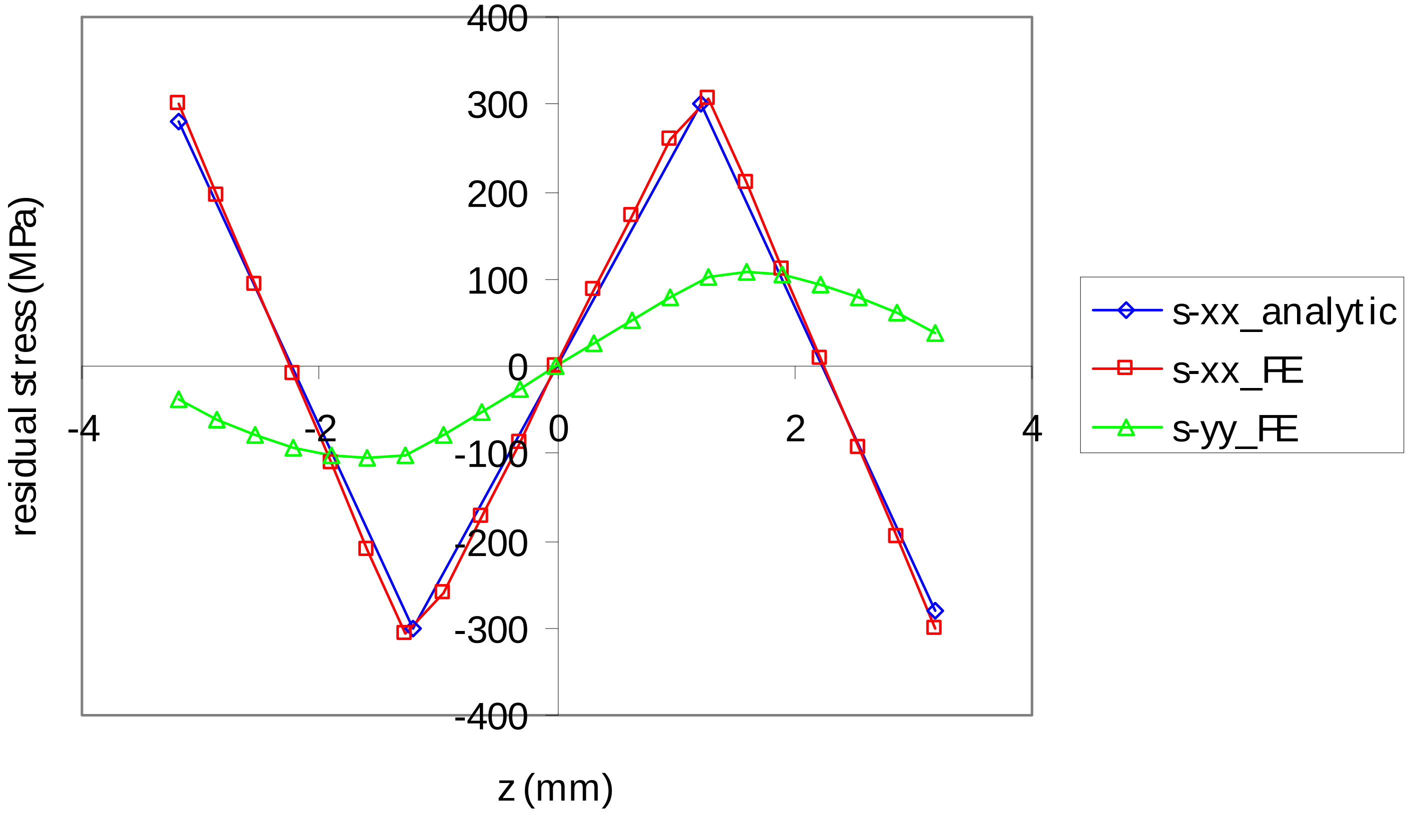
02 Stress-strain curve with roll



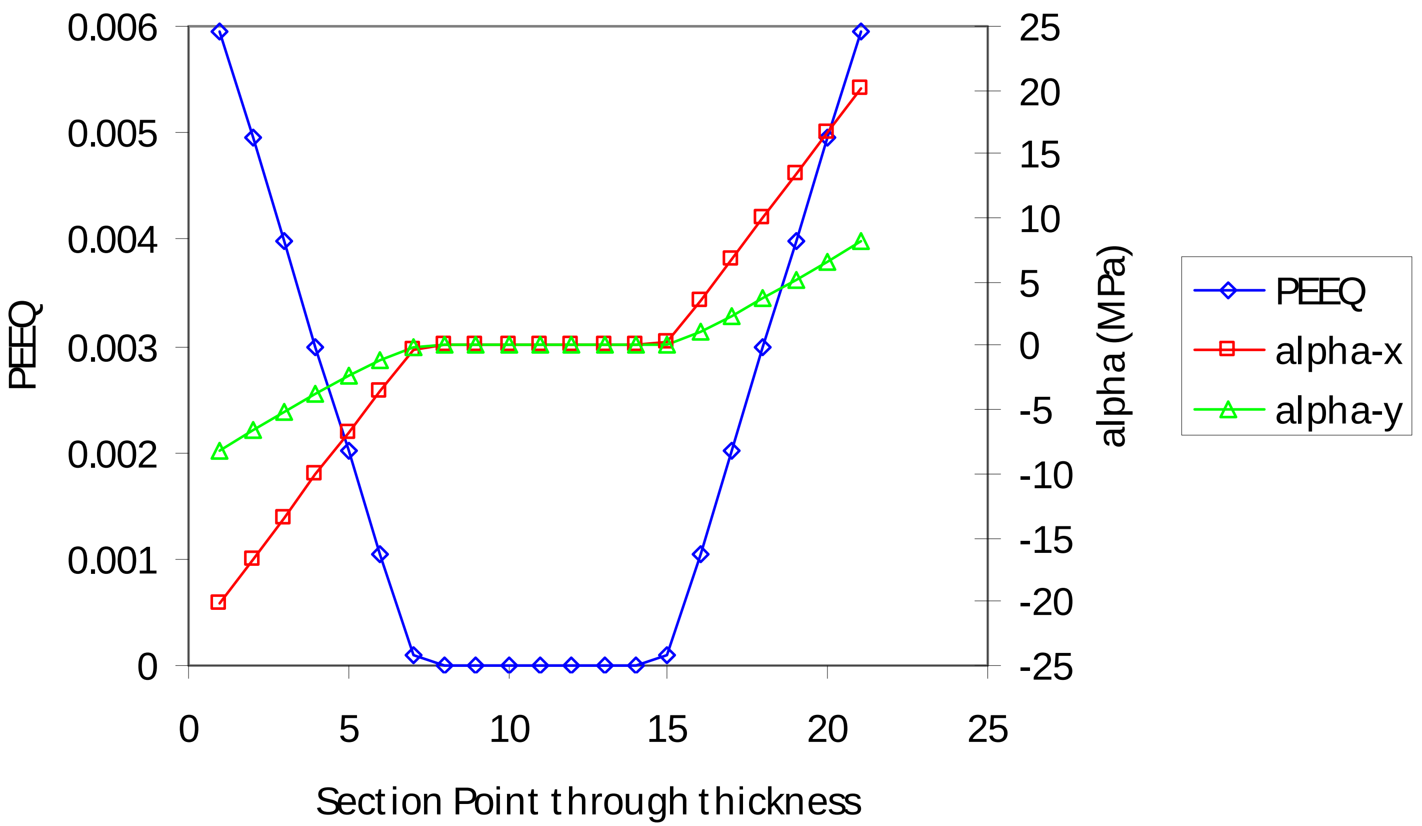
02 Residual stress in plate



02 Residual stress in plate

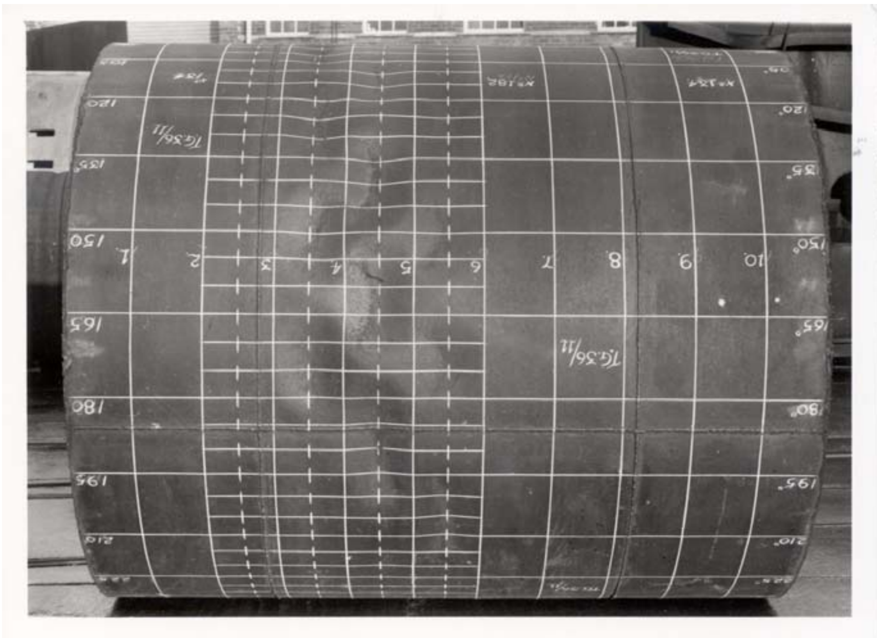


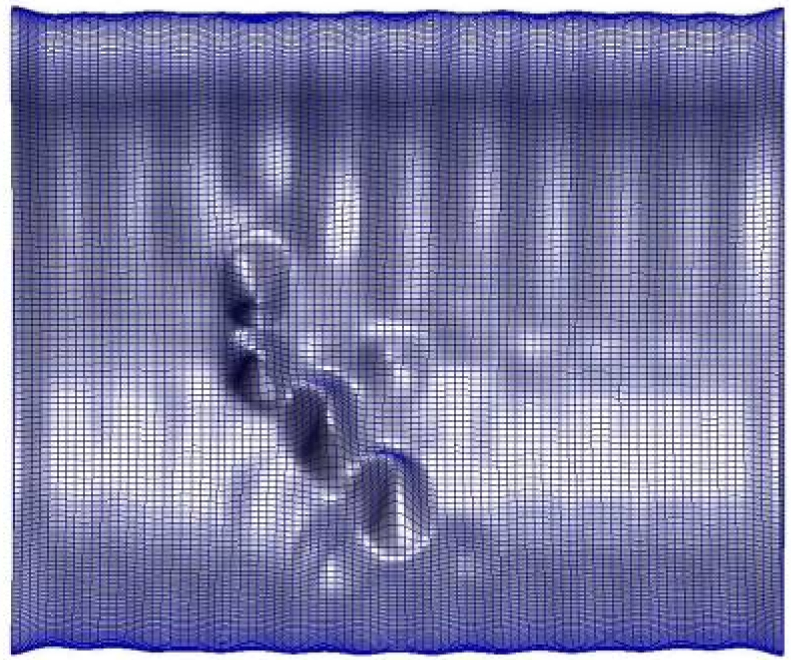
02 Residual plasticity in plate



02 Comparison of experiment and analysis

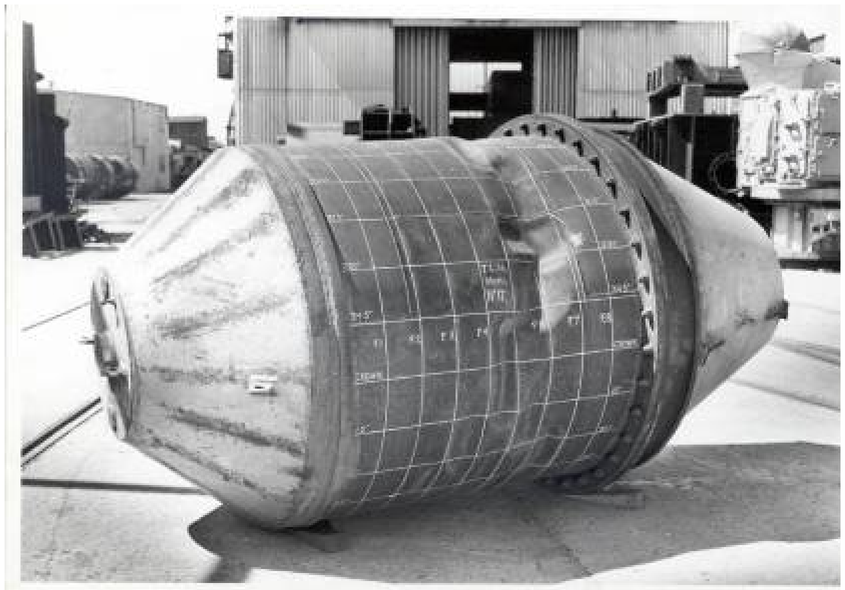
TG36 model 11

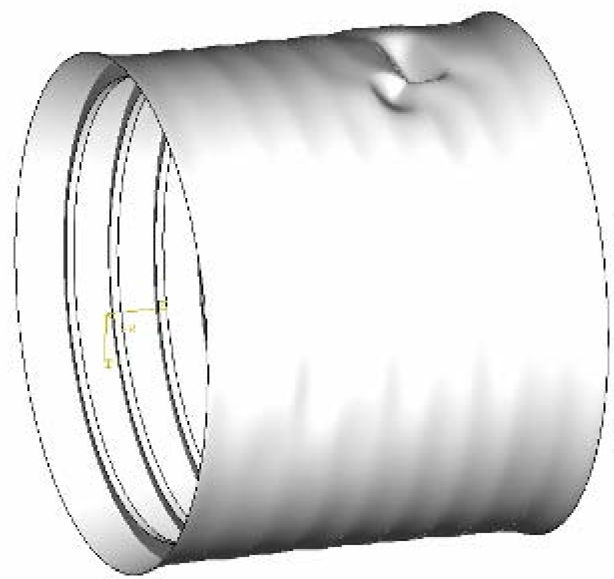




02 Comparison of experiment and analysis

TG36 model 17

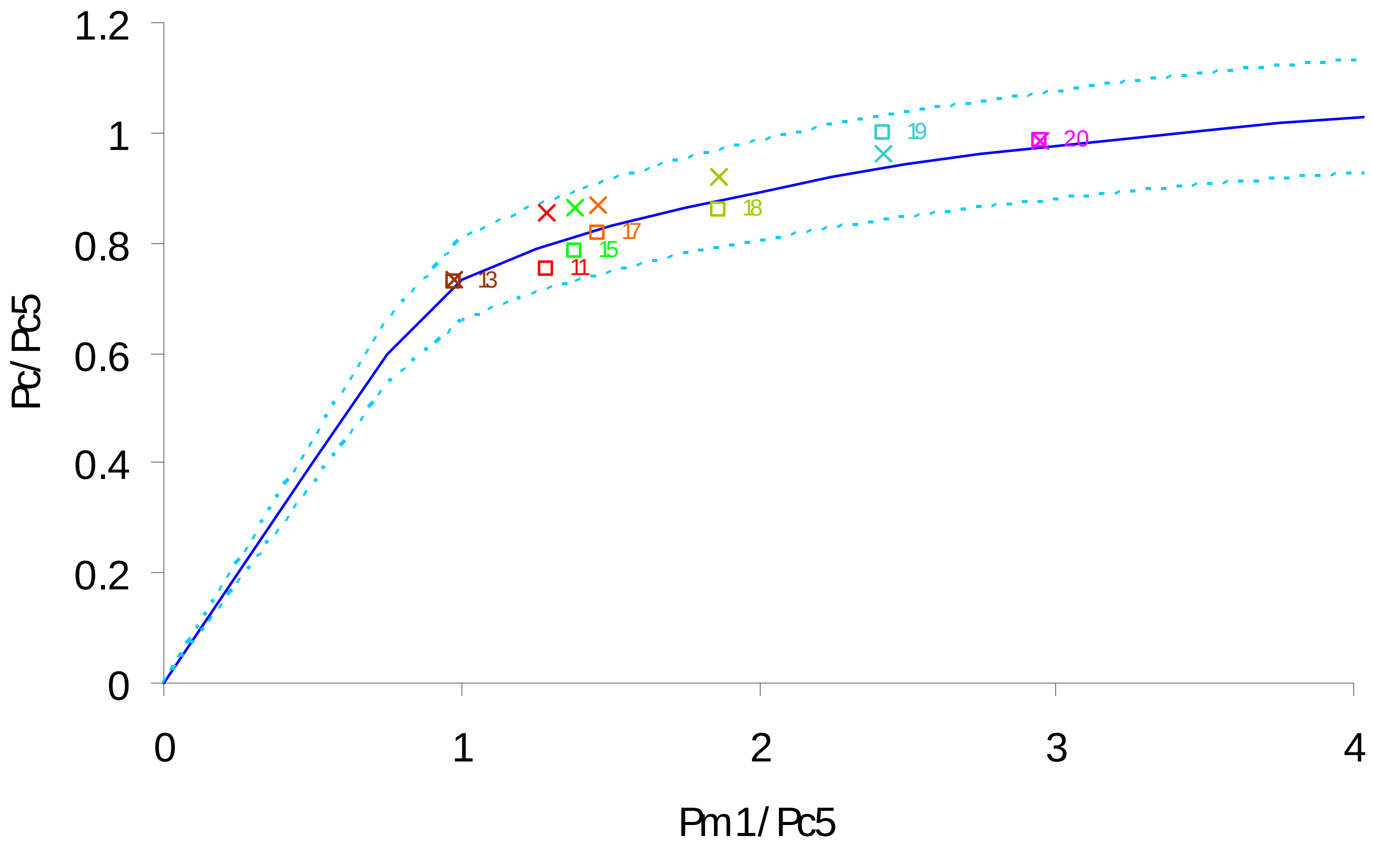




02 Results from short model tests

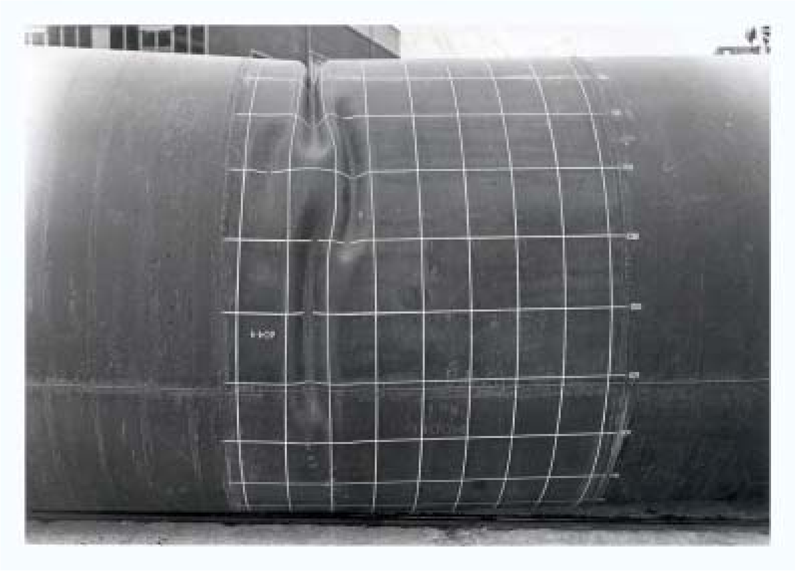
Model	Mode	P_{FE}/ P_{expt}
11	buckle	1.14 (1.006)
13	buckle	1.002
15	yield	1.098 (1.059)
17	buckle	1.062 (1.019)
18	yield	1.074 (1.054)
19	yield	0.963 (0.920)
20	overall	0.999

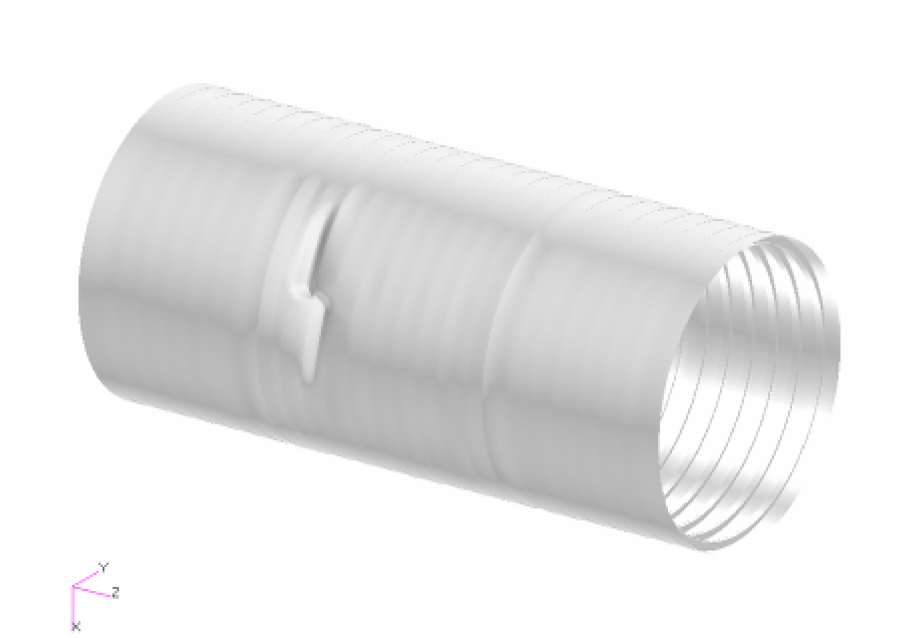
02 TG36 models



02 Comparison of experiment and analysis

25 frame model 1



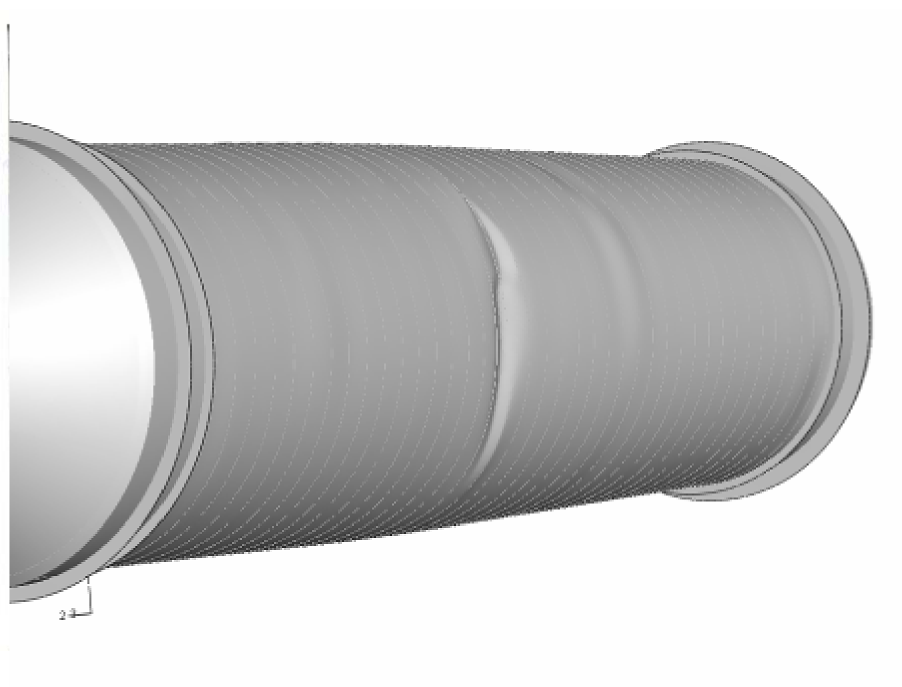


02 Comparison of experiment and analysis

36 frame model

02 Comparison of experiment and analysis

40 frame model



02 Results from long model tests

Model	Mode	P_{FE}/P_{expt}
25 frame	IF	1.017
25 frame	IA	1.059
28 frame	IF	1.015
29 frame	IF	1.052
36 frame	OA n=3	1.051
40 frame	OA n=2	1.087 (1.042)

IF = interframe

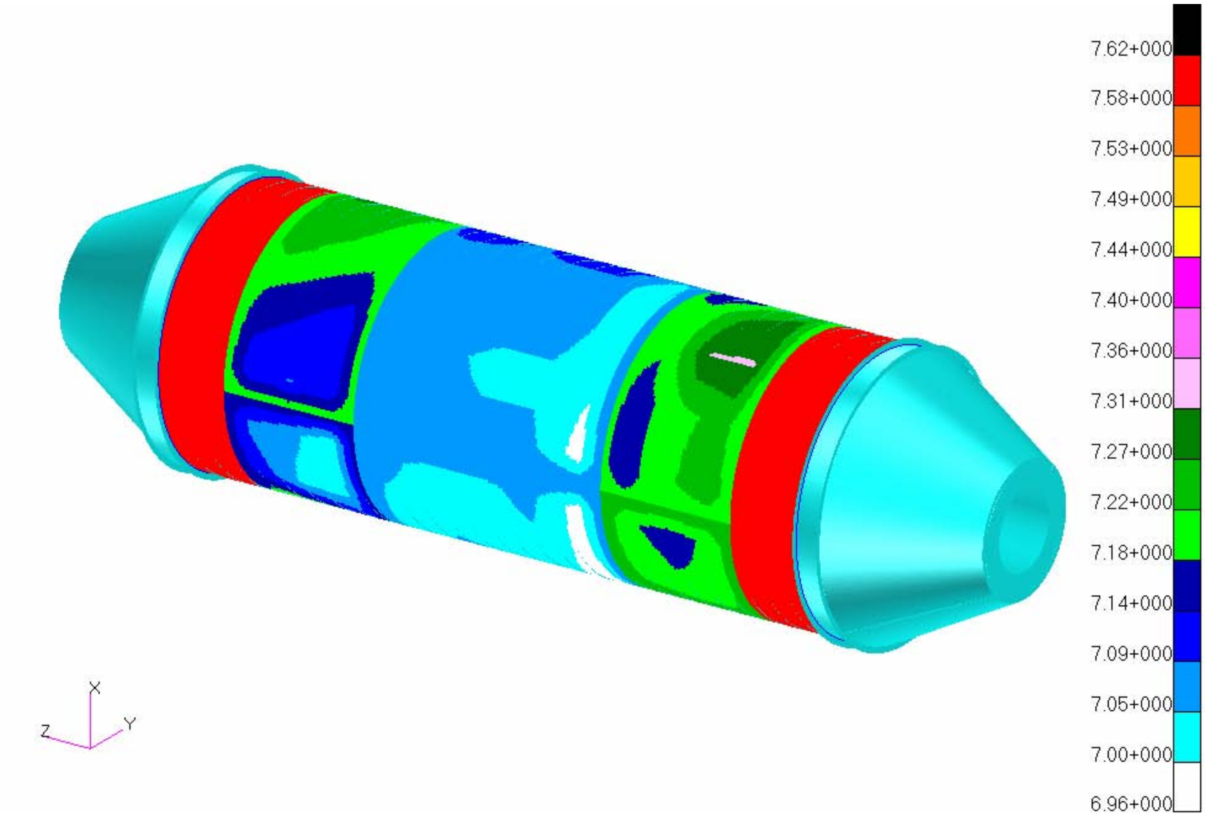
IA = interactive

OA = overall

03
Additional Model

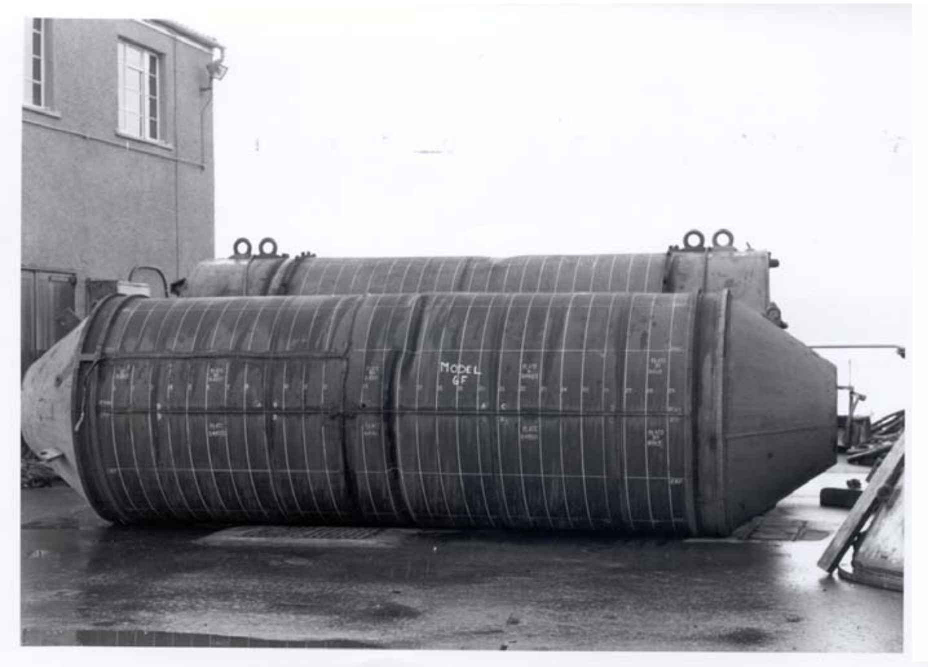
03 29 frame model

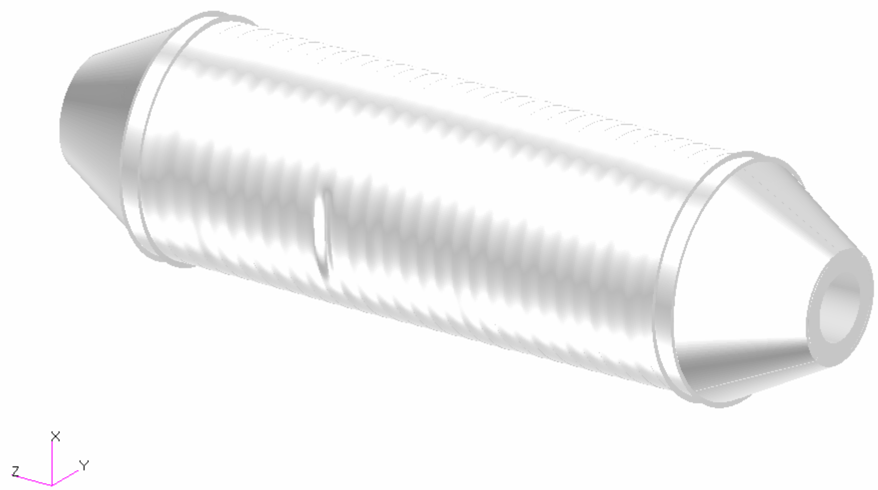
Contour plot showing measured thicknesses.



