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COMPOSITE HULL FOR AN AMPHIBIOUS VEHICLE

Design, Fabrication, and Testing of a
Composite Hull for a Tracked Amphibious Vehicle
Phase I and II Final Report

August 1988
Period Covered:
30 December 1983 - 31 October 1986

Prepared under Contract N00167-84-C-0023 for:

David Taylor Research Center
Bethesda, Maryland 20084

Prepared by:

Martin Marietta ~~Corporation~~
Aero & Naval Systems
103 Chesapeake Park Plaza
Baltimore, Maryland 21220

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In response to a Marine Corps request for a lightweight composite hull for amphibious vehicles, a glass reinforced plastic (GRP) hull for an M113A1 armored personnel carrier has been designed, fabricated, and tested under phases I and II of a David Taylor Research Center development program.

The one-piece, molded hull of epoxy E-glass woven laminate is joined to a welded aluminum lower hull to provide a lightweight, buoyant vehicle, armored on the sides, front and rear by 4-inch square ceramic tiles protected by thin aluminum sheet. Thickness of the composite material is 0.75 inch at the sides and 1.25 inch at the roof.

Design efforts were marked by a number of key developmental activities including structural design, stress analysis and material evaluation as well as fabrication of the hull. In addition to delivering test panels to DTRC, the contractor also conducted repairability

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A completed vehicle was delivered to the Marine Corps for field testing. The vehicle went through one year of rigorous field tests with no observable degradation of the composite hull.

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Program Manager

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PREFACE

This final report covers work performed by Martin Marietta Corporation, Aero & Naval Systems under Phases I and II of Contract N00167-84-C-0023, "Design Fabrication and Testing of a Composite Hull for a Tracked Amphibious Vehicle." It covers work performed from 30 December 1983 through 31 October 1986. The contracting officer's technical representative (COTR) for the program was Mr. Richard A. Swanek, Marine Corps Program Office, David Taylor Research Center, Bethesda, Maryland.

Mr. R.C. Curley was the Martin Marietta program manager responsible for planning and conducting all respects of the program.

Principal contributors to the Martin Marietta activities described in this report were: R.L. Bernstein, and E.L. May, C.S. Stoddard - structural design; R.M. Hill and A.P. DeCicco - Tooling, and C.T. Kogut, B.L. Rosenquist, R.D. Hoskins and R.G. Schmitt - Fabrication and Assembly.

ABSTRACT

In response to a Marine Corps quest for a lightweight composite hull for amphibious vehicles, a glass reinforced plastic (GRP) hull for an M113A1 armored personnel carrier has been designed and fabricated under Phases I and II of a David Taylor Research Center (DTRC) development program.

The one-piece, molded hull of epoxy E-glass woven roving laminate is joined to a welded aluminum lower hull to provide a lightweight, buoyant vehicle, armored on the sides, front and rear by 4-inch square ceramic tiles protected by thin aluminum sheet. Thickness of the composite material is 0.75 inch at the sides and 1.25 inch at the roof.

Design efforts were marked by a number of key developmental activities including structural design, stress analysis and material evaluation as well as fabrication of the hull. In addition to delivering test panels to DTRC, the contractor also conducted repairability and fabrication methods studies and provided production cost estimates and vehicle weight and flotation stability calculations.

A completed vehicle was delivered to the Marine Corps for field testing. The vehicle went through one year of rigorous field testing without any detectable degradation of the composite hull.

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ILLUSTRATIONS

TABLES

1.0 INTRODUCTION

The Marine Corps Programs Office of the David Taylor Research Center (DTRC) presently manages an Exploratory Development program, Marine Corps Surface Mobility, in which a technology base is being developed for future Marine Corps amphibious vehicles.

As a part of this program DTRC is pursuing the development of a lightweight composite hull for possible use on future amphibious vehicles. This development program was undertaken to demonstrate the technical feasibility of using composite materials for hull construction and to quantify possible weight and cost savings.

As an initial step in this program, Martin Marietta Aero & Naval Systems, under Phase I of a contract with DTRC, has designed a glass reinforced plastic (GRP) hull for an M113A1 armored personnel carrier (Figure 1-1). In Phase II of the contract, the GRP hull was fabricated, outfitted with Government furnished equipment, fittings and running gear from an M113A1 vehicle, and delivered for test and evaluation to the Marine Corps.

The principal objectives of the effort are:

1) Demonstrate that a lightweight reinforced plastic (RP) hull is feasible.

2) Determine whether an RP hull is affordable for use in a production vehicle.

3) Demonstrate that the maintainability, repairability, etc. of such a hull is acceptable.

Tasks performed during the Phase I effort included structural design, stress analysis, materials evaluation, fabrication and delivery of test panels, a repairability study, a fabrication methods study, a production cost estimate, and vehicle weight and flotation stability calculations.

The experimental hull design consists of a single piece GRP upper hull joined to an aluminum lower hull (Figure 1-2). The two hull sections are joined by a bonded and bolted lap joint. All openings in the GRP upper hull are surrounded by aluminum frames to protect the edges of the GRP laminate and provide a suitable interface with the Government furnished hatches, doors, covers, etc. installed on the hull. The sides, front and rear of the GRP structure are covered with ceramic tiles.

Tasks performed during the Phase II effort included detail design, fabrication and delivery of test panels, hull fabrication, vehicle assembly, and delivery of the vehicle to the Marine Corps for field testing. Results of the Marine Corps tests are included in this report.

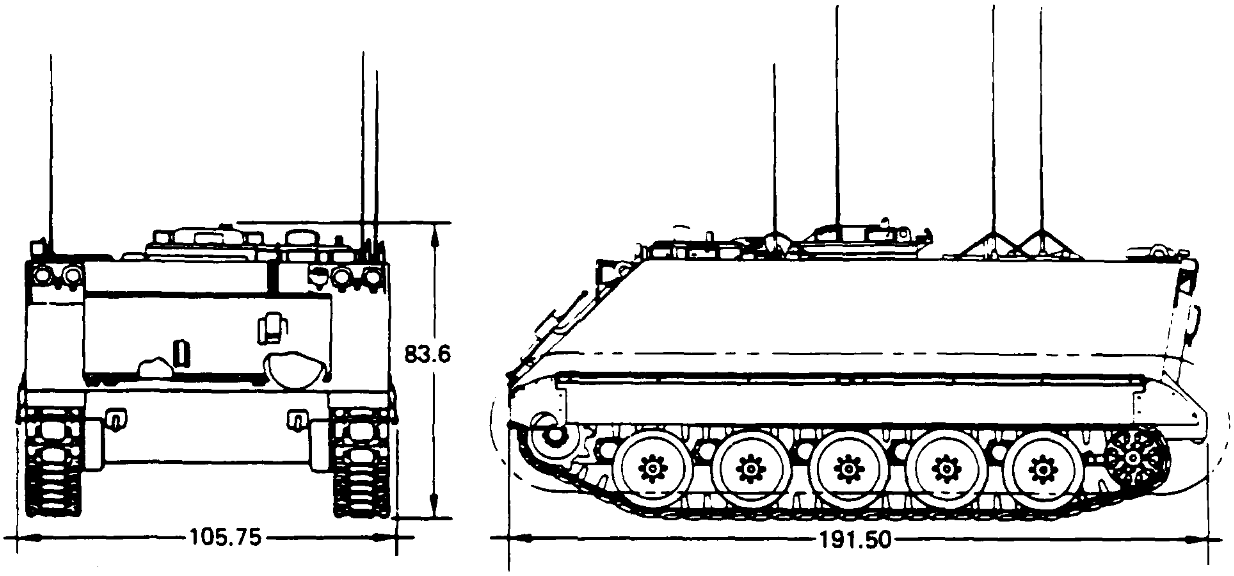


Figure 1-1. M113 Vehicle

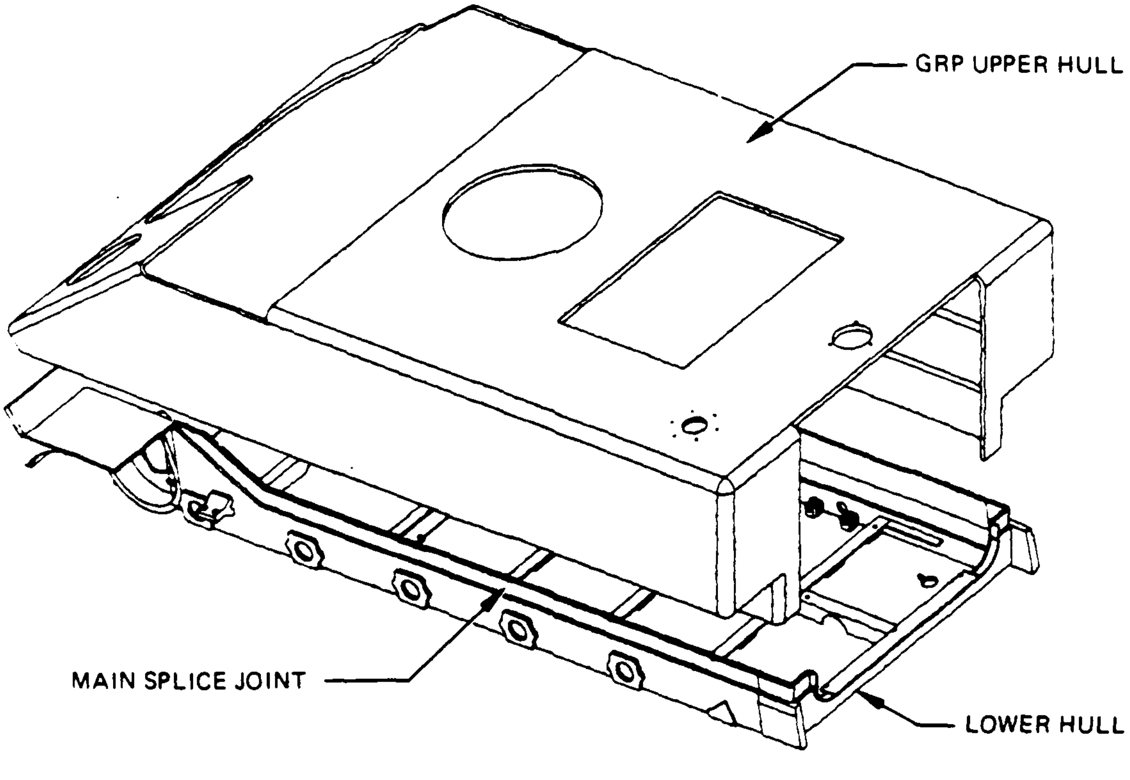


Figure 1-2. Upper and Lower Hulls

2.0 HULL DESIGN

The selected hull configuration consists of a monocoque GRP upper hull mechanically fastened and bonded to a welded aluminum lower hull (Figure 2-1). Design studies concluded that by using aluminum structure in those areas routinely subjected to high point and localized loads (e.g., areas such as the power plant and suspension system mounts) and GRP structure in all other areas, a functionally optimized lightweight vehicle could be derived.

The aluminum lower hull (Figure 2-2) is both physically and functionally similar to the lower aluminum pan used in the existing M113 vehicle. It provides interfaces for the drive train and suspension, the systems that impart the highest point loads into the vehicle, which are identical to those in the design of the present M113. All critical, highly loaded interfaces with the drive train suspension system are metal. This avoids the problems associated with attaching the highly loaded suspension components to composites. This configuration also alleviates concern relative to highly torqued fasteners in the suspension mounting areas. These areas require fasteners as large as 5/8 inch, torqued to values in excess of 100 foot-pounds. There are severe practical problems associated with using highly torqued bolts in composite structures, including insert twist-out and compressive creep during periods that the composite structure is under high loads. In addition to maintaining a simple, structurally sound method for attaching the above mentioned systems, the aluminum lower hull retains metal in the nose and floor plate areas which are subject to the worst impact and abrasion during service.

The GRP upper hull designed for the final configuration is molded in one piece (Figure 2-3). It utilizes the 0.75 inch wall and 1.25 inch roof thickness of E glass woven roving laminate recommended in the contract Statement of Work (SOW).

The selected GRP laminate is one optimized for structural properties as opposed to ballistic properties (i.e., a laminate having a structural epoxy resin and a woven roving treated with a resin compatible finish, in contrast to a laminate having the resin incompatible starch oil finish normally associated with ballistic GRP laminates). This choice was made because the structural integrity of the vehicle is dependent upon retaining the mechanical properties of the GRP laminate. This can only be achieved by utilizing a compatible finish which bonds the fibers to the Matrix to form an interface essentially impermeable to moisture. The commonly used incompatible finishes associated with ballistic applications (e.g., starch/oil) are known to be subject to high levels of degradation when exposed to moisture for extended periods of time and, therefore, have been discounted for use.

The armor configuration (Figure 2-4) is also as recommended in the SOW. A tile-to-hull bondline thickness and tile-to-tile gap of .062 inch were selected based on stress analyses (refer to Section 4.0). the preferred material for the tile protective cover is thin aluminum sheet.

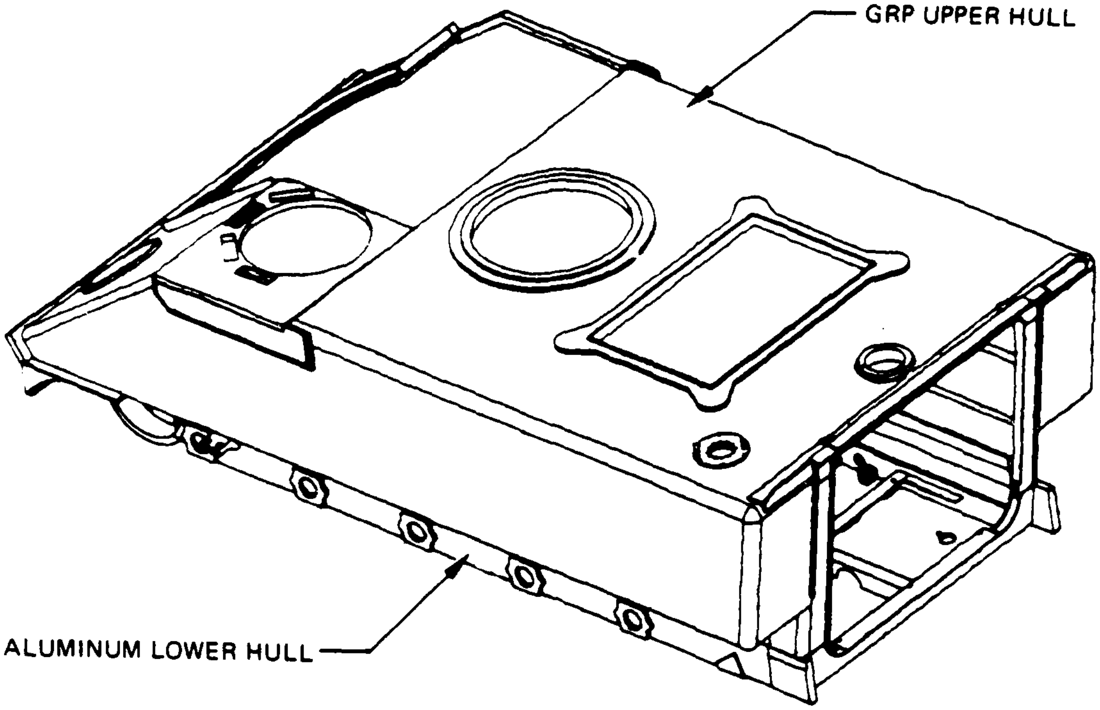


Figure 2-1. Hull Assembly

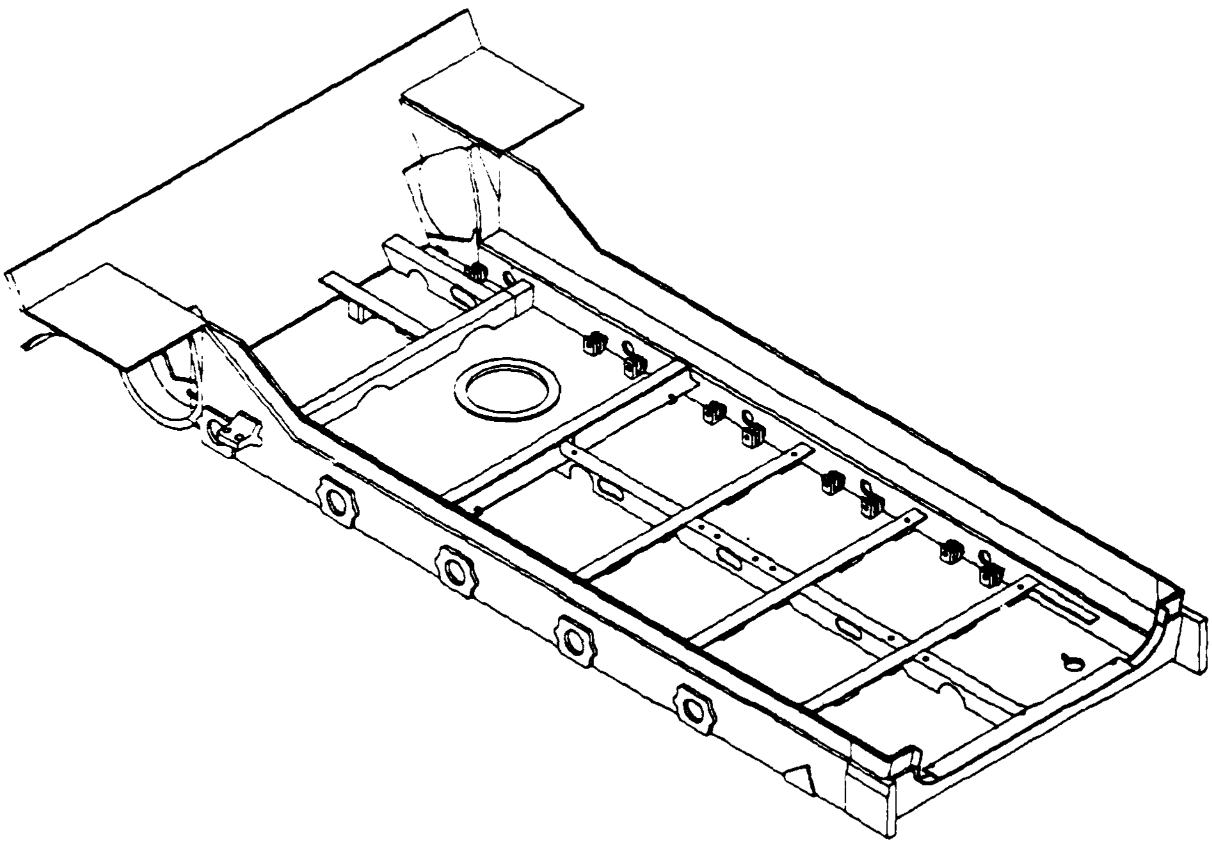


Figure 2-2. Aluminum Lower Hull

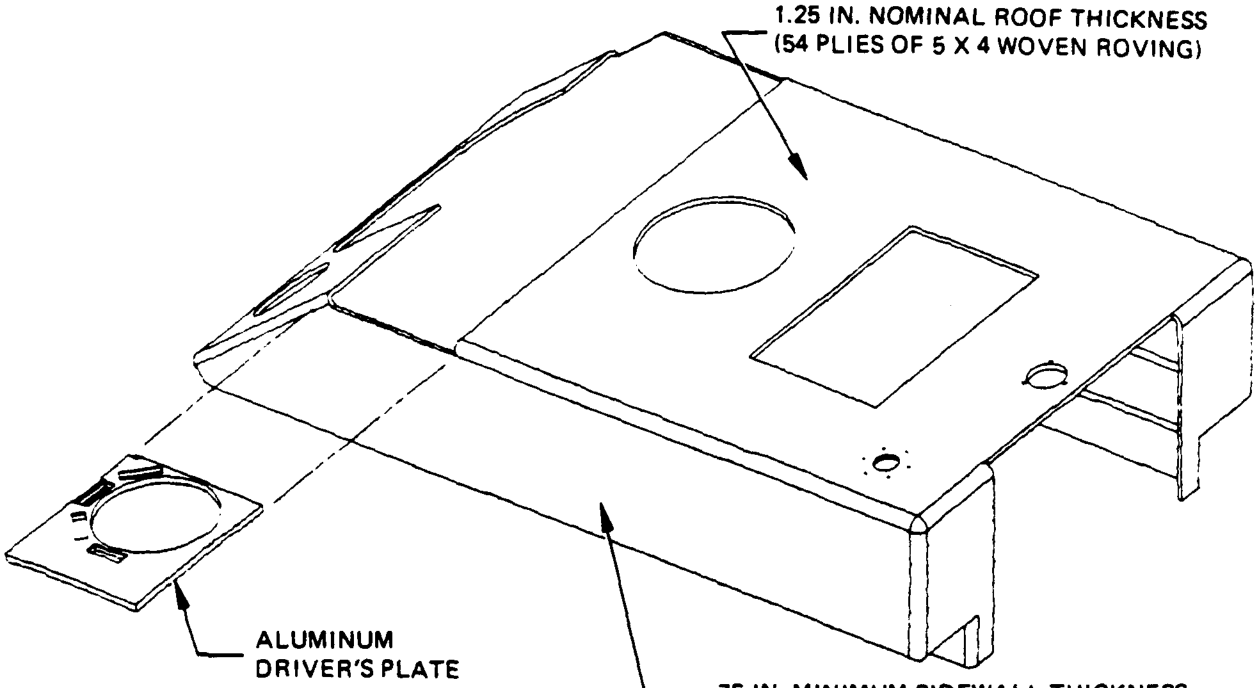


Figure 2-3. GRP Upper Hull

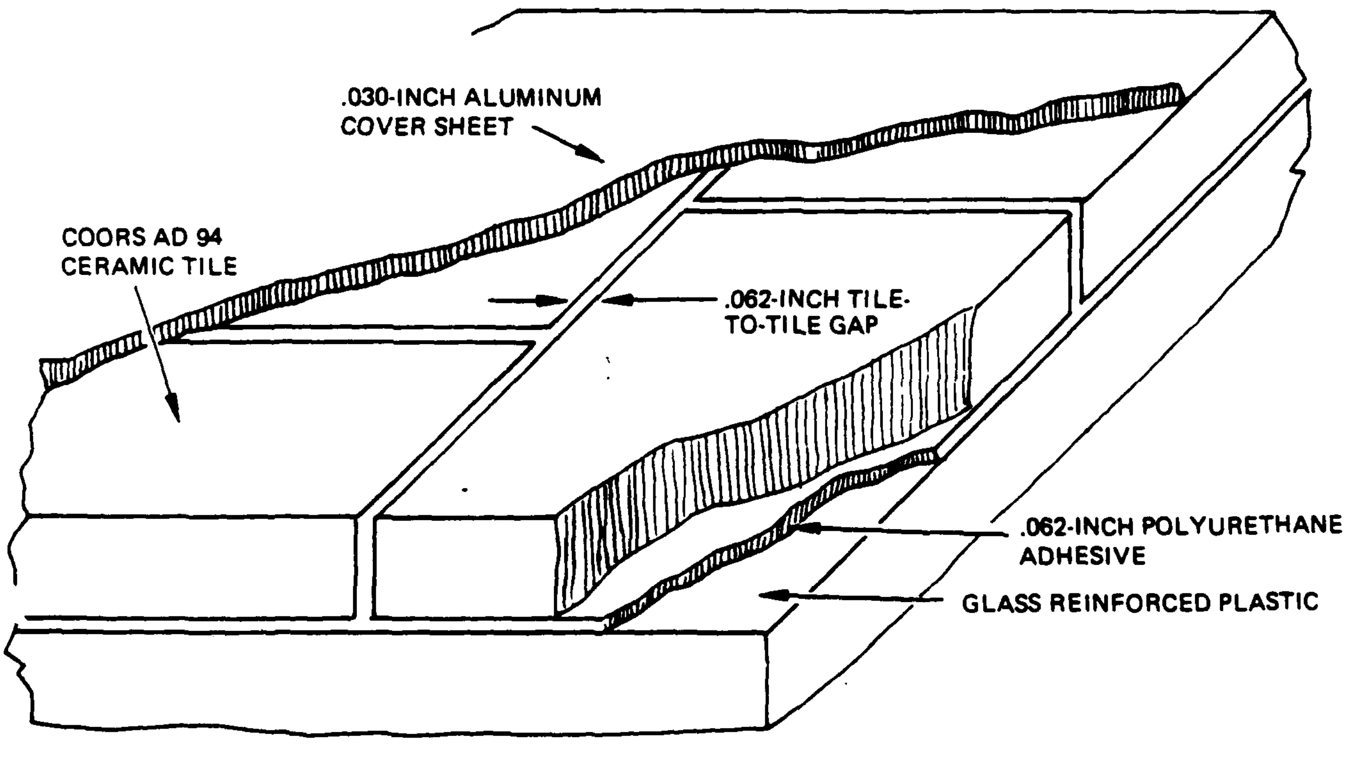


Figure 2-4. Armor Configuration

Another feature of the final design configuration is the simplicity of the mechanical joint used to attach the GRP upper hull to the aluminum lower hull (Figure 2-5). The design of this joint resulted from the requirement for watertightness rather than structural load transfer requirements. The bolt pattern and spacing determinations for the joint area were defined by combining routine composite material design practices with common watertight hull and boiler code design practices. The result is a joint configuration which is watertight and in which the fastener loading is low.

Other general design features of the final design configuration include: the use of aluminum rings and frames to protect exposed laminate edges from fraying and delamination due to traffic abuse (Figure 2-6), the incorporation of aluminum rub strips to protect the GRP in areas routinely subjected to severe abrasion (e.g., in the track channels -- Figure 2-7), and the complete sealing of edges and joints where the composite material is exposed to severe operational environments.

It is seen that both the rings and the frames are designed to accommodate the thickness variations inherent in the GRP construction by allowing bearing plates or edge guards to move relative to the rings and frames. Vehicle edges are fitted with aluminum guards to protect exposed edges of the ceramic tiles. Typical edge guard installations are shown in Figure 2-8.

A problem introduced by the use of GRP in the hull design is the treatment of attachments to the hull. In a metal hull, attachments are made by using tapped holes or welded brackets. This allows almost complete freedom as to when and where such attachments are made. With a GRP hull, welded attachments are not possible and there are usually limits on the load carrying ability of items bolted directly into the GRP.

The general design approach for this program is to keep attachments identical to those in the existing hull wherever possible (i.e., welded to the lower hull), to bolt through the GRP for upper hull when attachment loads are greater than 20 pounds and to bolt to the GRP hull, using inserts, for loads less than 20 pounds (Figure 2-9), with special consideration being given to lightweight objects which can be unintentionally or routinely used as a hand or foothold. Table 2-1 provides a summary of the selected mode of attachment for the vehicle equipment and controls to be incorporated in the composite vehicle.

Several features of the design result from the need to interface with existing M113 equipment. The envelope of the hull has been kept as close as possible to that of the M113 to avoid problems with equipment installations. An aluminum plate is used in an area around the driver's hatch that would be expected to be GRP (Figure 2-3). This plate is used because congestion caused by the hatch, periscopes, engine door and hull edge made it impractical to carry GRP construction into this area. The various offsets in the main joint result from avoiding the running of the joint through existing equipment installation in the front of the vehicle. In a GRP hull designed from scratch these and other design details could be simplified.

The complete hull assembly is detailed in Figure 2-10.

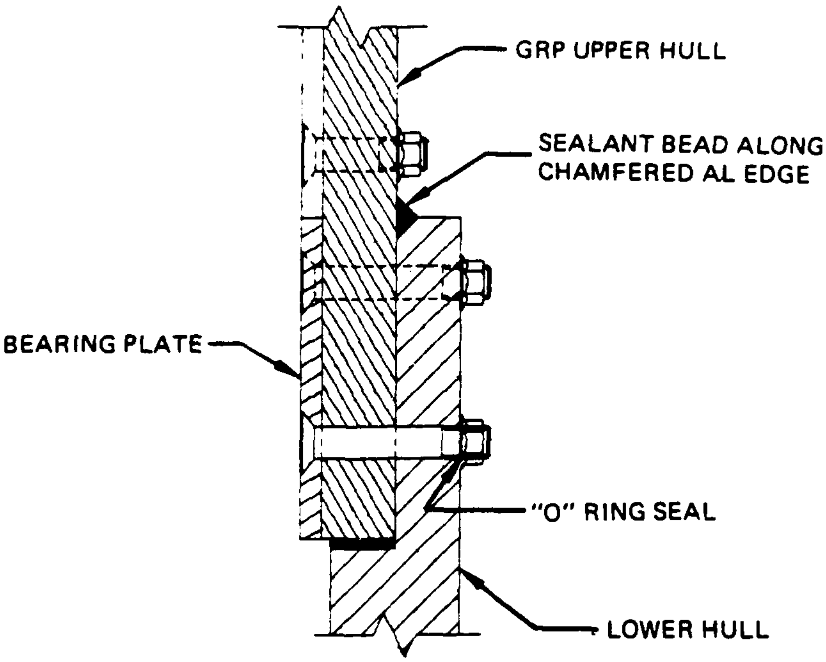


Figure 2-5. Main Hull Joint

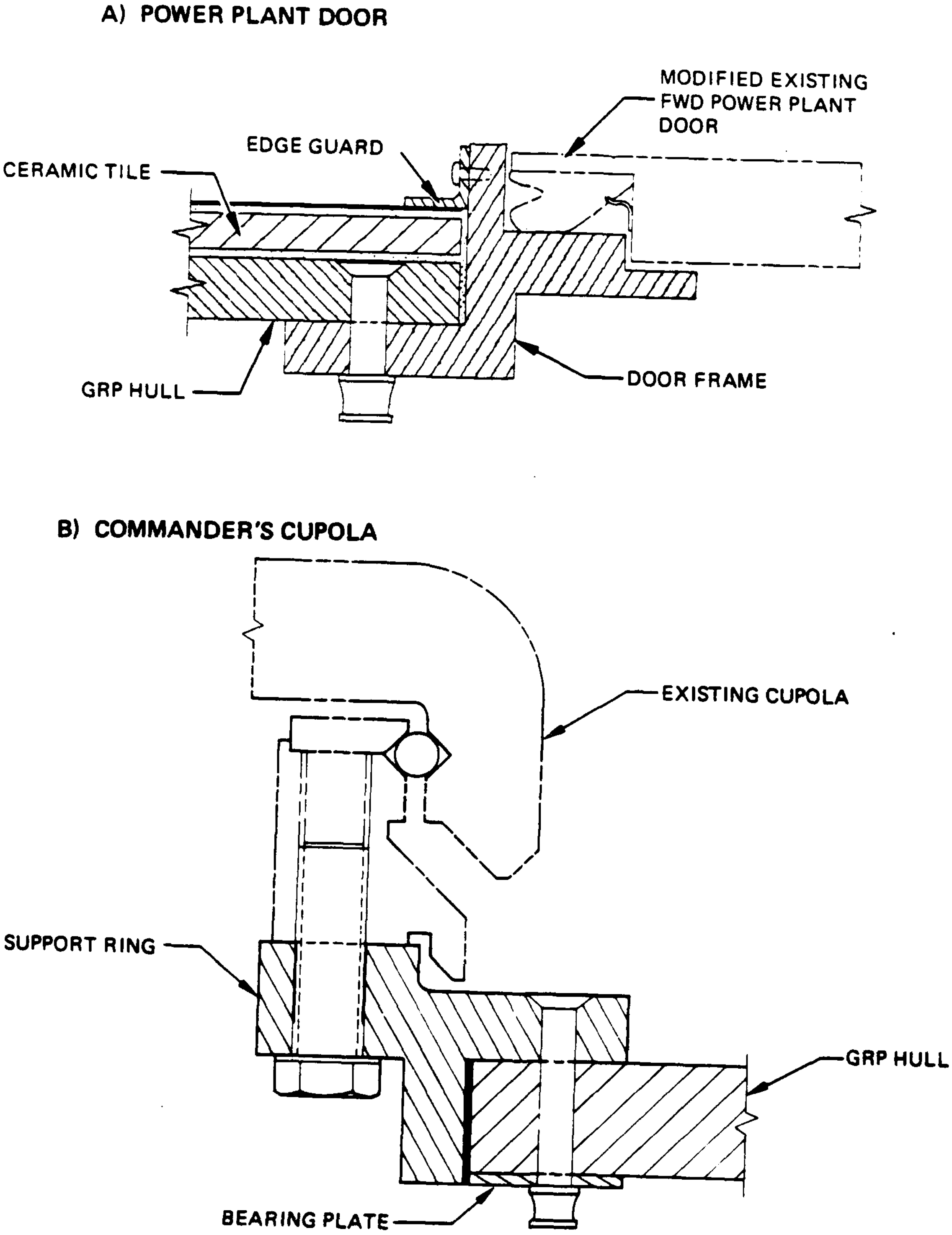


Figure 2-6. Cross Section of Typical Hull Openings

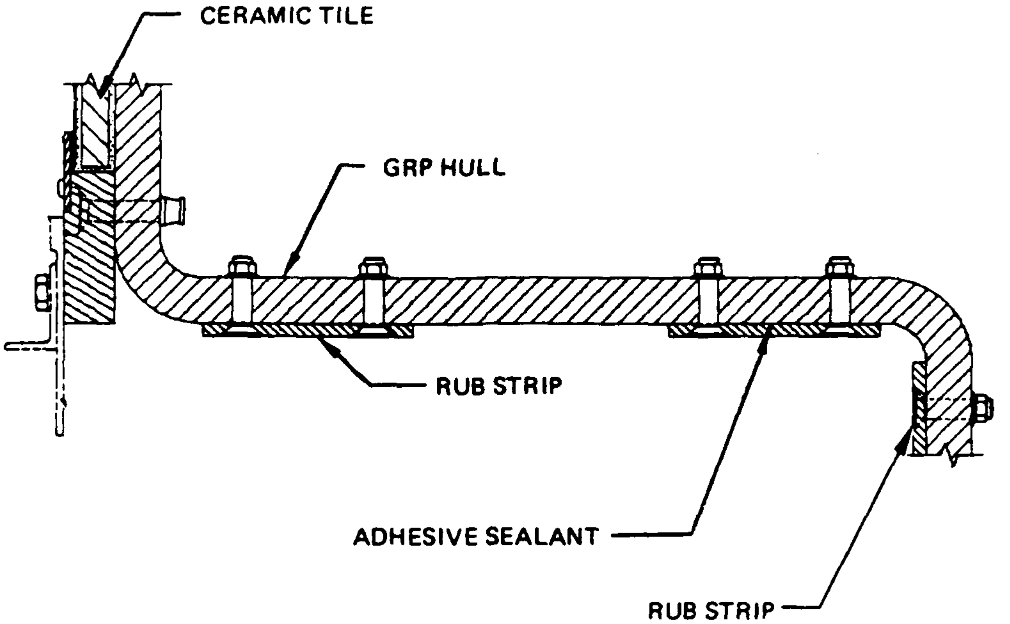
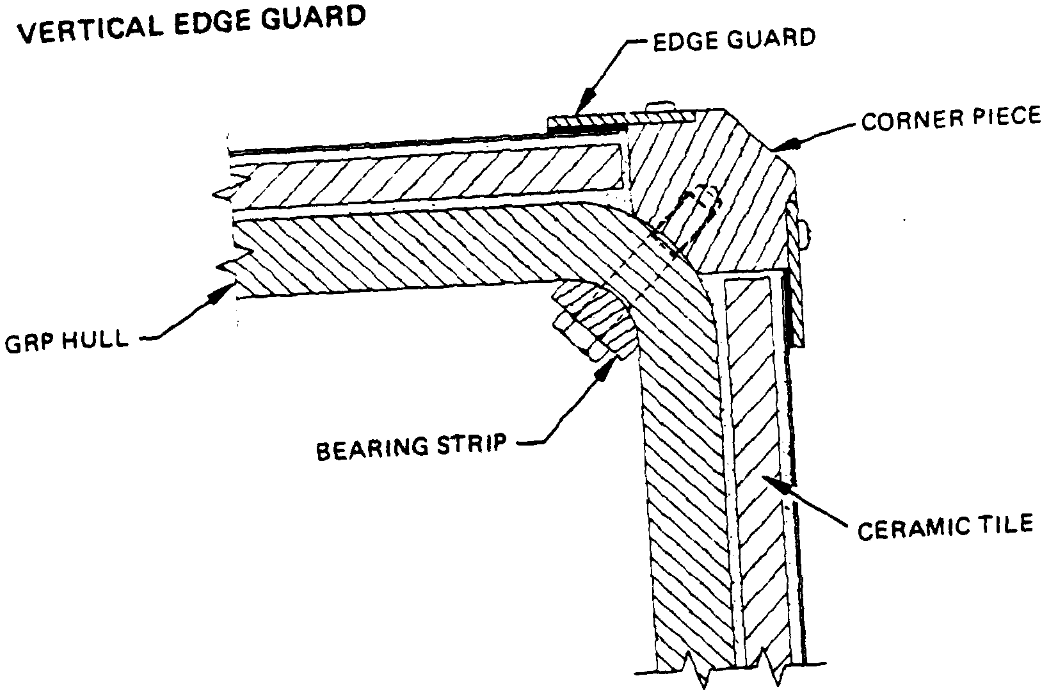


Figure 2-7. Rub Strip Installation

A) VERTICAL EDGE GUARD



B) UPPER EDGE GUARD

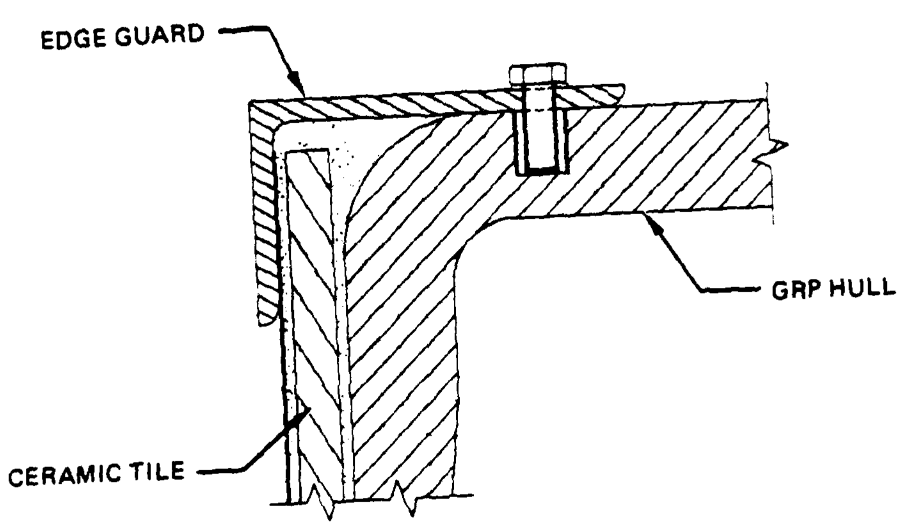
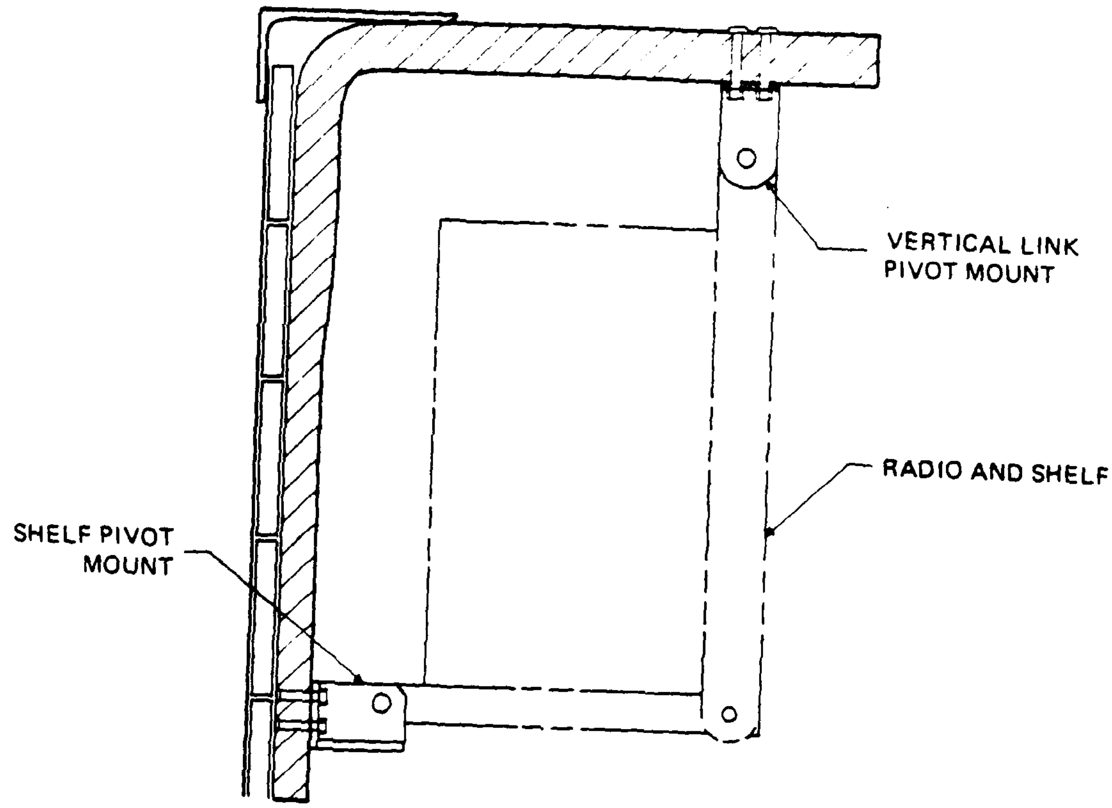


Figure 2-8. Edge Guard Installation

A) BOLT THROUGH GRP ATTACHMENT



B) BOLT TO GRP ATTACHMENT

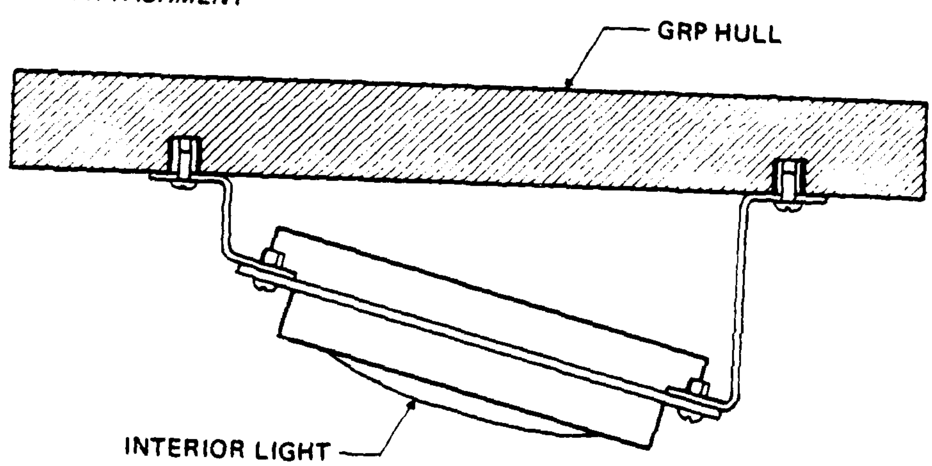
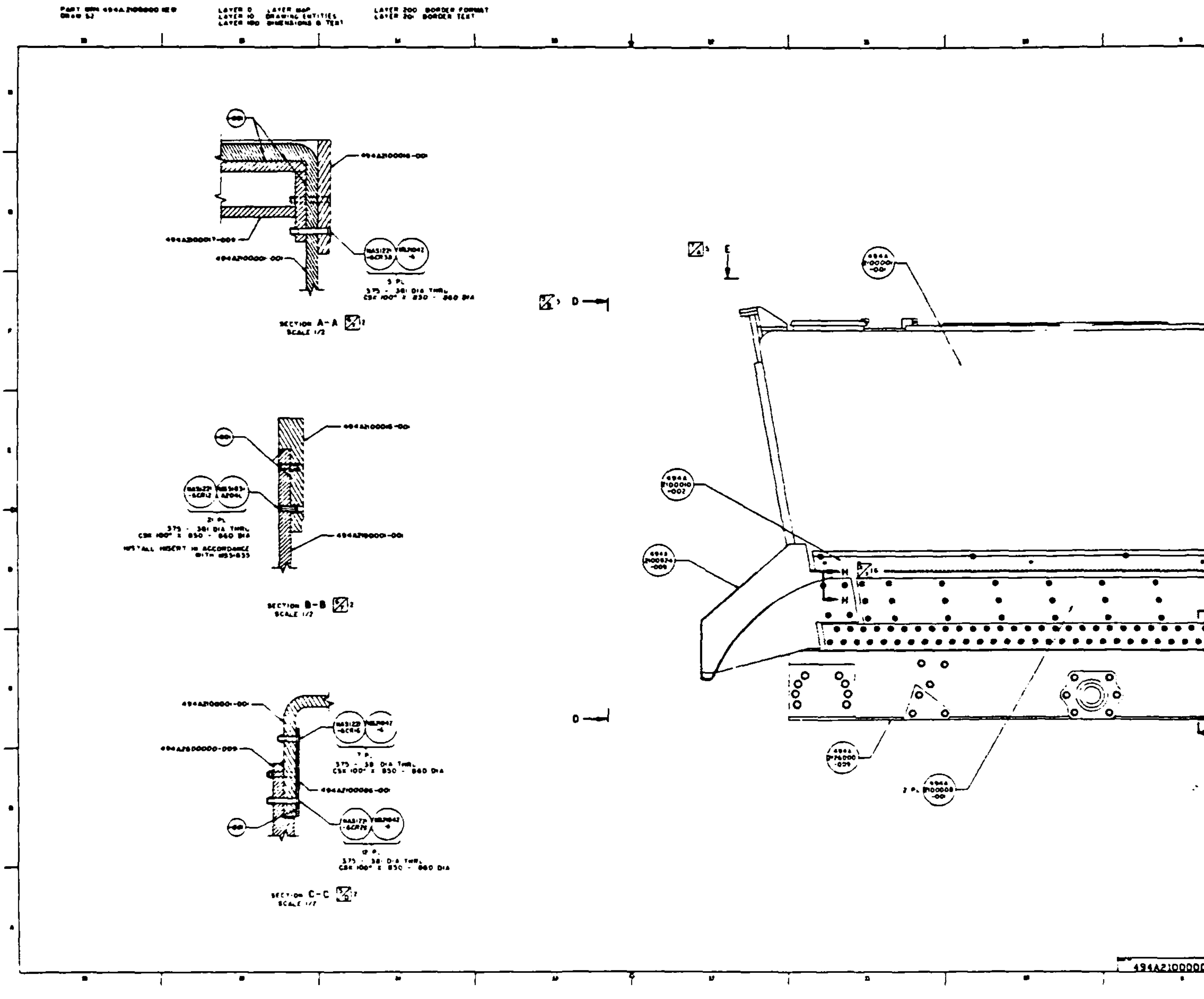