03 29 frame model, P_c/P_{expt} = 1.052

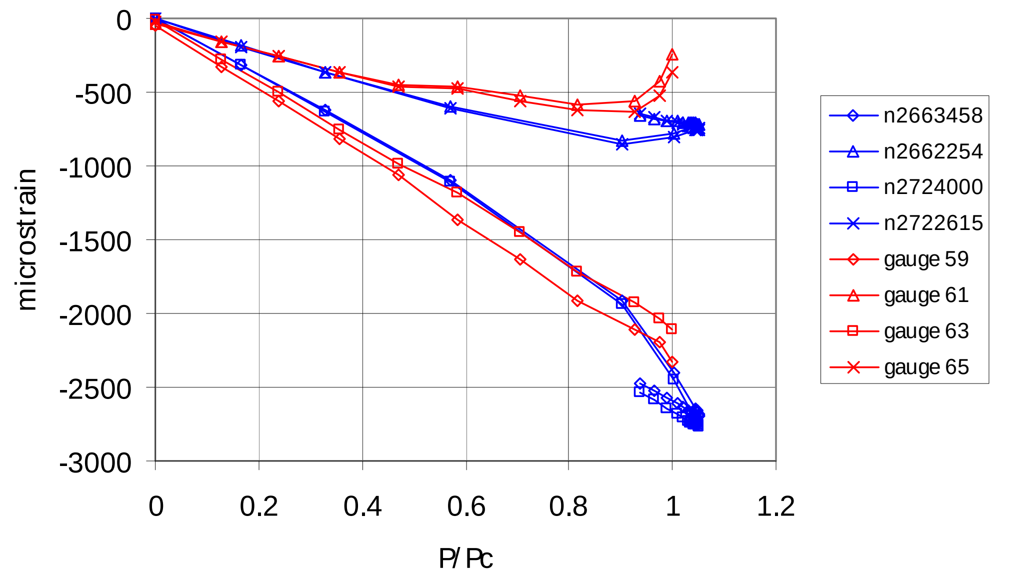
Predicted collapse location did not correlate with observation.





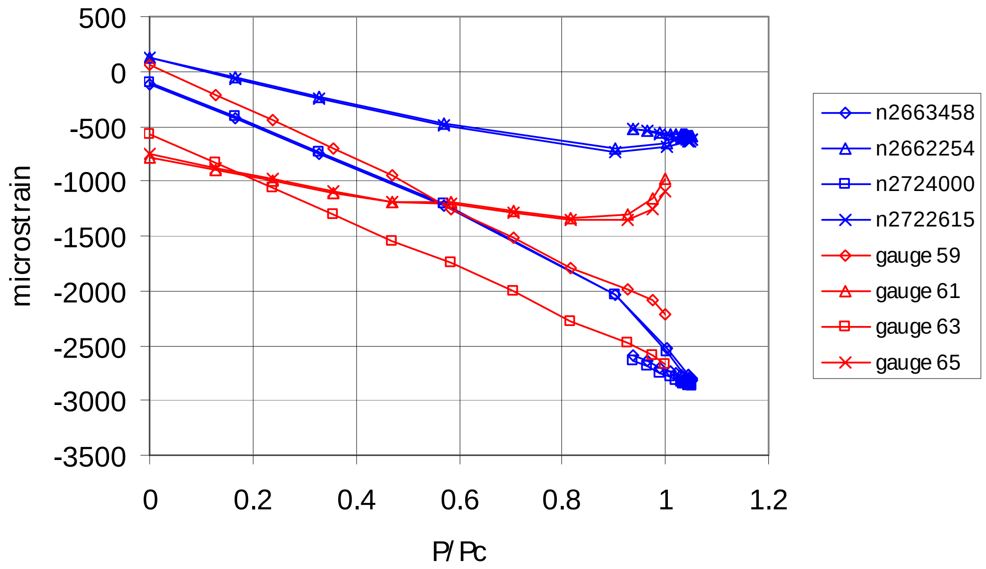
03 29 frame model

Comparison of measured and predicted strains from collapse run (initially zeroed).



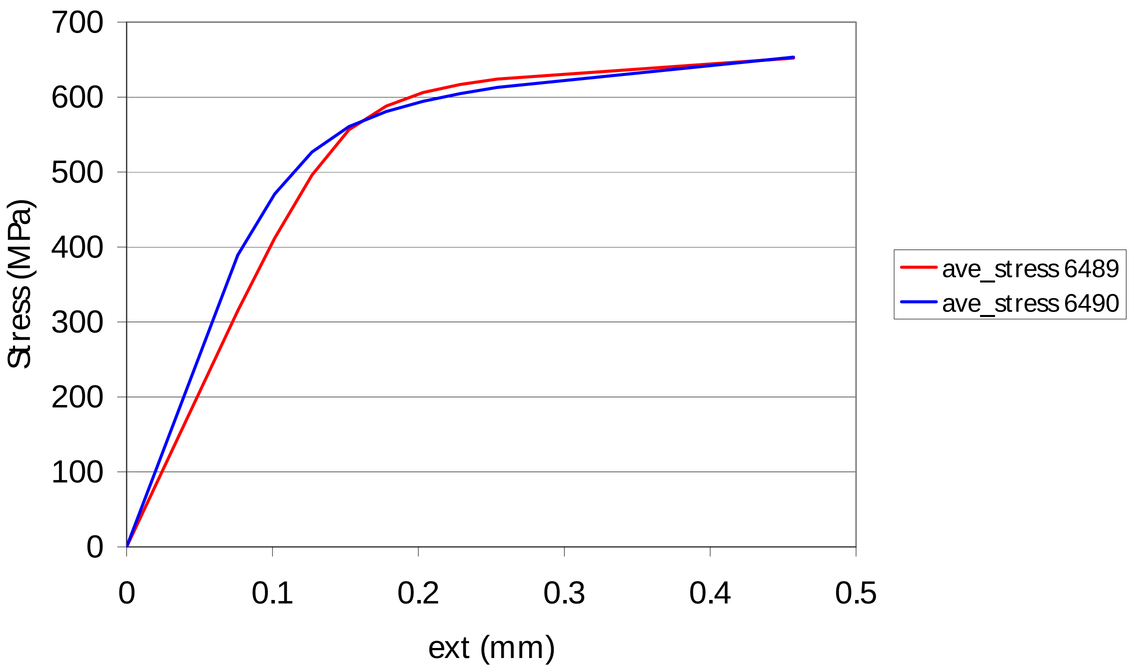
03 29 frame model

Comparison of measured and predicted strains from collapse run showing initial plastic strain developed in a previous aborted collapse run.



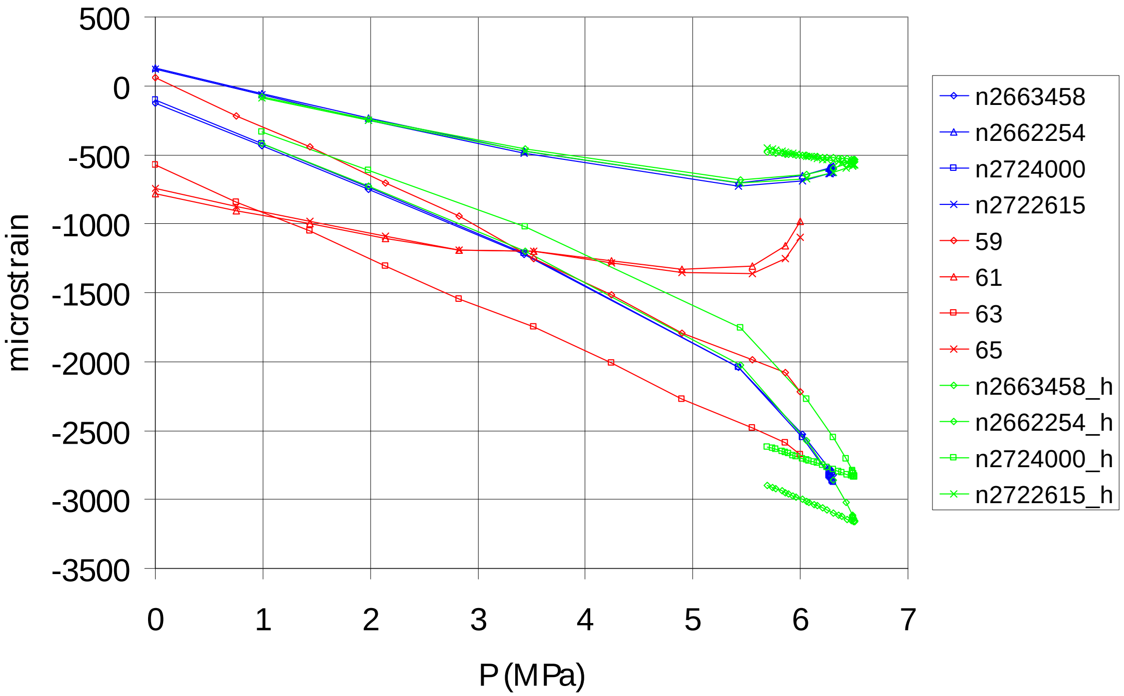
03 29 frame model

Initial slope equates to Young's moduli of 210 GPa and 260 GPa respectively



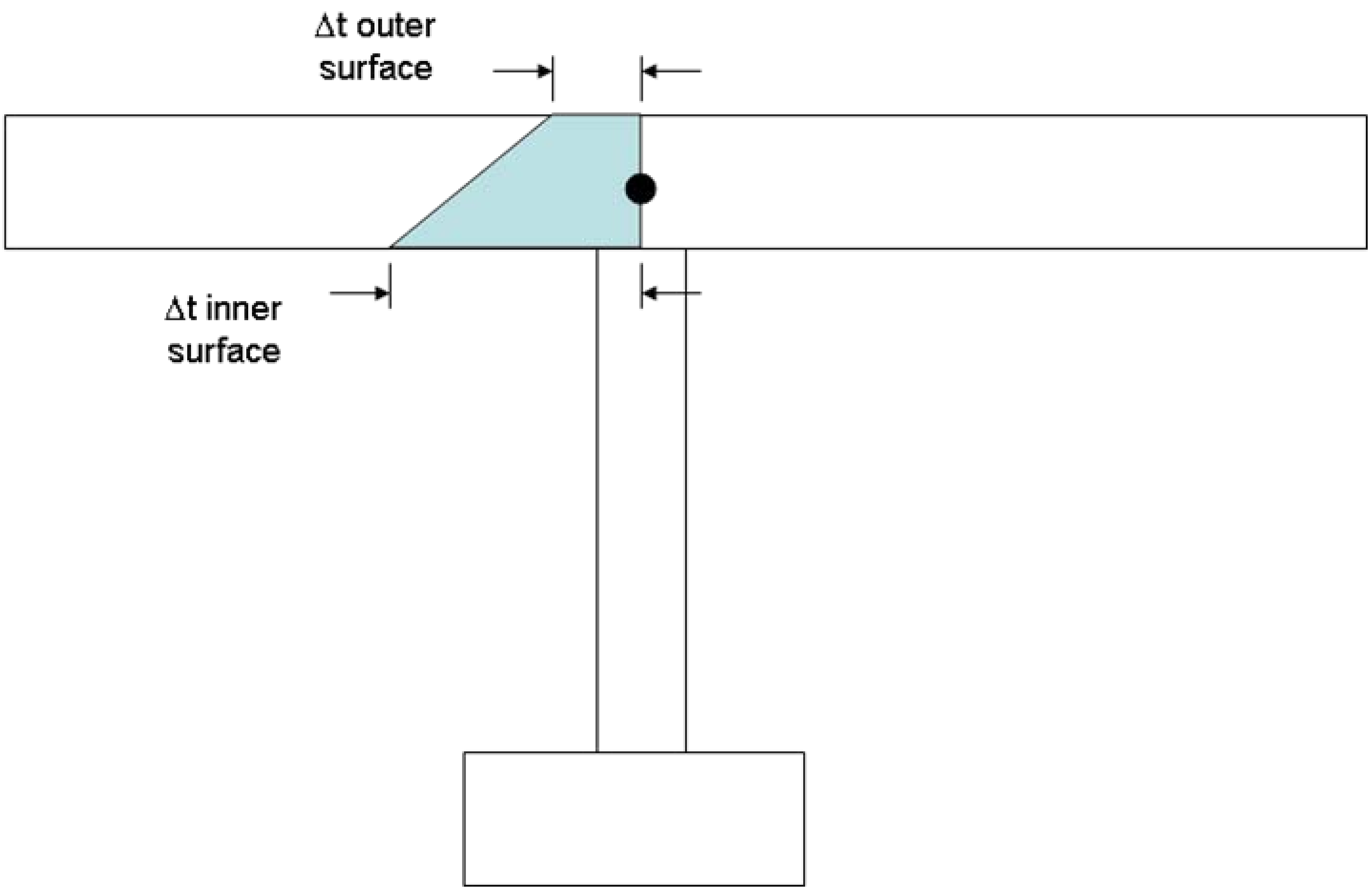
03 29 frame model, P_c/P_{expt} = 1.085

Analyses used a combined hardening model and accounted for residual stress, plastic strain, and hardening in plating and frame tables.

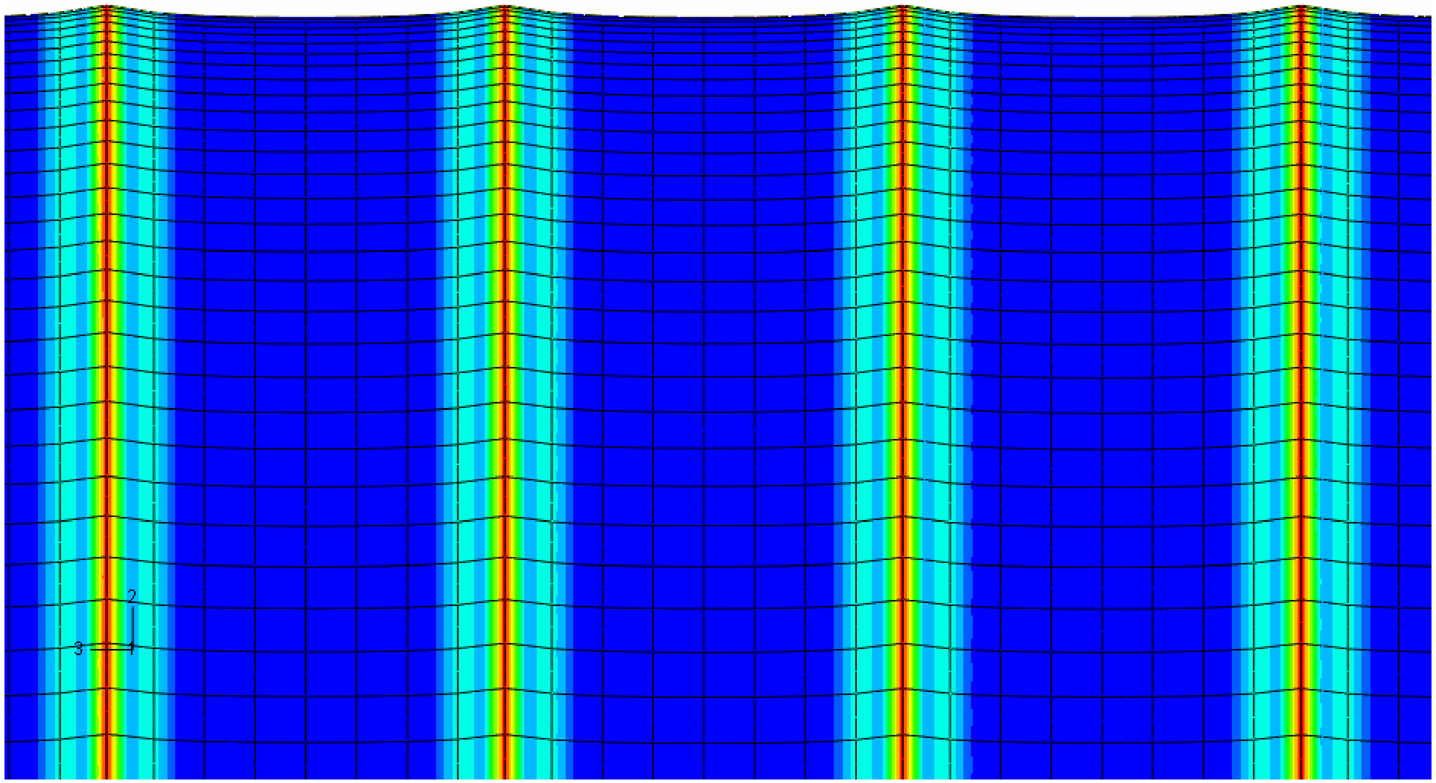


04
Welding Residual Stresses

04 Welding residual stresses



04 Welding residual stresses



04 Relative interframe collapse pressures

Case	Relative Pc	Relative decrease
Reference	1.0	-
With welding residual stresses	0.989	-1.15%
With equivalent interframe imperfection	0.999	~ -0.1%

Conclusions

- A validation exercise demonstrated that a partial safety factor of 1.06 could be used for FE prediction of pressure hull collapse.
  - If a procedure was followed.
- A subsequent model confirmed the PSF when the procedure was followed, but more accurate modelling of the material behaviour led to poorer agreement (PSF = 1.085)
- A ‘numerical experiment’ showed that the effect of residual stresses caused by welding the frames to the hull could be significant, i.e. more that just the effect of shape imperfections.

Outstanding issues

- Further work on modelling of material behaviour.
  - Rapid progress of commercially available codes.
- Modelling the residual effects of manufacture/fabrication.
  - Anisotropic material properties.
- Where do the remaining errors lie:
  - FE method itself?
  - Gaps in the physical data, e.g. plate thickness measurements?
  - As yet unmodelled effects?

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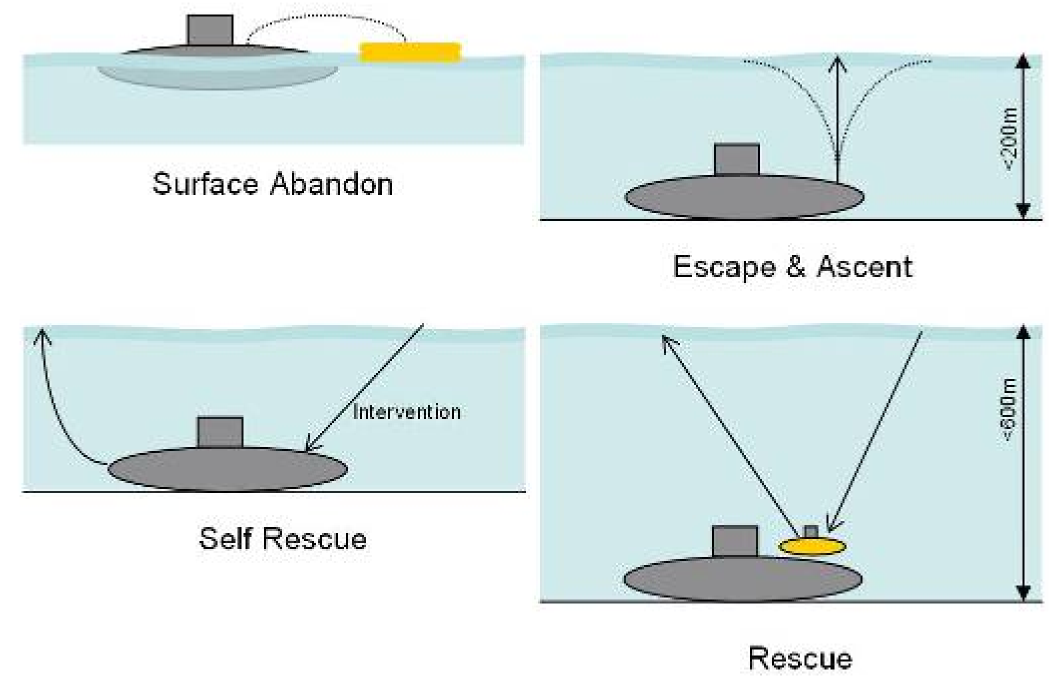
RN Submarine Escape, Rescue and Surface Abandonment System (SMERAS) requirements

PK Carnie, JW Taylor and AR Dent - QinetiQ Maritime Platforms

Cdr M Adams, RN and Cdr S Birchall, RN - Ministry of Defence

A presentation to: RINA Warship 08

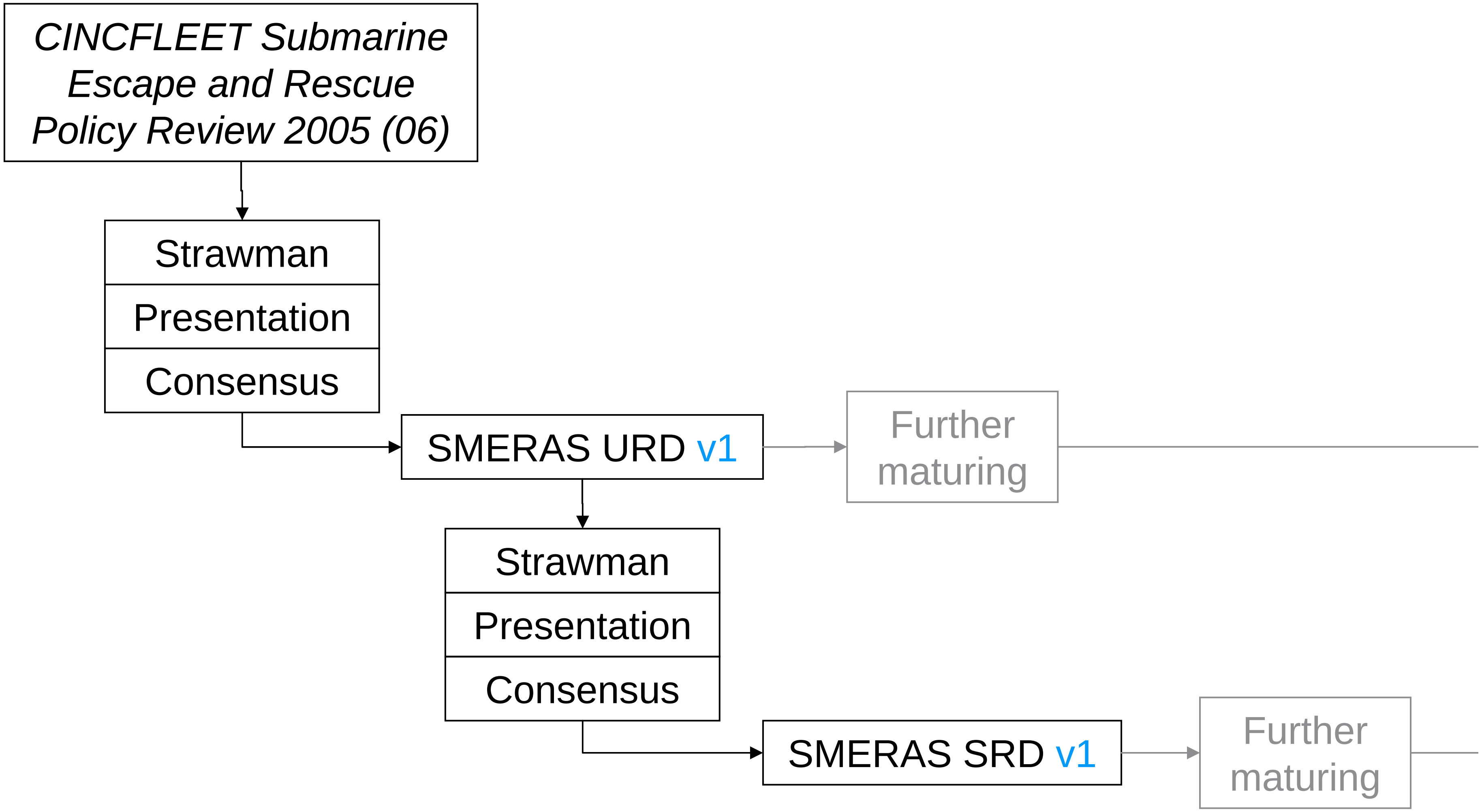
June 2008



Based on SMERAS URD Draft 2007

Agenda

01 Introduction



02 UK MoD use of Requirements engineering

Acquisition Governance	**Requirements Engineering**
Project Initiation	Outline URD with candidate KURs
Initial gate	URD with candidate KURs
Main gate	URD, SRD, KURs
Contract let	Contract
Assurance of military Capability	*Capability Assessment of in-service equipment and training provides assurance or identifies "capability gaps" in advance of, and beyond, the acquisition process*

02 Approach to defining SMERAS requirements

- Stakeholder community engagement and review of existing documents
- Define strawman proposal
- Review for inconsistencies, inadequate definition
- Stakeholder Reviews to iron out inconsistencies
- Deliver requirements document to support governance changes

- URD – October - December 2006
- SRD – December 2007 – May 2008

Strawman

Vision

Workshops

02 Unified Customer concept and Key stakeholders

- Sponsor - EC UWE BA/AS
- DE&S - DES SM IS ER and DES SM IS DASS
- User - FLEET-FOST, FLEET-CAP and Institute of Naval Medicine
- SIT – EC UWE Sc1
- Centre – RPNavy represented by EC UWE

- Note the diversity

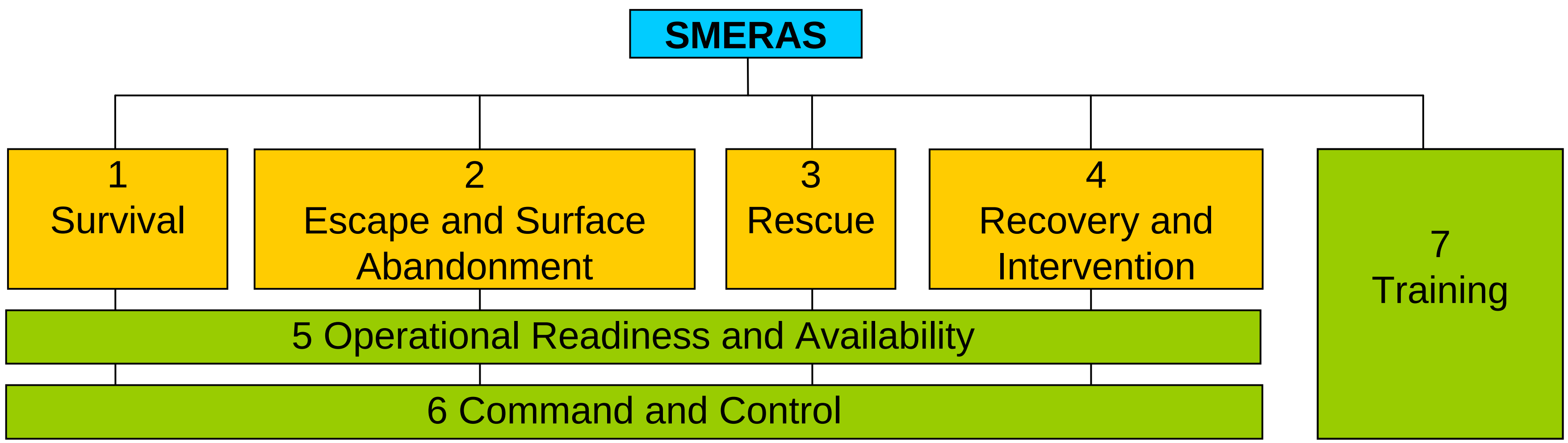
03 Rationale for SMERAS

- Diplomatic and military policy framework - encompasses Military Tasks, Defence Guidance, Strategic Assumptions, etc
- Secretary of State for Defence - Policy Statement on Health and Safety
- Navy Board policy

- For DISSUB or SASUB scenarios

04 User Requirements

"The user shall be able to maximise the survivors from a submarine that has sunk or that must be abandoned on the surface, whenever and wherever a Royal Navy submarine is operating."