Figure 2-9. Typical Equipment Installations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SECTION C-C

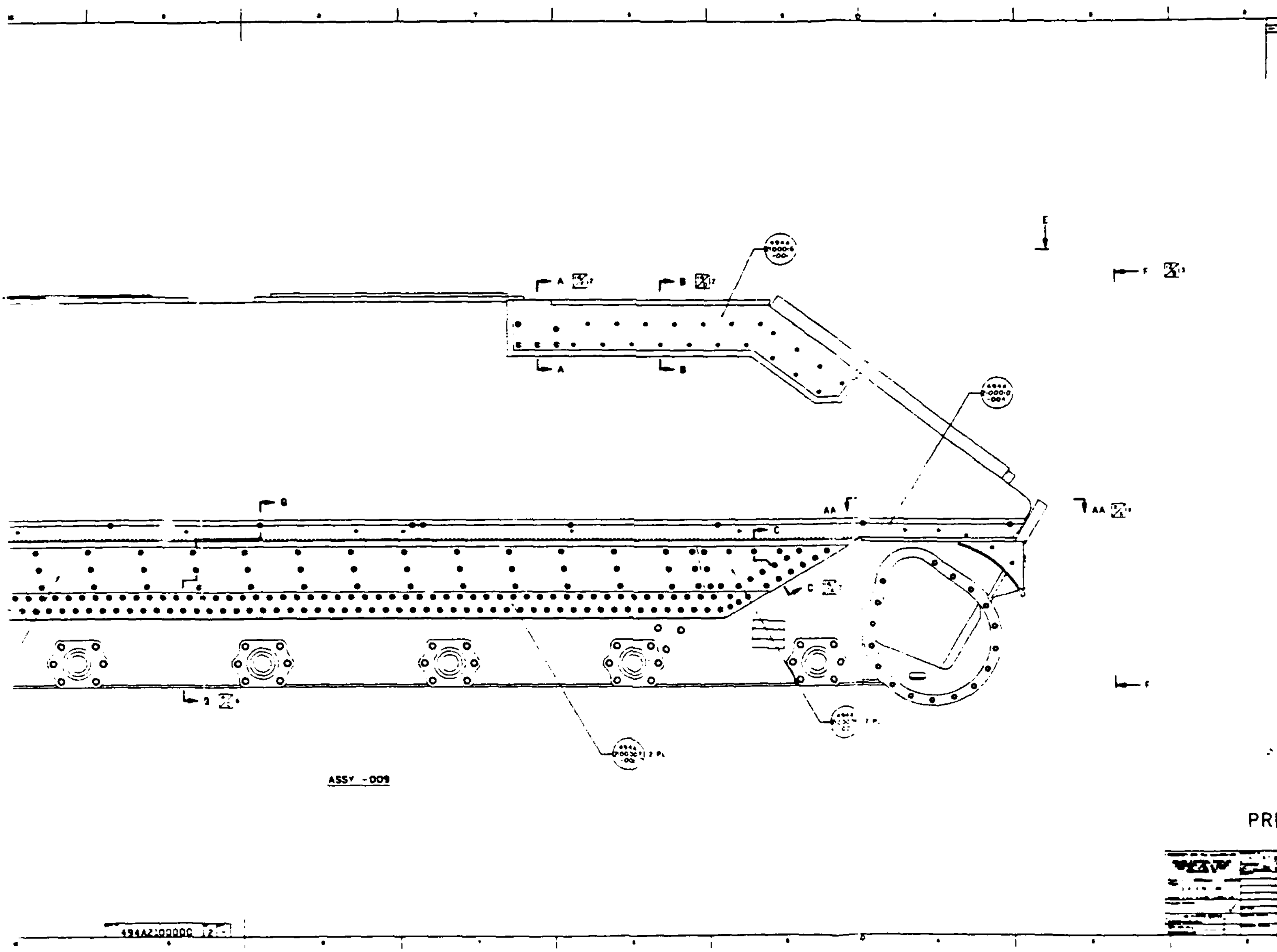


Figure 2-10. Upper and

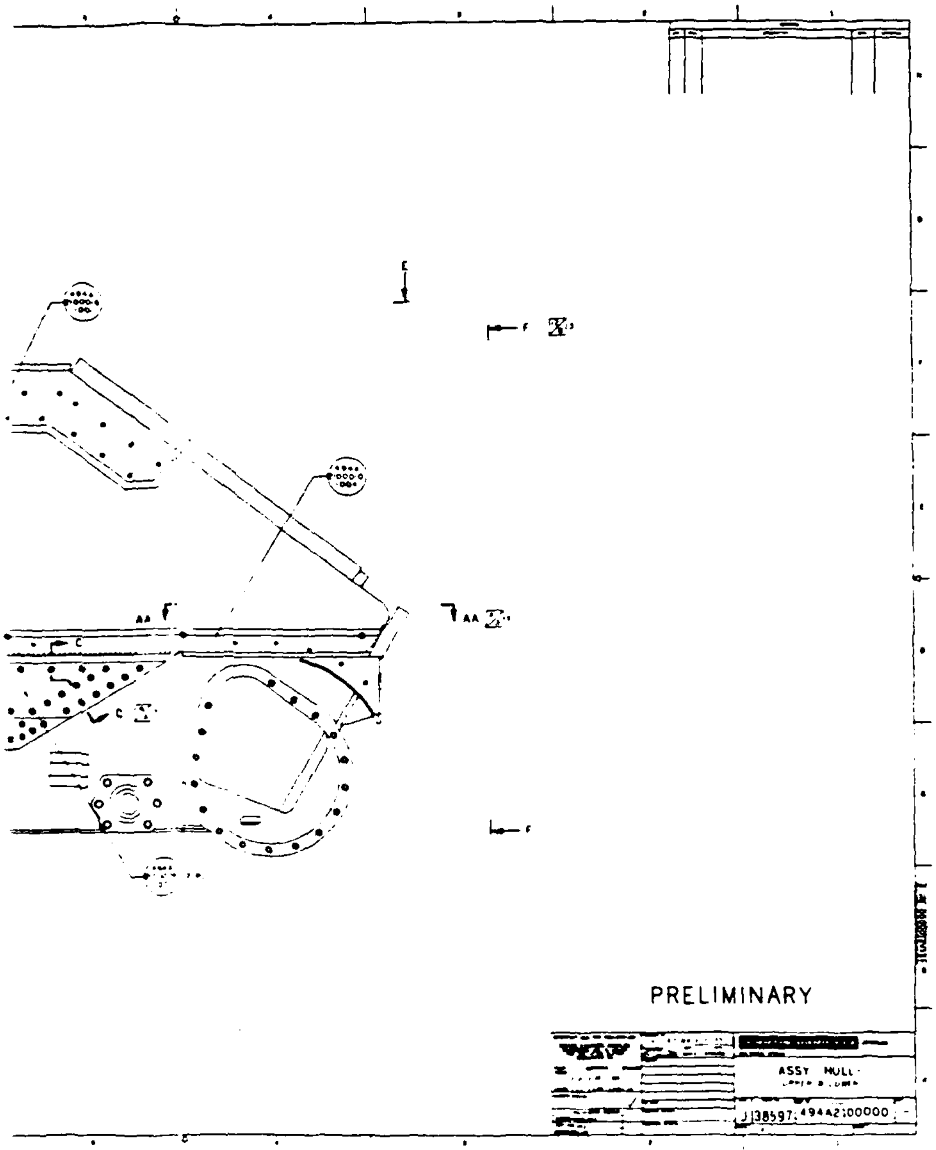
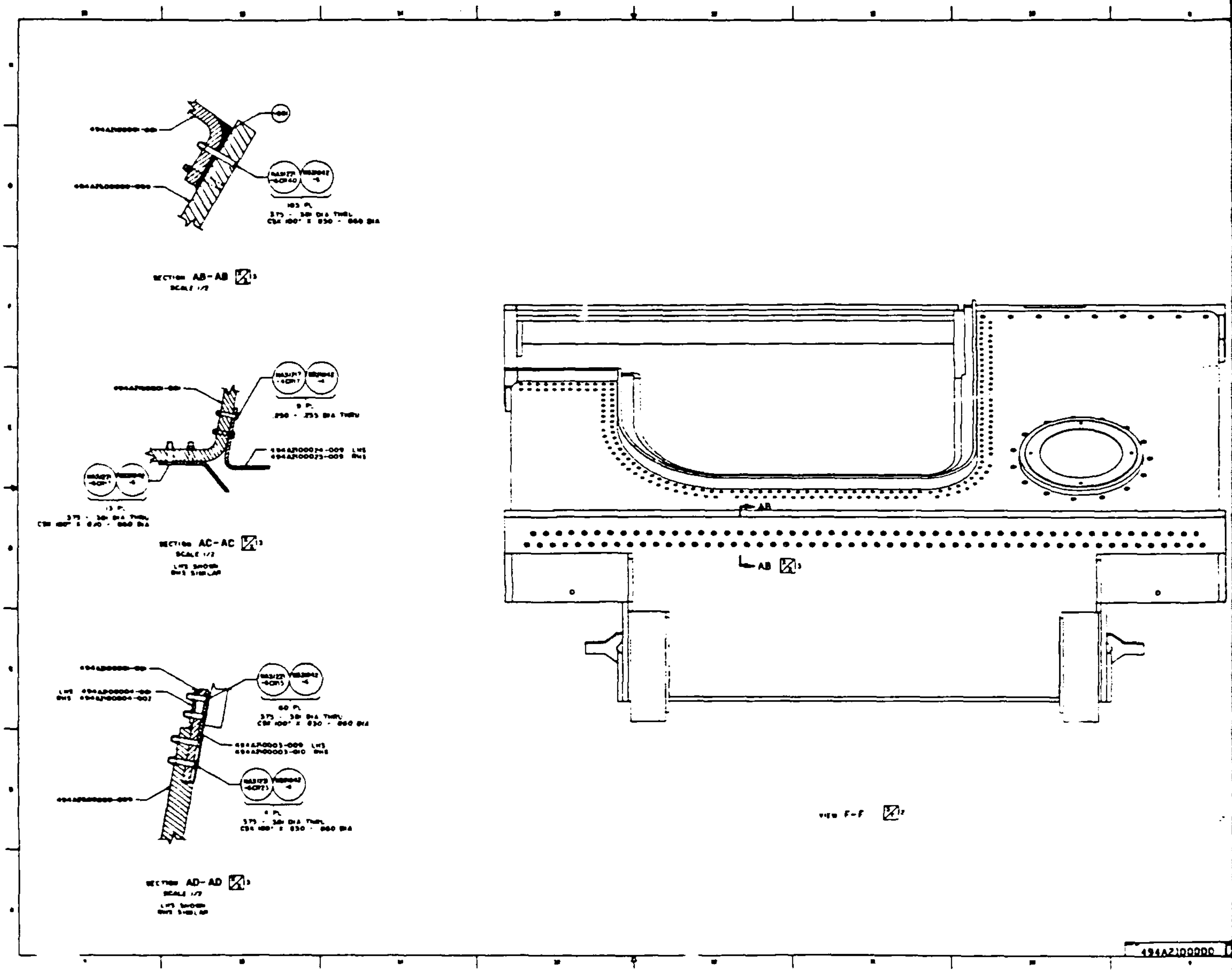


Figure 2-10. Upper and Lower Hull Assembly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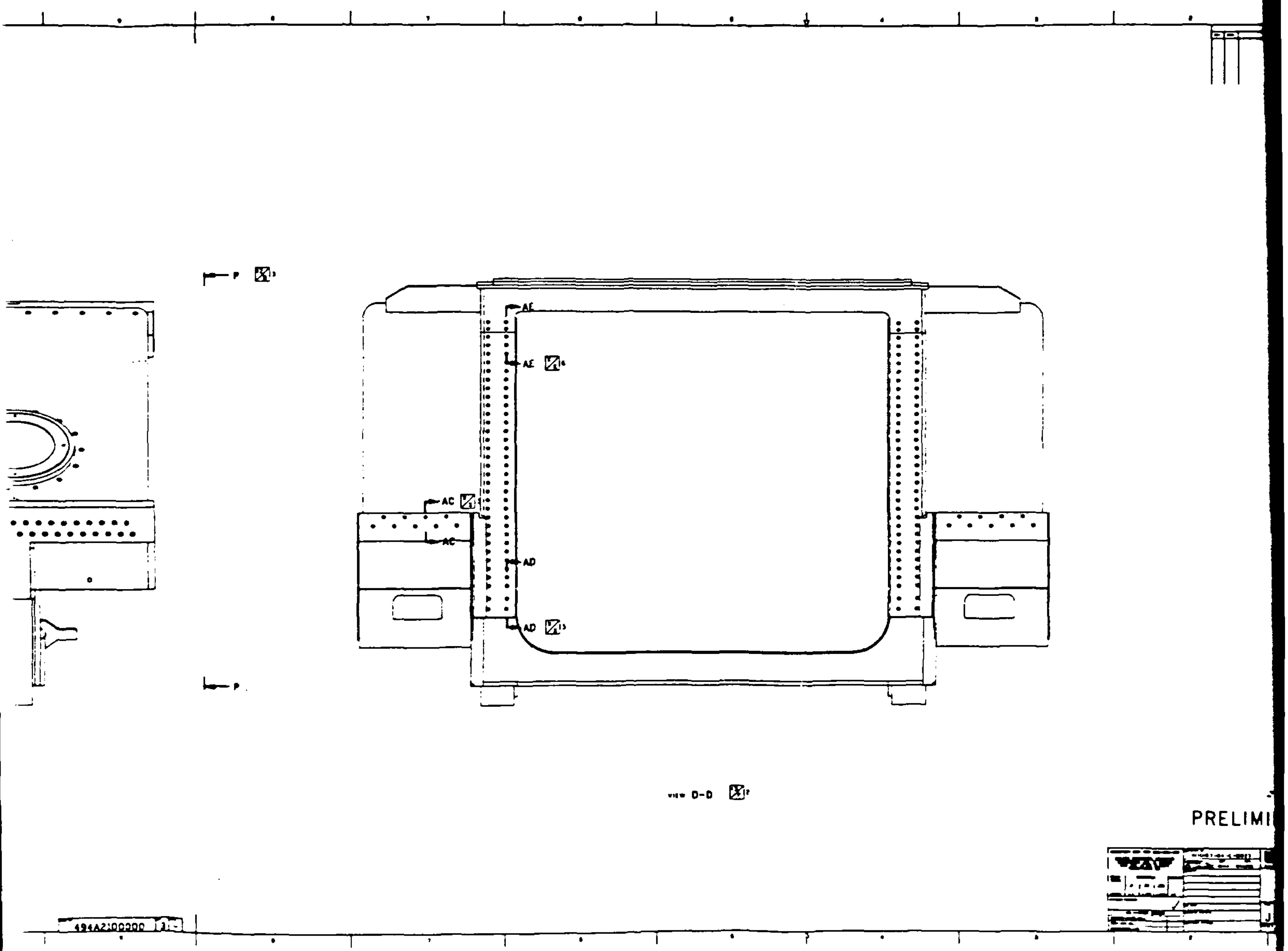


Figure 2-10. Upper and Lower Hull Assembl

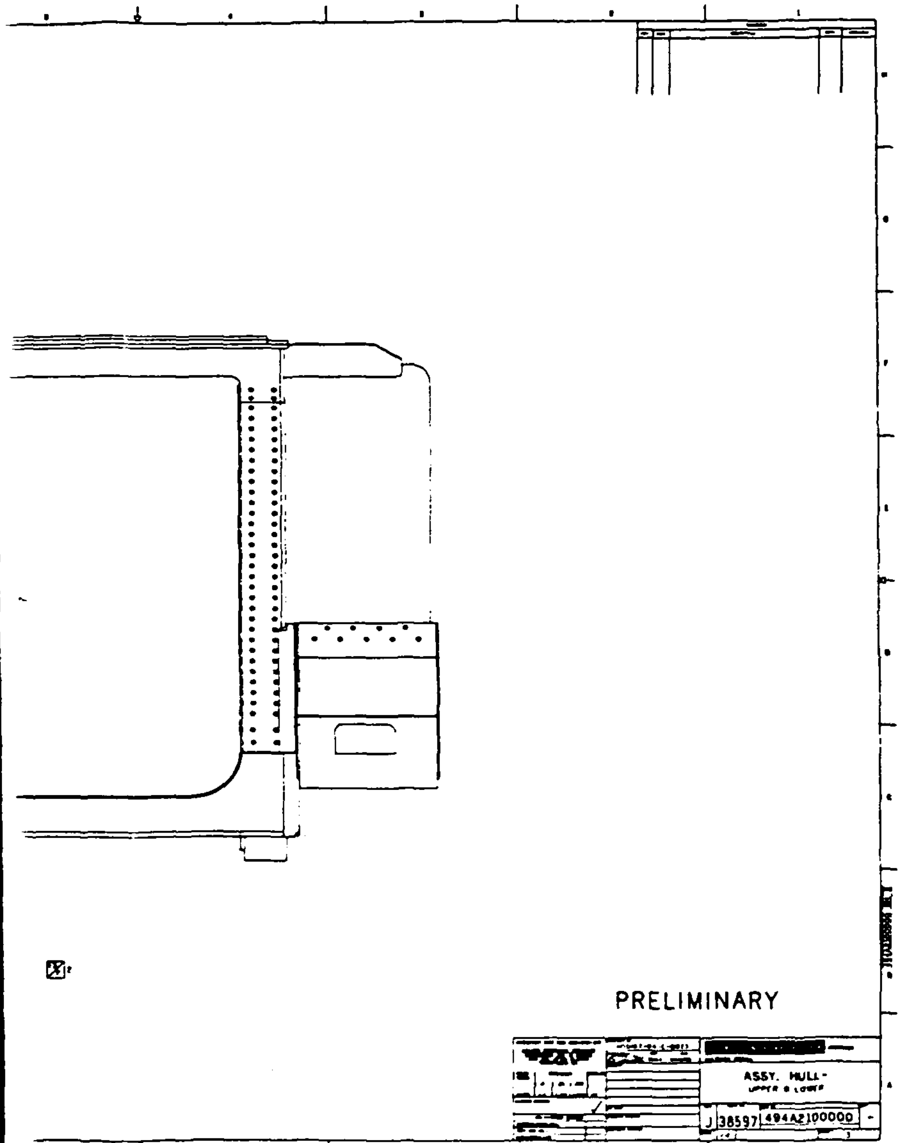
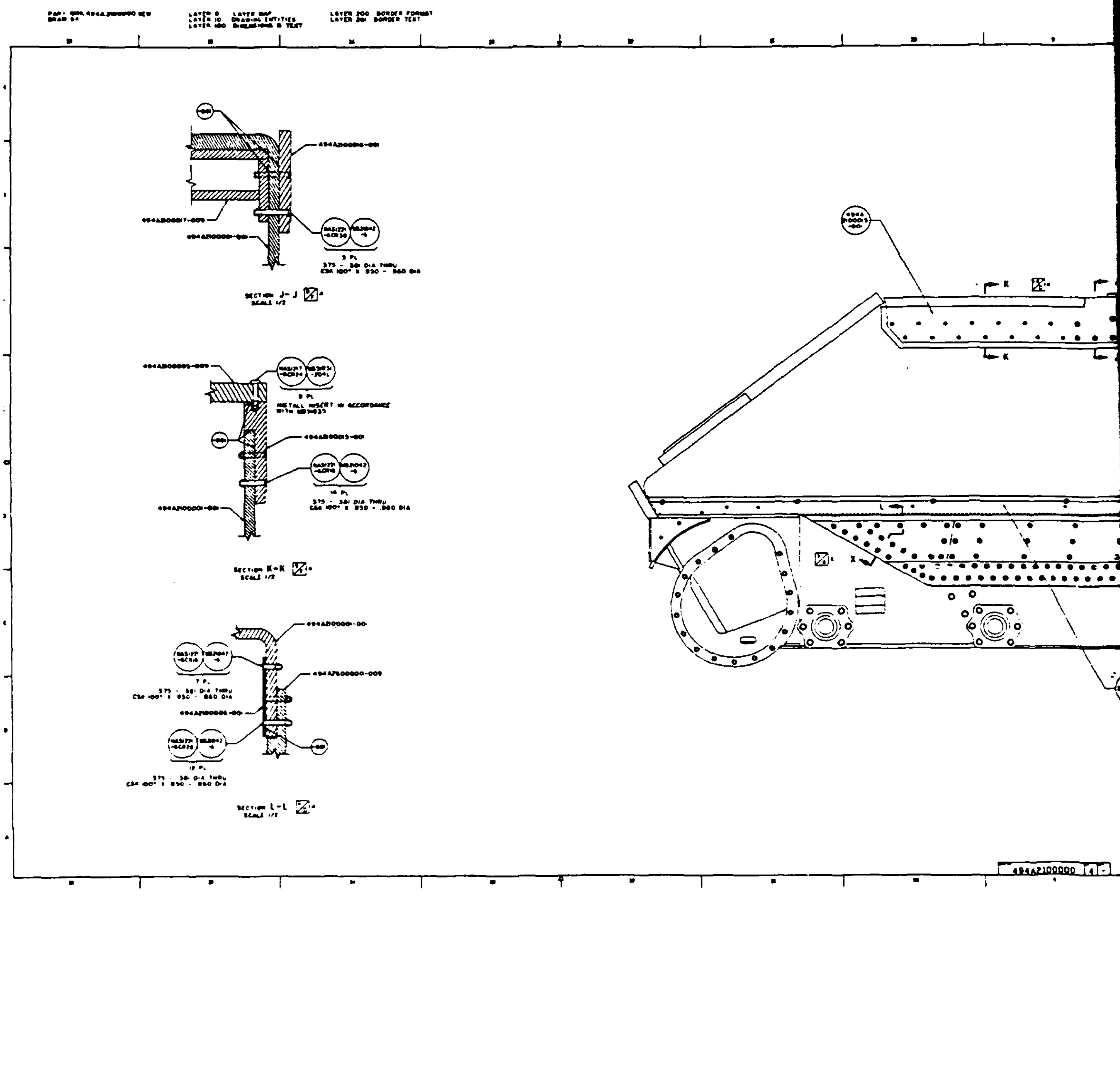


Figure 2-10. Upper and Lower Hull Assembly (Continued)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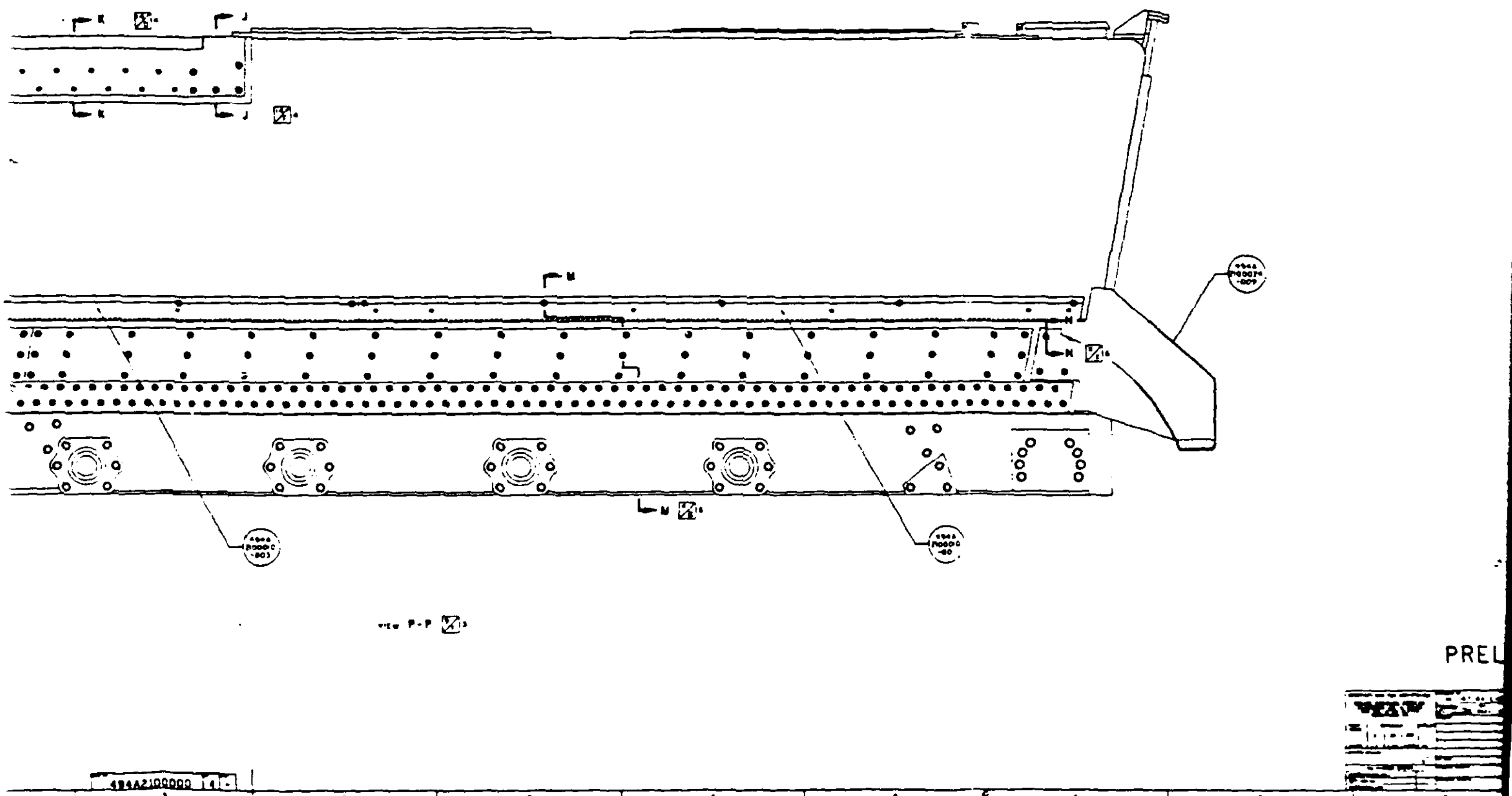

Figure 2-10. Upper and Lower Hull A

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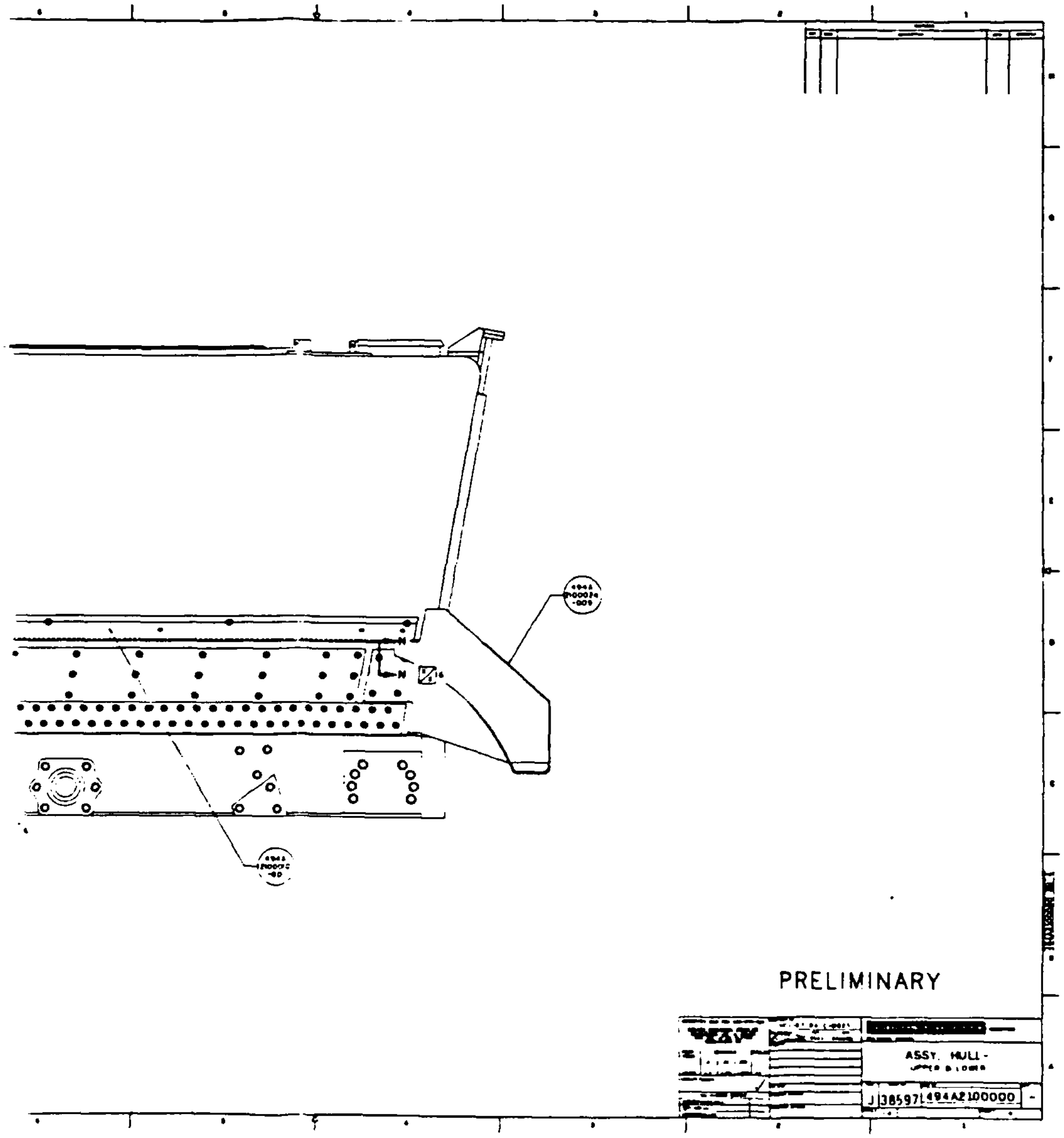

Figure 2-10. Upper and Lower Hull Assembly (Continued)

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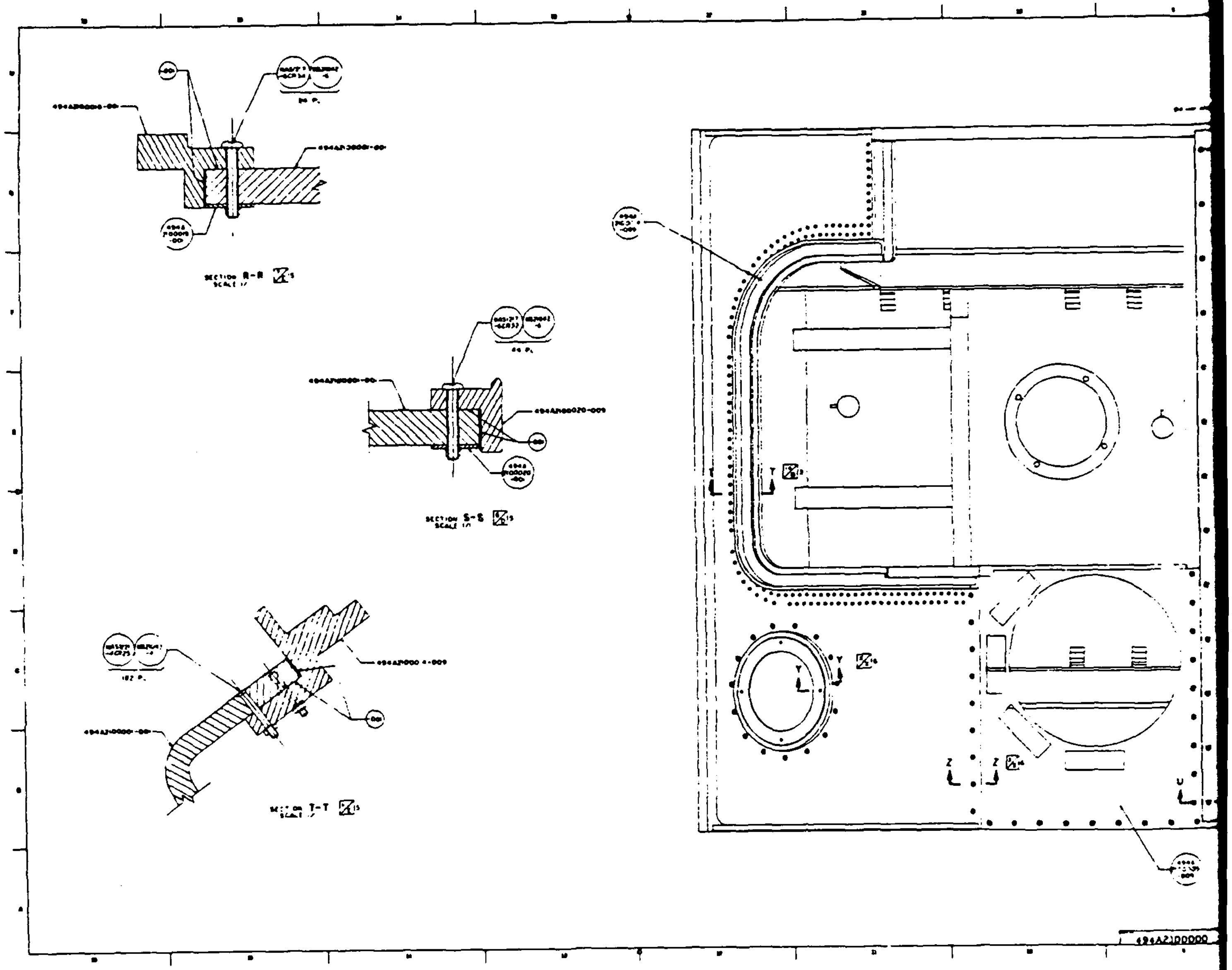
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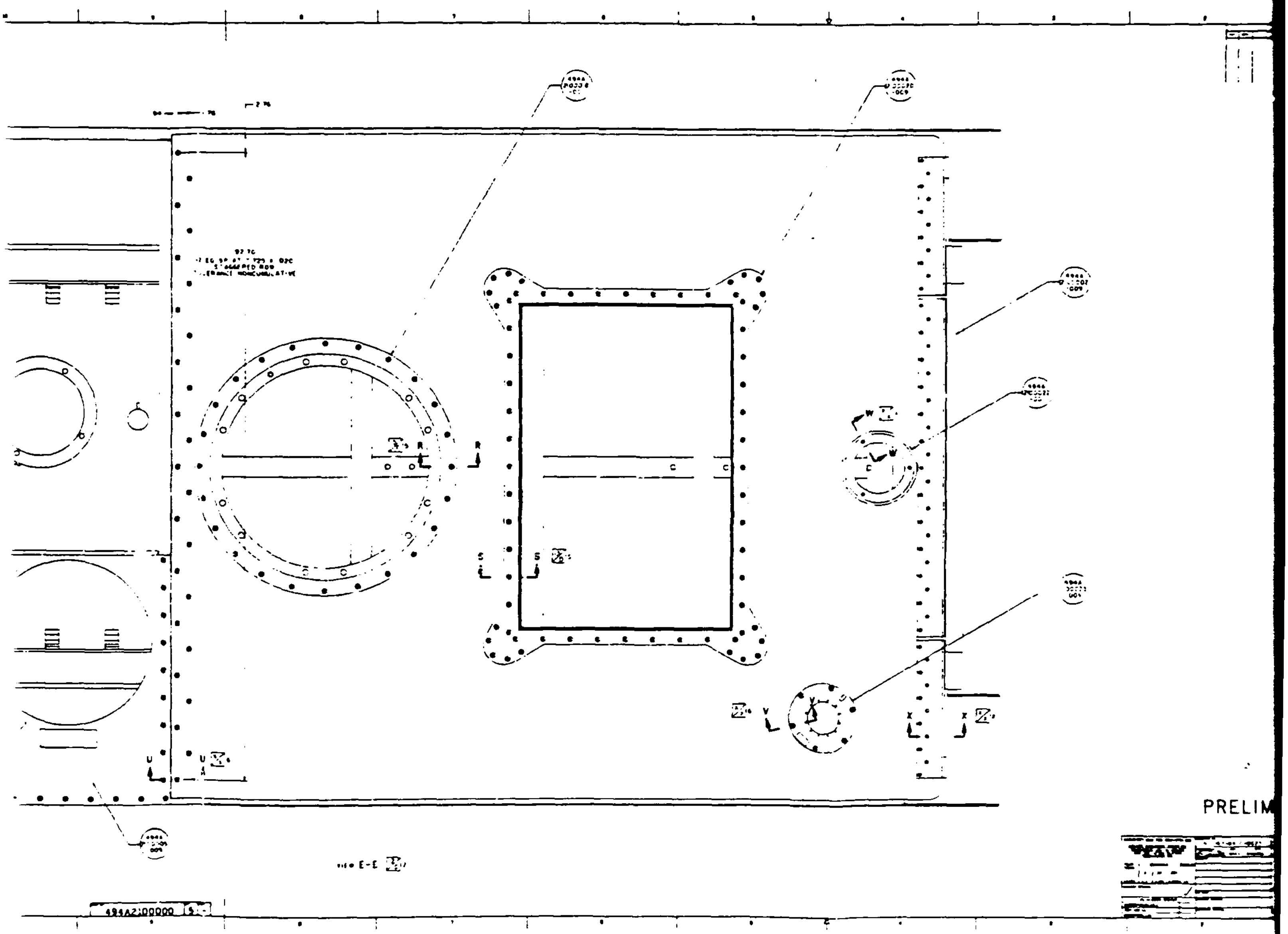

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Figure 2-10. Upper and Lower Hull Assem

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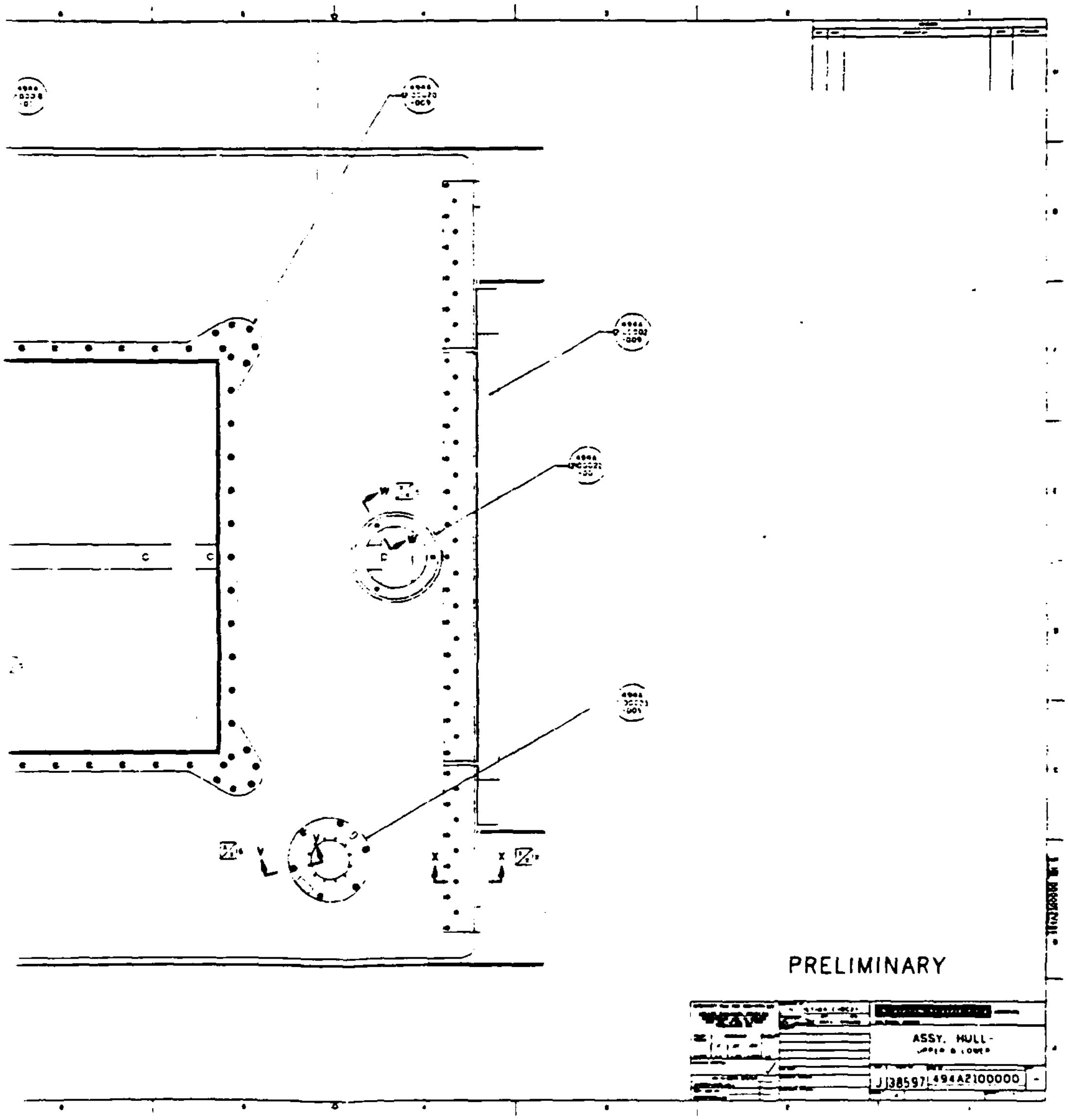


Figure 2-10. Upper and Lower Hull Assembly (Continued)

Table 2-1. Equipment Installation Summary

Item	Installation Method			
	Same as Existing	Bolted Through GRP HULL	Bolted Into GRP	Bolted Into Aluminum
Driver's Controls				
Steering	X			
Braking		X		
Throttle	X			
Shift	X			
Miscellaneous	X			
Instruments				
Instrument Panel	X			
Warning Light Panel	X			
Engine Cooling and Air Induction Systems	X			
Engine Exhaust System	X			
Trim Vane				
Hinges				X
Deploy Mechanism				X
Radio System				
Radios		X		
Antennae		X		
Cable Clips			X	
Lighting Systems				
Front, Right	X			
Front, Left		X		
Rear, Both				X
Interior			X	
Cable Clips			X	
Horn	X			
Battery Box			X	
Fire Extinguishers				
Fixed			X	
Portable			X	
Tubing			X	
Personnel Heater	X			
Driver's Seat	X	X		
Commander's Seat	X	X		
Troop Seats	X	X		
Driver's/Commander's Periscopes				
Deployed	X			
Stowed			X	
Bilge Pump System				
Pump	X			
Piping/Cable Clips			X	

3.0 REPAIRABILITY STUDY

The possible introduction of GRP hulls into the armored vehicle fleet raises significant questions about repairability. GRP hulls will require different repair equipment and technology than steel or aluminum hulls. From a practical standpoint it is virtually impossible to predict all possible damage cases that could occur on a hull; therefore, only repair of the damage cases contained in the contract SOW were analyzed.

The following combination of ballistic and non-ballistic damage cases and maintenance levels in the SOW were considered:

Damage Cases:

1) Roof - single, completely penetrating ballistic impact by a fragment simulating projectile which leaves a six-inch diameter damaged area. The hole in the damaged area is assumed to be two inches in diameter.

2) Sides - single ballistic impact by an armor piercing round completely penetrating and shattering a single ceramic tile but not the reinforcing GRP.

3) Sides - single ballistic impact completely penetrating and shattering the ceramic tile and the GRP causing a three-inch diameter damaged area. The hole in the damaged area is assumed to be one inch in diameter.

4) Sides - a ceramic tile completely pulled off the hull.

5) Overall - repairability of hull after collisions:

   a) The loss of a final drive unit which is torn from the hull during an impact.

   b) The loss of a front or rear fender due to impact.

   c) A hole in the vehicle hull caused by a collision with a tree, rock or other vehicle. The size of the damage area is assumed to be one foot in diameter with a through hull penetration area of six inches in diameter.

Level of Repair:

Level I - Repair of damage from Damage Cases 1) or 3) above by the vehicle crew so that the watertight integrity of the hull is restored.

Level II - Repair of damage from Damage Cases 1), 2), 3), or 4) above by a field/organizational maintenance unit so that the ballistic protection equivalency and watertight integrity of the damaged hull section is restored. For the purposes of this study, the services of a recovery vehicle can be assumed to be available to the damaged vehicle. Recovery vehicle equipment is listed in

Table 3-1. Other equipment such as heating pads, vacuum pumps, etc., can be specified to be on the recovery vehicle to effect the repair.

Level III - Repair of damage from cases 1) through 5) so that the structural and ballistic equivalency of the damaged hull section is restored. This level of repair would be carried out at the depot level, and it can be assumed that any tooling or material needed to effect the repairs would be available.