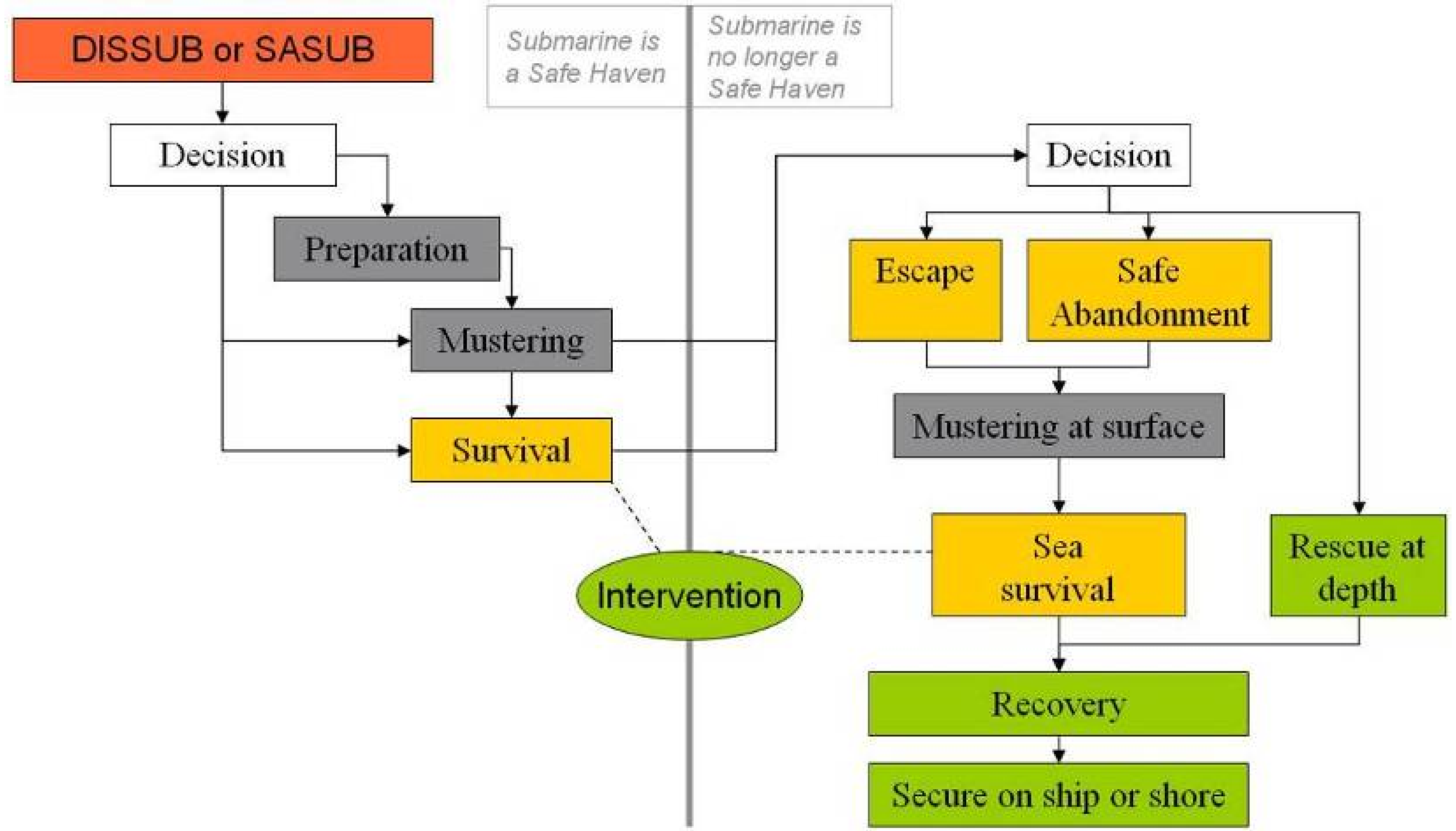


04 User Requirements

Priority	Definition	Trade-off Guidance & level
Key	Requirement is essential to mitigate an intolerable submarine personnel risk (for example to fulfil duty of care, equivalence with commercial safety legislation, or comply with international agreements on SMERAS)	Requirement MUST be implemented for the system to succeed. Considered untradeable by the capability sponsor.
1	Requirement is important to mitigate a significant submarine personnel risk.	Requirement WILL be implemented for the system to succeed. Trading will require reference back to the DEC via Capability Planning Group and SMERAS Focus Group.
2	Requirement mitigates a submarine personnel risk.	Requirement SHOULD be implemented for the system to succeed. Trading will require reference back to the CPG and SMERAS FG.
3	Requirement is useful to mitigate ALARP submarine personnel risks.	Requirement MAY be implemented for the system to succeed. Trading can be decided by the SMERAS FG.

ID	Descriptor	User Requirement
1	Survival	The user will be able to maximise the number of lives saved from those surviving the initial accident, without the provision of external support, until recovered to place of safety
1.1	Survival Capability - Subsurface	The user will be able to effect the survival of DISSUB personnel (with atmosphere, water, food) for 7 days (LB) following the initial accident without external assistance. (UB= 16 days)
1.2a	Survival Capability – following Surface Abandonment	The user will be able to effect the survival of personnel in the water at the surface for 5 days, following surface abandonment.
1.2b	Survival Capability – following Escape	The user will be able to effect the survival of personnel in the water at the surface for 24hrs (LB) following escape, with a UB of 5 days.
2	Escape and Surface Abandonment	The user will be able to affect the escape of all able personnel (LB) [all personnel (UB)] from a DISSUB without external assistance, from depths of 0 -200 metres (LB) [up to a maximum depth of 600m (UB)].
3	Rescue	The user shall be able to effect the Rescue of all able DISSUB personnel (LB), using devices external to the incident submarine, with a UB of all personnel.
4	Recovery	The user will be able to recover DISSUB/SASUB survivors from the water to medical triage and to appropriate medical care, before safe haven is compromised.
5	Operational Readiness and Availability	The user will be able to react to a DISSUB/SASUB emergency on any occasion with sufficient readiness and speed of response. The SMERAS capability shall be designed to be continuously available.
6.1	Localise DISSUB/SASUB	The user will be able to localise the position of the DISSUB/SASUB. Within x minutes.

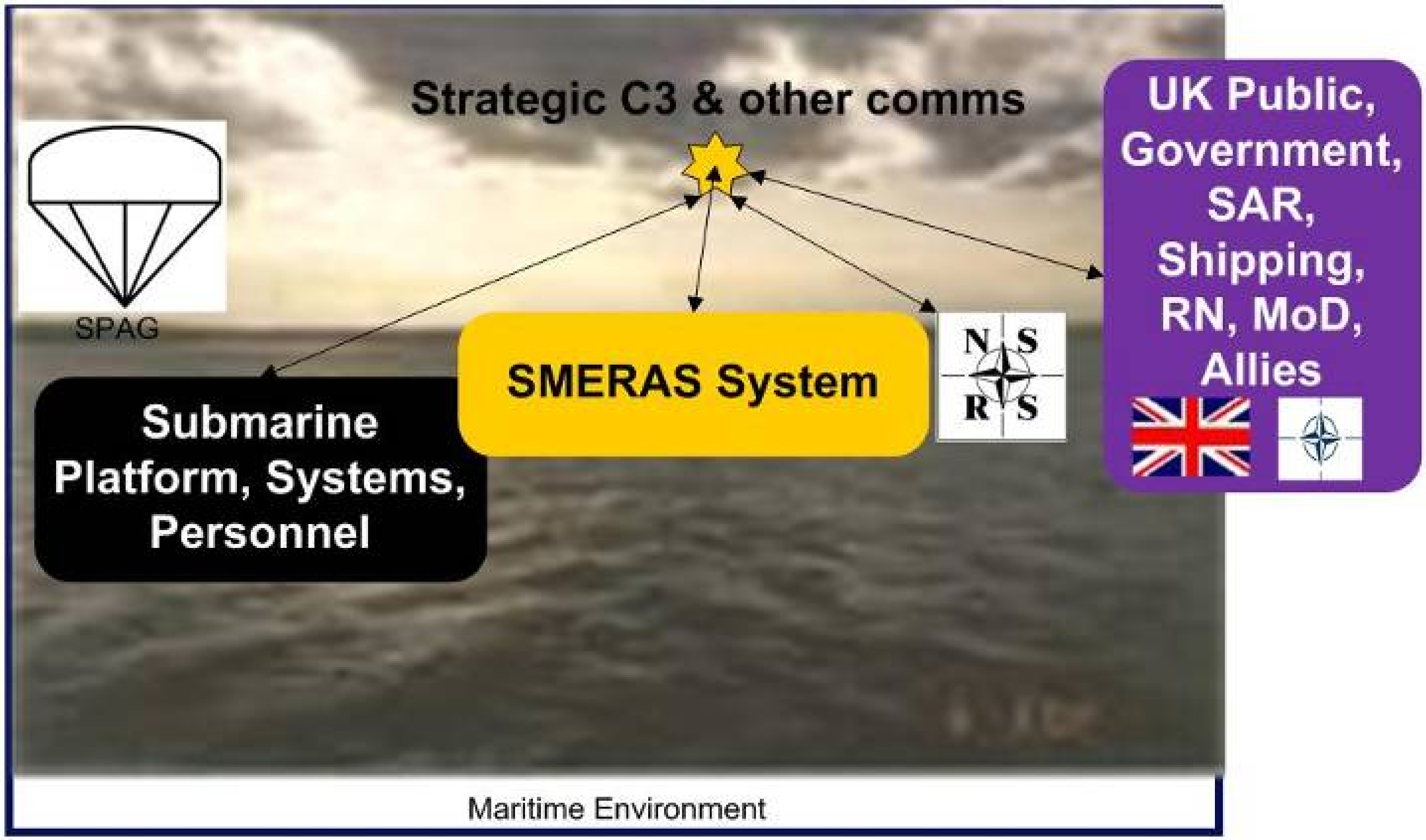
04 System and System Requirements



04 System and System Requirements

Trafalgar, Swiftsure, Vanguard, Astute & future RN submarines	Political and public perception and morals	International Naval and Civilian Search and Rescue systems
Submarine crew, their physiology, training and culture	**SMERAS system** including SPAG, NSRS	RN and MoD communication systems Fleet Incident Response Cell
Maritime environment (surface and sub-surface)		Shipping in area
Submarine Operation, Damage Control, Nuclear Safety and other RN Submarine systems	Other Submarine safety systems including NARO	MoD Acquisition systems and policies (eg safety mgt, standards)

04 System and System Requirements



ID	System Requirement or Constraint description
1	The system shall supply sufficient information and guidance for Command to recognise whether there is a need for survival, escape and or abandonment, the extent, and the timescale.
1.3	The system shall clearly communicate the escape and abandonment orders (including routes) to all on board.
2	The system shall support preparation to escape and abandon the submarine.
2.1	The system shall clearly alert the escape and abandonment decisions and geolocation to external authorities.
3	The system shall enable the survival of DISSUB personnel.
3.1	The system shall ensure that breathable Atmosphere is available to all DISSUB survivors
3.1.1	The system shall be able to monitor the DISSUB atmosphere
3.1.2	The system shall replenish oxygen in the DISSUB atmosphere to support survivors for 7 days (min) 16 days (max)
3.1.3	The system shall remove carbon dioxide (CO2) from the DISSUB atmosphere to a level not to threaten Survivors for 7 days (min) 16 days (max),
3.2.1	The system shall monitor DISSUB absolute pressure
3.3.1	The system shall ensure survivors have on board sufficient hydration for 7 days (min), 16 days (max)
3.3.2	The system shall ensure survivors have on board sufficient nutrition for 7 days (min), 16 days (max)

ID	System Requirement or Constraint description
3.4	The system shall enable survivors to monitor radiation levels and take appropriate action
4	The system shall support abandonment from the submarine casing either immediately or as directed by Command, to the temporary safe haven.
4.1	The system shall support egress from the submarine
5	The system shall enable the escape of survivors from the DISSUB without external assistance.
5.2	The system , where pressurised escape is used, shall minimise barotrauma and DCI
5.4	The system shall enable all survivors to escape within 8 hours (min) 4 hours (max), once the decision has been made to escape.
6	The system shall include a temporary safe haven on the surface to protect survivors that have escaped or abandoned without the provision of external support.
7	The system shall be continuously available to react to a DISSUB or SASUB emergency with sufficient readiness and speed of response.
8	The system shall be capable of operating in a world-wide environment.
9	The system shall ensure all personnel on board have knowledge of Escape, survival and Surface Abandonment procedures and equipment according to their status.
10	The system shall be as safe as reasonably practical.
11	The system shall enable mating of STANAG 1297 Rescue Systems with the platform

05 Benefits for Governance

- The URD and SRD will enable MoD to
  - Demonstrate compliance with MoD high level policy responsibilities;
  - Coherently manage capability, acquisition and support;
  - Affirm a formal requirement for new and ongoing SMERAS acquisition;
  - Negotiate equipment supply with platform IPTs;
  - Undertake Cost-Benefit / ALARP analysis where required;
  - Develop contractual requirements for SMERAS equipment supply; and
  - Inform and guide relevant research.
- See examples

06 Conclusions

- All key stakeholder groups took part
- Good agreement across stakeholders
- Consultation relatively short
- Stakeholders were given sufficient warning of timescales and most took part
- Background material supported timescale
- URD & SRD align with MoD guidelines

- Process is not complex but requires a focussed effort
- SMERAS capability continues to evolve to support governance
- May be applicable to other navies – but test rationale and stakeholder needs

Thank you … Any questions?

- Contact
  - Patrick Carnie
  - +44 1383 435246
  - +44 7917 577124
  - pkcarnie@qinetiq.com
  - www.qinetiq.com

QinetiQ

The Global Defence and Security Experts

“Where will our knowledge take you?”

Warship 2008

Submarine Escape and Rescue Operations – The Holistic Approach to Safety

Loren Roberts and John Turner,
BMT Isis Ltd

Glasgow, 11 June 2008

Scope of Presentation

- Introduction
- Submarine Rescue Systems
- A ‘Safe’ System
- Safety Regimes Applicable to a SRS
- The Risk Based Approach
- The Safety Case
- Claims-Argument-Evidence
- Conclusions

Introduction

- Submarine Escape and Rescue
- Types of Rescue System

Types of Rescue System

NSRS

RAN SERS

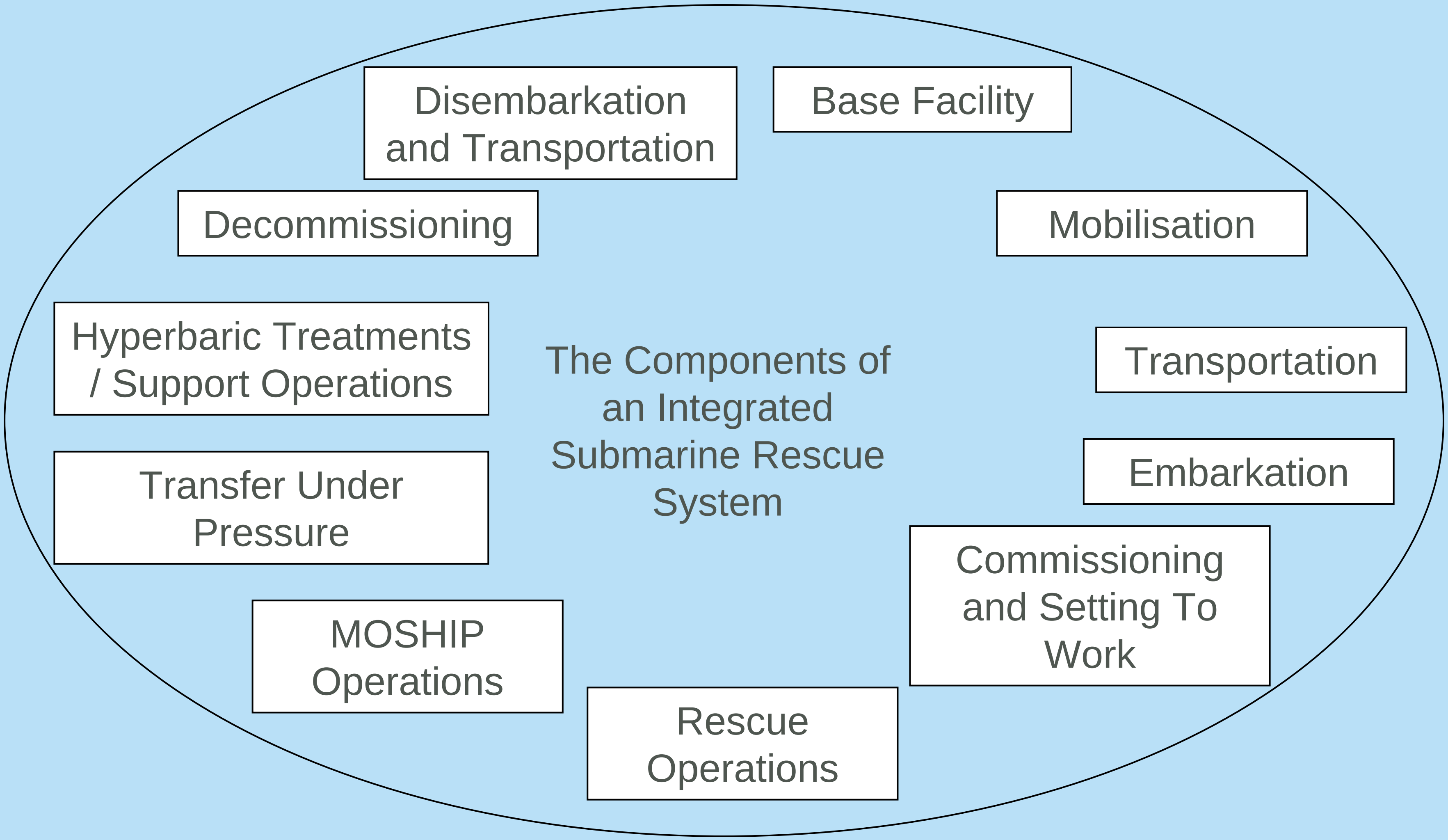
LR5

BMT Isis

Introduction

- Submarine Escape and Rescue
- Types of Rescue System
- Scope of the paper

Submarine Rescue Systems



A ‘Safe’ System

“A ‘safe’ system is a system that has an associated level of assessed safety risk that is acceptable to the stakeholder community.”

BMT Isis

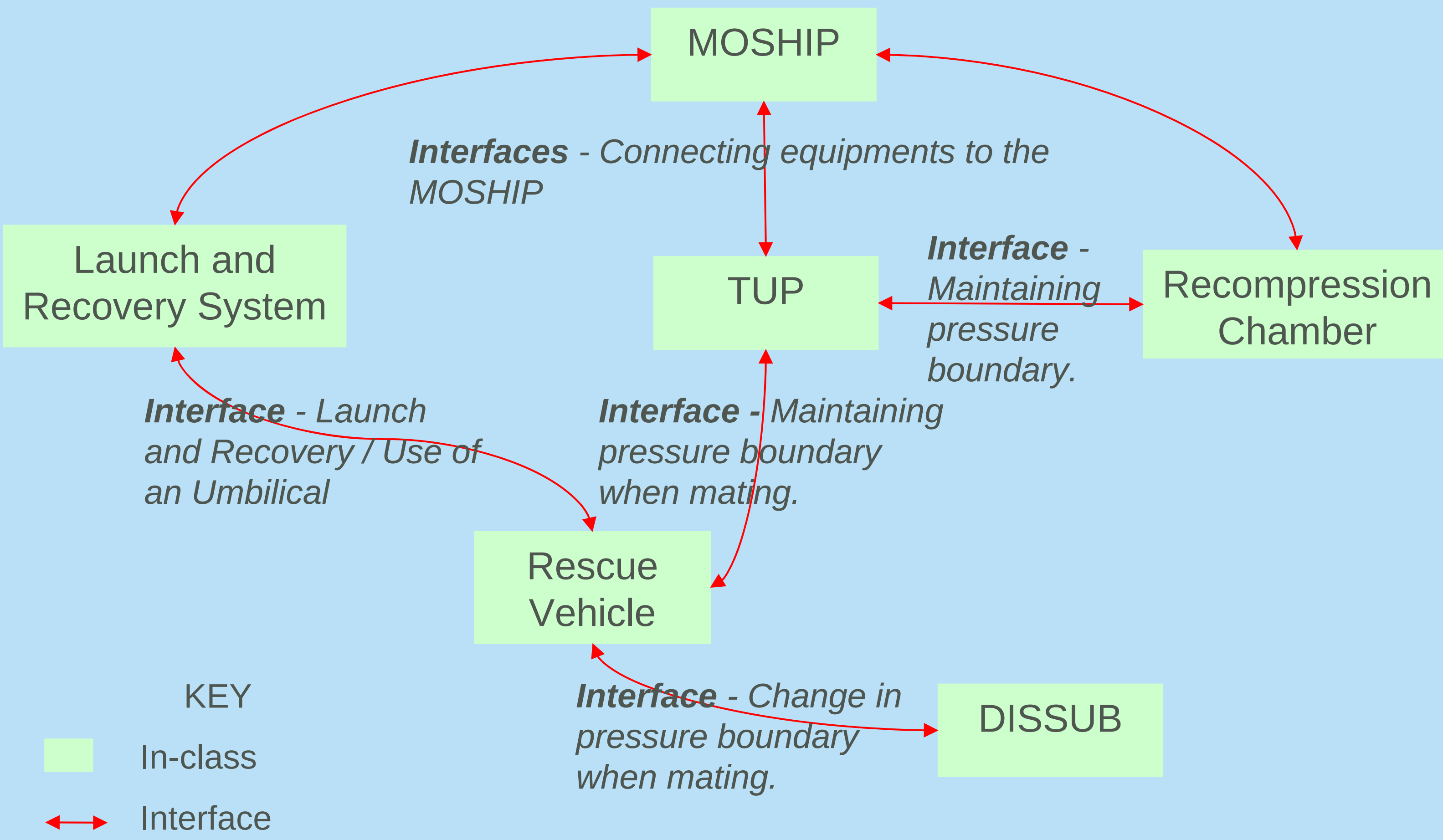
A Safe System

- **Why do we need a safe system?**
- **How can we achieve a safe SRS?**
  - Benefits of equipment “in-class”,
  - National or international legislation,
  - The risks associated with the interfaces between the SRS equipments.

Safety Regimes Applicable to A SRS

- Classification Society Rules
- UK MoD Key Hazard Areas
- International Standards
- A Risk Based Approach Within the Classification process

Interfaces that require a Risk Based Approach



BMT Isis

The Risk Based Approach

"The Risk Based Approach identifies Safety targets based on tolerability, acceptability and performance criteria specific to the system."

The Risk Based Approach

- **Hazard identification**
- **Risk Assessment and Analysis**
- **Hierarchy of Risk Reduction Techniques**
  - Eliminate the hazard;
  - Reduce the risk by implementing an engineered mitigation strategy;
  - Reduce the risk by implementing a mitigation strategy based on human factors.

The Risk Based Approach

- **“Existing” Safeguards**
  - Known to be in place and evidence can be provided to confirm this.
- **“Intended” Safeguards**
  - Expected to be in place but there is currently no evidence to confirm this.
- **“Proposed” Safeguards**
  - These are considered to have a potential risk reduction effect if implemented.
- **Management of Hazards**

The Holistic Risk Based Approach

- Considers a ‘system of systems’
- Interfaces are identified, risk assessed and managed.
- Recognises the importance of equipments “in-class”.

The Safety Case

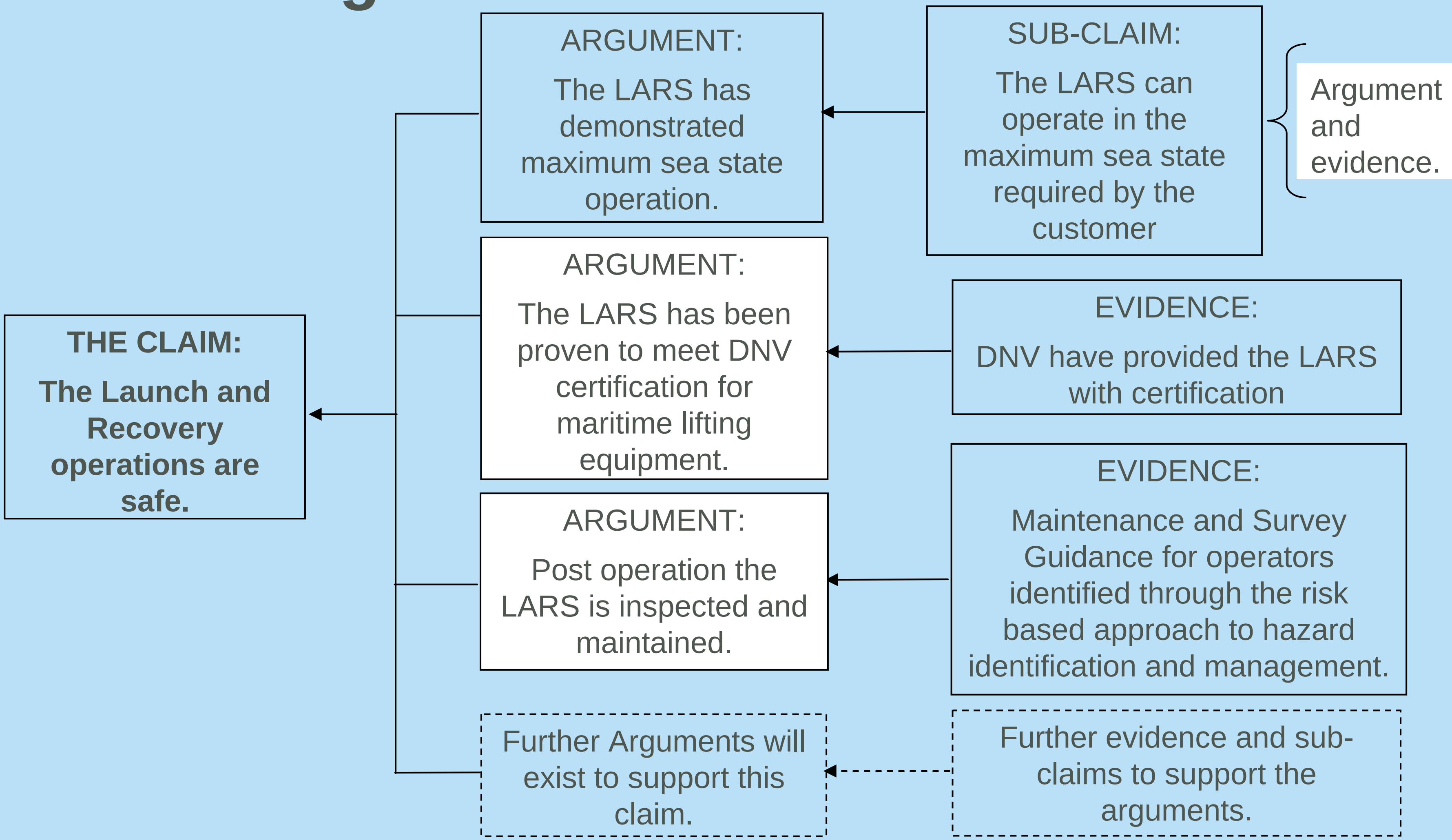
- **The Safety case is a body of evidence gathered together to support the claim that the system is adequately safe.**

- **Types of Safety Case Report**
  - The Preliminary Report
  - The Pre-construction Report
  - The Pre-operational Report
  - The Operational Report

Claims-Argument-Evidence

- **Justification Framework to Substantiate the Safety Claim.**
- **Classification Society rules can be used as evidence.**
- **The risk based approach provides evidence of the safety claim.**

Claims-Argument-Evidence



BMT Isis

Claims-Argument-Evidence

- Justification Framework to Substantiate the Safety Claim.
- Classification Society rules can be used as evidence.
- The risk based approach provides evidence of the safety claim.
- **The use of multiple arguments provides a comprehensive justification of the overall Safety Claim made for a system.**

Conclusions

- Key aspects required for a comprehensive and complete safety argument.
- Utilise a number of methods to provide evidence of the safety claim.
- Compliance with Classification Society Rules provides assurance for individual aspects of a SRS.
- National and International standards can also provide validation for safety claims.
- Utilisation of the Risk Based and Claims-Argument-Evidence approaches provide assurance of the complete system.

Thank you

Any Questions?

Loren Roberts and John Turner BMT Isis Ltd.

BMT Defence Services (Australia)

"Where will our knowledge take you?"

SUBMARINES, NAVAL ARCHITECTS & SYSTEMS ENGINEERING

G. MacDonald, BMT Defence Services, Australia.

Warship 2008
10 June 2008

AIM - Intent

Content xxxxx

AIM - Content

Defining What Systems Engineering is and is not

Exploring the Application of SE to a Submarine Program

Practical Example

Setting a Challenge for the Naval Architecture and Maritime Engineering Community

What is Systems Engineering

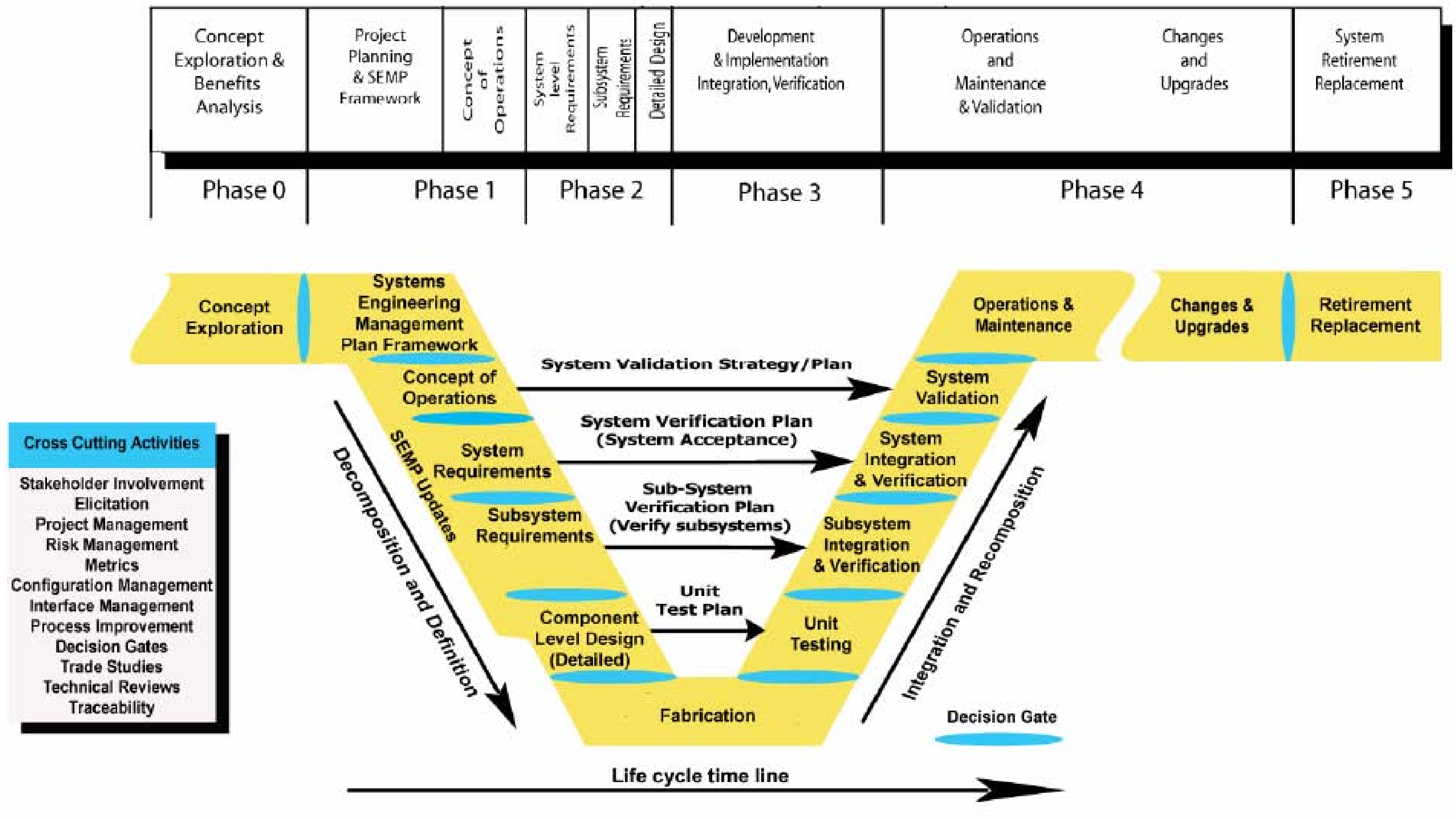
<u>HISTORY</u> - Systems Engineering dates back to Bell Telephone Laboratories in the early 1940s having been developed to manage the complexity of increasing nation wide telephone usage and the need for establishing exchanges and protocols to minimise the number of telephone lines required.