Table 3-1. Recovery Equipment and Auxiliary Power Unit

RECOVERY EQUIPMENT
Electrical Power Source:
Alternator (Engine Driven)
Rating: 12.5KVA, 0.8PF, 60 Cycle, 3 Phase, 4 Wire
Output: 120 VAC and 222 VAC
Speed: 3600 RPM
Hydraulic Power Source:
Pump (Engine Driven)
Pressure: 2200 PSI
Delivery Rate at 1800 Engine RPM and 1680 Pump RPM
Section 1: 32.0 GPM
Sections 2 and 3: 20.0 GPM
Section 4: 9.0 GPM
Air Compressor 2 Stage Reciprocating
Piston Displacement: 14.4 CFM
Operating Pressure: 145 PSIG to 175 PSIG
Speed: 720 RPM
Welder Power Supply:
Range
MIG Welding: 14-35 VDC, 250 Amperes
Metallic Arc (Stick) Welding: 75-200 Amperes, 40 VDC
Battery Charger:
Output:
24 VDC
35 to 40 Amperes
Charging Time (200 AH Battery): 8 Hours
Hydraulic Crane:
Horizontal Reach Maximum Boom Load Capacity: 6,000 Pounds
Boom Working Angle: 0 to 65 Degrees
Crane Swing-Moment Capacity: 14,000 Foot-Pounds
Crane Moment Rating: 129,000 Foot-Pounds
Crane Swing Speed (Azimuth Rotational Speed): 1.5 RPM

Table 3-1. Recovery Equipment and Auxiliary Power Unit (Continued)

Crane Winch and Recovery Winch:
- Crane Winch (Single-Line Rating): 6,000 Pounds
  - Line Speed:
    - First Layer: 25.6 FPM
    - Second Layer: 31.2 FPM
    - Third Layer: 36.7 FPM
  - Wire Rope:
    - Diameter and Classification: 1/2 inch, 6 x 19 Wire
    - Breaking Strength: 23,000 Pounds
    - Length: 85 Feet
- Recovery Winch:
  - Line Pull:
    - Low Speed:
      - Bare Drum: 30,000 Pounds
      - Full Drum: 18,200 Pounds
    - High Speed:
      - Bare Drum: 6,830 Pounds
      - Full Drum: 4,140 Pounds
  - Line Speed:
    - Low Speed:
      - Bare Drum: 22 FPM
      - Full Drum: 36 FPM
    - High Speed:
      - Bare Drum: 97 FPM
      - Full Drum: 160 FPM
  - Wire Rope:
    - Diameter and Classification: 3/4 inch, 6 x 37 Wire
    - Breaking Strength: 48,600 Pounds
    - Length: 278 Feet

AUXILIARY POWER UNIT

General:	
Output at 3600 RPM Engine	
Governed Speed:	150 AMP Continuous
Maximum Output:	240 AMP for 10 Min
Voltage:	24 to 28 VDC
Engine:	
Model:	Petter AC-2
Type:	4 Cycle, Diesel, Air Cooled
Number of Cylinders:	2
Rated Horsepower at 3600 RPM Engine Governed Speed:	12
Generator:	300 AMP
Nominal Voltage:	24 VDC
Alternator:	5 KW at 3600 RPM
Nominal Voltage:	120 VAC

The first consideration made in selecting repair approaches was the environment in which the repair would be carried out. The expected environments for the various levels of repair are summarized in Table 3-2.

Table 3-2. Repair Environments

Level I (Crew)	Level II (Field/Organizational)	Level III (Depot)
o -40 to +120°F o Precipitation o Mud o Oil o No Utilities* o No Special Tools	o -40 to +120°F o Shelter o Limited Utilities* o Special Tools	o +65 to +90°F o Shelter o Utilities* o Special Tools o Machine Shop

* Electric Power, Compressed Air, Water.

On the basis of the environment at the crew level, all but the simplest repairs being made by the crew were ruled out. Lack of special tools rules out the cutting out and replacment of damaged areas. Both the extremes of temperature and the contaminated environment rule out the use of "body putty" or adhesively bonded patches. Since repairs at this level only concern restoring watertight integrity of through penetrations, simple mechanical devices such as the one illustrated in Figure 3-1 are considered to be the most effective approach to crew level repairs. The repair device consists of an aluminum cup large enough to cover the damaged area, a sponge rubber gasket to seal between the periphery of the cup and the hull, a threaded stud long enough to project through the hull, a washer and a nut. The repair device would be carried as part of the standard vehicle equipment. In use the stud would be pushed through the hole in the hull from the outside, the nut and washer installed, and the nut tightened down to compress the gasket and form a seal between the cup and hull. Alternative designs which might be completely installed from the inside or outside of the hull are possible. These would utilize a toggle at the end of the stud and have a provision for compressing the gasket by turning a nut from the cup side. Installation time for this type of repair device would be on the order of five minutes from start to finish. Obviously, there will be areas of the hull where this repair method cannot be used; for the hull design developed in this program, corners and the main joint are two such areas. Contoured cups could be fabricated to accommodate corner repairs. There is probably no practical way of making crew level repairs in the main joint area of the hull due to the uneven surface and poor access. It should be noted that the same access problem exists in the track/suspension area of any armored vehicle and would probably preclude crew level repairs on that area of a totally metal hull.

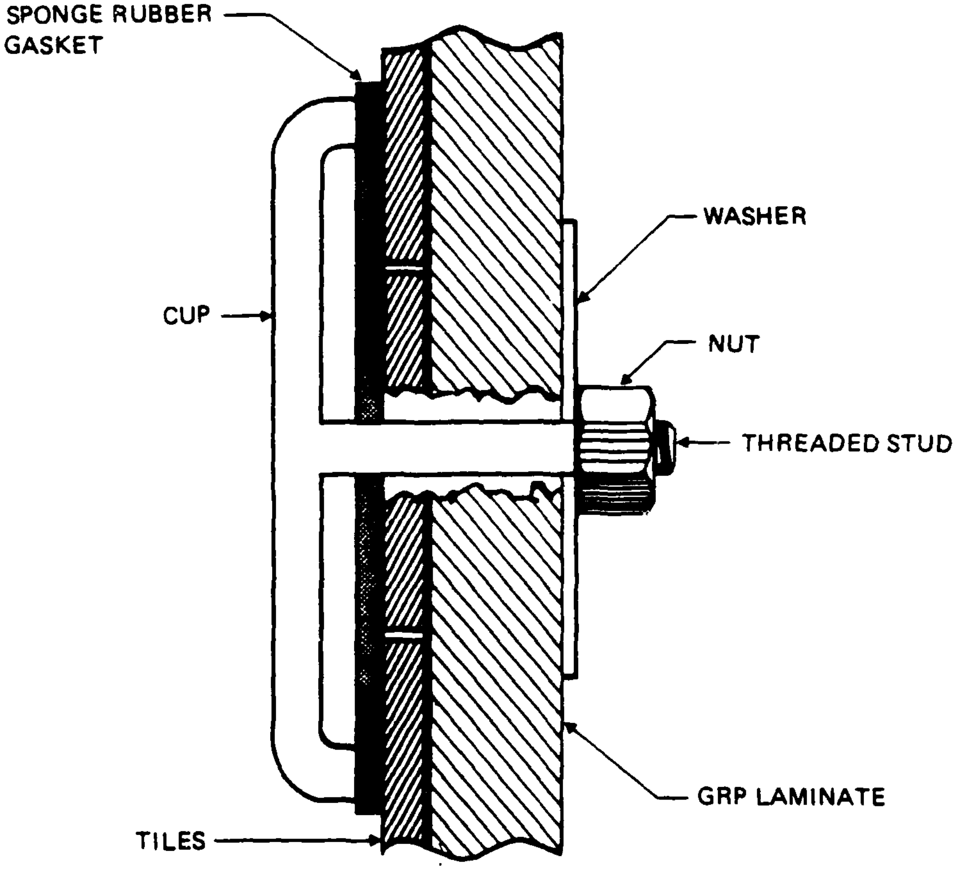


Figure 3.1. Typical Crew Level Repair

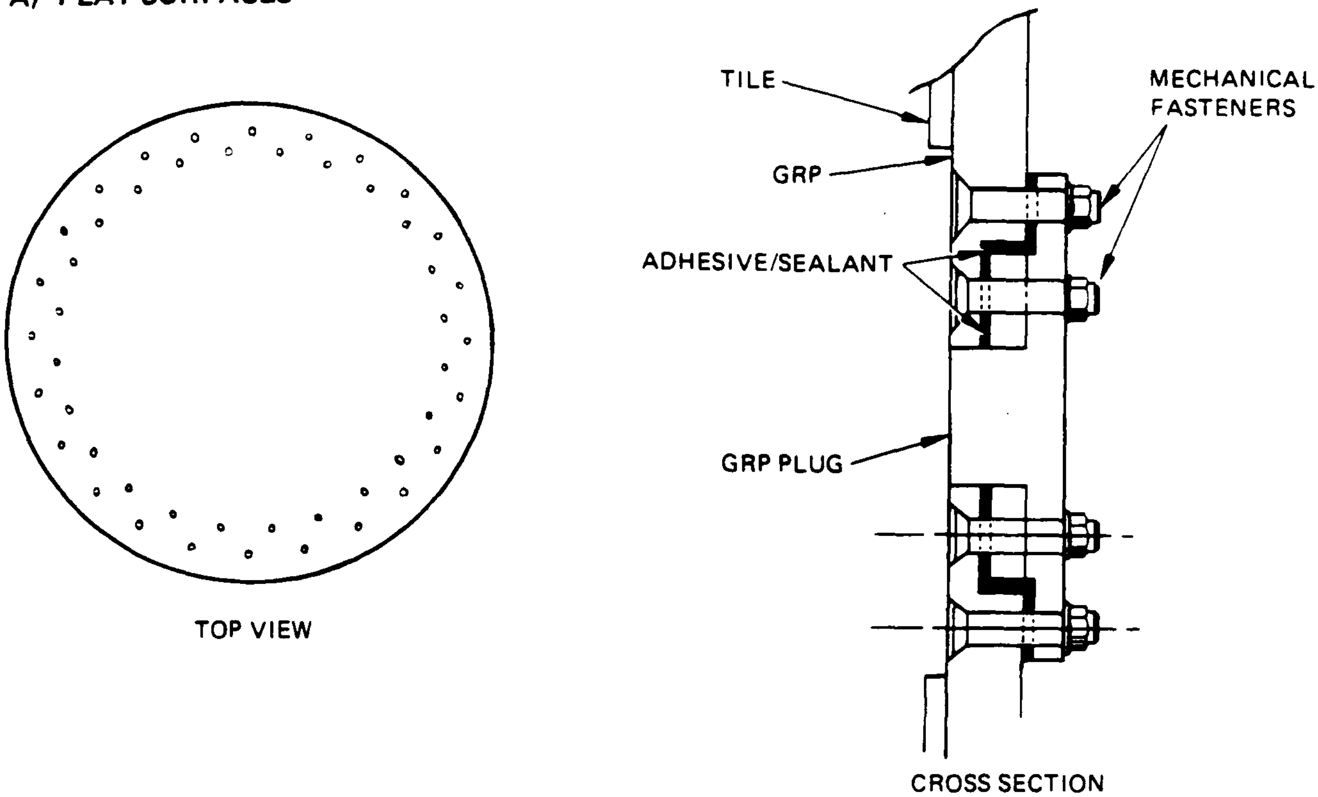
The Level II and III repairs differ from one another only in the complexity of the repairs that can be accomplished. At the field/organizational level it is assumed that local heating and shelter will be available. This plus common hand tools, equipment to flush away dirt and oil from the damaged area, and prefabricated patches will allow the use of bolted and bonded repairs to restore structural integrity in areas of penetrating and non-penetrating ballistic damage of the type described in cases 1) through 4).

Repairs to items in damage case 5) will require more extensive facilities than those required for the other damage cases because the extent of the damaged area may not be obvious and the extent of the damaged area can be highly variable. The fact that the extent of the damage may not be readily apparent requires that nondestructive inspection (NDI) equipment be available to map the extent of damage. As a minimum, ultrasonic and x-ray equipment will be required. Because the extent of damage can vary, the standard patches used at the field/organizational level will not be useable in all cases; therefore, specially prepared patches will require machine shop facilities capable of machining thick GRP material.

The repair procedure recommended for Level II and III repairs is a bolted and bonded patch similar to those illustrated in Figure 3-2. Bonded-only repairs are not recommended because of the uncertainty of being able to clean the damaged laminate well enough to reliably obtain high strength bonds and the time required to process a bonded-only repair. A hull which has been damaged in service will have been exposed to an unknown variety of materials which could impair the strength of a bonded repair. Removing these contaminants completely so that a reliable bond can be obtained between a patch and a hull is very uncertain because cleaning processes must be tailored to specific contaminants. Because of the uncertainty involved in the cleaning process, a bonded and bolted repair procedure is recommended. In this approach all loads are carried by the bolts and the adhesive acts as a sealant and a shim to fill gaps caused by tolerances on the patch and cut out area.

The sequence of operations involved in each repair scheme is summarized in Table 3-3. The cleaning of areas to be repaired would be accomplished by flushing with water and solvent. Removal of damaged areas and preparation of edges of the surrounding material can be accomplished with hand held power tools such as saws and routers. Patches would be installed with adhesive on the faying surfaces, fastener holes drilled and fasteners installed. The adhesive could then cure without further attention. Local heat would be applied to the repair area to dry it after cleaning and to aid in curing the adhesive at ambient temperatures below about 60°F.

A) FLAT SURFACES



B) CORNER REPAIR

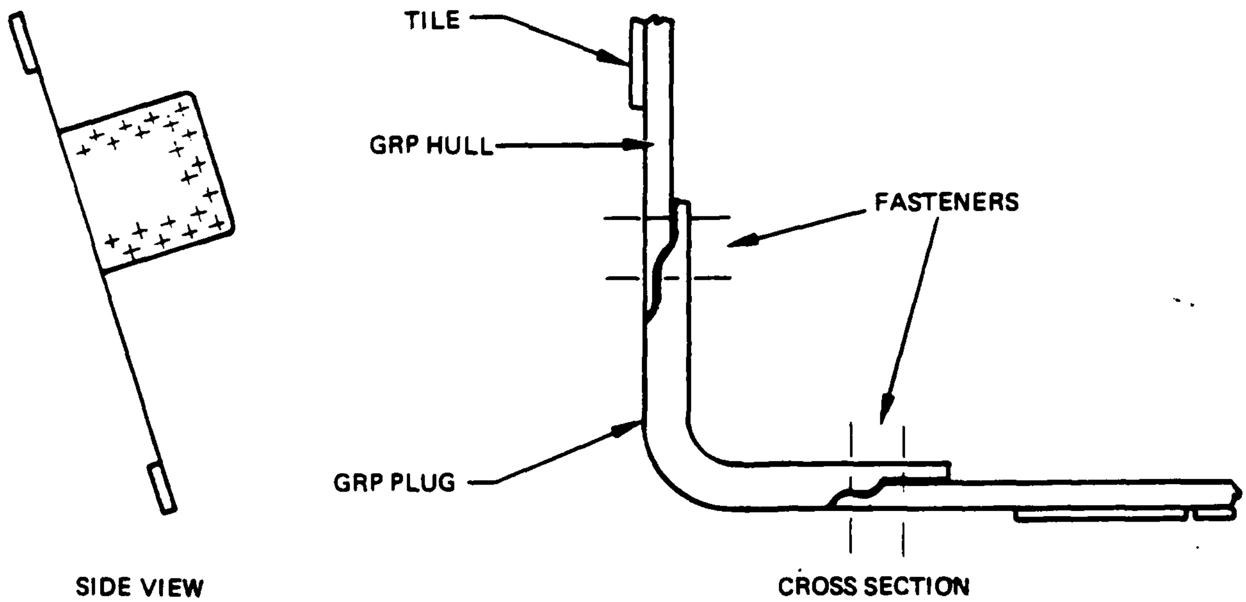


Figure 3-2. Field/Organizational and Depot Level Repair

Table 3-3. Repair Procedures

Crew	Field/Organizational
o Install Clamp/Plug	
Depot	
o Warm repair area	o Strip hull of all components
o Clean repair area	o Clean hull
o Remove damaged material	o NDI to define damaged areas
o Prepare edges	o Remove damaged areas
o Clean repair area	o Repair as above
o Install plug	
o Match drill fastener holes	
o Remove plug	
o Apply adhesive	
o Reinstall plug	
o Install Fasteners	
o Allow adhesives to cure	

The time to perform repairs using prefabricated patches would be one to two hours for installation of the patch plus the time to cure the adhesive. Adhesive cure time would depend on the temperature, but would not require operator attention. Adhesive cure time could be as long as 24 hours.

The procedure for replacement of fenders on this vehicle design is similar to that performed on the present aluminum M113 vehicle. The front fender attaches to the aluminum lower hull and the installation is practically identical to present procedures on the aluminum M113 vehicle. Rear fenders would be bolted in place and could be easily removed and replaced.

Since the final drive installation is identical on both vehicles, replacement of a lost unit would use existing procedures.

One unique problem of the GRP hull exists when a welded repair is required in aluminum immediately adjacent to GRP. Heat input during the welding can seriously damage the adhesive and/or GRP. Heat sinks will be required to protect the organic materials. In a few cases, separation of the metal to GRP interface will be required. This can be accomplished by removal of mechanical attachments and softening the adhesive by heating and removing the damaged metal.

Experiments are required to develop guidelines for this type of repair.

Repair tool and material requirements above those in current vehicles and shops are summarized in Table 3-4.

Table 3-4. Special Tool/Material Requirements

o Crew - None	o Depot - Same as Field/Organizational - NDI equipment
o Field/Organizational - Hot air blower - Vacuum pump - Router and cutters - Grinder (hand held) and rotary files - Pyrometer - Flushing solvent	 - Adhesive kits - Plastic film - Sealant tape - Breather - Hand tools - Repair materials - Drill

4.0 STRUCTURAL ANALYSIS

The GRP hull is shown in Figures 2-1 through 2-10. It is made up of a GRP upper hull attached to an aluminum lower hull. The two are joined by a bolted, bonded joint at water line (WL) 25.5. For structural analysis, a minimum 0.75 inch wall thickness and a 1.25 inch roof thickness were used. "B" Basis allowable stress and stiffness properties were used in the analyses. The allowables were developed from 0° and 90° lamina data. The "SQ5" composite analysis computer code was used to generate laminate properties. The allowable strength for the aluminum alloys used (5083, 5086, and 6061) were obtained from MIL-HDBK-5C. The strengths of screws and bolts were obtained from National Aerospace Standards (NAS) data sheets.

The results of the structural analyses[1] are summarized in the following paragraphs. Structural analyses were performed for the loads outlined in Table 4-1. This table indicates the cases in which a finite element analysis was employed and those that were analyzed by hand. Table 4-1 includes all operational loads defined in the SOW, plus a rail transport load condition based on an 8 mph railroad humping impact. The original 12g longitudinal rail humping load was reduced to a 6g load because analysis predicts the towing eyes used to tie the vehicle down during transport would fail at 6g. All defined load conditions are considered limit loads. The hull has been designed so that no detrimental, permanent deformation occurs at design limit load conditions and no failure occurs at design ultimate load conditions.

Consideration has been given to the effects of repeated loadings resulting from transportation and operation. Since no M113 operational load cycle data is available, a service life cannot be quantified. Standard fatigue resistant design techniques have been employed to minimize the impact of fatigue on the service life.

The factors of safety in Table 4-2 have been applied to the mobile operation and transportation loads.

1 M. Fisher, J. Wang, and A. Rosenwach, Composite Hull Tracked Amphibious Vehicle (M113), Structural Analysis Report, Martin Marietta Report No. BR 00230, August 1984.

Table 4-1. Summary of Limit Load Cases

Load Case No.	Source of Load Cases	Description	FEM
1	SOW	60% fore/aft slope 30% side slope	No
2 A,B,C,	SOW	Temperature range of -40°F to +120°F A. Lower hull at 32°F/GRP cap at 120°F B. Lower hull/GRP cap at 120°F C. Lower hull/GRP cap at -40°F	Yes
3	SOW	500 lb horizontal impact load on front of vehicle (e.g. tree knockdown)	No
4	SOW	Diagonal support by two diagonally opposed road wheels at the extreme front and rear of the vehicle	Yes
5	SOW	Towing eye attachment point load, 9000 lbs total	Yes
6	SOW	50,000 lb vertical impact at roadwheel station number one, port and starboard	Yes
7	SOW	Center wheel (station 3) support condition with roadwheels supported against sponson	Yes
8	AMCP-706-357[2]	Lifting eye load per fitting 0.35 x vehicle combat weight, cable to be 45° maximum from vertical	Yes
9 A,B,C,	AMCP-706-357	Rail transport loads: A. $\pm$ 2g vertical B. $\pm$ 6g longitudinal C. $\pm$ 3g transverse Vehicle tied down with front and rear towing eyes	Yes

2 Engineering Design Handbook, Automotive Series, Automotive Bodies and Hulls, AMCP-706-357, Hq, U.S. Army Materiel Command, April 1970.

Table 4-1. Summary of Limit Load Cases (Continued)

Load Case No.	Source of Load Cases	Description	FEM
10 A,B	SOW	A. Uniform load of 100 lbs/inch on floor beam. B. 5,200 lbs applied at the center of the floor beam.	No
11	SOW	Load case 10 A,B plus the maximum bending moment from the suspension system loads	No
12 A,B	SOW	A. 3g vertical load on the engine/transmission, transfer case and differential mounts B. 3g horizontal load on the above mounts	No
13	SOW	Load case 12 A,B and a 5,600 lb vertical load on transmission mount (Army Ordance Drawing 10865618 Sheet 5, Part No. 10932830)	No
14	SOW	Load case 12 A,B and a 5,600 lb downward load on engine mount (Army Ordanance Drawing 10865618 Sheet 5, Part No. 10932830)	No
15 A,B,C,D, E,F	SOW	A. 4,800 lbs applied inward toward the vehicle as shown in Figure 4-1.	No
		B. 10,000 lbs vertical load applied at the outboard roadwheel as shown in Figure 4-1.	No
		C. 4,800 lbs applied outward from the vehicle as shown in Figure 4-1.	No

Table 4-1. Summary of Limit Load Cases (Continued)

Load Case No.	Source of Load Cases	Description	FEM
		D. The combination of 33% of the load specified in B above and 200% of the load specified in C above	No
		E. The combination of 33% of the load specified in B above and 100% of the load specified in C above	No
		F. The combinations of 100% of the load specified in A above and 66% of the load specified in B above	No
16	SOW	42,000 lbs horizontal load at the centerline of the outboard idler wheel	No
17	SOW	28,000 lb load applied vertically to the outboard idler wheel from the bottom of the idler wheel	No
18	SOW	5,000 lb load applied to the shock absorber mount in the direction of the shock, 33° from the horizontal	No
19	SOW	42,000 lb. force applied to the idler adjuster to hull attachment in the direction of the adjuster	No
20	SOW	A. Final drive attachment load of 42,000 lbs applied horizontally at the center of the sprocket carrier	No
		B. 28,000 lbs vertical load applied upward and toward the sprocket at an angle of 30° to the horizontal	
21	Design Requirement	Water fording pressure, 8" freeboard	Yes

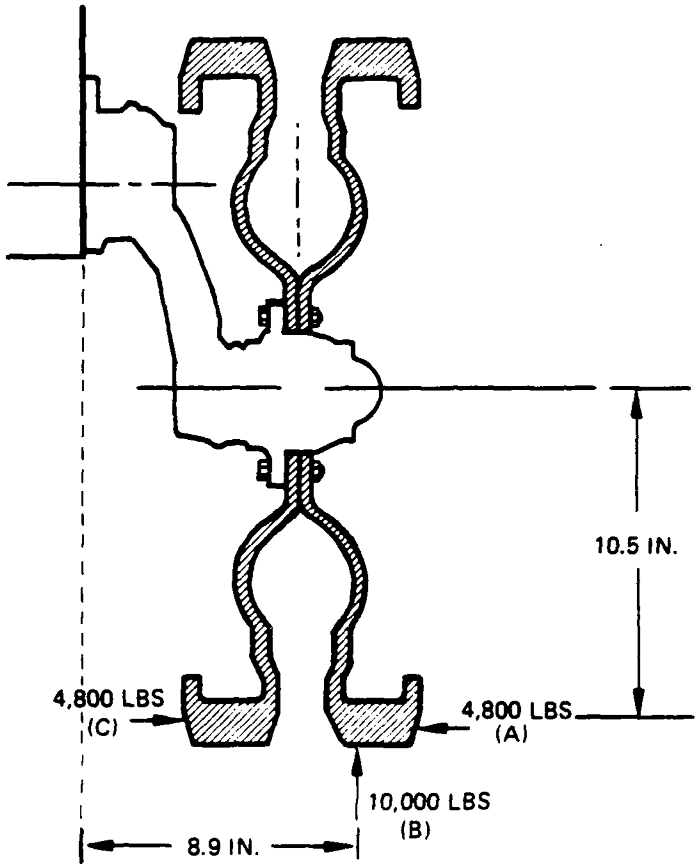


Figure 4-1. Suspension Loads

Table 4-2. Safety Factors for Mobile Operation and Transportation

Item	Yield Factor of Safety	Ultimate Factor of Safety
Basic structure - metallic	1.00	1.50
Basic structure - composites, tension	N/A	1.50
Basic structure - composites, compression	1.00	1.50
Fitting Factors - *metallic	1.15	1.15
Fitting Factor - *composite	N/A	1.15
Bearing Factor - *composite	N/A	2.00
Bearing factor - *metallic	N/A	2.00
Lifting & Tiedown - metallic	3.33	5.00
Lifting & Tiedown - composite	N/A	5.00

*These factors are not applied simultaneously
N/A = not applicable

Deflection analysis shows that the vehicle performance is not adversely affected by the deformations and displacements encountered in normal operations. The following items were checked:

1) Hatch and door openings, hatch and door function

2) Door frame to door gaps - underwater

3) Hull splice to pan - underwater watertightness

4) Drive system clearances

5) Tile stresses due to hull deflection.

Temperature magnitudes and gradients caused by the environment and vehicle operation were considered in the structural analysis. The following temperature extremes were combined with the highest design loads:

1) Lower hull at 32°F/GRP cap at 120°F

2) Lower hull and GRP cap at 120°F

3) Lower hull and GRP cap at -40°F

The geometry and sizes used in the structural analysis were based on minimum dimensions and gages. Where the misalignment or tolerances peculiar to a particular installation could have an appreciable effect on the calculation of loads or stress magnitudes with respect to the applicable factors of safety, these effects were analyzed.

Criteria for minimum fastener spacing and edge distances are shown in Table 4-3.

Table 4-3. Minimum Fastener Spacing and Edge Distances

Material	$\frac{d}{t}$	Fastener Edge Distance	Fastener Spacing	Fastener Row Spacing
GRP	All	2.5d	5d	4d
Aluminum	<1	1d+0.06"	5d	4d
Aluminum	≥ 1	2d	5d	4d

d= Fastener diameter
t= Thickness of thinnest sheet in joint

MSC/NASTRAN version 62A was used to perform linear static finite element analysis (FEA) of the M113 composite hull. The vehicle was placed in equilibrium for all FEA load cases through the application of appropriate inertia forces and boundary conditions.

The combinations of load and temperature cases run are as follows:

1) Temperature range of -40°F to +120°F, no applied load:

   a) Lower hull at 32°F/GRP cap at 120°F
   b) Lower hull/GRP cap at 120°F
   c) Lower hull/GRP cap at -40°F

2) Diagonal support by two diagonally opposed road wheels at the extreme front and rear of the vehicle:

   a) Without temperature case
   b) With -40°F temperature case

3) 50,000 lb vertical impact at roadwheel station number one, port and starboard:

   a) Without temperature case
   b) With 32°F lower hull/120°F GRP cap temperature case
   c) With 120°F temperature case
   d) With -40°F temperature case

4) Center wheel (station 3) support condition with roadwheels supported against sponson (no other wheels touching) -- without temperature case

5) Lifting eye load per fitting, .35 x vehicle combat weight, cable to be 45° maximum from vertical:

   a) Without temperature case
   b) With -40°F temperature case

6) Rail transport loads.

   a) $\pm$ 2g vertical:

      (1) Without temperature case
      (2) With -40°F temperature case

   b) $\pm$ 6g longitudinal:

      (1) Without temperature case
      (2) With -40°F temperature case

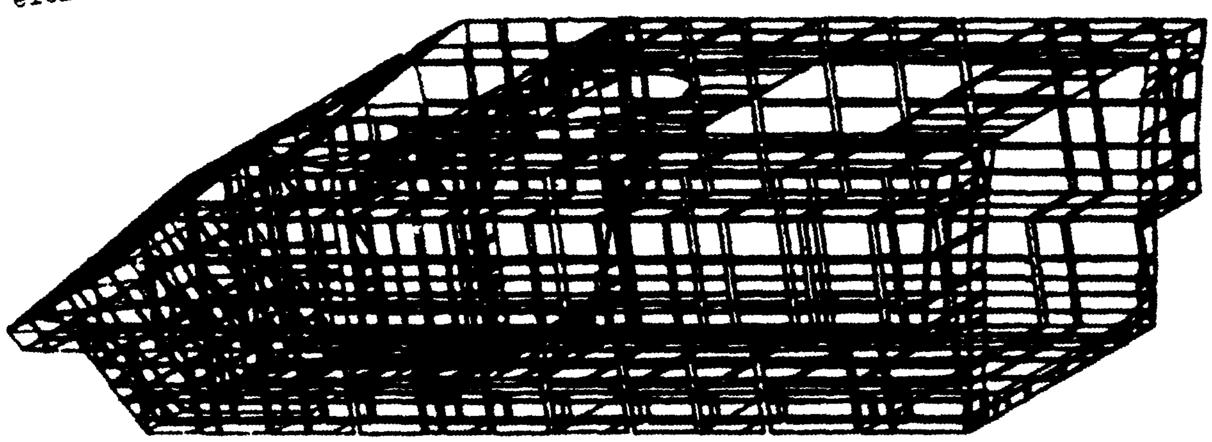
   c) $\pm$ 3g transverse:

      (1) Without temperature case
      (2) With -40°F temperature case

7) Water fording pressure, 8" freeboard -- without temperature case

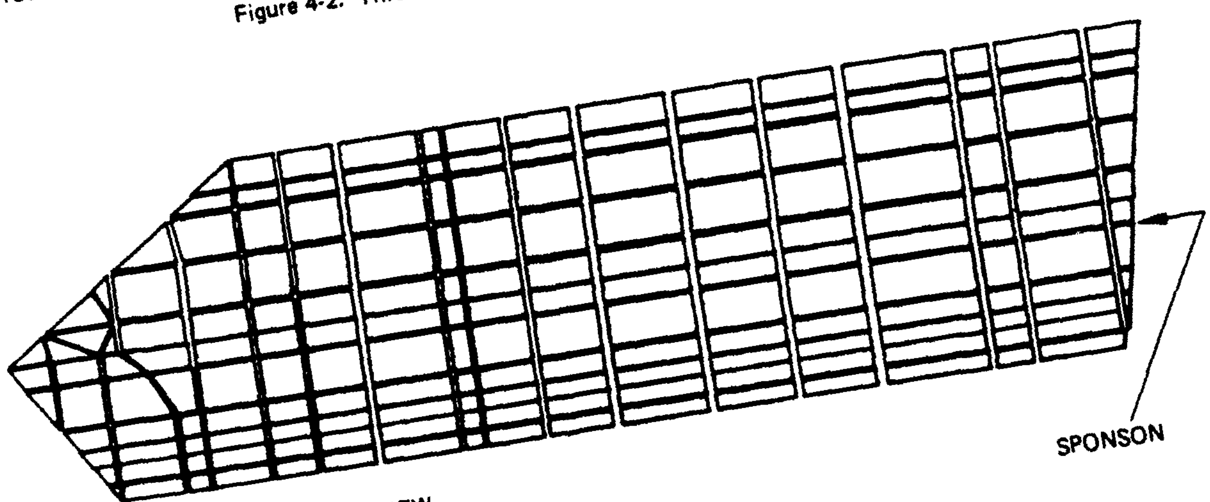
The load cases were used to determine the internal loads for the hull. For analysis these internal loads were combined with the load cases in Table 4-1 to determine the worst case loads.

The M113 hull was modeled primarily with QUAD4 and TRIA3 isoparametric membrane/bending elements. The composite laminate was input through the use of the PCOMP bulk data card. MAT8 cards were used to input the anisotropic material properties of the composite material. The NASTRAN program generates the required PSHELL cards containing the membrane and bending stiffnesses for the plate elements. A total of 1303 QUAD4 and 120 TRIA3 elements were used. CBAR elements were used for the wheel arms and stiffening rings around the cutouts. CONROD elements were used for the tie down and lifting cables. Figures 4-2 through 4-5 outline the FEM elements.



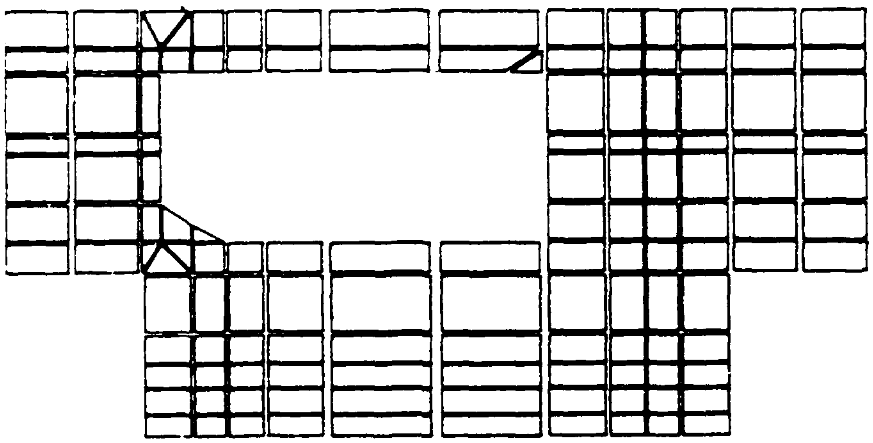
8652 DEGREES OF FREEDOM
1559 ELEMENTS

Figure 4-2. Three-Dimensional View of Finite Element Model

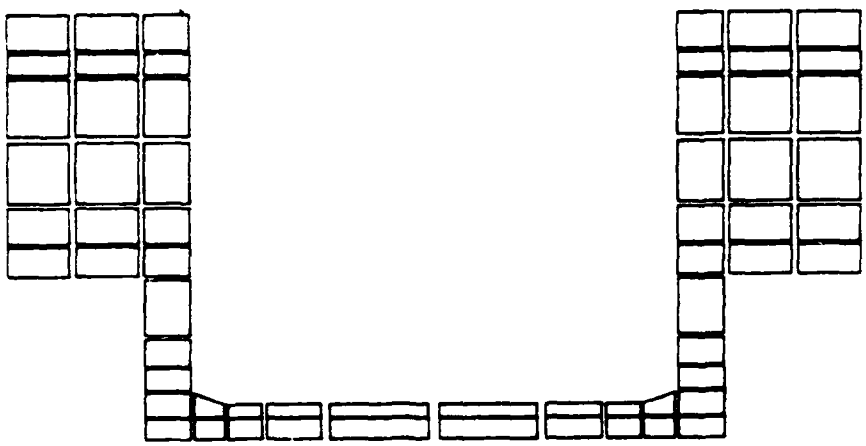


LEFT SIDE VIEW
(RIGHT SIDE, MIRROR IMAGE)

Figure 4-3. Side View of Finite Element Model



FRONT VIEW



AFT VIEW

Figure 4-4. Front and Aft View of Finite Element Model

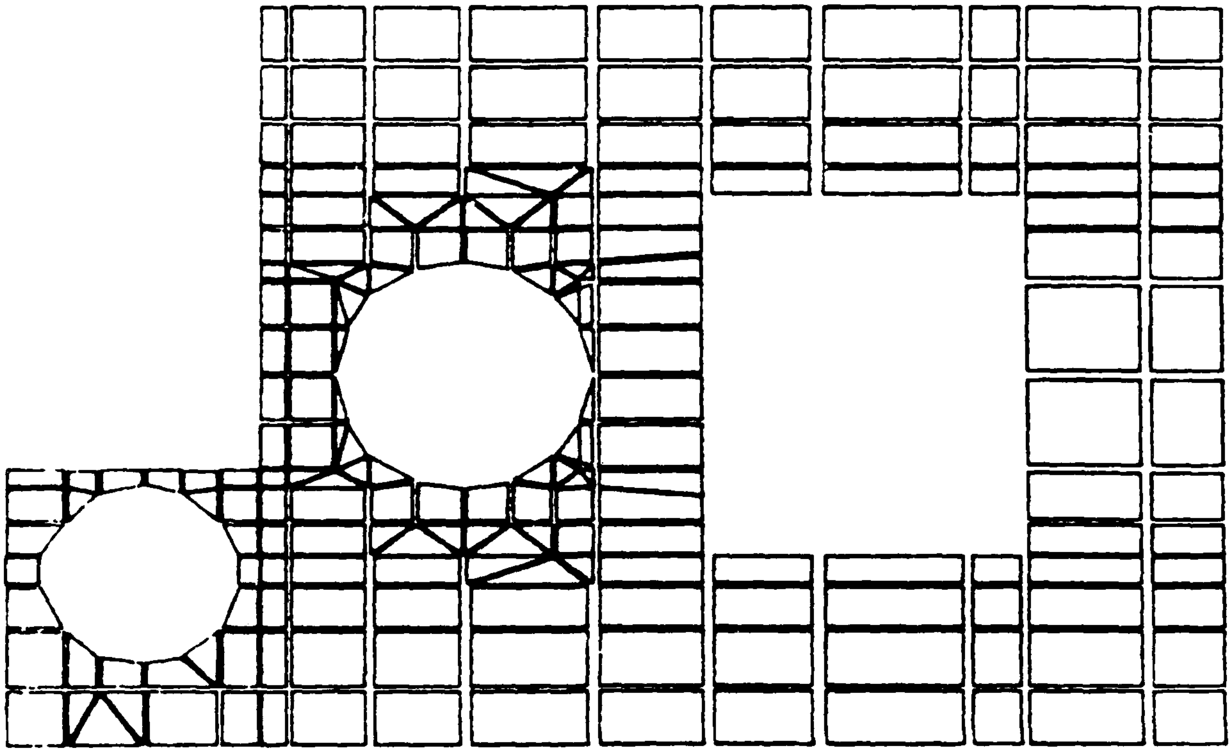


Figure 4-5. Top View of Finite Element Model

The minimum margins of safety for each of the major components on the hull are shown in Table 4-4. A conservative approach was taken throughout the analysis. For the GRP upper hull, the highest single panel loads from the finite element runs were combined with the 140°F/wet GRP design allowables to determine the minimum margin of safety. For the aluminum lower hull, as-welded allowables were utilized whenever a highly stressed area was located near a welded joint. For the load cases analyzed by hand, the load cases supplied in the SOW were combined with the worst case finite element model results to determine the minimum margin of safety. Margins of safety were positive for all cases analyzed.

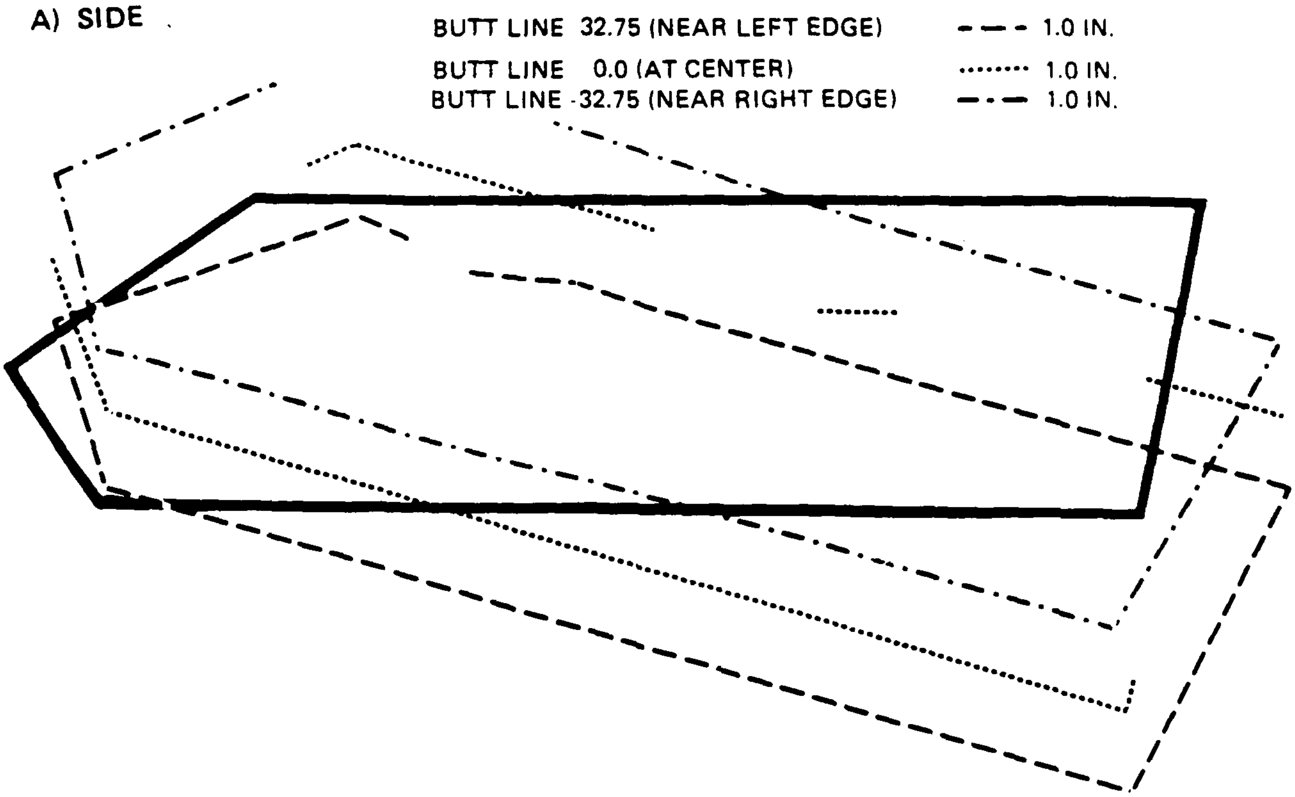
Table 4-4. Minimum Margins of Safety

Location	Material	MS	Load Case
Roof	1.5" Aluminum	Large*	1g down + 6g aft + Temp**
Roof beam	0.5" Aluminum	Large	1g down + 6g fwd + Temp
Front upper	1.5" Aluminum + 0.75" GRP	2.2	1g down + 6g aft + Temp
Front lower	1.5" Aluminum	0.54	1g down + 6g aft + Temp
Rear	1.5" Aluminum	Large	1g down + 3g side
Right sponson	0.5" Aluminum + 0.75" GRP	2.75	1g down + 6g aft + Temp
Left sponson	0.5" Aluminum + 0.75" GRP	3.38	1g down + 6g aft + Temp
Left upper side wall	0.75" GRP	Large	1g down + 6g aft + Temp
Left lower side wall	1.5" Aluminum	0.73	50,000 lb at bump stop
Right upper side wall	0.75" GRP	Large	1g down + 6g aft + Temp
Right lower side wall	1.5" Aluminum	0.75	1g down + 6g aft + Temp
Engine bulkheads	0.25" Aluminum	1.22	1g down + 6g aft + Temp
Stiffening gussets	0.75" Aluminum	Large	1g down + 6g aft + Temp
Engine Mount	Aluminum stiffener	0.58	Rail transport 2g up plus 5,600 lb vertical load
Shock absorber Mount	0.625" Aluminum	0.31	Load case 18
Rear Idler Mount	1.5" Aluminum (1" plate welded)	0.08	42,000 lb horizontal load
Lower Side Wall	0.75 GRP	1.14	50,000 lb impact
Lower Side Wall	0.75 Aluminum	0.19	50,000 lb impact
Suspension attachment	0.5" Aluminum	.03	Load case 15

* Large = greater than 4

** Temp = thermal load superimposed on design load

All load cases were plotted to determine the overall deflections of the hull. Cross-sectional plots were made at stations 28.81, 71.37, 111.0, 162.62, and at butt lines + 32.75, -32.75, and 0.0 for the load cases where significant deflections are predicted, see Figures 4-6 through 4-8. The largest deflection was for the diagonal support case