The US Department of Defense embracing the discipline in the late 1940s in support of the initial development of missiles and missile-defense systems.

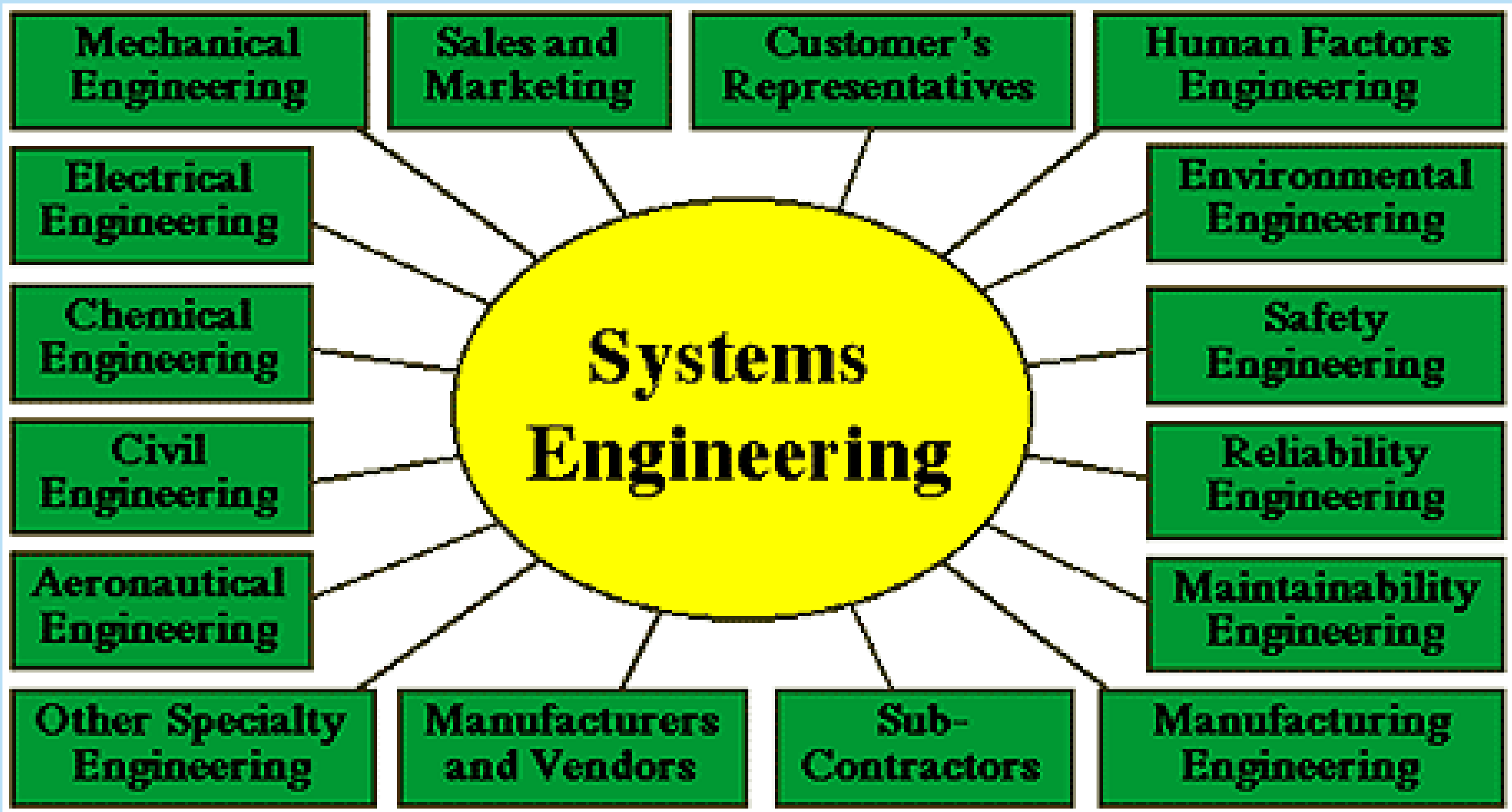
The Defence Departments desire to formalise the methods, develop new techniques and educate it's scientists and engineers led to the establishment of a training program at MIT to teach the subject in 1950.

<u>DEFINITION</u> - The discipline of Systems Engineering consists of a body of rigourous engineering process which can be applied to the most complex acquisition projects to achieve successful delivery and through life support. It is about the key creative processes that transform concepts into system designs, and the key technological and management processes that enable system development to proceed in an orderly, interdisciplinary fashion - maximising opportunities to meet client's needs while minimising risk.

What is Systems Engineering



What is Systems Engineering



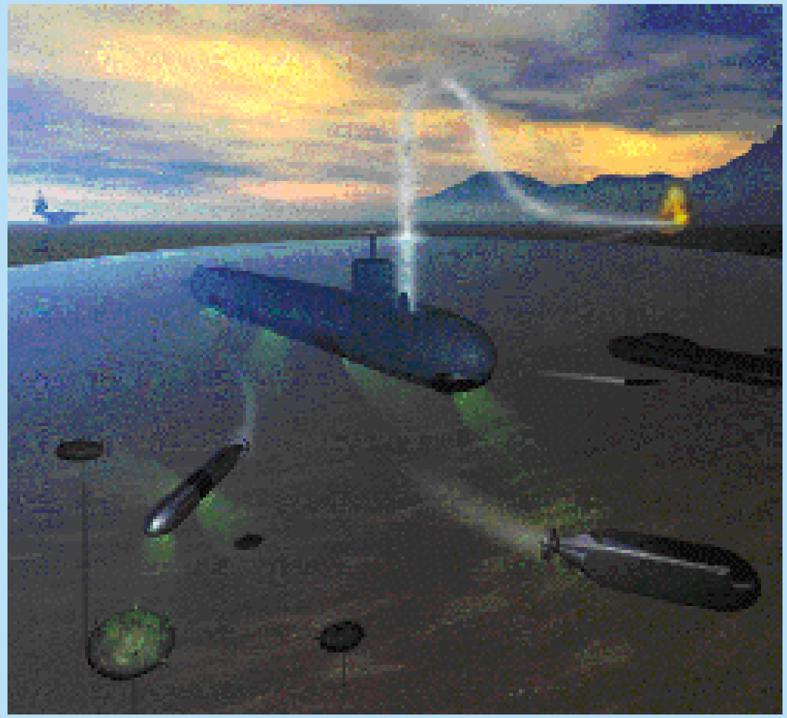
SYSTEMS ENGINEERING IS NOT -

- A Field of Engineering in the Traditional Sense (ie. Mechanical, Civil, Electrical etc)
- Project Management – Rather the Management of the application of Engineering

Application of SE to a Submarine Program

WHAT IS A SYSTEM

- A group of interrelated or interdependent elements which interacting with one another in an organized fashion forming a complex whole focused towards achieving a common purpose or goal.
- May consist of diverse elements such as personnel, equipment, software, infrastructure.



Application of SE to a Submarine Program

THE SUBMARINE SYSTEM – A CAPABILITY TO ACHIEVE MILITARY EFFECTS

- **Gain military advantage through the covert collection of intelligence;**
- **Achieve asymetric advantage through concentration of adversary forces on ASW activities tying up or slowing down enemy assets/actions through hunting for sub;**
- **Exert control/exclusion in a maritime area of operations**
- **Interdiction of maritime commercial trade**
- **Blockade foreign ports and restrict ocean transport eg mine laying**
- **Support special force activities through the covert deployment/extraction of forces in the littoral environment**
- **Exploit enemy defence vulnerability to land strike from covert platforms;**
- **Maritime strike of hostile submarines and surface ships;**

Application of SE to a Submarine Program

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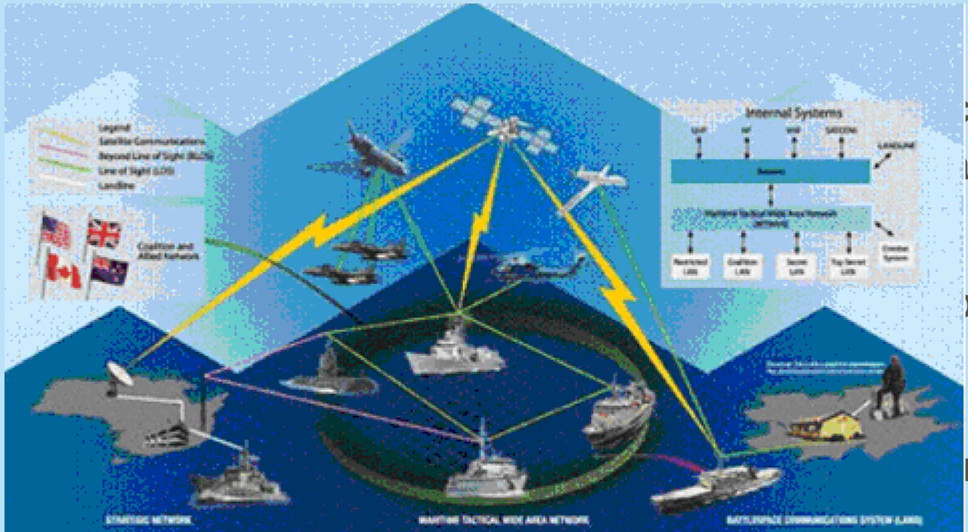

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Application of SE to a Submarine Program

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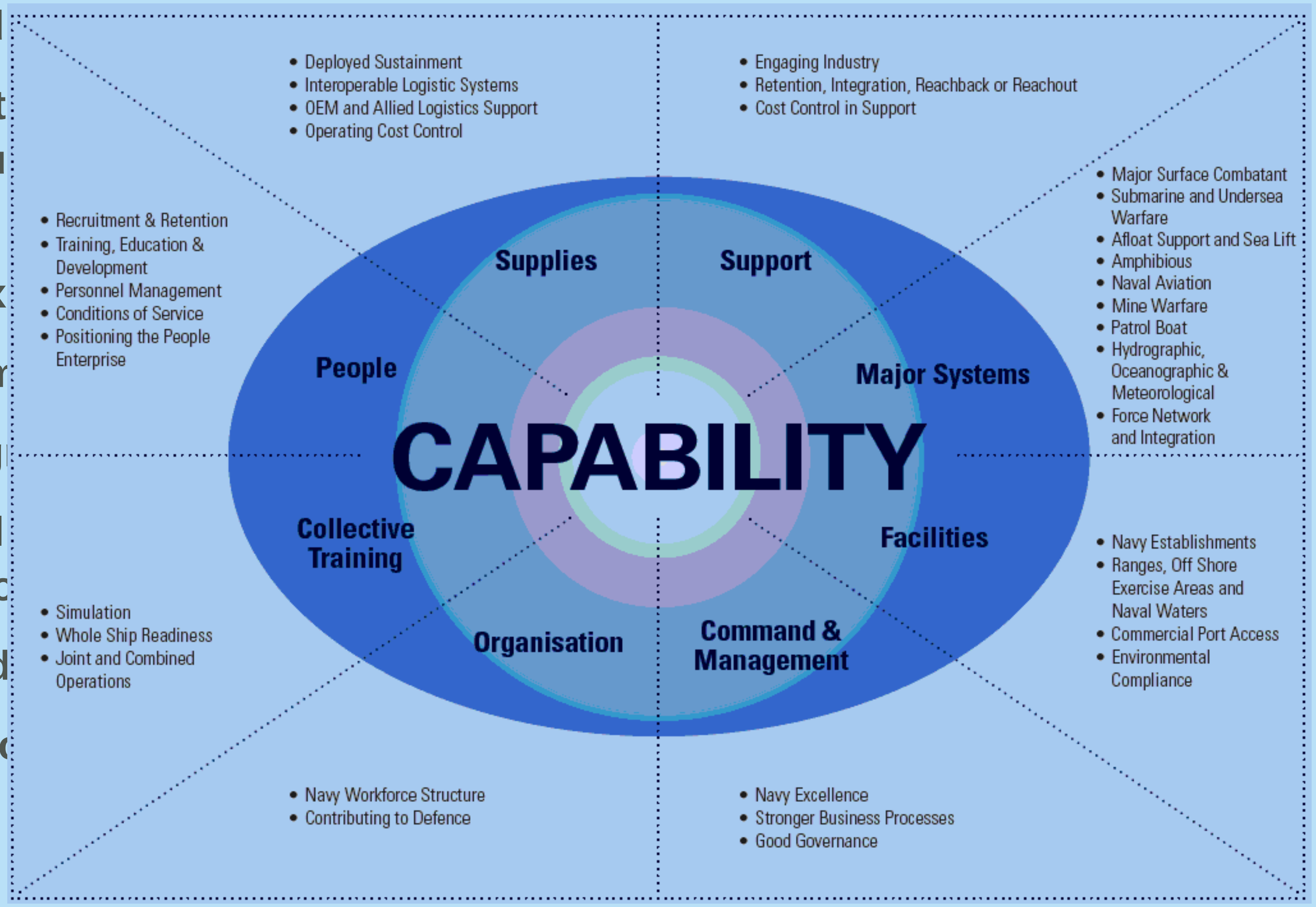

Application of SE to a Submarine Program

THE SUBMARINE SYSTEM

Submarines are arguably the most complex engineering systems produced by man and as such is a key candidate for embracing a methodology established for that role.

A succesful Submarine System is one that achieves the desired military capability through an integrated FIC framework in an “efficient and effective” manner while within the constraints of “best value for money”.

This is the ultimate performance measure for acceptance by the military staff.

The Systems Engineering Methodology provides the best means of capturing the overall requirement of this complex system and managing it through the life of the project to achieve success against this performance measure.

Application of SE to a Submarine Program

Contents

Application of SE to a Submarine Program

ContentsThe weapons, communications and combat system element of submarine design already implement the approach and hence in the interest of an integrated/ harmonised approach with a common approach and vernacular should improve efficiency.

Application of SE to a Submarine Program

TECHNICAL PERFORMANCE MANAGEMENT

Practical Example – Surface Warfare Strike Capability

CAPABILITY WBS

Practical Example – Surface Warfare Strike Capability

SYSTEM/SUB SPECIFICATION

SYSTEM REQUIREMENTS – Modes and States; Functional; Performance; Constraints (Safety Requirements, Design & Construction Constraints; Personnel Related Requirements; and System External/Internal Interface Requirements

MOE/MOP

REQUIREMENTS VERIFICATION

CONFIGURATION OPTIONS

OPTION TECHNICAL DESCRIPTION & ANALYSIS

OPTION EVALUATION

PROPOSED OPTION - Technical Description; Design Assumptions; Applicable Standards & Specifications; Equipment/Materials List; Design Calculations; ILS Products; Program Details – Cost & Schedule; Technical Risk Assesment; and Safety Assesment

Practical Example – Surface Warfare Strike Capability

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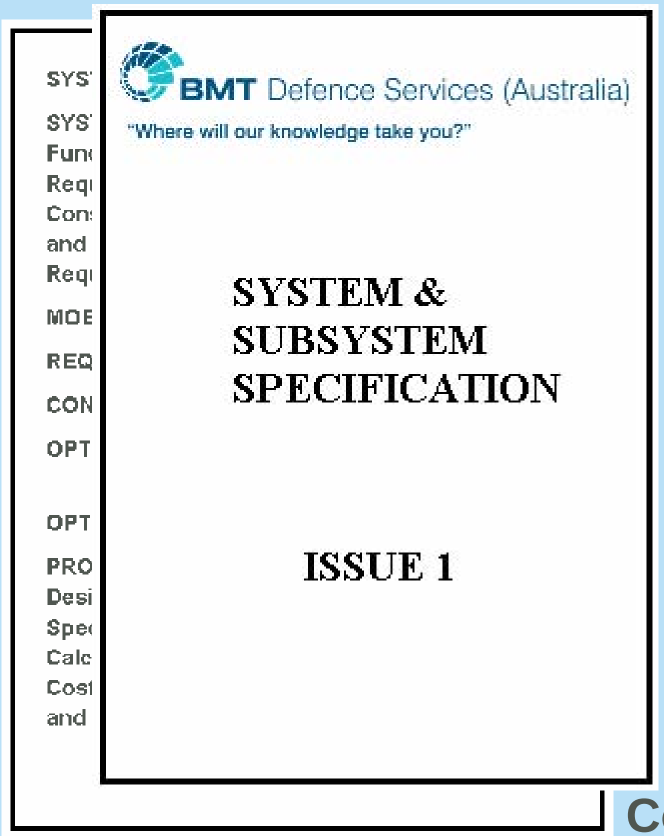
Concept Design

Practical Example – Surface Warfare Strike Capability


BMT Defence Services (Australia)

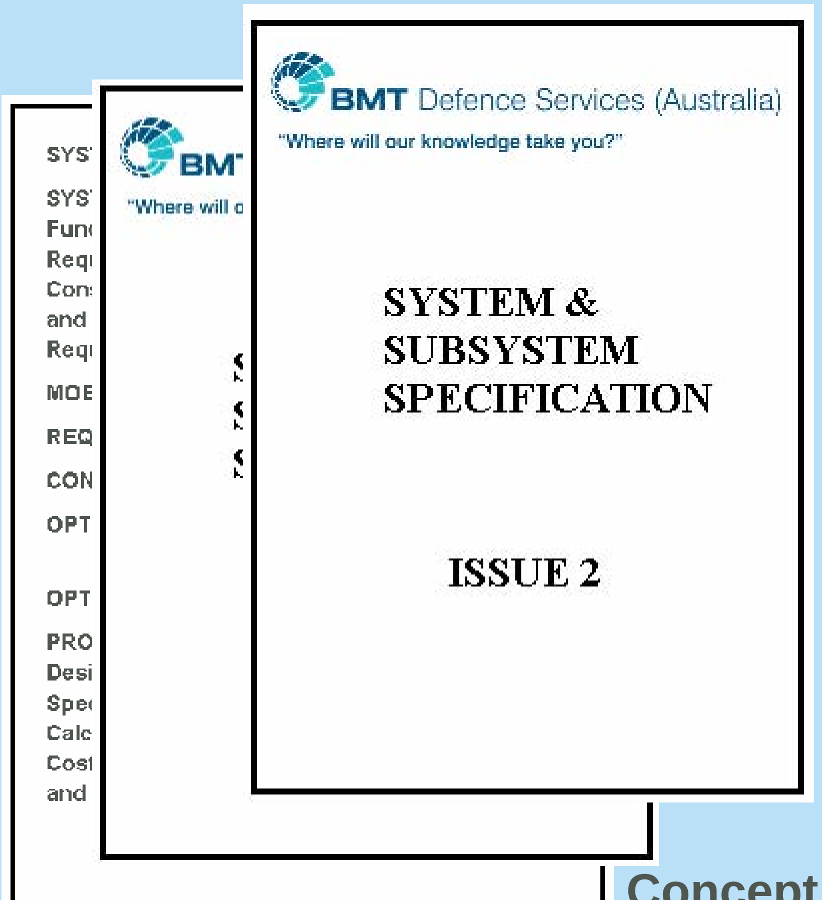
"Where will our knowledge take you?"

SYSTEM &
SUBSYSTEM
SPECIFICATION

ISSUE 1

Concept Design

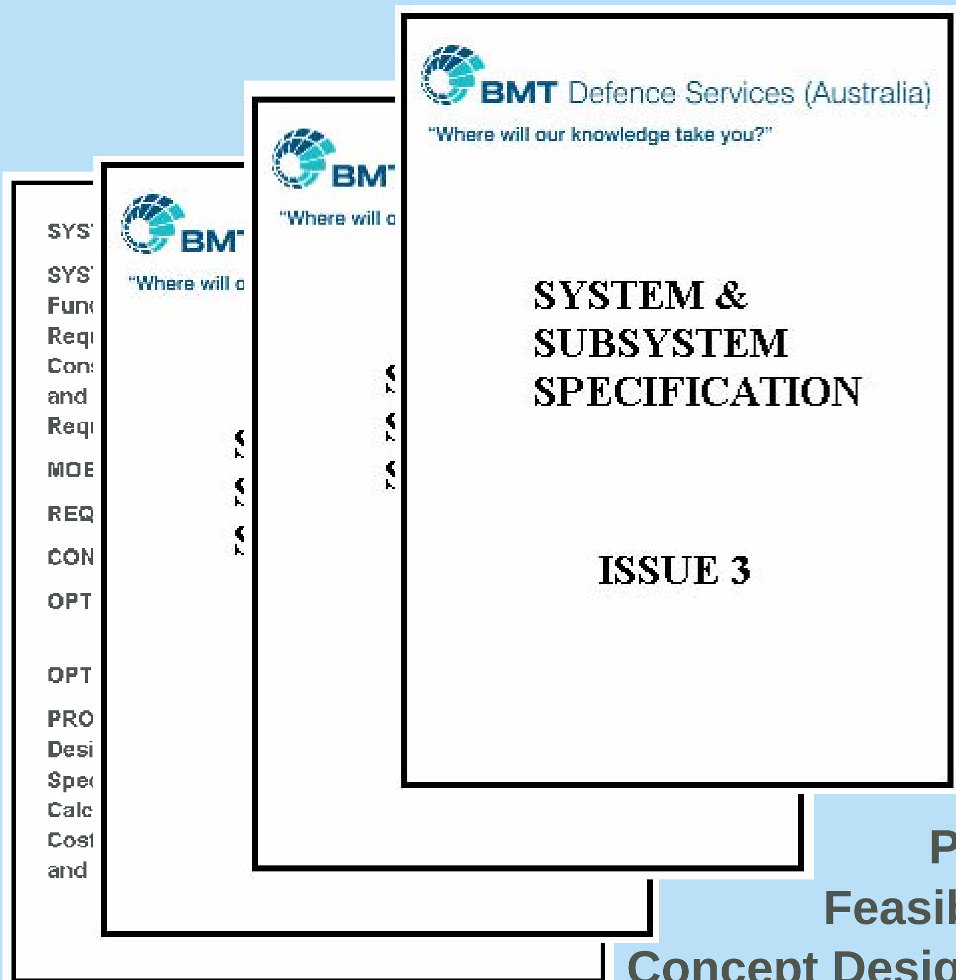
Practical Example – Surface Warfare Strike Capability



Feasibility Design

Concept Design

Practical Example – Surface Warfare Strike Capability

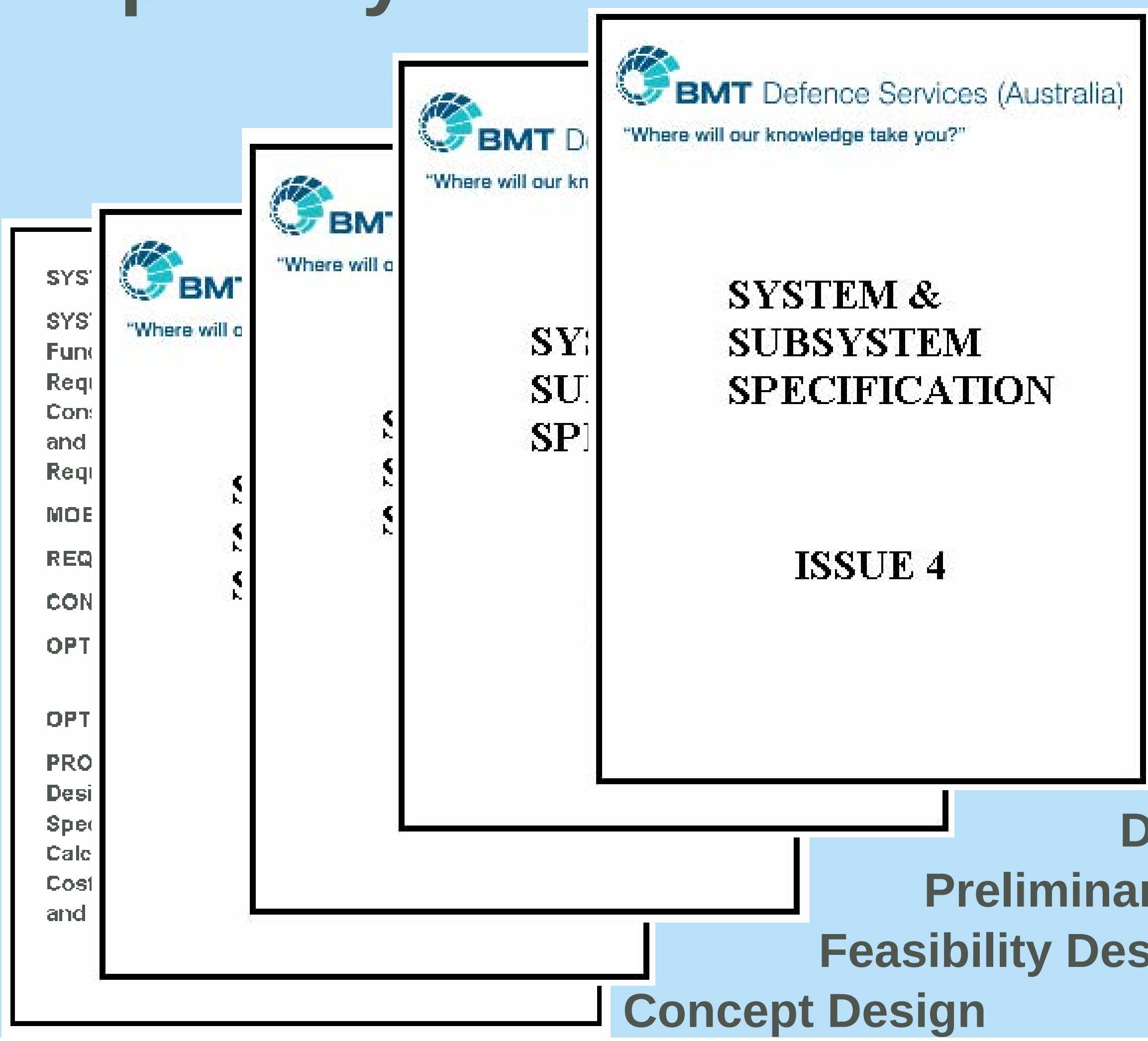


Preliminary Design

Feasibility Design

Concept Design

Practical Example – Surface Warfare Strike Capability



Detailed Design

Preliminary Design

Feasibility Design

Concept Design

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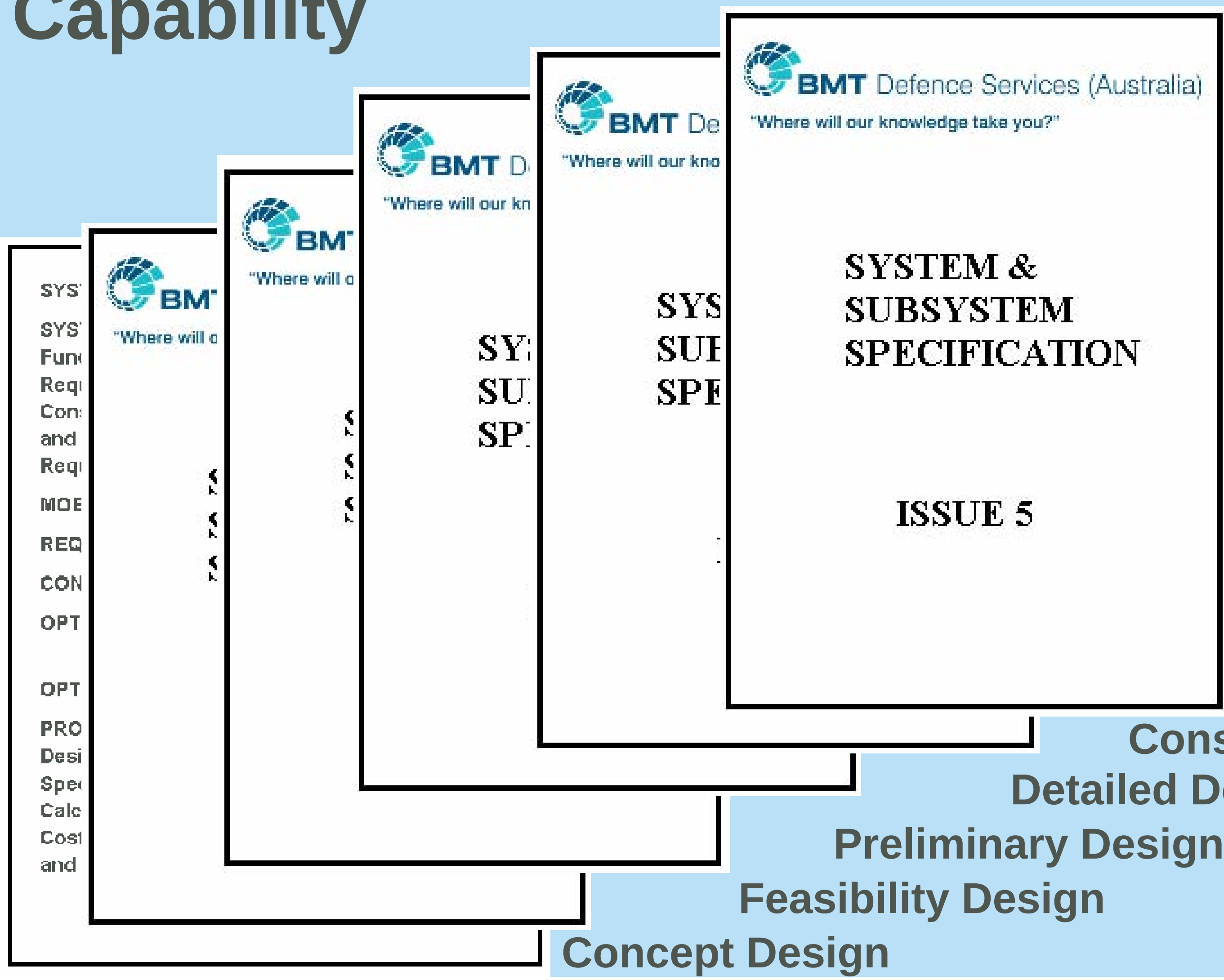

Construction

Detailed Design

Preliminary Design

Feasibility Design

Concept Design

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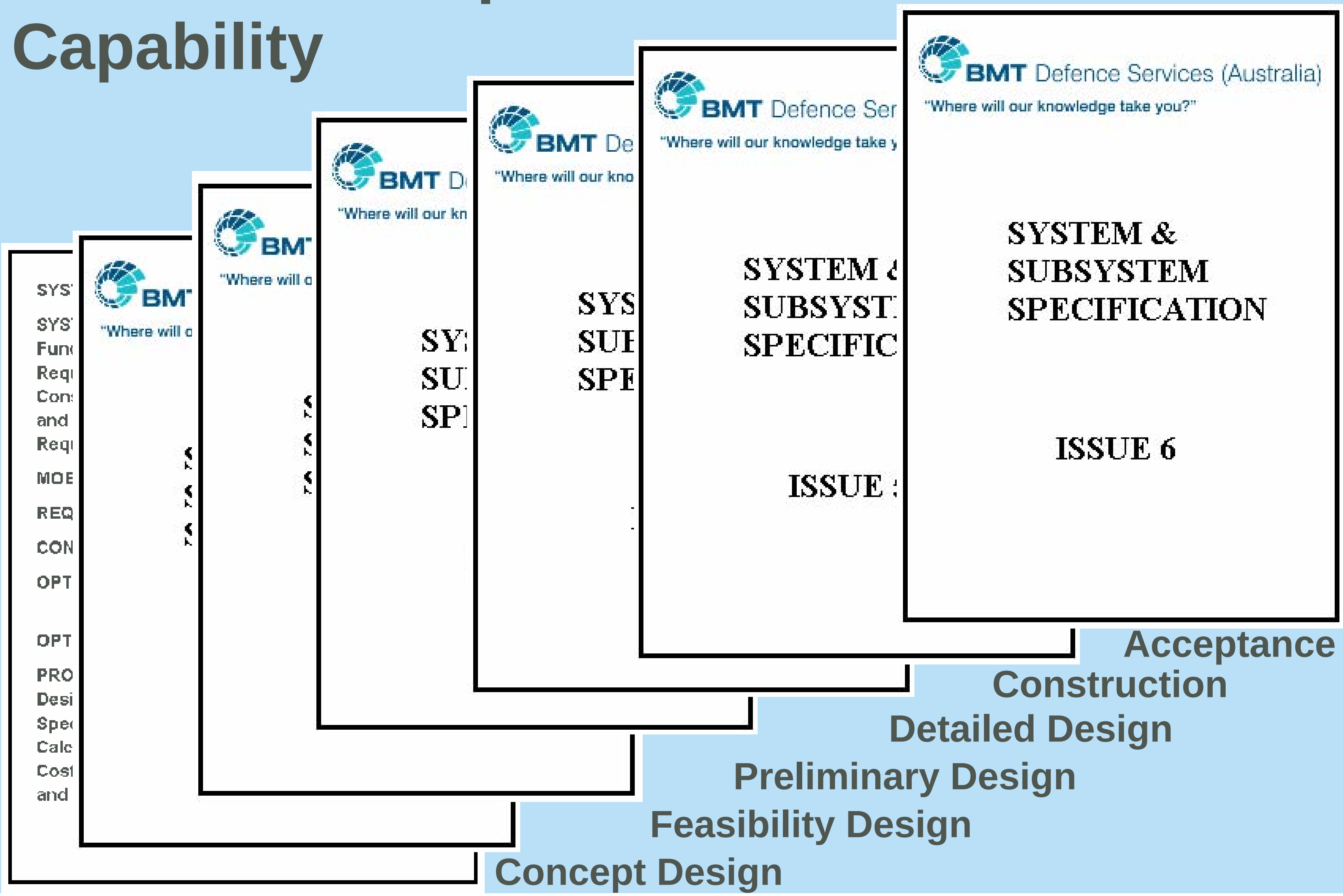

Acceptance
Construction
Detailed Design
Preliminary Design
Feasibility Design
Concept Design

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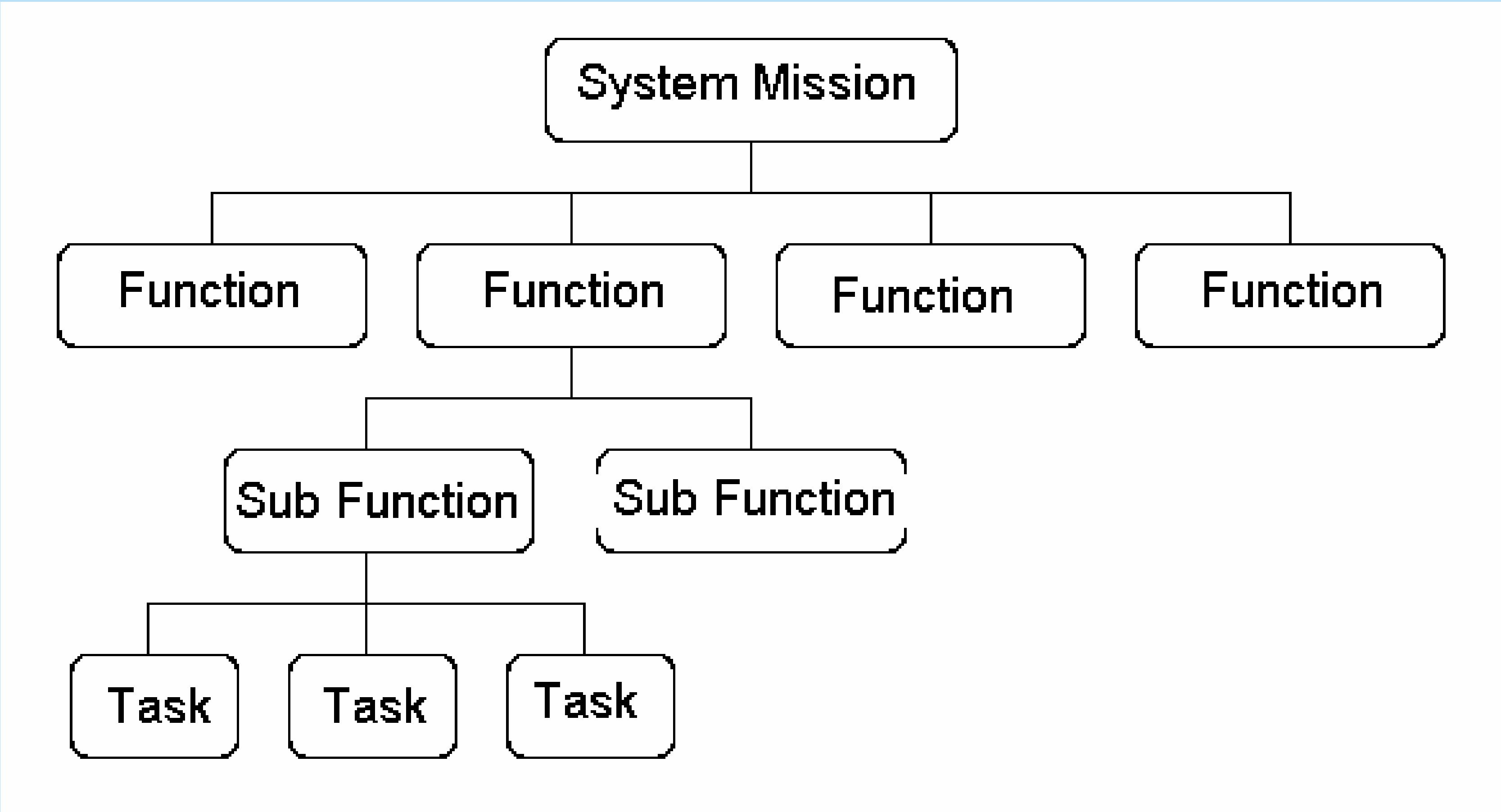
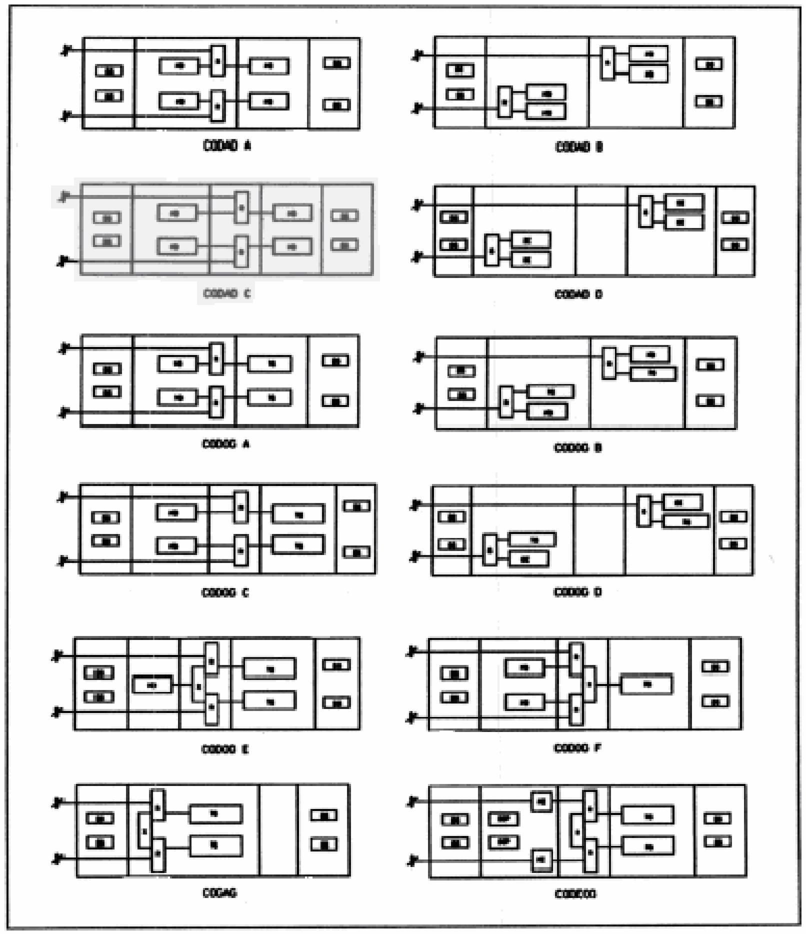


Practical Example – Surface Warfare Strike Capability



Design Level	Level Name
1	Capaility Element
2	System
3	Sub-system
4	Sub-system element
5	Assembly
6	Component

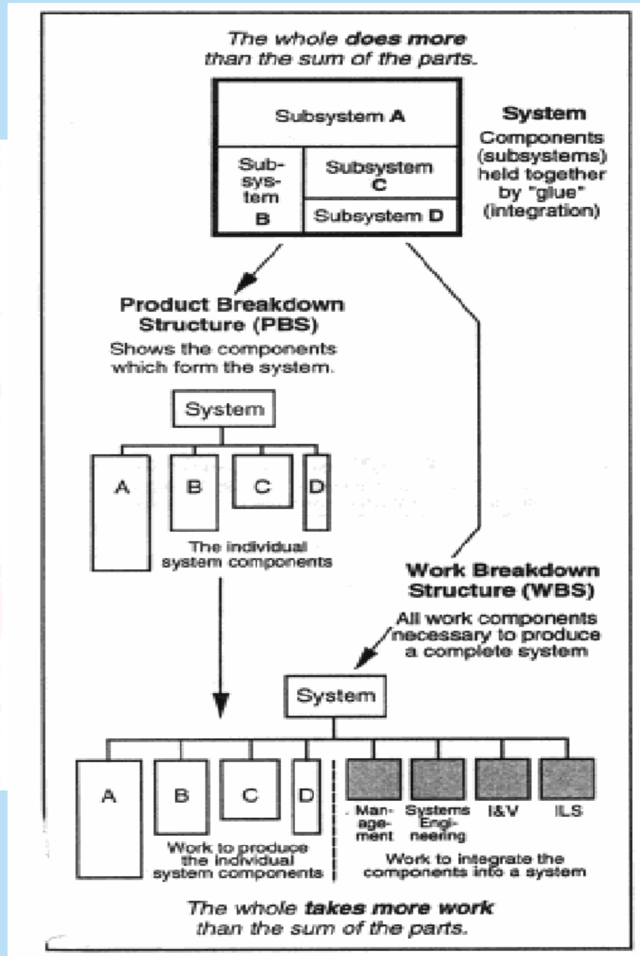
Practical Example – Surface Warfare Strike Capability

SEARCH FOR THE LEAST COST DESIGN (with continuous design var

CONFIGU-RATIONS	Optimum Type	SPACINGS: Number of Web-frames	SPACINGS: Second. Frame (Δ_c)	SPACINGS: Stiffeners (Δ_L)	Duct keel bulkhead. Plate Thickness	LEAST COST: COST SAVING (%) (see 1) Between 2 successive steps	LEAST COST: COST SAVING (%) (see 1) Cumulated saving	WEIGHT (%)
	Shown change(s) between 2 successive steps							
1- ALSTOM	MARS BV	N_W	$\Delta w/3$	Δ_L (Alstom)	100%	0.00%	0.00%	100% (ref)
2- MET8 E00	Least Cost	N_W	$\Delta w/3$	Δ_L (Alstom)	105%	-1.39%	-1.39%	98.34%
3- MET8 E90	Least Cost	N_W	$\Delta w/3$	1.15 Δ_L	105%	-2.46%	-3.85%	101.61%
4- MET8 B90	Least Cost	N_W -3	$\Delta w/3$	1.15 Δ_L	130%	-6.40%	-10.25%	104.73%
5- MET8 F90	Least Cost	NW -3	$\Delta w/4$	1.15 Δ_L	100%	1.67%	-8.58%	103.42%
6- MET8 F	Least Cost	N_W -3	$\Delta w/4$	1.28 Δ_L	100%	-0.53%	-9.11%	105.29%

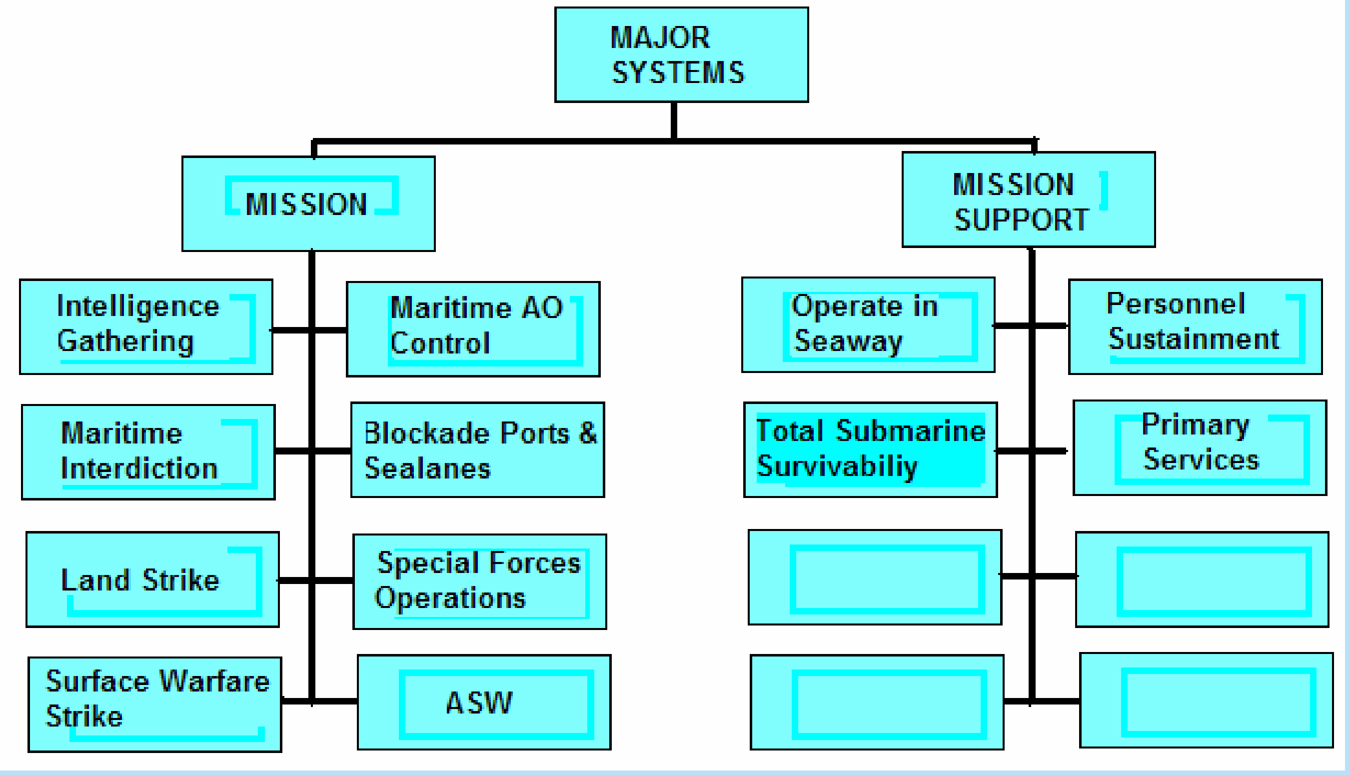
(*) Stiffener spacing too large ==> cost savings of 0.5% but increased straightening work ==> not effi

(1 Variation induced by the changes occured between two configurations.



Practical Example – Surface Warfare Strike Capability

SYSTEM REQUIREMENTS – Modes and States; Functional; Performance; Constraints (Safety Requirements, Design & Construction Constraints; Personnel Related Requirements; and System External/Internal Interface Requirements



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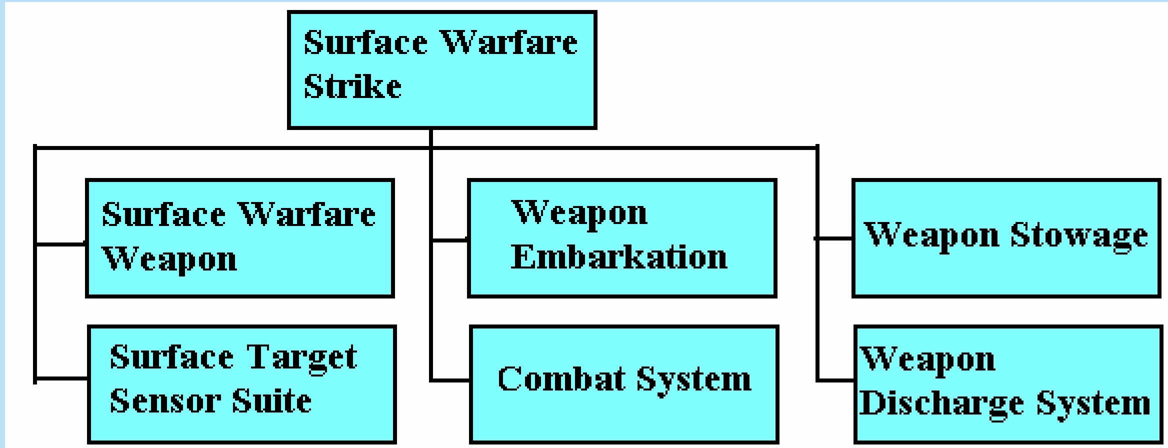

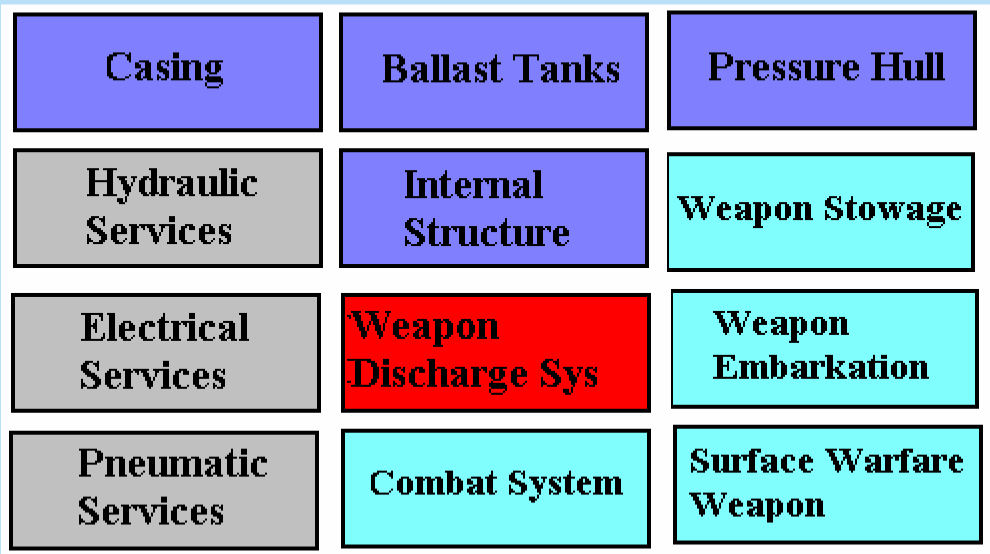

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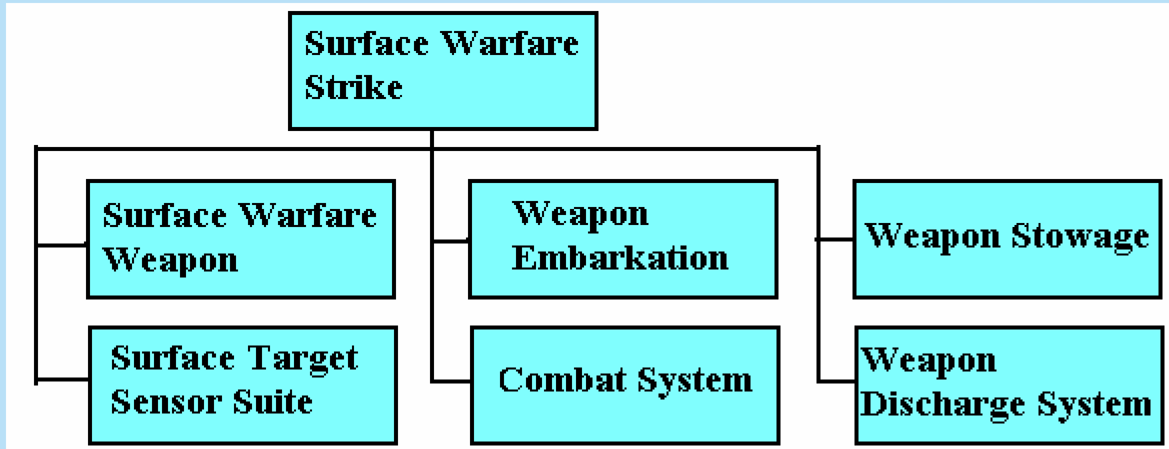

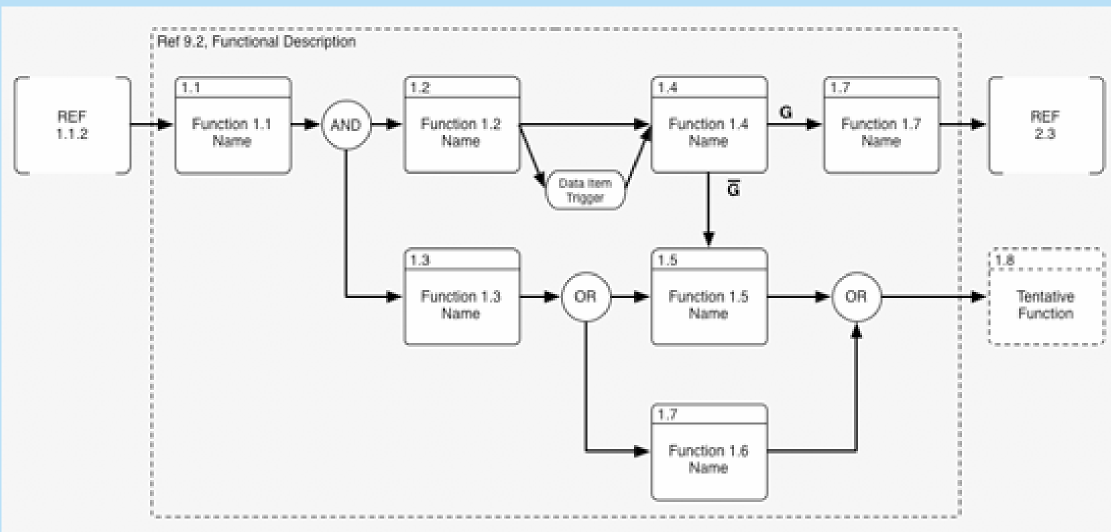

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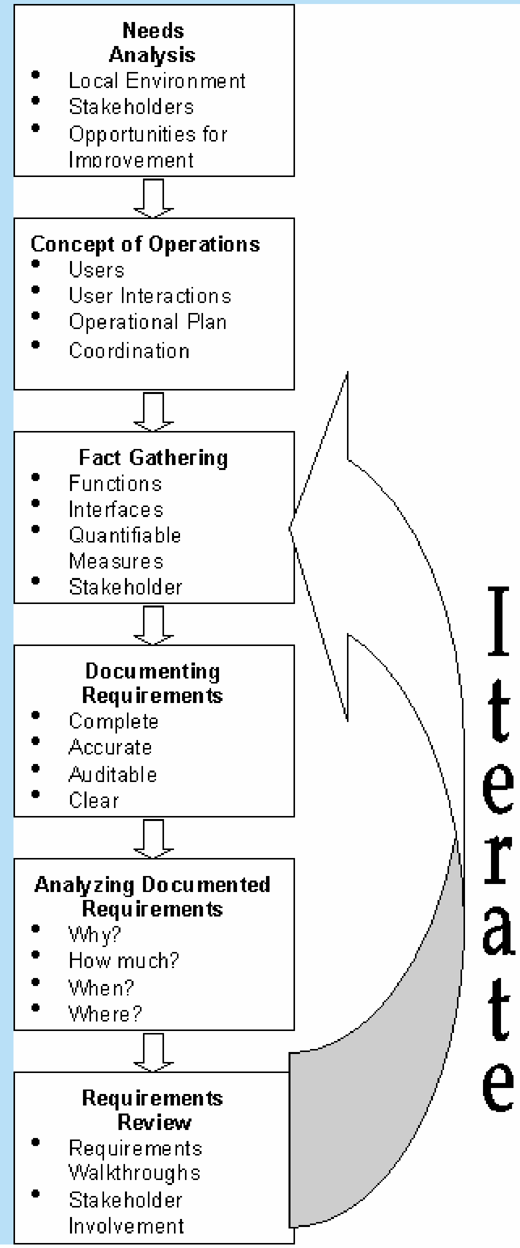