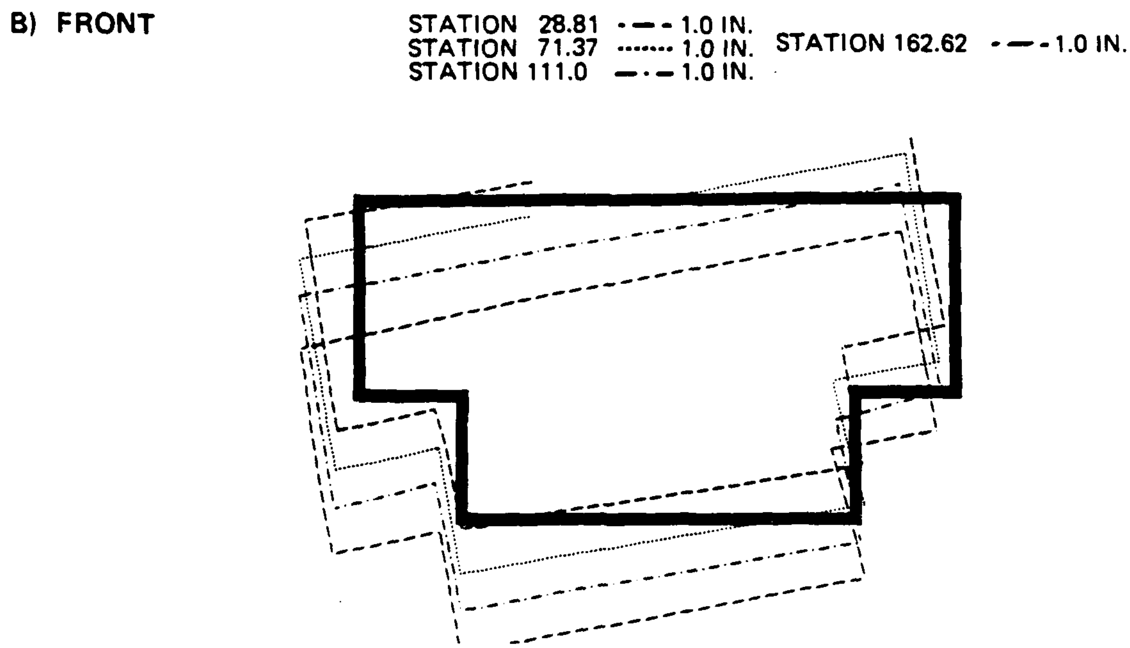
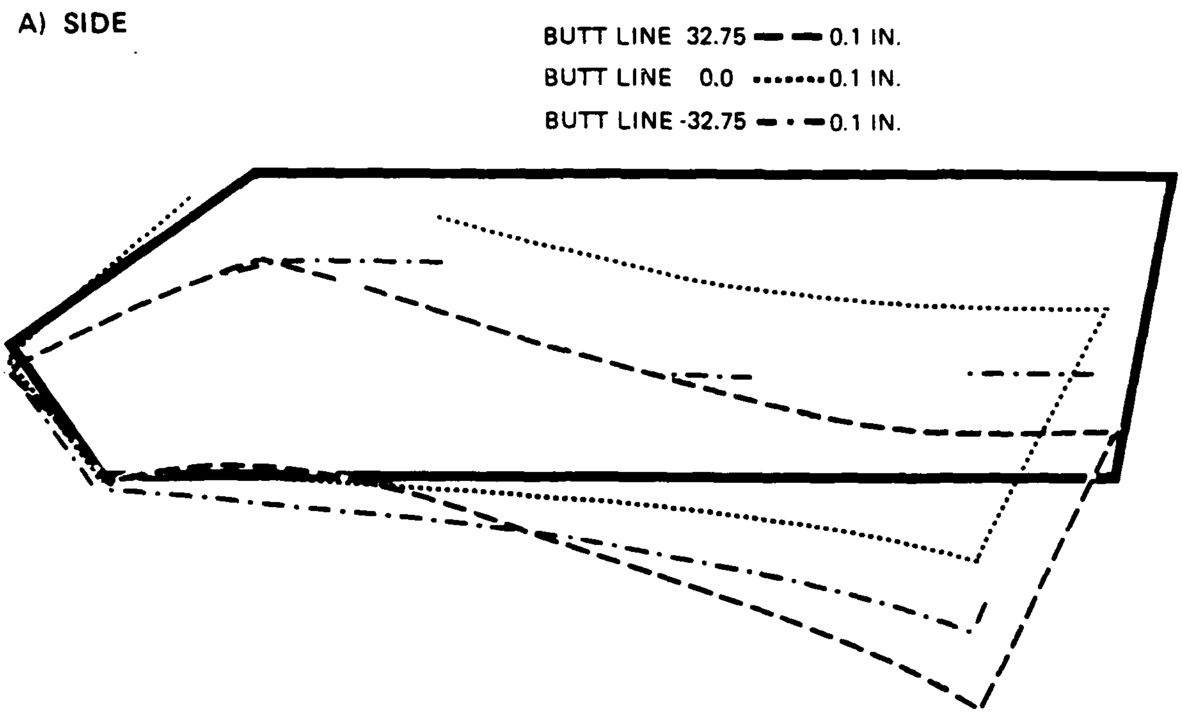


Figure 4-6. Diagonal Support Load Case at -40° F



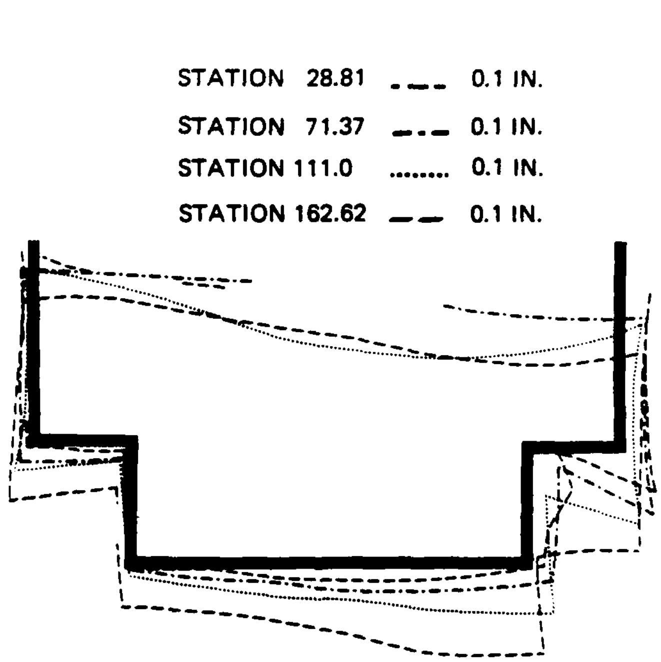
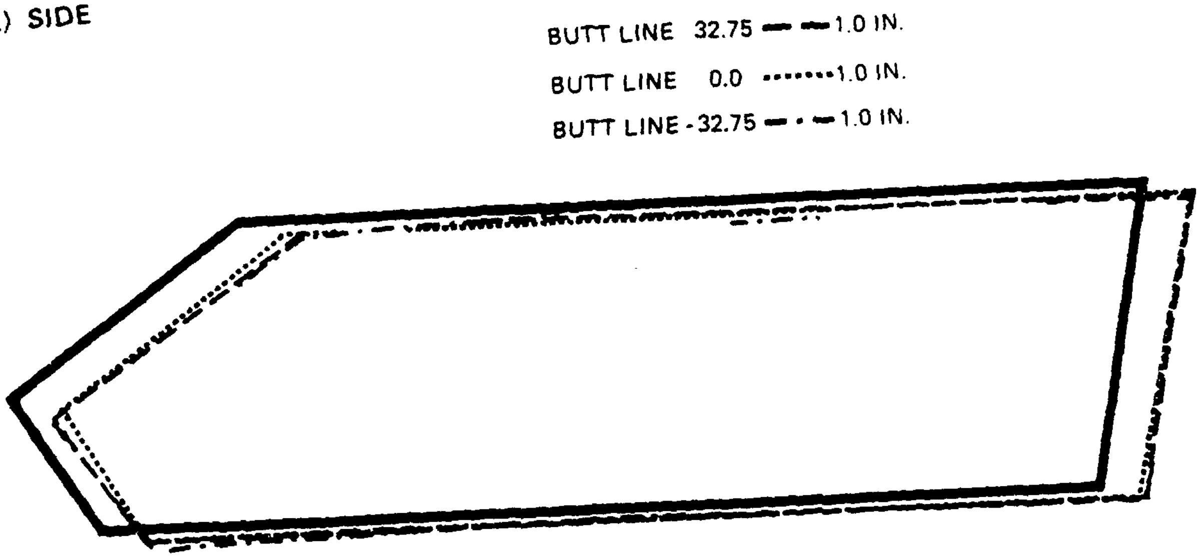


Figure 4-7. Load Case, 50,000 Lbs Applied at Bump Stop at -40° F

A) SIDE



B) FRONT

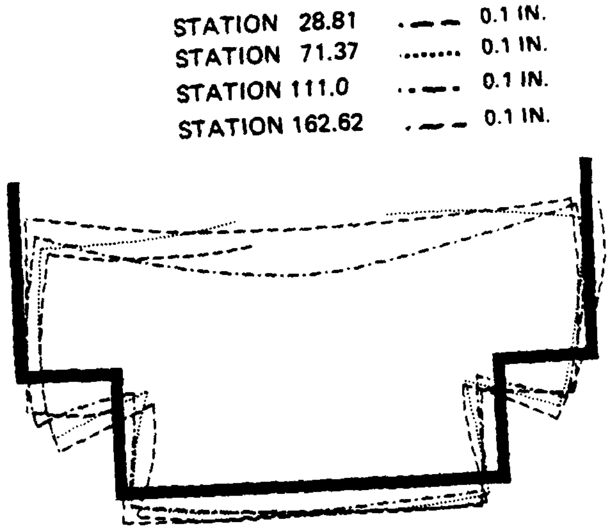


Figure 4-8. Load Case 1g Down + 6g Aft at -40°F

where a maximum deflection of the hull of 4.5 inches is predicted. The maximum relative deflection of the hull was for the rail transport (2g down) load case with a 0.5 inch deflection over 100 inches in the roof forward of the cargo hatch cutout. The maximum relative deflection of the sponson corner area was 0.25 inches for the rail transport (6g forward) load case. Distortion of the engine mounts was also checked. The maximum relative deflections in this area result from the diagonal support load case. The method of engine mounting, using three attachment points, allows rotation of the front mount that will be adequate to isolate the engine from structural deflections.

All openings in the hull were checked to ensure that hatches will open and close under the worst case load conditions. Distortions of the cargo hatch, driver's cupola, commander's cupola, engine hatch and rear ramp were plotted. The driver's cupola and commander's cupola showed distortions less than 0.15 inches for the worst combination of external load and thermal conditions. The cargo hatch showed a maximum distortion of 0.4 inch. The front and rear opening were checked for relative lateral deflections of the hatch and frame which could cause leakage. The maximum relative distortions are shown in Table 4-5.

Table 4-5. Distortion of Openings

Location	Operational Load		Transport Load	
	Load Case	Relative Deflection	Load Case	Relative Deflection
Front engine hatch	50,000 lb impact	0.01"	6g aft	0.024"
Rear ramp	Diagonal support	0.24"	3g side load	0.416"

The maximum distortion is for the rear ramp showing a 0.416 inch mismatch. This mismatch is within the seal overlap width and will not cause binding of the ramp since a 0.5 inch gap has been provided between the ramp and coaming. It should also be noted that this worst case is only a momentary rail transport condition.

Both the front and rear doors were also checked for the maximum deflection away from the watertight seal for all load cases. The worst case deflections are summarized in Table 4-6.

Table 4-6. Hatch to Frame Maximum Perpendicular Gap

Location	Operational Load		Transport Load	
	Load Case	Max Gap	Load Case	Max Gap
Front engine hatch	Diagonal support	0.06"	Rail transport	0.285"
Rear ramp	All cases	0.01"	All cases	<0.01"

All deflections for the operational load cases are within the 0.25 inch allowable deflection of the seals.

The following issues concerning the attachment of ceramic tiles to the composite upper hull were analyzed: minimum tile gap, minimum bondline thickness, and maximum adhesive modulus.

Because the tiles are very brittle compared with the composite laminate (i.e., strain allowables of 600 micro inches/inch vs 9400 micro inches/inch), they must be isolated from the structural deflections of the hull. A study was performed using a 2-D finite element model to determine the effect of bondline thickness on tile stress and gap spacing for various size tiles. The results for tile gap spacing shown in Figure 4-9 indicate very little change in tile spacing with a change in tile size. Tile stresses were higher for the 6 inch tile but still below the allowable. From these findings it was apparent that tile size could be selected based on other design criteria. A 4 inch x 4 inch tile was selected for the prototype hull to provide a good balance between the number of tiles required for assembly, tile gap area and tile availability.

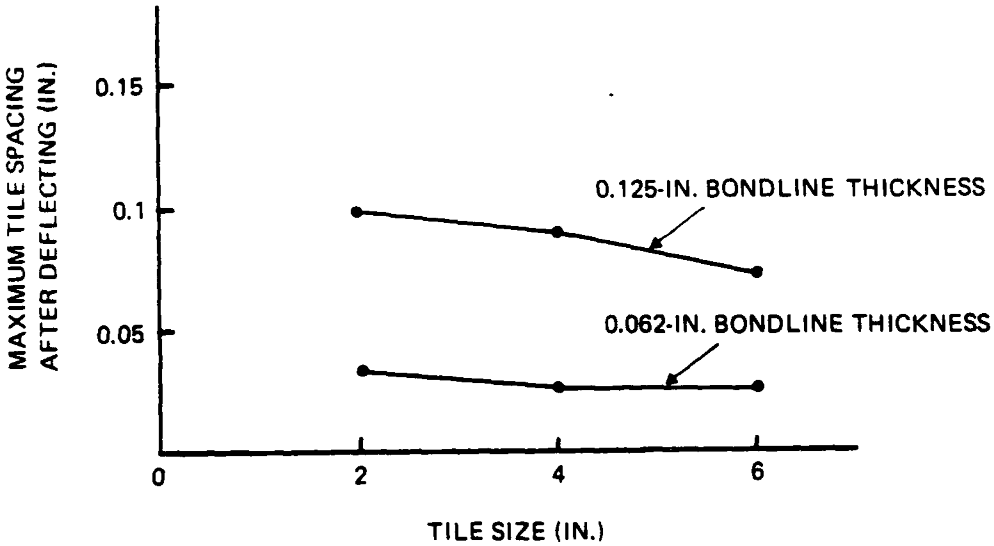


Figure 4-9. Effect of Bondline Thickness on Tile Gap Spacing

After selection of the 4 inch tile size, further analysis was performed to determine the effects of bondline thickness and adhesive modulus on the tile stresses and change in gap spacing. Figures 4-10 and 4-11 show the effect of bondline thickness and adhesive modulus on tile stress due to axial and bending loads, respectively. Based on these curves a maximum adhesive modulus of 20,000 psi (at the lowest design temperature of -40°F) and minimum bondline thickness of 0.062 inch was selected. These criteria will maintain low tile stresses for all operational conditions as shown in the curves.

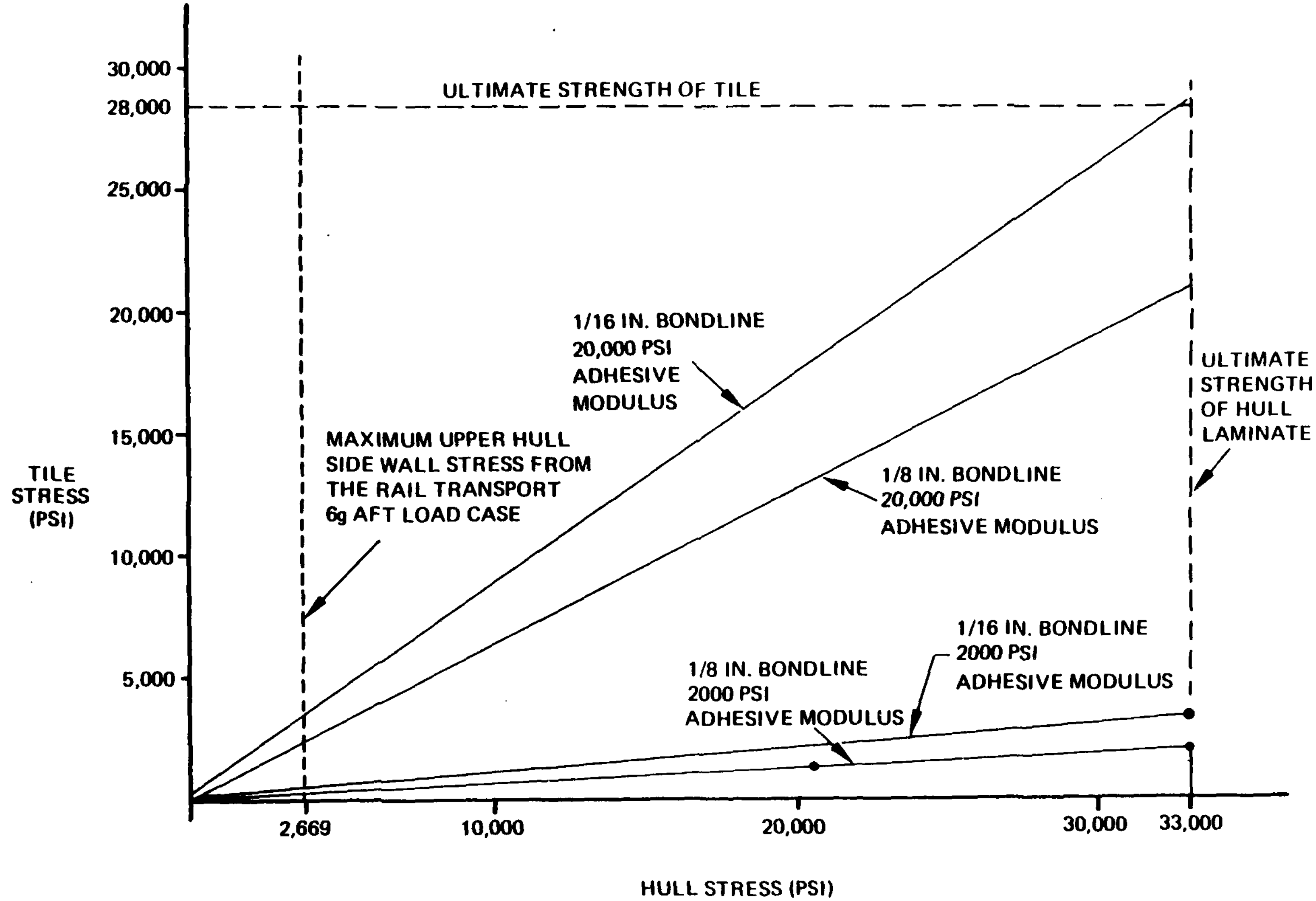


Figure 4-10. Tile Stress – Axial Load

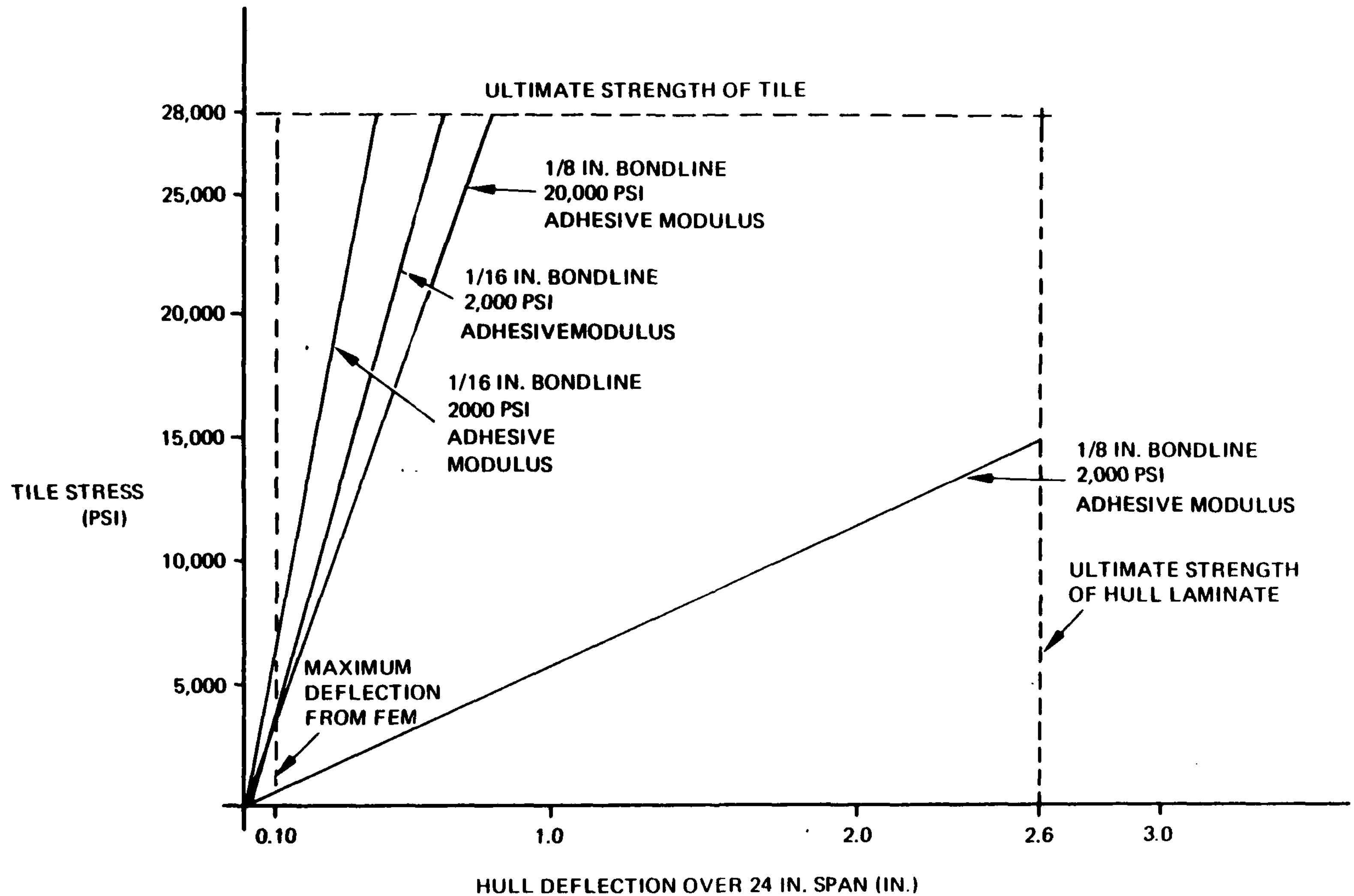


Figure 4-11. Tile Stress – Bending

Figure 4-12 shows the change in tile gap spacing due to bending deflections of the hull. As shown on the curve, the tile gap spacing is expected to change only slightly with the maximum deflections of the upper side wall of the hull. Conservatively, a minimum tile spacing of 0.062 inch was selected based on the expected change in tile gap spacing if the hull were to reach the maximum compressive strain allowable.

The maximum spacing on the tiles was set at 0.0925 inch based on manufacturing tolerances. This spacing is slightly smaller than the 0.125 inch maximum spacing outlined in the SOW and should result in improved ballistic performance. A summary of the dimensions for tile attachment is shown in Table 4-7.

Table 4-7. Tile Attachment Design

Maximum adhesive modulus - 20,000 psi at -40°F
Maximum tile gap spacing - 0.095 inch
Minimum tile gap spacing - 0.0625 inch
Minimum bondline thickness - 0.0625 inch

A series of mechanical properties tests[3] were run on EF5FR/woven roving laminates to provide data for establishing "B" basis design allowables. The test matrix in shown in Table 4-8 and the test results are summarized in Table 4-9. All tests were run on 0.250 inch nominal thickness laminates. Tension, compression, flexure, interlaminar shear and the coefficient of thermal expansion tests were run in the 90° (fill) direction of 0, 90 panels. Bearing tests were run on quasi-isotropic panels using a 0.25 inch fastener in a hole located 0.750 inch from the end of the specimen. In-plane shear tests were run on a ± 45° laminate. Wet specimens were conditioned 21 days at 140°F and 90% relative humidity. Laminate fabrication procedures are described in Section 8.0 of this report.

Table 4-8. Design Allowable Test Matrix

Test	-40°F	Ambient	140°F Wet	200°F
Tension	3	5	4	3
Compression	2	3	6	3
Flexure	0	4*	3	0
In plane shear	3	3	5	0
Interlaminar shear	0	4	3	3
Pin bearing	3	3	5	3
Coefficient of thermal expansion	- - - - 3 - - - -			

*Ambient, wet

3 William A. Dick and Dale W. Wilson, Mechanical Design Allowable Tests for Candidate M113 Glass Reinforced Materials, Test Report, Composites Technology Associates, Inc., Newark, Delaware, June, 1984.