Practical Example – Surface Warfare Strike Capability

MOE/MOP

Practical Example – Surface Warfare Strike Capability

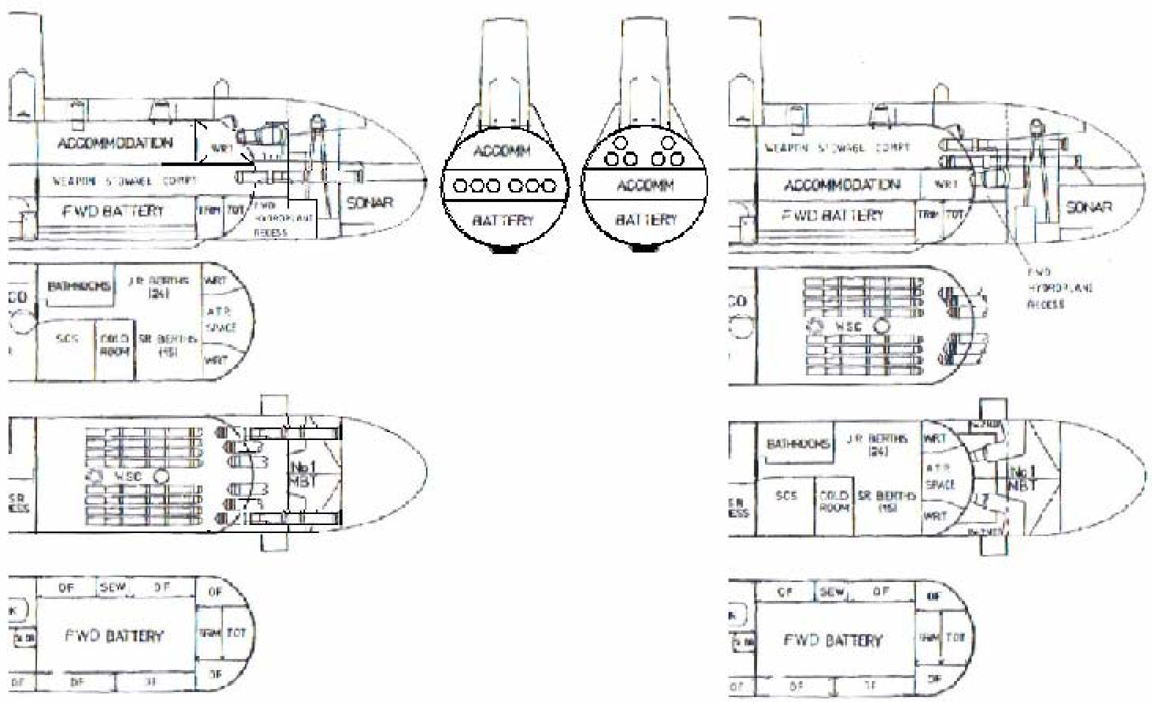
REQUIREMENTS VERIFICATION

	Requirement 1	Requirement 2	Requirement 3	Requirement 4	Requirement 5	Requirement 6	Requirement 7	...	...	...	...	...	...	...	...	...	...	Requirement n
Test 1	x			x														
Test 2		x			x													x
Test 3			x					...	...	...	...	...	...	...	...	...	...	
Test 4						x		...	...	...	...	...	...	...	...	...	...	
Test 5							x	...	...	...	...	...	...	...	...	...	...	x
Test 6						x		...	...	...	...	...	...	...	...	...	...	
...								...	...	...	...	...	...	...	...	...	...	
...								...	...	...	...	...	...	...	...	...	...	
...								...	...	...	...	...	...	...	...	...	...	
Test 12																		
...								...	...	...	...	...	...	...	...	...	...	
...								...	...	...	...	...	...	...	...	...	...	
...			x					...	...	...	...	...	...	...	...	...	...	
...								...	...	...	...	...	...	...	...	...	...	
...								...	...	...	...	...	...	...	...	...	...	
Test n					x													x

Spec. Paragraph	Title	Verification Method				Verification Paragraph	Verification Task Number
		Test	Analys.	Demo	Exam		
1.0	Tag Behavior			●		V_1.0	12.0
1.1	RF Communications	●				V_1.1	4.0
1.1.1	Warehouse Environ.			●		V_1.1.1	11.0
1.1.2	Program w/MtagPro			●		V_1.1.2	11.1
1.1.3	Antenna Design		●			V_1.1.3	1.1
1.1.4	Antenna Size/Shape				●	V_1.1.4	1.0
1.1.5	RF Trans. Bandwidth	●				V_1.1.5	3.2
1.1.6	RF Trans. Carrier Freq.	●				V_1.1.6	3.0
1.1.7	RF Trans. SNR	●				V_1.1.7	3.1
1.1.8	RF Trans. FSK-4	●				V_1.1.8	3.3
1.2	Tag Data			●		V_1.1.2	11.1
1.2.1	Microcontroller Mem.				●	V_1.2.1	2.1
1.2.2	Microcontroller Mem.				●	V_1.2.2	2.0
1.3	Clock Frequency	●				V_1.3	4.1
1.4	Software				●	V_1.4	2.2
1.41					●		
1.42					●		
1.5	Tag Power Consump.	●				V_1.5	7.1
1.5.1	Battery Power	●	●			V_1.5.1	5.1A
						V_1.5.1	5.2T
1.5.2	Battery Size				●	V_1.5.2	5.0
1.5.3	Voltage Regulator	●			●	V_1.5.3	6.0E
						V_1.5.3	6.1T
1.5.4	Low-voltage Alarm	●				V_1.5.4	6.2
1.5.4.1		●				V_1.5.4.1	7.0
1.5.4.2		●					
1.6	Waterproof Enclosure	●				V_1.6	9.0
1.7	Tag Weight				●	V_1.7	10.0
1.8	Enclosure Dimensions				●	V_1.8	8.0

Practical Example – Surface Warfare Strike Capability

CONFIGURATION OPTIONS



Practical Example – Surface Warfare Strike Capability

OPTION TECHNICAL DESCRIPTION & ANALYSIS

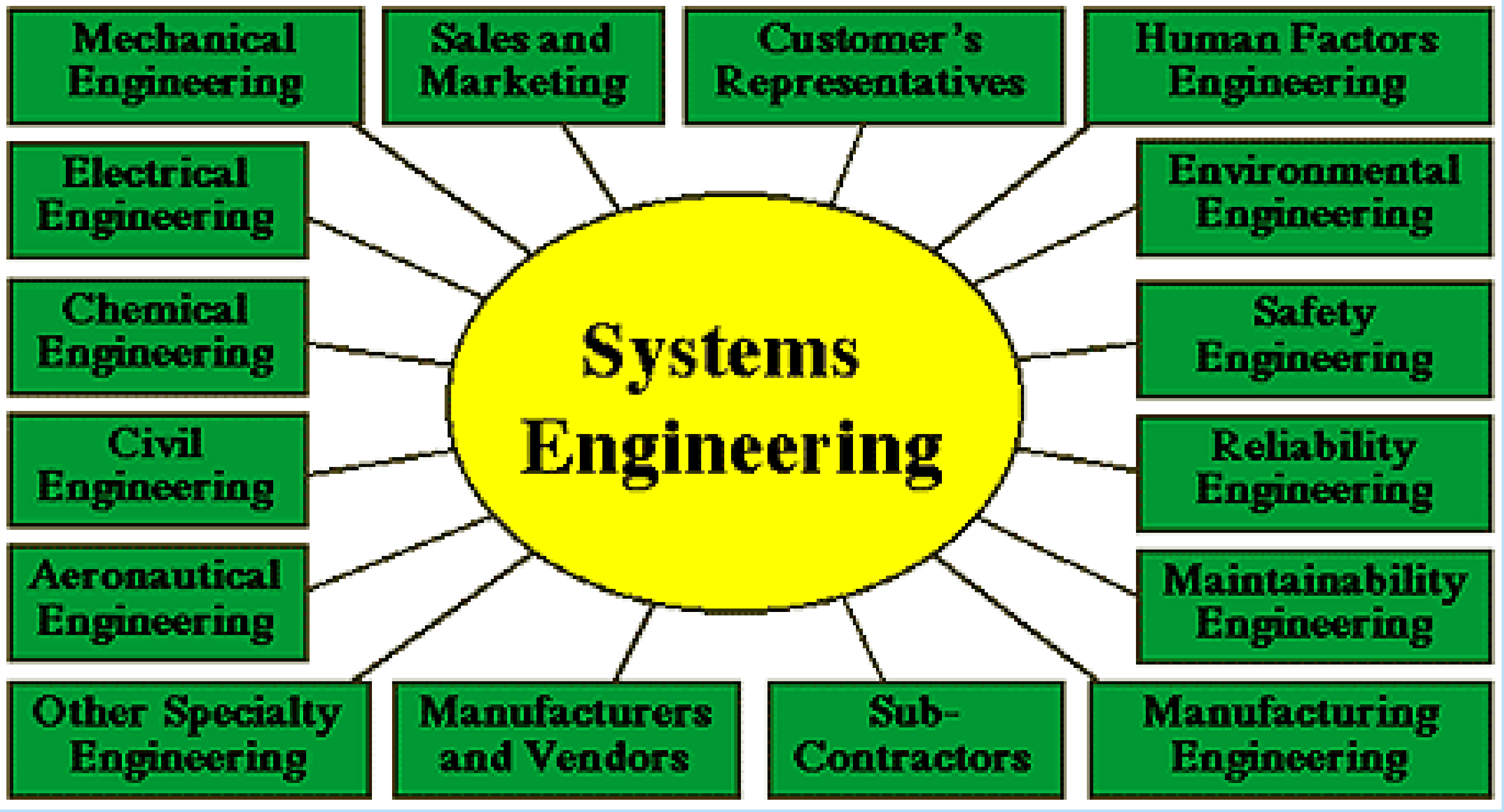
Practical Example – Surface Warfare Strike Capability

OPTION EVALUATION

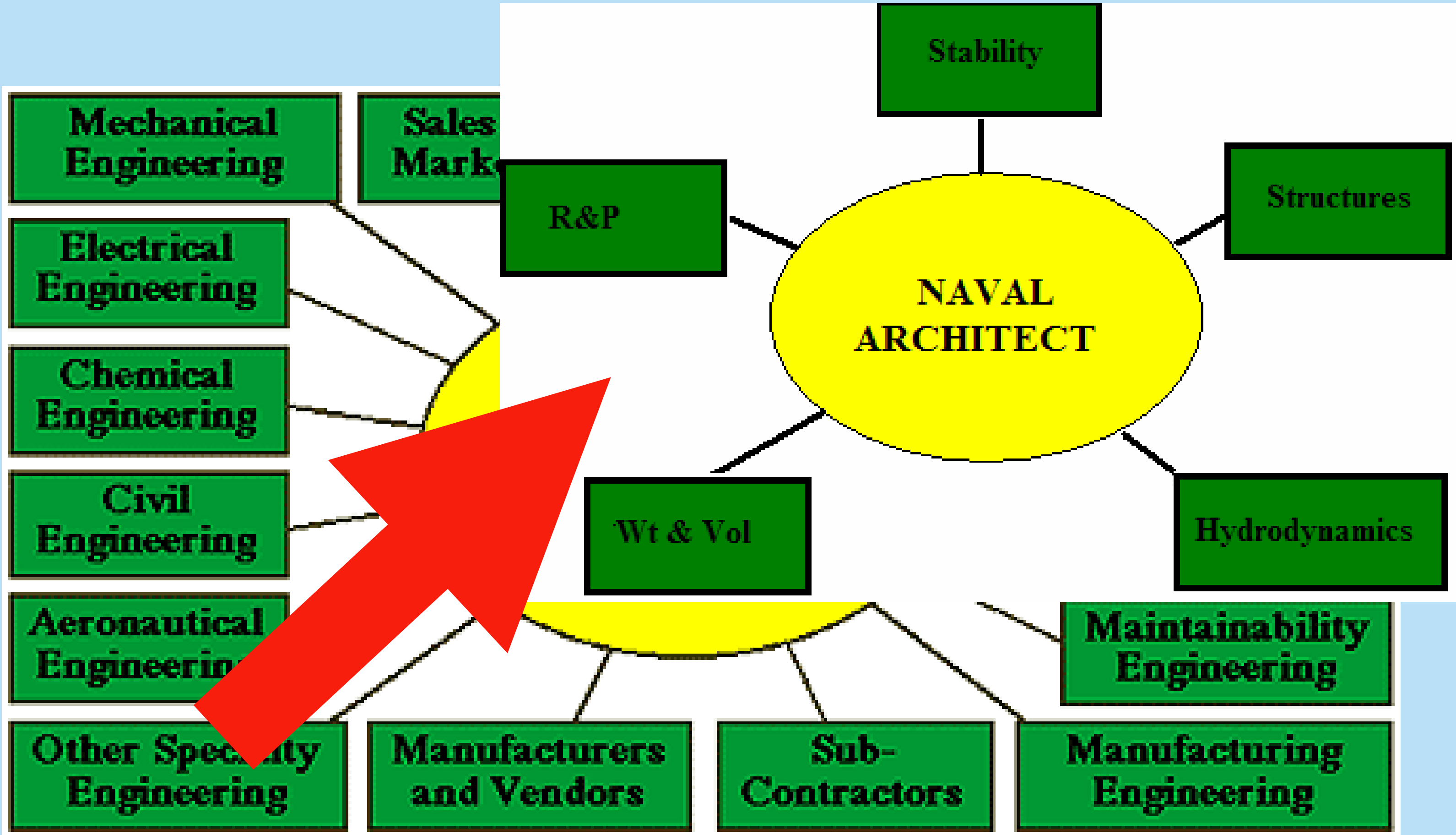
Practical Example – Surface Warfare Strike Capability

PROPOSED OPTION - Technical Description; Design Assumptions; Applicable Standards & Specifications; Equipment/Materials List; Design Calculations; ILS Products; Program Details – Cost & Schedule; Technical Risk Assesment; and Safety Assesment

The Challenge



The Challenge



The Challenge

Content

The Challenge

Content

RINA WARSHIP CONFERENCE THE APPLICATION OF SE IN SUPPORT OF WARSHIP DESIGN & MODIFICATION

ESTABLISH A CHAPTER OF INCOSE – MARITIME SYSTEM ENGINEERING

Thank you - Questions

de&s

The Delivery of the Successor Deterrent Submarine Concept Design - A Collaborative Approach

Peter Fitzpatrick FEIT, BAE Systems Submarine Solutions
Chris Edmonds, MRINA, Babcock Marine
Jason Bryars, Defence Equipment & Support

MINISTRY OF DEFENCE

Programme Background

- Government White Paper - The Future of the United Kingdom's Nuclear Deterrent was published in December 2006
  - A submarine based system provides the most effective deterrent
  - Vanguard class likely to start leaving service from the early 2020s
  - Around 17 years to design, manufacture and commission a replacement
  - Participation in the US life extension programme for the Trident D5
- Parliament voted positively on this in March 2007
- Merger of the DPA and DLO to form the Defence Equipment & Support, including the new DGSM Organisation in April 2007
- The formation of the Future Submarines IPT announced in April 2007
  - True collaborative IPT involving both MoD and Industry
  - 'Best athlete' principle for appointments
  - No 'man marking'

Presentation Outline

- This presentation will discuss and draw initial conclusions on:
  - The issues and challenges in setting up a collaborative team from across the submarine enterprise
  - The role, structure and method of working of the IPT
  - The development and management of the User and System requirement
  - The planning and the delivery of a viable Submarine Concept Design
  - The delivery of affordable and available submarine platforms

Setting up an Enterprise-wide Collaborative Team …

Setting up an enterprise-wide collaborative team

- The Submarine 'market' in the UK is effectively shrinking
- The natural corporate response to a shrinking market is to seek to increase market share at the expense of the other participants
- However, where a market has reduced to a minimum level, this simply transfers activity between virtual monopolies of expertise and can lead to the loss of key expertise to the nation
- This was recognised in the Defence Industrial Strategy, which sought to ensure that:
  - The UK's strategic submarine capability could be to sustained
  - the UK submarine programme represented value for money
- It recognised that this was only achievable by increased collaboration within the Submarine Enterprise

Setting up an enterprise-wide collaborative team

- This transition from competitive to collaborative behaviours represents the first challenge faced in establishing the FSMIPT
- The culture of an organisation sets the behaviour of its staff, and such cultures are notoriously difficult to change
- This organisational culture is reflected in policies and processes of each company and in the MoD and is also embedded in the behaviour of its staff
- The challenge posed by the UK Successor Deterrent Programme is not to change the culture in a single company, but to change it in four organisations – all at the same time
- Each collaborative partner has found that the adoption of a collaborative approach has ‘clashed’ in one way or another with established policies

Setting up an enterprise-wide collaborative team

- In terms of process, the collaborative approach presents both issues and opportunities:
  - Four different organisations bring with them different approaches
  - The collaborative approach does enable processes from each organisation to be benchmarked and good practice identified
- The integration of four different IT Infrastructures and ‘business systems’ is proving a challenge
  - Each participant has selected major tools to meet its own needs
  - Even simple email exchange can prove difficult initially
  - Significant efforts will be required to provide an effective collaborative environment for the design of the submarine

Setting up an enterprise-wide collaborative team

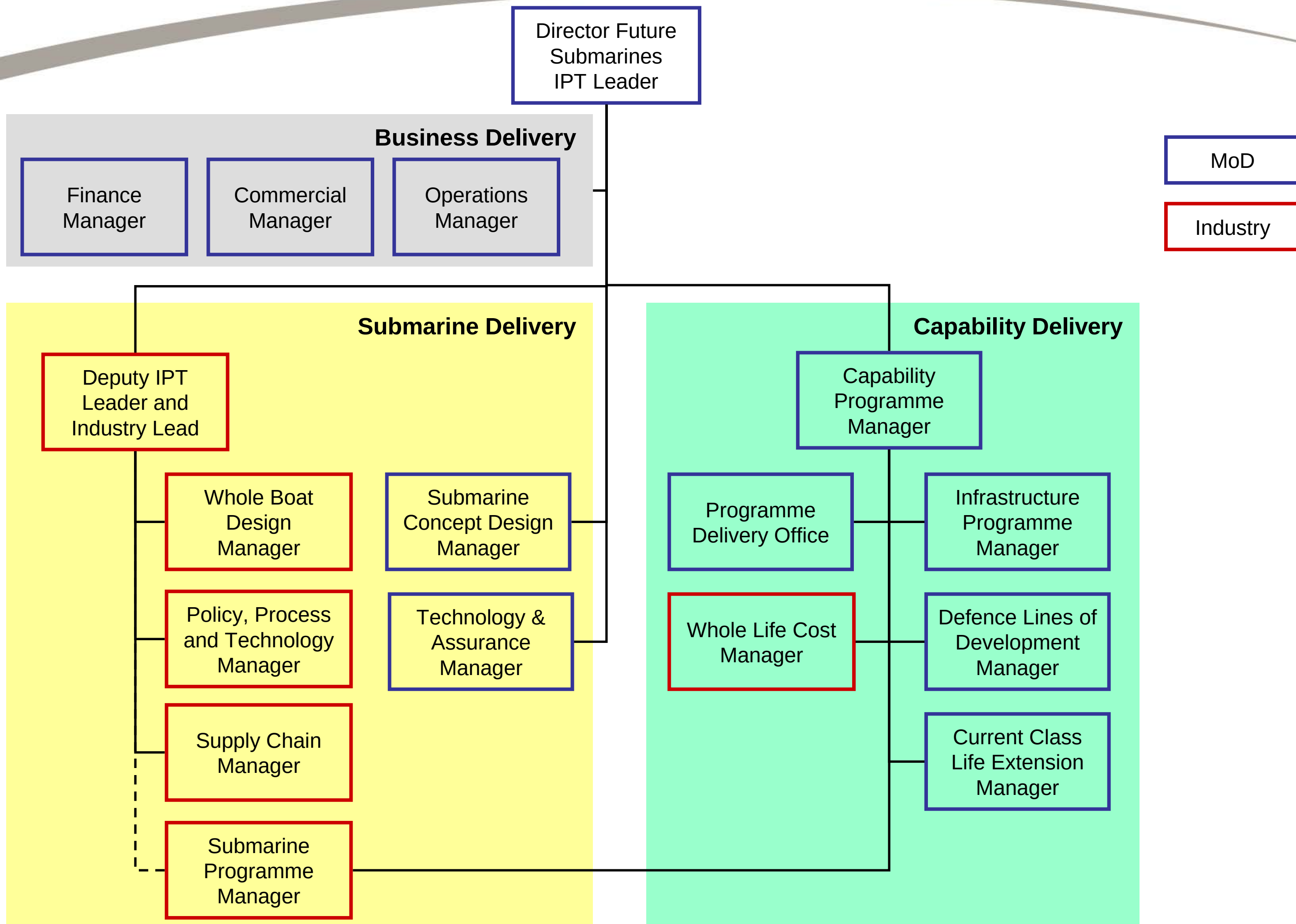
- The most difficult challenge is likely to be ensuring that the team exhibit constructive behaviours
- Our behaviours are usually the unconscious result of experience
- A key factor in changing behaviours from competitive to collaborative will be to ensure that the basis for our behaviours is consciously understood
- At a high level, this can be achieved by including incentives in contracts to reward the right, collaborative behaviours
- At a team and individual level, experience has shown the value of equipping staff with a basic understanding of the drivers that result in effective and ineffective behaviours within the team

The Role, Structure and Method of Working of the Integrated Project Team …

The role, structure and method of working of the IPT

- The Future Submarines IPT must essentially work at three levels:
  - Capability Delivery
    - The delivery of the complete 'deterrent capability' requires the co-ordination of a large and complex set of organisations
  - Submarine Delivery
    - The design and delivery of a new class of submarine is also not an inconsiderable task
  - Business Delivery
    - Finally, the development of appropriate Business Cases, including financial and commercial considerations should not be forgotten

The role, structure and method of working of the IPT



The role, structure and method of working of the IPT

- The Capability Delivery element of the organisation is responsible for:
  - The co-ordination of the large number of organisations within Government necessary for the continuation of the deterrent capability
  - Ensuring that the necessary actions are taken across all elements of the Defence Lines of Development
  - The development, maintenance and delivery of an integrated programme capturing all of the necessary activities at a high level
- In addition, this part of the organisation is charged with developing an adequate understanding of the Whole Life Costs of the overall programme

The role, structure and method of working of the IPT

- The Submarine Delivery element of the organisation is responsible for the delivery of the Submarine Concept Design
- At a high level, this comprises:
  - The record of the key decisions made during the Concept Phase
  - The Submarine Concept Design Definition
  - The Design Policies that set the 'design direction' for the completion of the submarine functional and detailed design
- The organisation also ensures that the Client and Industry parts of the team work closely together promoting effective and timely decision making and enabling requirement/performance trades

The role, structure and method of working of the IPT

- The Business Delivery element of the organisation is responsible for the financial and commercial management of the programme
  - The commercial construct reflects the collaborative strategy of the programme while preserving a client-provider relationship
  - The contractual arrangements a collaboration agreement and associated financial incentives that are available to all of the industry partners
- This part of the organisation is also responsible for developing and presenting the programme’s business case for scrutiny within the MoD “HQ”, Defence Equipment and Support, and by wider government

The development of the User and System Requirement …

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The development of the User and System Requirement

- In general, recent major defence programmes have been ‘requirement-based’. While this has some obvious advantages, there a number of significant issues that can arise as the result of this approach:
  - The definition of a complete, consistent and correct requirement for such a complex system is notoriously difficult
  - The customer broadly gets exactly what was asked for over a decade ago, not necessarily what he needs now
  - The imprecise nature of any such requirement specification coupled with a limited understanding (in both the MoD and Industry) of the capability/cost equation is also a crucial factor contributing to cost overruns in these large, complex programmes

The development of the User and System Requirement

- The Successor Deterrent programme has consciously decided to take a different approach:
  - Cost is king in the capability/cost/time equation – there are some crucial requirements for a nuclear deterrent submarine but in principle, all requirements can be traded against cost
  - Requirements can, and should, be challenged. Proposals for slightly reduced performance for significantly reduced cost will be considered, and this is actively happening
  - The requirement set will reflect the factors that are crucial for the submarine to be able to perform its defined role. This will include constraints such as the maximum limits of the current supporting shore infrastructure

The development of the User and System Requirement

- The intention is that the User Requirement will remain ‘fluid’ during the Concept Phase to enable capability / requirement / cost trades to take place
- Towards the end of the Concept Phase the User Requirements will be baselined
- At this stage, the System Requirement for the submarine will be drafted, together with a Submarine Design Specification that will capture the high-level design decisions made during the phase.

The delivery of a viable Submarine Concept Design …

The delivery of a viable Submarine Concept Design

- The collaborative approach has enabled us to collectively determine the key aspects that need to be undertaken during the Concept Phase. These are:
  - The determination of the key user requirements for the submarine
  - The identification of the key decisions that must be made
  - The development of Design Principles and supporting strategies and policies for significant elements of the submarine design
  - The development of a common understanding of Whole Life Cost
  - The development of the Business Case for the programme
  - The development of the processes, tools and infrastructure for the future phases of the programme
  - The development of a single integrated programme

Experience so far …

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de&s

Experience so far

- The first six months of the Concept Phase programme has presented a number of challenges, some expected and others less so
- In these early stages is it evident that a collaborative approach is paying dividends:
  - The key Design Principles being adopted by all concerned
  - Design Strategies have been developed collaboratively in a very short period to begin the process of embedding these principles into the submarine design
  - A single common programme for the delivery of the Concept Phase by all collaborating partners has also been established

Experience so far

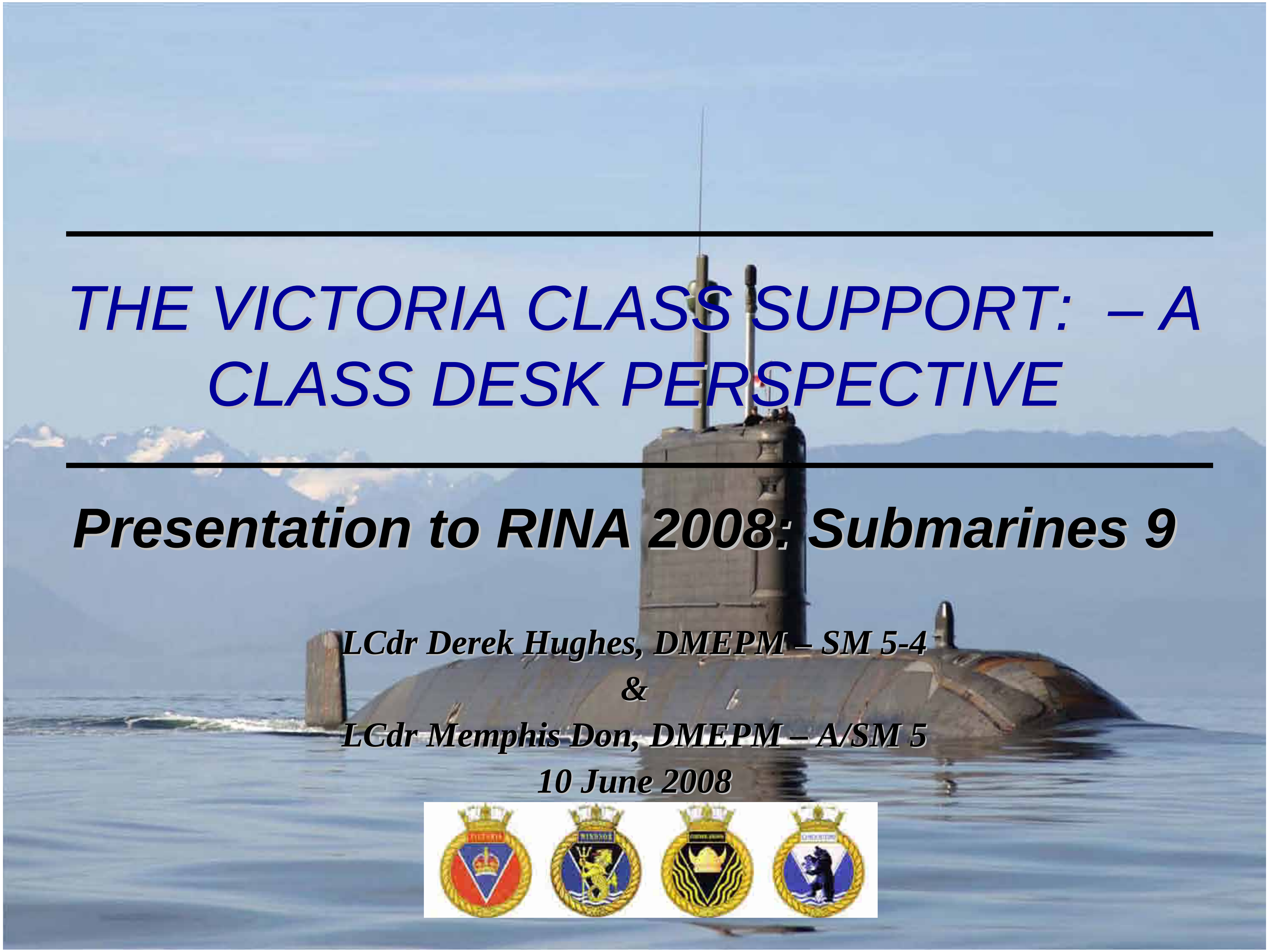
- Other successes include:
  - The population the team that will deliver the Concept Design from across industry, with all of the collaborating partners being engaged in the selection of the best person for the job
  - The key processes required to deliver the Concept Phase are now established and have involved all of the collaborating partners

Experience so far

- We have, of course encountered some difficulties:
  - A number of areas have found it difficult to identify and engage engineers with the experience to contribute to the programme. This is particularly the case for Systems Engineering and Strategic Weapon Systems
  - It has proved more difficult than expected to provide an IT and communications infrastructure for the programme – this is exacerbated by the large number of MoD and industry participants and the necessary security considerations

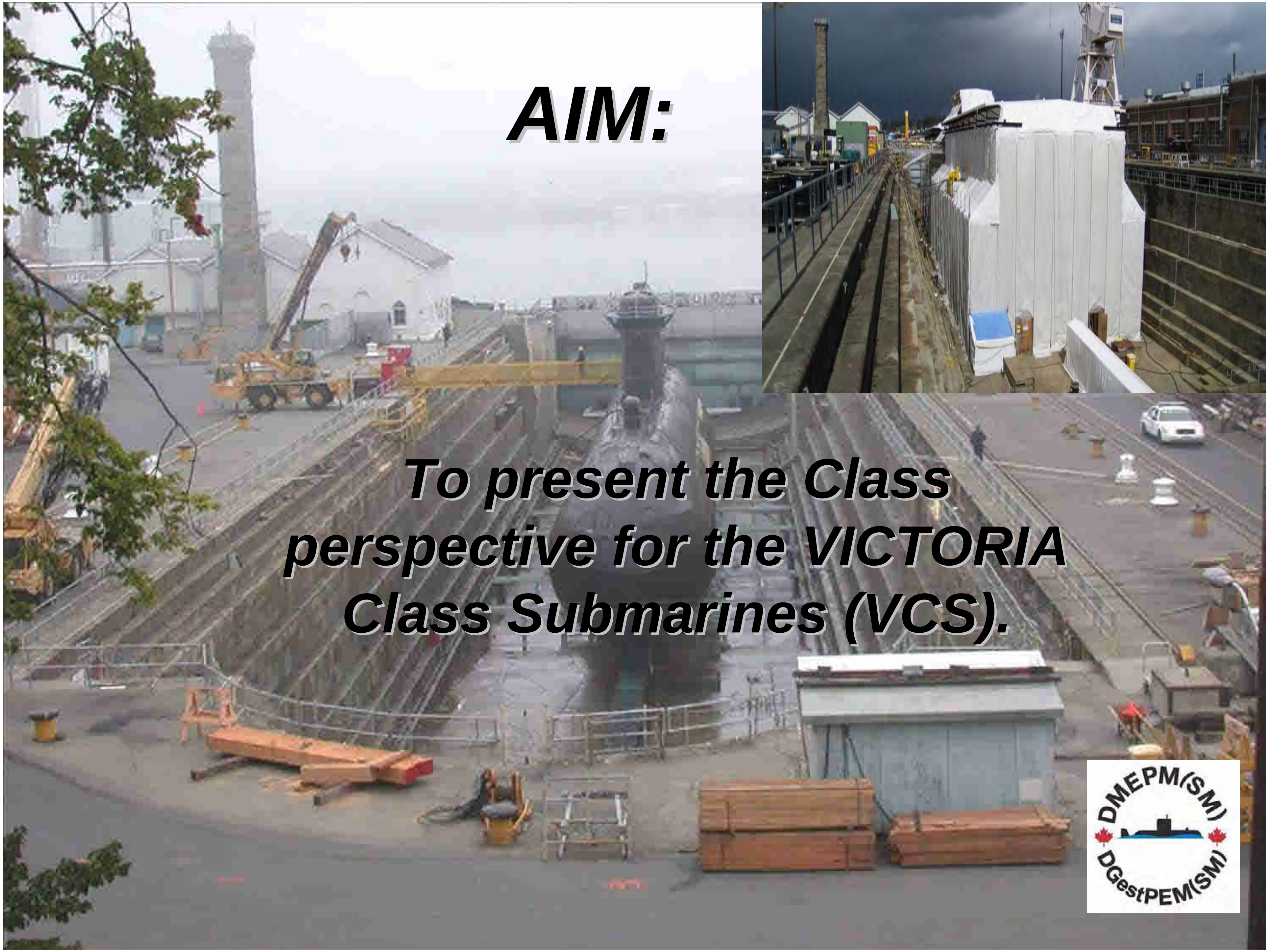
Summary

- The first six months of this programme have underlined the fact that the knowledge and resources to deliver this programme successfully can only be deployed collaboratively, since no one company or the MoD has the full range of expertise and resources necessary.
- Finally, the delivery of this programme within cost and programme constraints presents a very real challenge. Working together we can set the programme of 'in the right direction' to achieve a successful outcome


THE VICTORIA CLASS SUPPORT: – A CLASS DESK PERSPECTIVE
Presentation to RINA 2008: Submarines 9
LCdr Derek Hughes, DMEPM – SM 5-4
&
LCdr Memphis Don, DMEPM – A/SM 5
10 June 2008

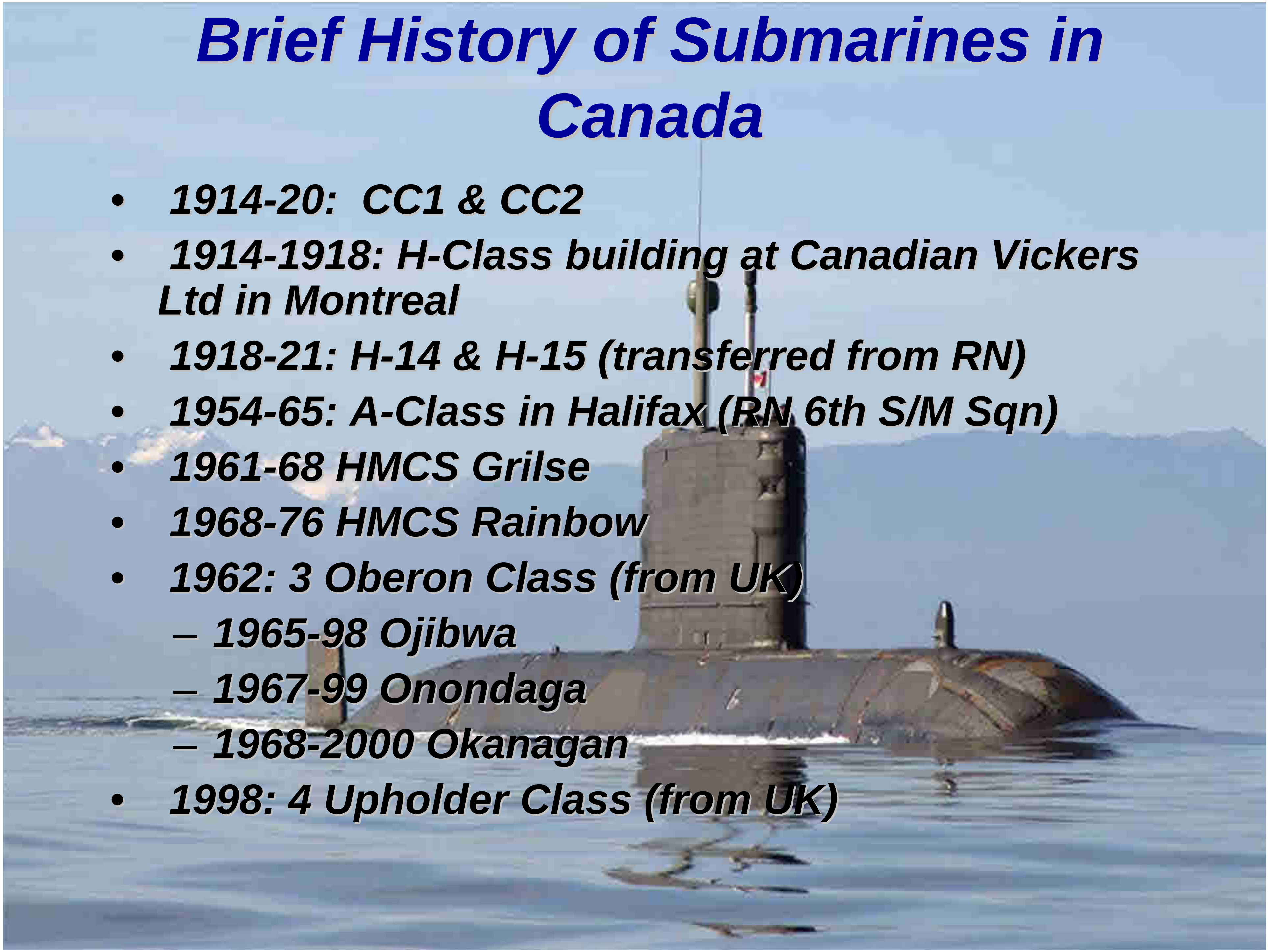
AIM:

To present the Class perspective for the VICTORIA Class Submarines (VCS).



Outline

- ***History***
- ***The Class Plan… getting the job done!***
- ***EDWP Challenges***
  - ***Early;***
  - ***Current;***
- ***Successes!!***
- ***Lessons Learnt***

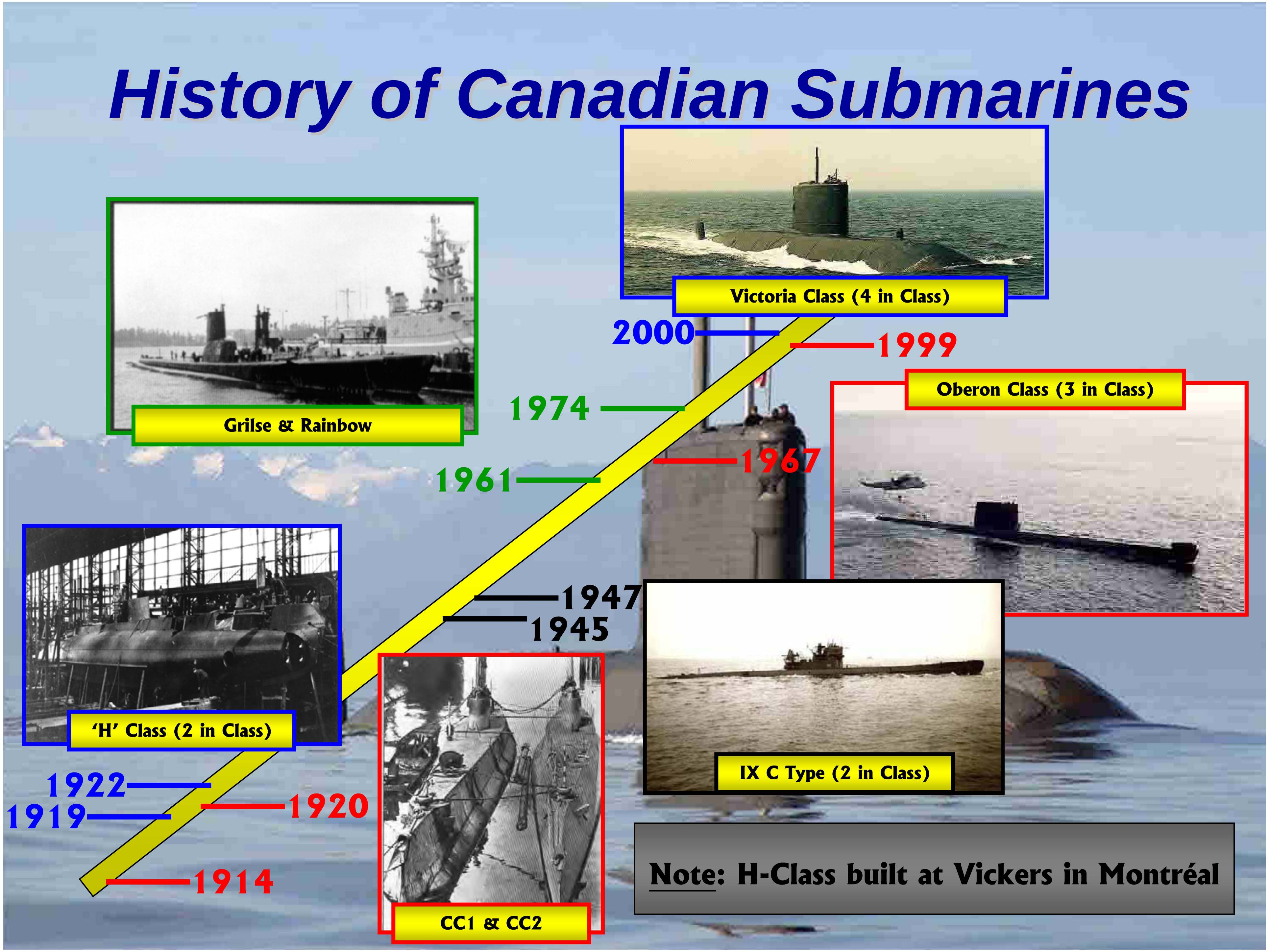

Brief History of Submarines in Canada
• 1914-20: CC1 & CC2
• 1914-1918: H-Class building at Canadian Vickers Ltd in Montreal
• 1918-21: H-14 & H-15 (transferred from RN)
• 1954-65: A-Class in Halifax (RN 6th S/M Sqn)
• 1961-68 HMCS Grilse
• 1968-76 HMCS Rainbow
• 1962: 3 Oberon Class (from UK)
– 1965-98 Ojibwa
– 1967-99 Onondaga
– 1968-2000 Okanagan
• 1998: 4 Upholder Class (from UK)

Comparison of OBERON & VICTORIA Class Submarines

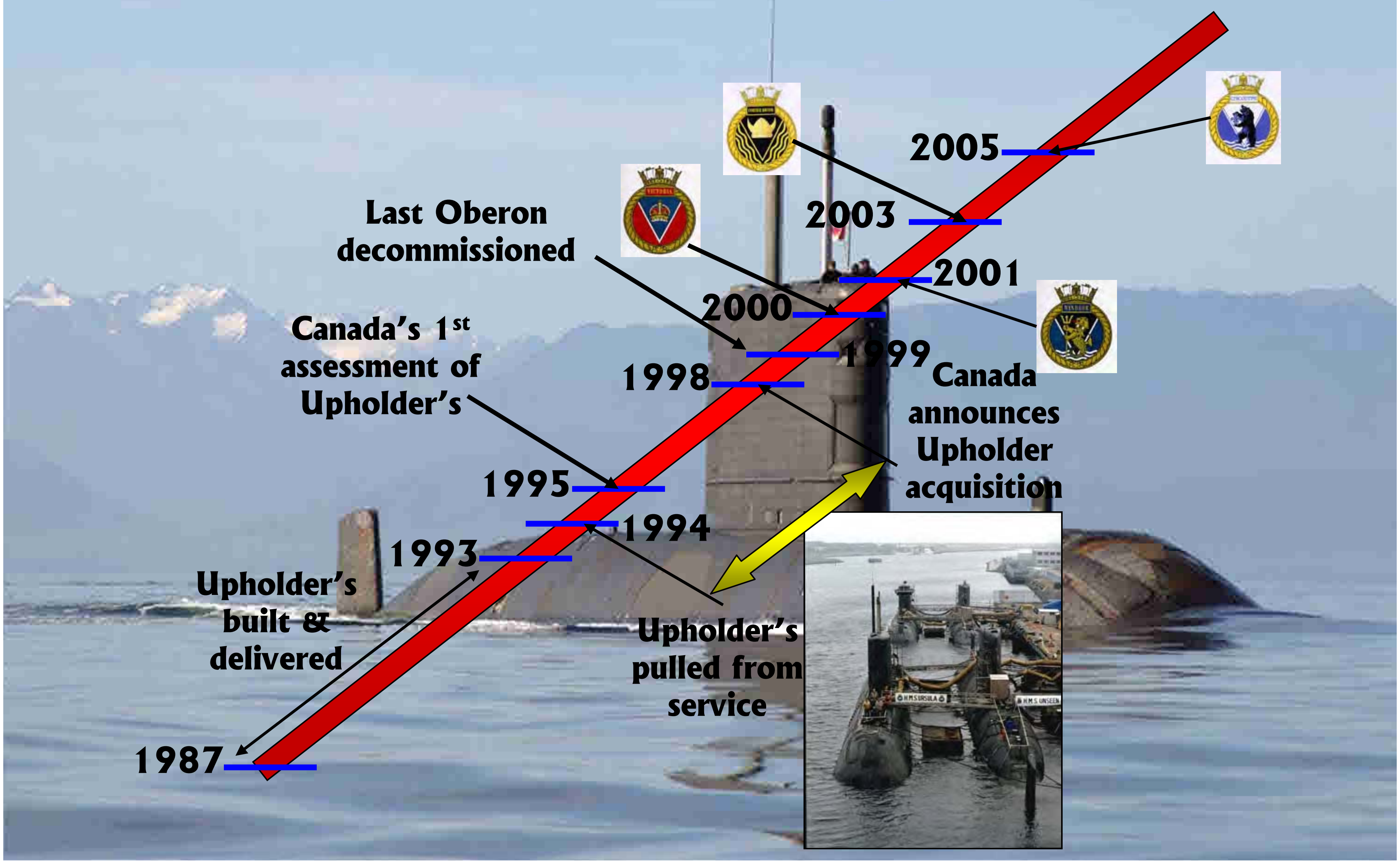
SUBMARINE CHARACTERISTICS

OBERON	CHARACTERISTIC	UPHOLDER
2030 tons	Displacement (Surfaced)	2168 tons
2410 tons	Displacement (Dived)	2455 tons
295 ft / 90 m	Length	231 ft / 70 m
> 500 ft / 150 m	Diving Depth	> 650 ft / 200 m
12 knots	Speed (Surfaced)	12 knots
17 knots	Speed (Dived)	20 knots
9000 nm @ 12 knots	Range	8000 nm @ 8 knots
2 diesels/ 2 motors/ 2 shafts	Propulsion	2 diesels/ 1 motor/ 1 shaft
65	Complement	49
6 forward	Torpedo Tubes	6 forward
20	Torpedoes	18

Source: Janes' Fighting Ships


History of Canadian Submarines
Victoria Class (4 in Class)
2000
1999
Oberon Class (3 in Class)
Grilse & Rainbow
1974
1967
1961
1947
1945
'H' Class (2 in Class)
IX C Type (2 in Class)
1922
1920
1919
1914
CC1 & CC2
Note: H-Class built at Vickers in Montréal

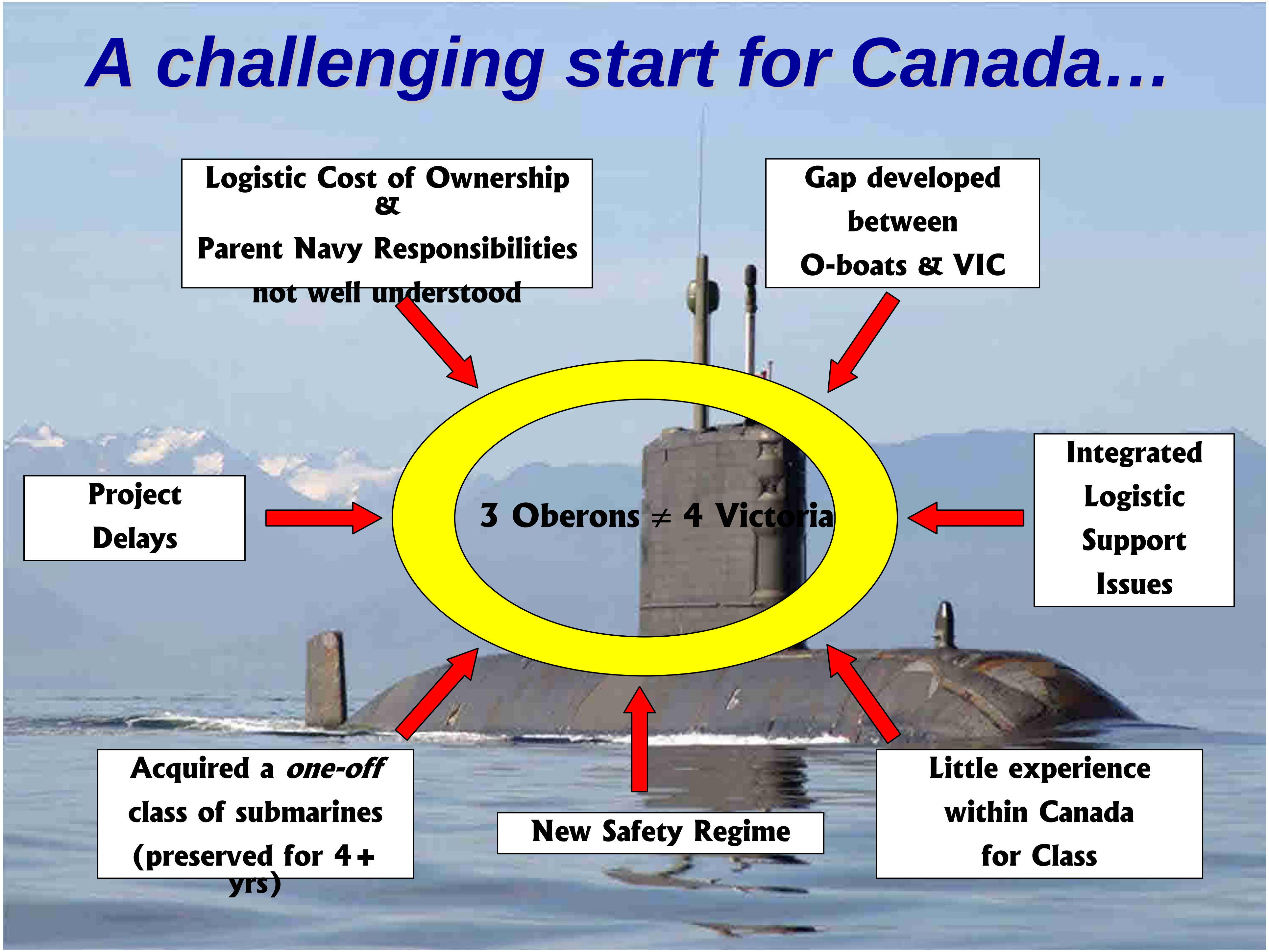
History of the Class



Oberon vs Victoria

Mat Cert - Quality Assurance Requirements

Oberon Class	QA Req'ments	Victoria Class
x	SUBSAFE Program	√
Safe-to-Dive Certificate	Material Certification	√
x	Licensing for Sea	√
x	1st Level Systems	√
x	QA Live Files	√
Relatively few existed	Non-Conformances	√
x	Formal Audits	√


A challenging start for Canada…
Logistic Cost of Ownership & Parent Navy Responsibilities not well understood
Gap developed between O-boats & VIC
Project Delays
3 Oberons ≠ 4 Victoria
Integrated Logistic Support Issues
Acquired a one-off class of submarines (preserved for 4+ yrs)
New Safety Regime
Little experience within Canada for Class


Challenges – 9 yrs into programme…
Challenges of follow-on ISSC
Streamlining of Materiel Certification processes
TDP difficulties. Multiple Databases exist
• Ops Availability less than optimal
• Maintenance periods too long
Obsolescence
Impact of Ops Pause & loss of experience
Understanding Logistic Cost of Ownership
Transition to Management Information System
Resources stretched (HR & $)

VIC EDWP Roles and Relationships

CMOG 4 & VIC Crew

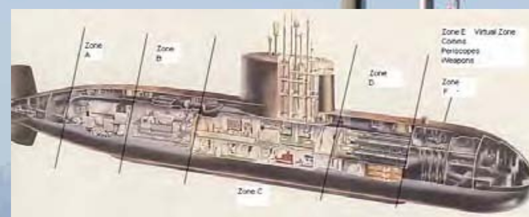
Operator and Custodian

DGMEPM

Customer and Design Authority

DCOS FTA

Mat Cert and DA



FMF CB

Prime Contractor

Vic Ships Ltd

Sub Contractor

MARPAC N3

TRP Authority

PWGSC

Contracting Authority

Weir Strachan Henshaw

Weapons

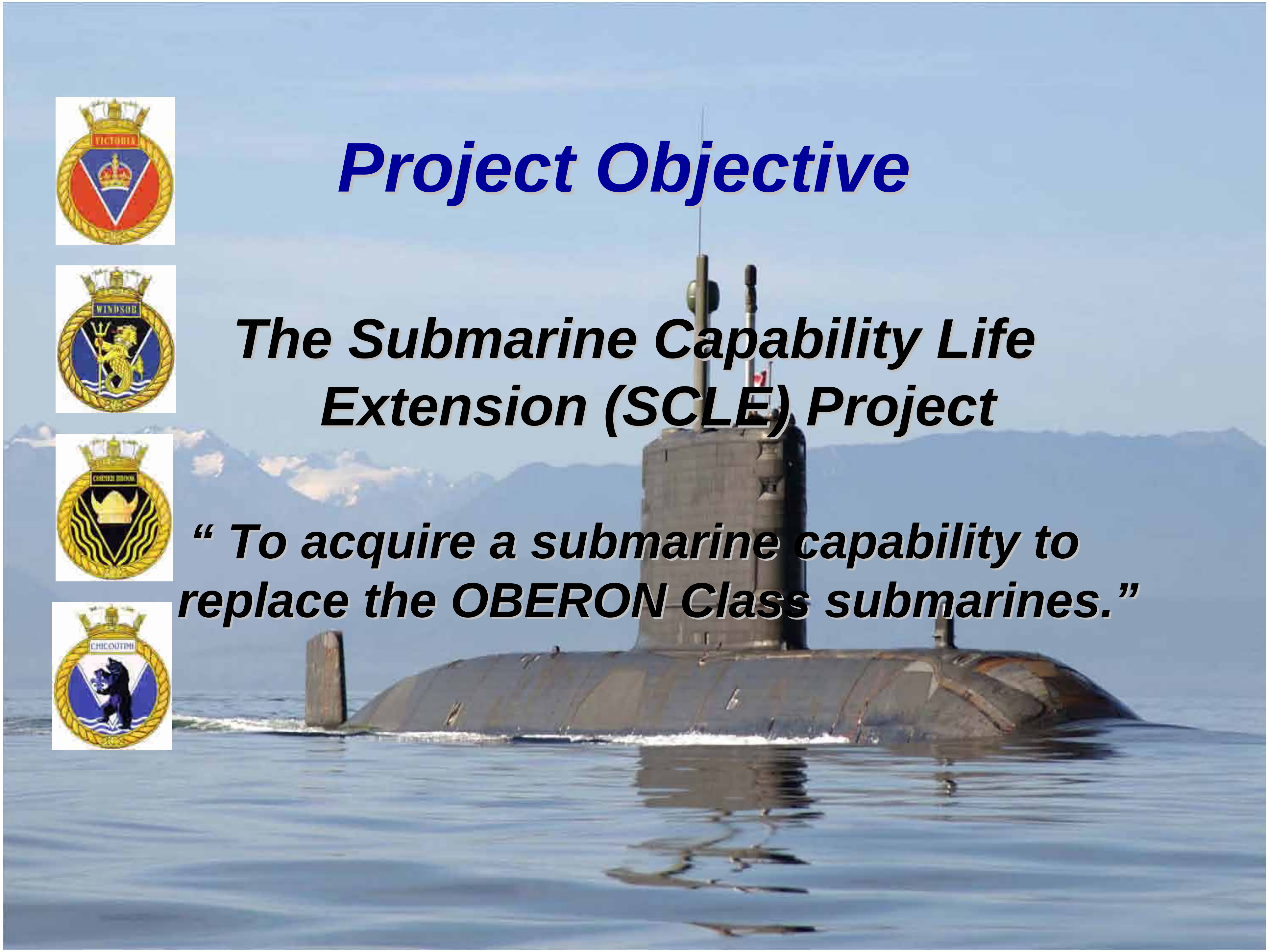
NDQAR (P)

Customer's Rep

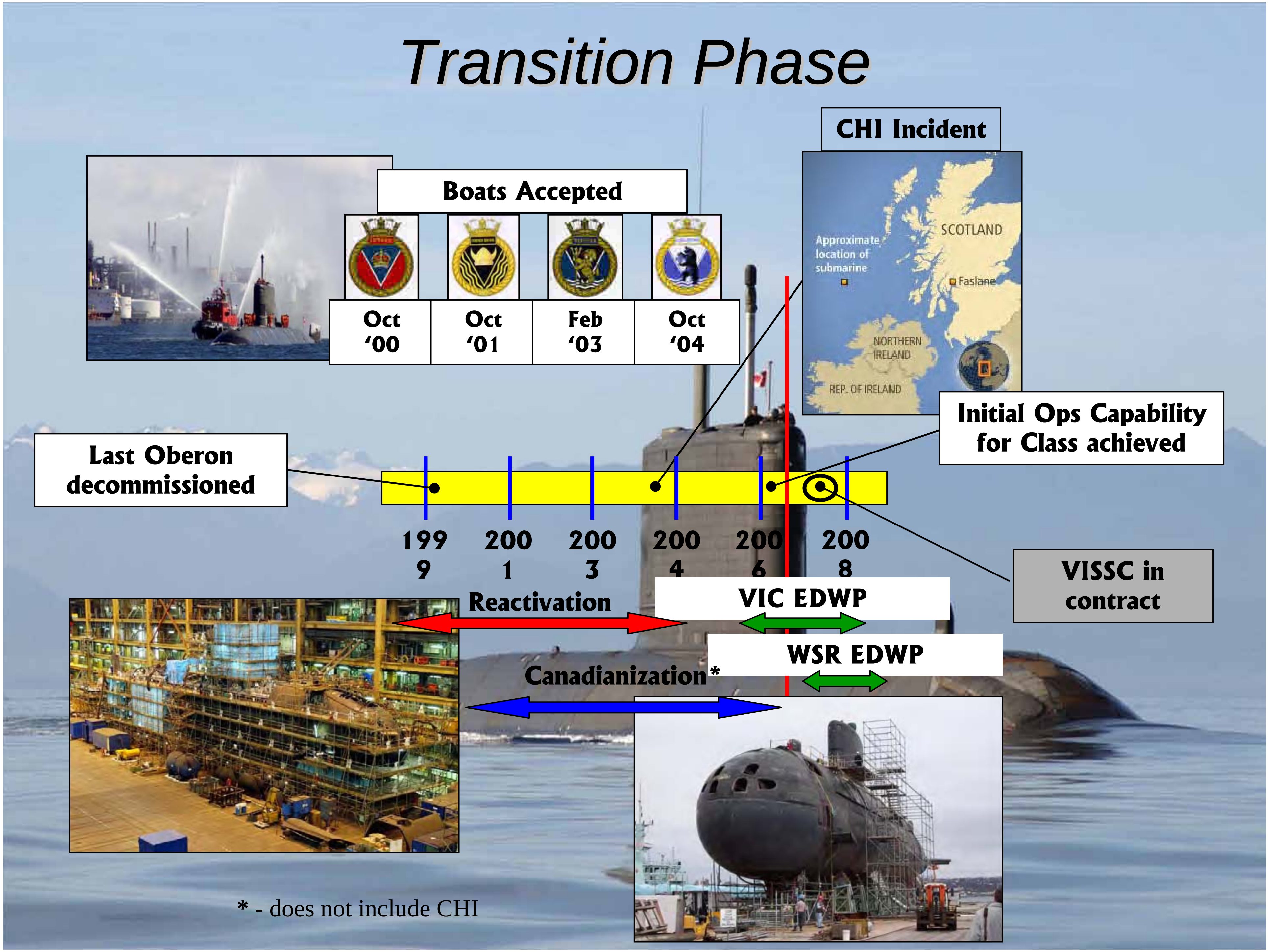
Current Successes..

- Canada still has 4 relatively new submarines
  - Experience/knowledge to support & operate increasing
    - West Coast presence - HMCS VICTORIA arrival
      - CHI/VIC in industry – earlier engagement
        - Contributing to submarine int'l Eng community
          - Sealift capability proven
            - VIC weapons discharge trial
              - Personnel training numbers increasing
                - Integrated Ops with allies

The Submarine Project



VICTORIA
WINDSOR
CORNER BROOK
CHICOUTIMI
Project Objective
The Submarine Capability Life Extension (SCLE) Project
“ To acquire a submarine capability to replace the OBERON Class submarines.”


Transition Phase
CHI Incident
Approximate location of submarine
SCOTLAND
Faslane
NORTHERN IRELAND
REP. OF IRELAND
Boats Accepted
Oct '00
Oct '01
Feb '03
Oct '04
Last Oberon decommissioned
Initial Ops Capability for Class achieved
1999
2001
2003
2004
2006
2008
VISSC in contract
Reactivation
VIC EDWP
WSR EDWP
Canadianization*
* - does not include CHI

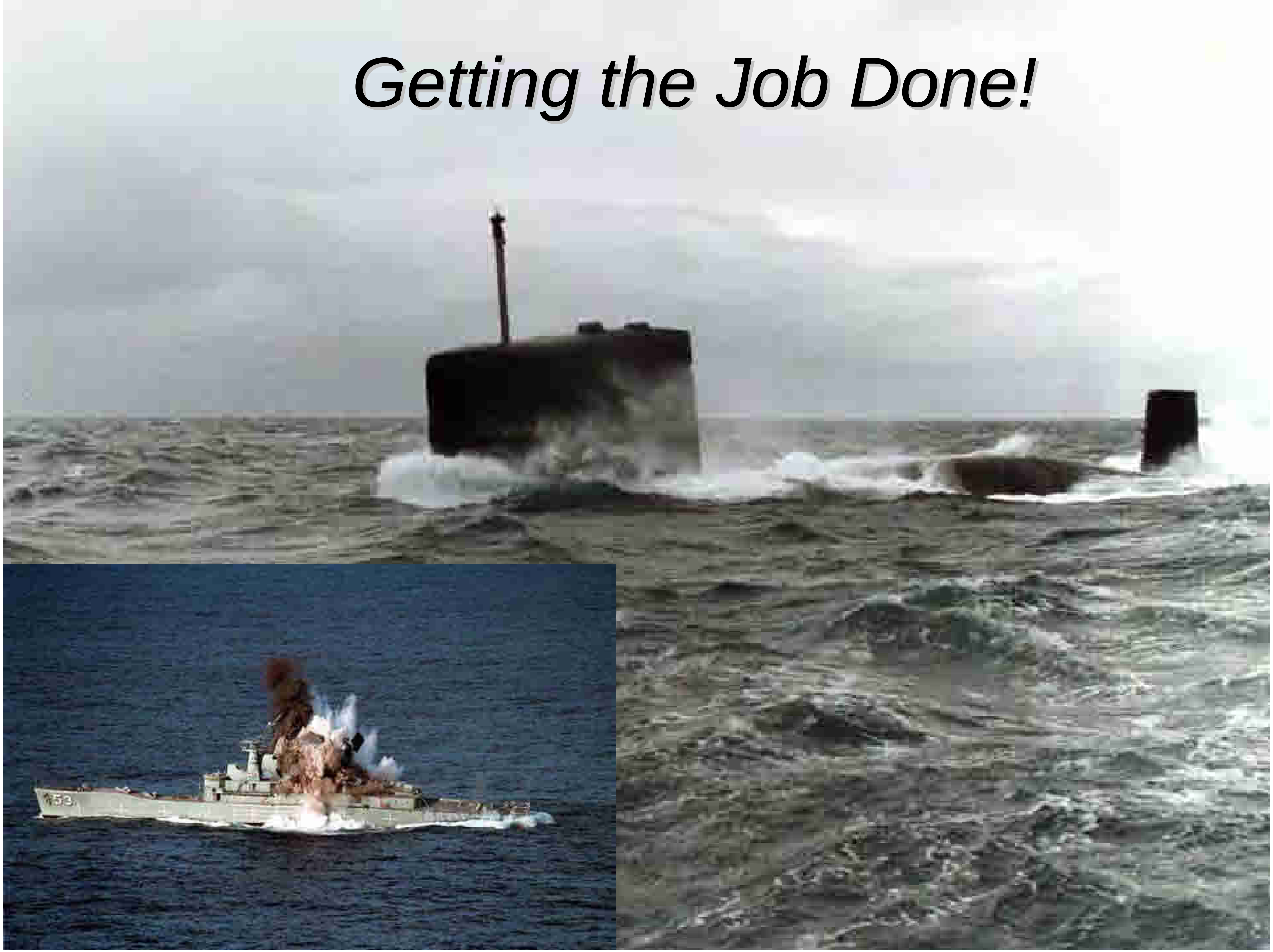
DDH Hanger - Barrow

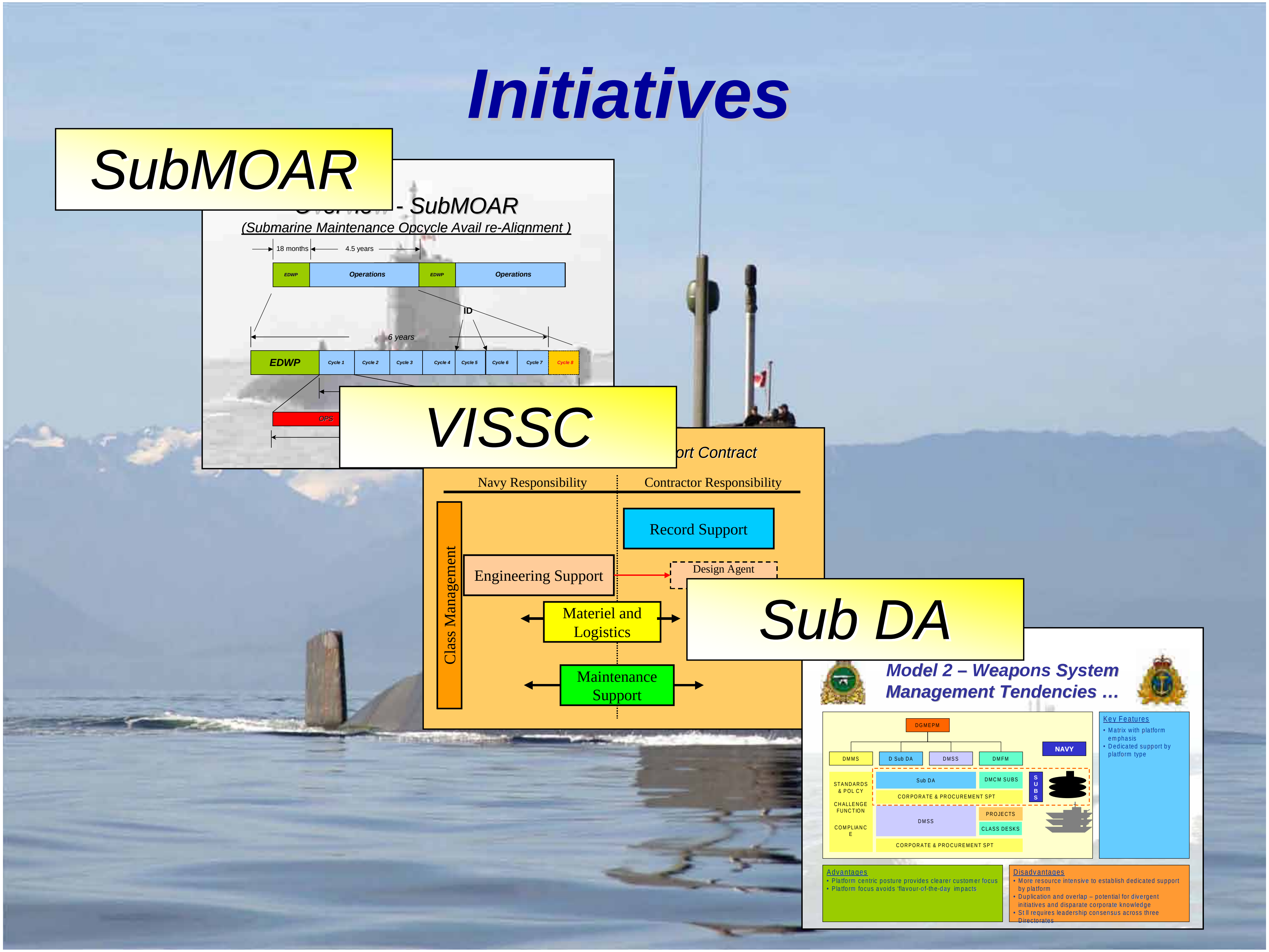
Reactivation/Canadianization


Transition Challenges
• Technologically advanced platform
• Lay-up & Reactivation Issues
• Technical Issues
• Developing a new SUBSAFE Culture
• Canadianization of UK Documentation & Processes
• Material Provisioning
• Bi-coastal submarine operations

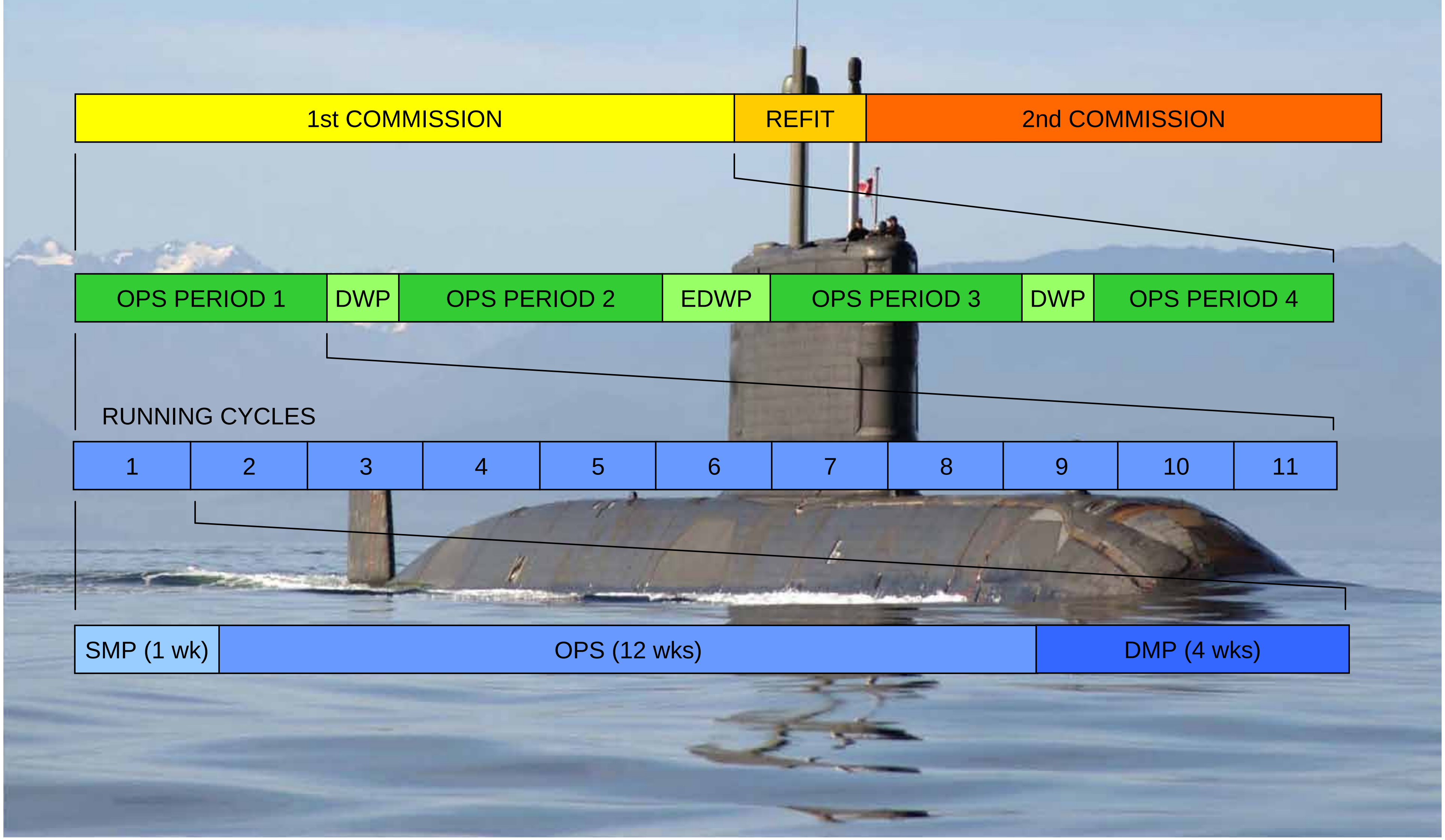
New Sub School

Getting the Job Done!

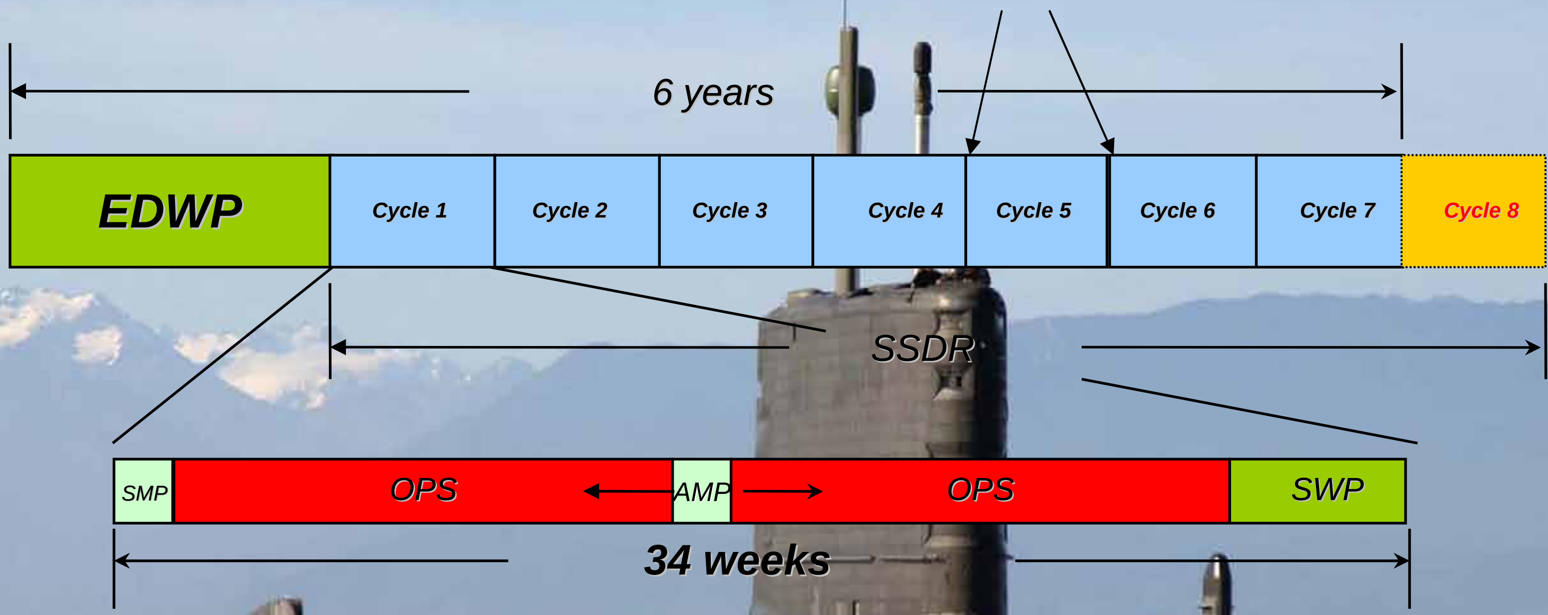



Initiatives
SubMOAR
- SubMOAR
(Submarine Maintenance Opcycle Avail re-Alignment)
18 months
4.5 years
EDWP
Operations
EDWP
Operations
ID
6 years
EDWP
Cycle 1
Cycle 2
Cycle 3
Cycle 4
Cycle 5
Cycle 6
Cycle 7
Cycle 8
OPS
VISSC
ort Contract
Navy Responsibility
Contractor Responsibility
Class Management
Record Support
Engineering Support
Design Agent
Materiel and Logistics
Maintenance Support
Sub DA
Model 2 – Weapons System Management Tendencies …
DGMEPM
DMMS
D Sub DA
DMSS
DMFM
NAVY
STANDARDS & POL CY
CHALLENGE FUNCTION
COMPLIANC E
Sub DA
DMCM SUBS
CORPORATE & PROCUREMENT SPT
S U B S
DMSS
PROJECTS
CLASS DESKS
CORPORATE & PROCUREMENT SPT
Key Features
• Matrix with platform emphasis
• Dedicated support by platform type
Advantages
• Platform centric posture provides clearer customer focus
• Platform focus avoids 'flavour-of-the-day impacts
Disadvantages
• More resource intensive to establish dedicated support by platform
• Duplication and overlap – potential for divergent initiatives and disparate corporate knowledge
• St ll requires leadership consensus across three Directorates

The Maintenance Profile



Phase 1 Deliverable – New 6 Year OPCYCLE



7 week SWP + 1 week SMP

2 week (notional) AMP to be scheduled as required within ops period

26 week ops period

12 week ID notionally sched at end of cycle 4 or 5 (tbc by phase 2) based on opsked and material requirements. ID cycle to be lengthened by 4 weeks.

Cycle 7 has no SWP

Cycle dates are fixed but within the cycle SWPs can be moved. Never more than 8 months between SWP

Materiel Certification Flexibility – one contingency cycle exists (cycle 8). SSDR valid to end of cycle 8, PM exists for cycle 8

Summary Data: 2M & below

SUBMOAR														
Before SubMOAR									SubMOAR					
SKILL SET								TOTALS	SKILL SET					TOTALS
	SS		RF		No Skill Set Assigned					SS		RF		
Periodicity	STARRED	NON STARRED	STARRED	NON STARRED	STARRED	NON STARRED	NO STATUS		Periodicity	SAFETY CRITICAL	NON SAFETY CRITICAL	SAFETY CRITICAL	NON SAFETY CRITICAL	
Occasional/ Daily	3	90	0	2	0	15	0	110	Occasional / Daily	3	34	0	0	37
Weekly	12	178	0	0	5	20	1	216	Weekly	2	69	0	0	71
Monthly	31	255	0	0	0	2	0	288	Monthly	9	101	0	0	110
2 Monthly	0	9	0	0	0	0	0	9	2 Monthly	1	9	0	0	10
3 Monthly									3 Monthly	0	1	0	0	1
No Frequency Applied	0	2	0	0	0	0	0	2	Sub Total SubMOAR PM					229
Sub Total Line Items								625						
									Removed					44
									Remove					310
									Removed Equipment					42
									Sub Total					396
TOTALS								625						625

Work Package

- Initial concept was "Essential Defects and Extended Docking" (EDED). In a few cases "REFIT" is appropriate primarily in the areas of all the Weapons Handling and Discharge Systems (WHDS), approx 15%
- The levels of the work packages were also influenced by the following factors:
  - First of class work to be performed;
  - Unfamiliarity with platform and systems;
  - Stringent MATCERT criteria;
  - Need a baseline for rest of class;
  - Risk adversity; and
  - Boat launched in 1989, thus hull has been wet for 16 yrs.

Key Project Assumptions

- *All Material & SPTATE will be available as reqd;*
- *FMF and Sub-Contract resources will be available as planned (~3200 DLHs/wk);*
- *Design Authority turn-around of Deviations and Waivers within 48 hours;*
- *Class Desk approval of Arisings within 48 hours;*
- *Plan will be predicated on 2 shifts per day, five days per week. Graveyard (1st) shift will be utilized to de-conflict work.*

Risks

- ***Timely identification and delivery of <u>material</u> with correct documentation;***
- ***Steep learning curve for FMF on a new platform;***
- ***Unique challenge of integration of Contractor and FMF workforce;***
- ***WHDS/SSE contract, working closely with LCMMs; and***
- ***Arisings are estimated at 35-40% where typically we have seen 40% in surface fleet DWP and refits.***


The Programme Plan
Transition to EDWP Completion…
Cost
Time
Scope
Arisings
… to TRP & Ops

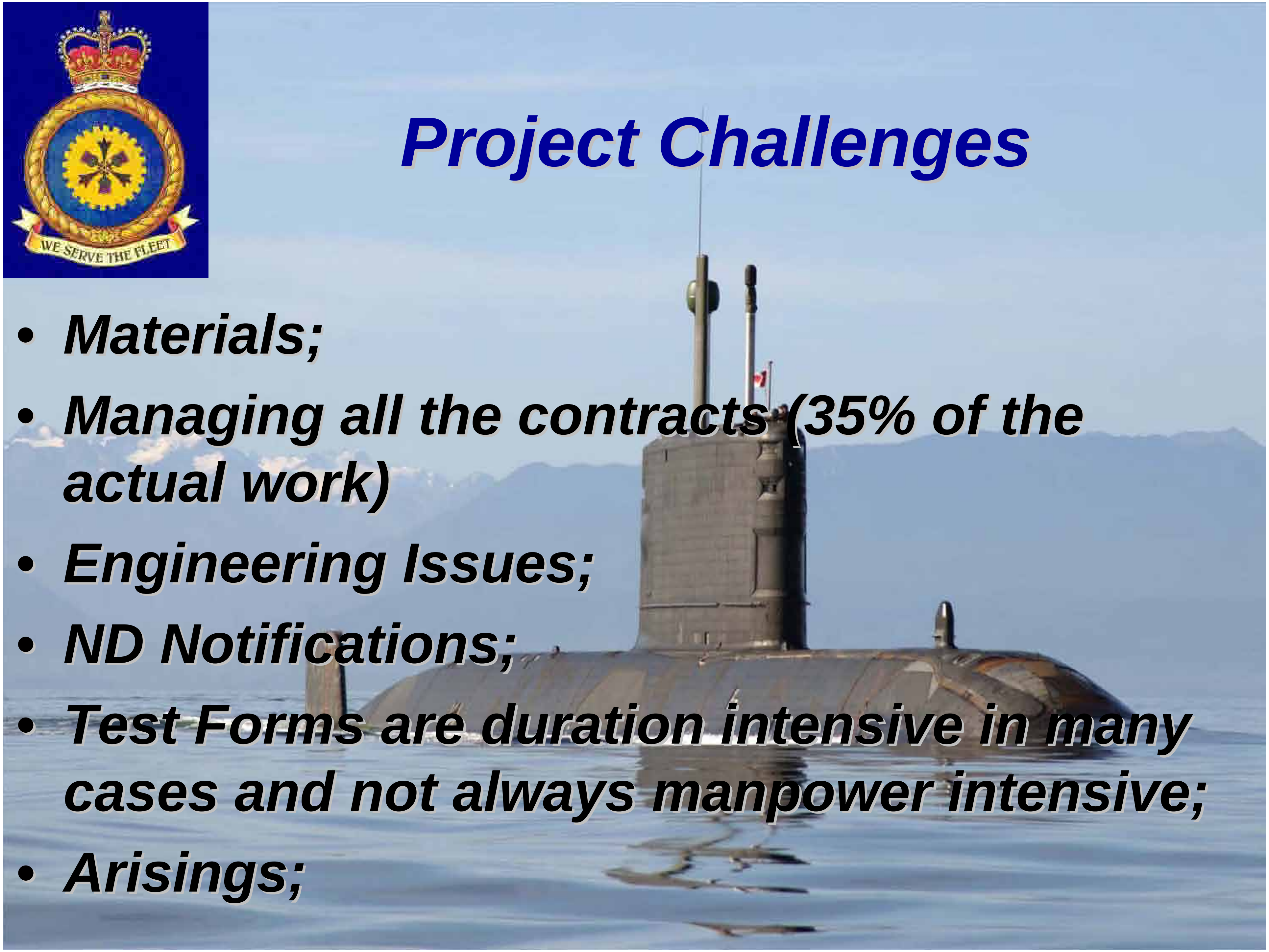
Contracts i.e. WHDS/SSE

VIC EDWP Overview

- *Apr 04 - dedicated FMF Project Management team for VIC EDWP established*
  - *Original start date - Jun 04*
    - *Delayed to - Nov 04*
    - *Moved to - Jan 05*
    - *Extended to - Jun 05*

- *197 Specifications and 31 ECs*
  - *Baseline Package - Feb 05*
  - *1st Supp - Jun 05 (Total change to previous package)*
  - *2nd supp - Aug 05 (material changes)*
  - *3rd supp - Mar 06 (8 Weapons and ATP Specs)*

- *Materials*
    - *Initial review (04 – 05) – 2400 Line Items*
    - *June 06 - 7527 Line Items*
    - *Sept 06 - 11,000 Line Items*
    - *Nov 2007 - 20,000 Line Items*



Project Challenges

- ***Materials;***
- ***Managing all the contracts (35% of the actual work)***
- ***Engineering Issues;***
- ***ND Notifications;***
- ***Test Forms are duration intensive in many cases and not always manpower intensive;***
- ***Arisings;***

FMF Cape Breton

FMF Cape Breton

- *DND Strategic asset*
- *1200 employees (120 of which are military)*
  - *Engineering Section (150 People)*
  - *Production Section (800 People)*
  - *Business Section*
  - *Quality Management*
  - *HR Section*
  - *Corporate Services Section*
  - *VIC EDWP Project (up to 250 people)*
- *VIC EDWP uses up to 1/3 of output capacity*
- *Under contract with DGMEPM to complete the VIC EDWP*
- *Unit is set up to mainly deal with 1st and 2nd level maintenance, not 3rd level maintenance*

VIC EDWP Concepts

- *Dedicated Project Team*
- *Dedicated Production, Planning, Engineering, Materials, Quality and Contracts team*
- *Contracting "whole specifications" to outside industry (originally went with 18 Specs to VSL)*
- *Use of Primavera and a project management tool*
- *First use of MASIS (SAP Application) for major 3rd level naval activity*
- *Development of WIP program for total internal control and tracking of materials*
- *Use of WINSETS for submarine system lock out protection*
- *Manned EDWP with VICTORIA's crew*
- *Deviated from a master materials list (could not keep up on changing material picture)*
- *Weapons work would be under another contractor with FMF CB production staff working as sub-contractor labour.*
- *Zone Production concept transitioning back to system concept upon completion*

VIC EDWP Work

Control Room- AXP prior to removal

Control Room- AXP after removal

Dent Cut-out

Obsolescence

SSDR Extensions

Extensions since CHI Incident		
Submarine	Extension	Length
Victoria	**Jun 05**	**6 mths**
Windsor	**Jun 06**	**12 mths**
Windsor	**Dec 06**	**6 mths**
Corner Brook	**Jul 08**	**24 mths**

Planned Extension		
Submarine	Extension	Length
Corner Brook	**June 11**	**3 yrs**

CHICOUTIMI Fire and Transport

VIC EDWP Experience
Leverage → WSR EDWP

- ***Specification Maturity;***
- ***Material identification and ordering;***
- ***Work Package appreciation;***
- ***Overall Planning;***
- ***Tools (Primavera, MS Project);***
- ***Limitations of Learning – will not be able to capture all lessons learned in conducting the work.***

WSR and CHI (Halifax, NS)

WSR and CHI - Mar 08

CHI May 08

Key Lesson's Learned

- ***Work package defined 12 months prior to execution phase;***
- ***Specifications grouped to proper parent systems;***
- ***Mature material lists with each specifications;***
- ***Proper identification and pre-staging of materials prior to execution phase;***
- ***Value of dedicated production resources and project management team;***
- ***Need for a robust "project management" planning tool;***
- ***Need to do "Pre-EDWP" surveys to reduce arisings and scope creep;***
- ***Need for high levels of engineering support; and***
- ***Systems approach works better for ease of scheduling and cost.***

Key Lesson's Learned

- ***Culture change (West) for true 3^{rd} level activity which results in longer delays in implementing changes***
- ***Contracting out only smaller portions of specs or common work vice "whole specifications" Both have pro's and con's***
- ***Up Rev or specifications and master material list as required***
- ***Systems or specifications approach to the work package***
- ***Demand placed on the logistics team much higher (use to 1^{st} and 2^{nd} levels of maintenance)***
- ***Impact of obsolescence and need for local suppliers***
- ***Need to get parts into the Repair Loop early and R&O contracts well established***

Project Successes!!

- **Start of First EDWP for VCS!!**
- **First true Materiel Picture_Lessons Learnt;**
- **Resolution of several class Engineering Issues;**
- **Significant PM work for FMFCB (teamwork);**
- **Quality Submarine skill set development;**

Project Challenges!!

- **Materials still a challenge!!**
- **Engineering Issues ongoing**
- **Focus on Project Plan Development to complete EDWP**
- **Managing Production and Engineering progress across the platform**
- **Around the corner (contracts, equipment delivery to plan, arisings, paperboat, etc..)**


The only thing that ever really frightened me during the war was the U-boat peril
Winston Churchill
The Future …


Questions ?
LCdr Derek Hughes, SM 5-4
LCdr Memphis Don, A/SM 5
WE SERVE THE FLEET
DMEPM(SM)
DGestPEM(SM)