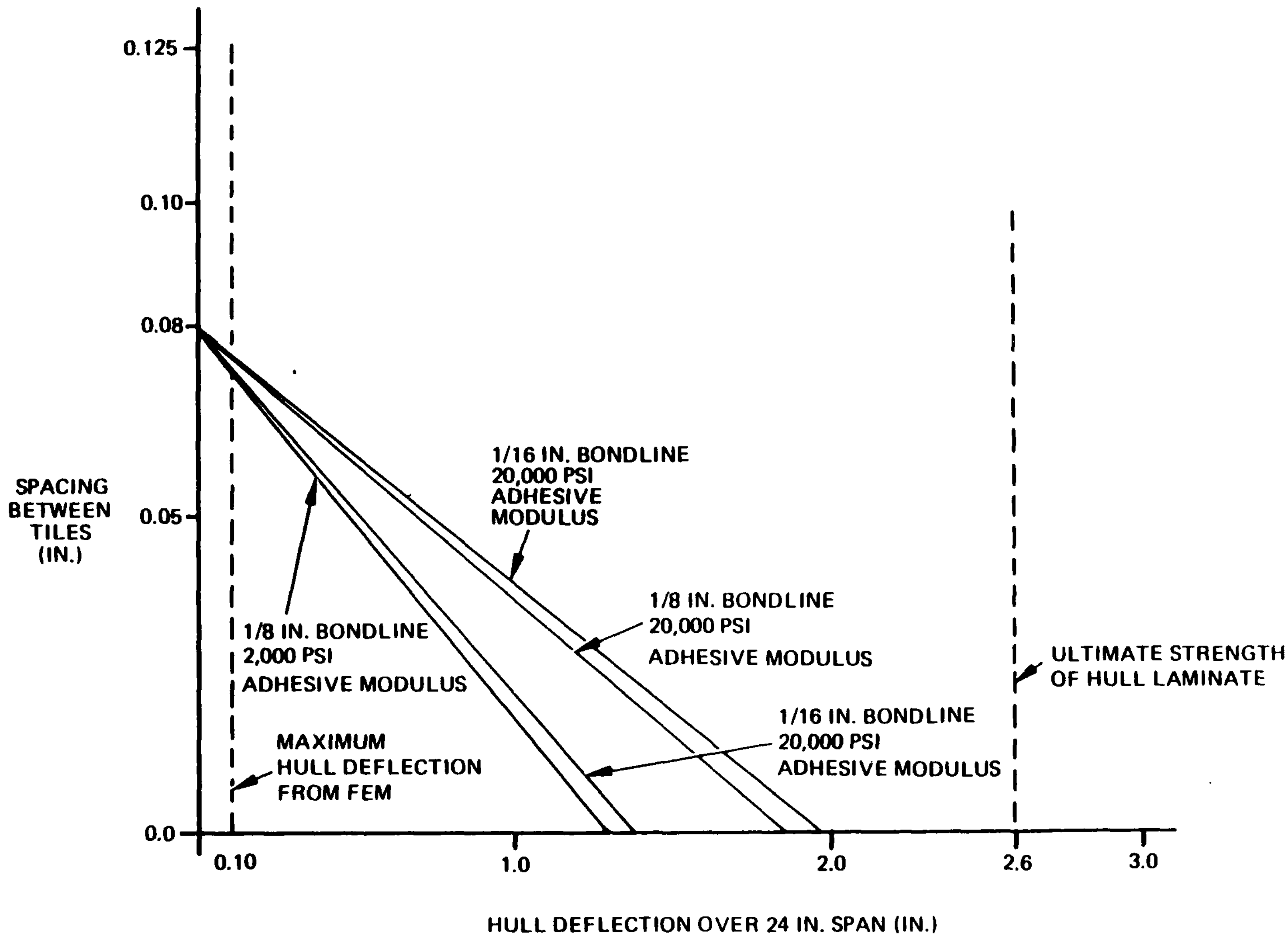


Figure 4-12. Tile Spacing

Table 4-9. Summary of Test Results

	-40°F	Ambient	140°F Wet	200°F
Tension Test				
Ultimate strength (Ksi)	70.57	64.01	49.34	48.00
Modulus (Msi)	3.57	3.54	3.55	3.07
Poission's ratio	-	0.15	0.11	0.09
Compression Tests				
Ultimate strength (Ksi)	54.04	45.97	27.23	22.14
Modulus (Msi)	3.85	3.82	-	3.29
Flexure Tests				
Ultimate strength (Ksi)	-	44.23	24.93	-
Modulus (Msi)	-	4.12	3.56	-
In-Plane Shear Tests				
Ultimate strength (Ksi)	7.78	6.52	3.52	-
Modulus (Msi)	0.75	0.79	0.27	-
Interlaminar Shear Tests				
Ultimate strength	-	5.5	3.0	1.8
Pin Bearing Tests				
First damage strength (Ksi)	-	23.1	17.4	20.4
Ultimate strength (Ksi)	-	35.6	28.6	27.5
4% hole elongation (Ksi)	18.8	21.1	21.4	3.7
Coefficient of Thermal Expansion				
Longitudinal (μ in/in/°F)		7.95	8.37	
Transverse (μ in/in/°F)		7.34	7.12	

5.0 MATERIALS AND PROCESSES

The primary consideration in selecting materials for the GRP hull was structural adequacy. Consideration was also given to the material characteristics identified in the contract Statement of Work (SOW) as candidates for improvement. These additional characteristics were:

1) Non-combustibility
2) Resistance to decontamination agents used in chemical warfare
3) Water absorption
4) Resistance to environmental factors such as ozone, ultraviolet radiation, etc.
5) Resistance to materials that might be expected in the operating environment such as diesel fuel, hydraulic fluid, battery acid, etc.
6) Resistance to thermal effects from hot environments and sunlight exposure
7) Resistance to abrasion and non-ballistic impact
8) Field repairability of ballistic and non-ballistic damage.

The materials selected for use in the GRP hull are shown in Table 5-1.

Requirements established for the GRP laminate were:

- Fire retardant
- Moisture resistant
- -40°F to +200°F operating capability
- Resistant to vehicle operating fluids.

Other material characteristics were relegated to secondary importance because of a lack of materials performance data, lack of a definable environment or an assessment that there were no serious problems. For example:

- Data base on the response of materials to chemical warfare decontamination agents is extremely sparse

- Only a qualitative assessment of abrasion and impact resistance was possible because that environment is not defined

- Ozone and ultraviolet light resistance of the GRP hull material is of minimal importance because the hull is protected from exposure by paint, tile, abrasion resistance covers, etc.

During Phase II two changes were made to the material selections made in Phase I:

1) The GRP hull material was changed

2) Three variations of the baseline tile attachment/coversheet scheme were used on the final hull.

Table 5-1. Materials Used

MATERIAL DESIGNATION	SOURCE	LOWER HULL	RINGS/ FRAMES	HULL LAMINATE	TILE ADHESIVE	COVER ADHESIVE	PROTECTIVE COVER	ALUMINUM TO GRP BONDING
MXB 7701/24 oz. Woven Roving	Fiberite West Coast Corp. Orange, CA			X				
5083 H112 Aluminum Alloy (QQ-A-250/6)	Various	X						
6061 T6 Aluminum Alloy	Various		X					
EA9330 Adhesive	Hysol Division Dexter Corporation Pittsburg, CA							X
Uralane 8089 Adhesive with 88060 Primer	Furane Products Co. Los Angeles, CA				X	X		
VHB 4945 Adhesive	3M Company St. Paul, MN				X	X		
Techthane -90SS	Technical Urethanes Clearbrook, VA						X	

During the early part of Phase II, it was observed that the processing characteristics of the GRP material, Eli Sandman Company's EF5FR resin with a 4X5, 24-ounce-per-square-yard woven roving fabric, originally chosen for the hull was highly erratic. This variable processing behavior was deemed unacceptable for full scale hull fabrication and alternate sources for GRP material were contacted. The material finally selected was Fiberite Corporation's MXB 7701/24 oz woven roving. This material utilizes a toughened epoxy resin system, which is cured at 250°F as the matrix. A series of tests were run to verify critical mechanical properties of laminates made from the new material.

Mechanical properties were determined on 1/4-inch thick laminates. The material was procured in preimpregnated form with 32 to 35 percent resin by weight and a fabric areal density of 22 to 26 ounces per square yard. The material was cured in an autoclave for two hours at 100 psi and 250°F. The layups were processed to provide a "net" resin cure (i.e., the layups were bagged so no resin was lost into bleeder plies; all resin was retained in the laminate). This approach minimizes variations in laminate thickness and resin content.

The test results are summarized in Table 5-2. Detailed test results are contained in Reference 2.

Table 5-2. *Summary of Test Results*

	Ambient	140°F Wet	200°F
Tension Tests			
Ultimate Strength (Ksi)	64.5	57.9	53.3
Modulus (Msi)	4.08	4.28	3.59
Poisson's ratio	0.15	0.10	0.14
Compression Tests			
Ultimate Strength (Ksi)	63.2	42.3	39.3
Modulus	3.95	-	-
Flexure Tests			
Ultimate Strength (Ksi)	-	49.3	-
Modulus (Msi)	-	4.63	-
Notched Tension Tests			
Ultimate Strength (Ksi)	29.7	24.5	24.0
Modulus (Msi)	2.82	2.74	2.21
Interlaminar Shear Tests			
Ultimate Strength (Ksi)	-	4.6	3.7
Pin Bearing Tests			
First Damage Strength (Ksi)	17.7	12.6	11.5
Ultimate Strength (Ksi)	22.3	16.3	13.8
4% Hole Elongation (Ksi)	8.3	5.4	4.3

Two variations to the baseline tile attachment configuration were added to the program to obtain producibility and performance data on configurations other than the baseline. The Variations were:

- use of an abrasion resistant polyurethane layer rather than aluminum as the protective cover on the right (engine) side of the hull
- use of a pressure sensitive adhesive to attach the tiles and cover sheets on the rear of the hull.

The urethane cover material was Techthane-90SS, an extremely tough, sprayable, room-temperature curing, polyurethane elastomer manufactured by Technical Urethanes, Inc., Clearbrook, Virginia. This material was applied by spraying directly over tiles that were bonded to the GRP side wall. The tiles were prepared for spraying by solvent wiping and priming with Techthane-FC primer. The primer was allowed to dry at room temperature for 2 hours prior to applying the urethane elastomer. The Techthane-90SS coating was sprayed on as a 50 percent solids solution using an airless spray gun. The coating was built up in coats about .015 inch thick with a drying time of 15 to 20 minutes between coats. The total coating thickness was nominally .062 inch. The properties of room temperature cured Techthane-90SS are given in Table 5-3.

Table 5-3. Typical Properties of Techthane-90SS

Tensile Strength (ASTM-D412), psi	4,600
Tear Strength (ASTM-D624, Die-C), pli	350
(ASTM-D470, Split), pli	90
100% Modulus (ASTM-D414) psi	1,200
Elongation (ASTM-D412), %	410
Hardness, Durometer A	90
Rebound, Bashore, %	40
Adhesion, (ASTM-D429), pli	70

The other variation in tile attachment was the use of a pressure sensitive adhesive film in place of urethane elastomer. The material used was 3M Company's VHB 4945, a double coated acrylic foam tape. The use of this material allows tiles to be attached to the hull by simply pressing them into place. No cure time or separate adhesive is required. The use of a pressure sensitive adhesive offers labor savings in production and has potential for use in rapid field repairs. The properties of the VHB-4945 Tape are summarized in Table 5-4.

Table 5-4. Performance Characteristics of VHB 4945 Tape

Peel Adhesion, 90° (lb/in)	20
Normal Tensile Strength (Psi)	120
Shear Strength @ 72°F (Psi)	1,500
Shear Strength @ 150°F (Psi)	500
Shear Strength @ 200°F (Psi)	500

The tiles selected are the same composition as recommended in the SOW, 94% alumina. The Coors Procelain Company's grade AD94 is the specific material selected.

The tile bonding adhesive selected is a two-component room temperature curing polyurethane (M&T Chemicals, Inc., Furane Products Division Uralane 8089). Some properties of this material are summarized in Table 5-5. This selection was based primarily on its ability to meet the modulus requirement of 20,000 psi at 40°F (refer to Section 4.0) and its good peel strength. A critical unknown about this material is its resistance to CW decontamination agents, particularly DS2. CW decontamination agent resistance is not considered critical to the present feasibility demonstration, but it is a significant item for an operational vehicle.

Table 5-5. Furane 8089 Adhesive Properties

Temp	-40°F	72°F	140°F
Modulus	23,675 psi	1,092 psi	365 psi
T-Peel	95 lb/in	42.5 lb/in	--
Elongation	42%	131%	76%
Lap Shear	3295 psi	827 psi	410 psi

Selection of three protective coatings for the material verification test panels for delivery to DTRC was done on a qualitative basis because no adequate definition of the abrasion/impact environment is available. The three selected coatings are:

- Thin (.032 inch) aluminum sheet
- Two-ply style 220 Kevlar 49 fabric/Uralane 8089 polyurethane elastomer laminate
- Two-ply style 220 Kevlar 49 fabric/Hysol 9330 toughened epoxy resin laminate.

All of the covers were bonded over the ceramic tiles with a thick (~.040 inch) layer of the Uralane 8089 adhesive.

The protective cover configurations were selected to provide a range of protection. The thin aluminum sheet with a thick elastomeric bond line provides high abrasion and cut resistance, and because the aluminum is stiff, will distribute impact loads over a wider area than the other two approaches, thus reducing stresses on the tiles. The Kevlar/urethane laminate was chosen as an approach which would act like a rubber pad to dissipate impact energy and still have toughness and tear resistance provided by the Kevlar reinforcement. The Kevlar/toughened epoxy laminate provides an intermediate protective layer which should both spread and dissipate impact energy.

Five panels using each protective cover were fabricated and delivered to DTRC for testing.

All panels were 18 inches square and consisted of the basic 0.75 inch minimum thickness woven roving laminate, 1/2 inch thick 94% alumina ceramic tiles, and the protective cover sheets. To obtain verification of the selected laminate process, the GRP laminate were prepared as 3/4-inch thick, 96-inch by 40-inch panels. The 18-inch square panels were cut from the large panels. No problems were encountered in fabrication the large panels. Nylon tear plies were laid up on both faces of the panels and cured in place during the laminate cure. Those plies, that are removed just prior to bonding or finishing, protect the laminate surface from contamination that could interfere with the adhesion of paint or adhesive.

Laminated protective covers were prepared by making a wet layup of two plies of style 220 Kevlar fabric and a nylon tear ply on an aluminum caul plate. The layups were allowed to cure at room temperature under contact pressure.

Tile bonding and cover sheet bonding were accomplished in the same process. The surfaces of the Kevlar and GRP laminates were prepared for bonding by removing the nylon tear ply. The aluminum cover sheet was prepared by a sodium dichromate/sulfuric acid etch and the tiles were cleaned by vapor degreasing. The aluminum and tiles were primed with Furane 88060 primer. Precured urethane elastomer spacers were bonded to the tiles to control tile spacing. The spacers were 0.063 inch thick on the bottom and sides of the tiles to control tile-to-GRP and tile-to-tile bondline thickness, and 0.040 inch thick at the top of the tiles to control tile-to-cover bondline thickness. Temporary dams were placed around the periphery of the GRP panels and an excess of Uralane 8089 adhesive was poured in the dammed area. The tiles were then pressed into the uncured adhesive until they bottomed out on the spacers. Then the cover sheet was placed over the tiles and pressed down until it contacted the spacers on top of the tiles. Excess adhesive was scraped away and the panels were placed in an oven at 150°F to cure. Preparation for painting consisted of application of wash primer (DOD-P-15378D) to the aluminum cover sheets and peel ply removal on GRP and Kevlar laminates. The panels were finished coated with MIL-C-46168A polyurethane paint.

On the basis of providing ease of manufacture, the thin aluminum sheet was selected as the baseline protective cover at the end of Phase I.

The adhesive/sealant selected for the main joint and around the hatch rings, door frames etc., is Dexter Corporation, Hysol Division's Hysol 9330, a high strength toughened epoxy. This material provides high strength plus enough resiliency to accommodate the deflections occurring at joints and openings.

One key consideration in the selection of materials for amphibious vehicles is seawater corrosion. Even though the major construction materials selected -- GRP, 5000 series aluminum alloys and 6000 series aluminum alloys -- have excellent corrosion resistance, there are still potential corrosion problems to be dealt with in joint and fastener areas. The corrosion problems of concern are: galvanic corrosion, stress corrosion cracking, and crevice corrosion.

The best approach to preventing galvanic corrosion is to use materials that are electrochemically compatible such as GRP and aluminum. The practical choice of compatible fastener materials is limited to aluminum, titanium and plastic. Because aluminum and plastic fasteners are relatively low in strength and easily deformed, the fastener material of choice for a production hull program is titanium. For this feasibility demonstration program, obtaining titanium fasteners in small quantities in the sizes needed may present a problem in both cost and schedule. In the event that titanium fasteners cannot be obtained, the fall back position is to use stainless steel fasteners for the feasibility demonstration hull. These fasteners would be installed with wet sealant to minimize corrosion. It is believed that the corrosion problem associated with using stainless steel fasteners can be tolerated for the present program, they are not recommended for a production vehicle. Cadmium plated steel fasteners are not used for two reasons.

1) Cadmium has been shown to promote stress corrosion cracking of 5083, the aluminum alloy used in the lower hull, in a marine environment

2) When the cadmium plating is scraped off the steel by track slap or other abrasion, the fastener would corrode very rapidly.

Crevice corrosion is a problem in any aluminum structure where cracks or crevices that seawater can enter exist. In the GRP hull design there are numerous areas of potential crevice corrosion problems. The approach to eliminating or controlling crevice corrosion is to minimize the open volume in cracks or crevices by using faying surface sealing, wet fastener installation, etc.

6.0 FABRICATION

The general approach to fabricating the prototype hull is shown in Figure 6-1. The fabrication approach used for the feasibility demonstration hull differed from a production approach only in that hand labor and set up were used in lieu of hard tooling and automated techniques.

6.1 Tooling

The only major tool used in the manufacture of the demonstration hull was the upper hull lay-up mold. This large multiple piece tool was used for the lay up and cure of the GRP upper hull laminate. An overall view of the tool during its assembly is shown in Figure 6-2. It consisted of a central load bearing structure made up of square extruded aluminum pieces welded together. The actual lay-up surface consisted of brake-formed pieces of 1/4-inch thick aluminum plate with interior bulkheads to rigidize each individual section. The sections of the layup surface were bolted to the load bearing truss. The sections were arranged so the central truss could be removed first and the geometrically trapped sections of the layup surface could be slid inward until they were free to be removed from the cured layup. Since the interior dimensions of the GRP upper hull are critical to a proper fit-up with the lower hull and installation of some M113 equipment, the tool was sized to compensate for the differential thermal expansion between the GRP laminate and the aluminum tool.

To facilitate transportation and use, the lay-up tool was mounted on a wheeled platform that had provisions for tilting the tool to provide easy access to the hull track channels during lay up.

Joints between the elements of the tool were sealed from the inside with a room temperature curing silicone rubber prior to use.

6.2 Upper Hull Fabrication

The GRP upper hull was fabricated in two stages; a basic 3/4-inch thick laminate and a 1/2-inch thick roof doubler. The 3/4-inch thick laminate makes up all of the surfaces of the upper hull. The doubler was added inside the roof area of the 3/4-inch thick layup to bring the total roof thickness up to 1-1/4 inches.

Prior to beginning the layup, the aluminum tool was solvent wiped with clean solvent and coated with Frekote 33 release agent. The overall 3/4 inch thick laminate was then laid up. The ply sequence of the layup is shown in Table 6-1. Also included in the table are the roll number and properties of the preimpregnated woven roving used in each ply. The layup was debulked under vacuum bag pressure for a minimum of one hour every second ply to ensure that female radii were properly compacted and to avoid "puckering" of the male radii and corners. Figure 6-3 shows the hull layup in progress. Debulking was accomplished by placing one ply of breather material over the layup, applying a nylon film vacuum bag and evacuating the bag to a pressure of less than 26 torr. All debulks were

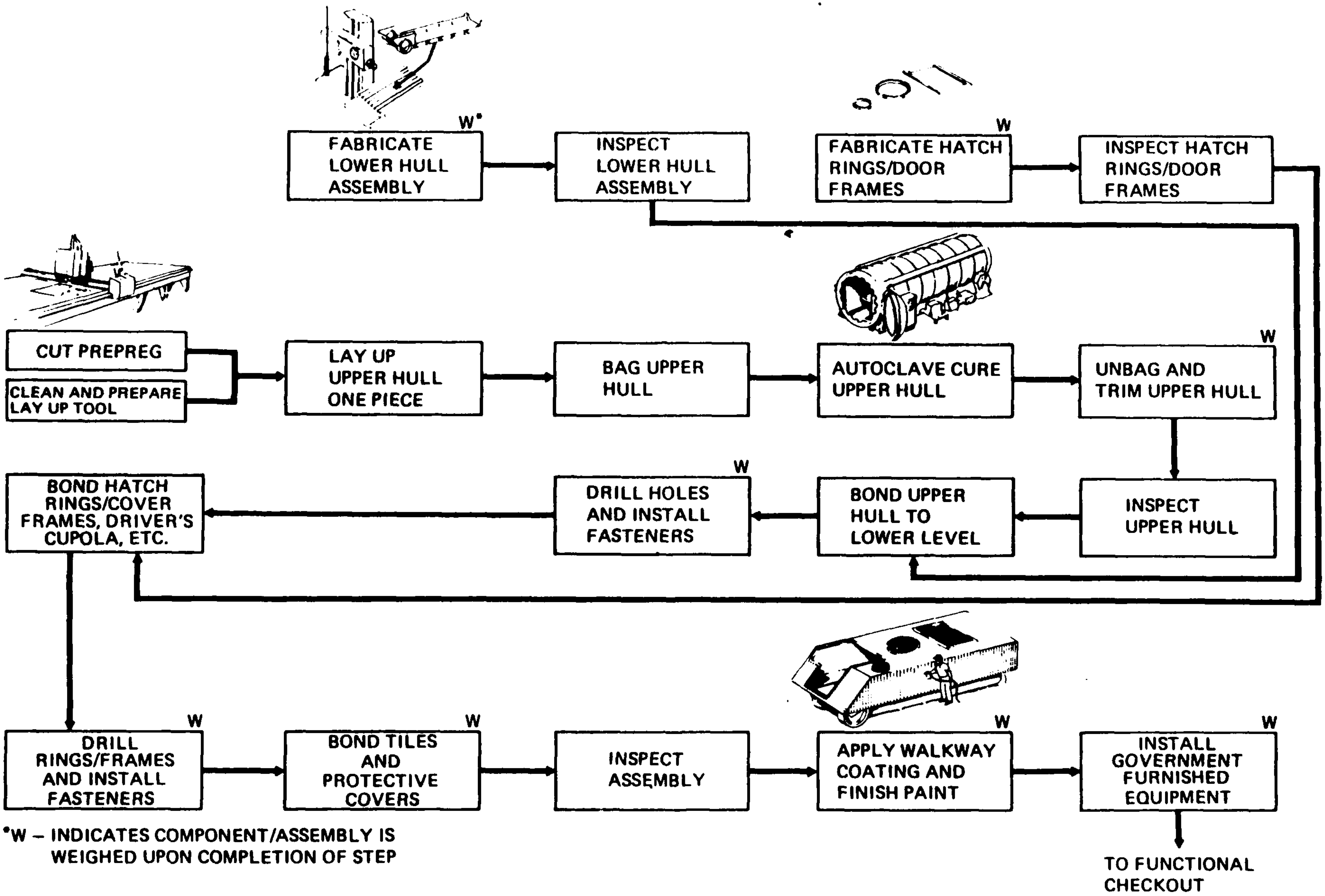


Figure 6-1. M113 Hull Fabrication Flow

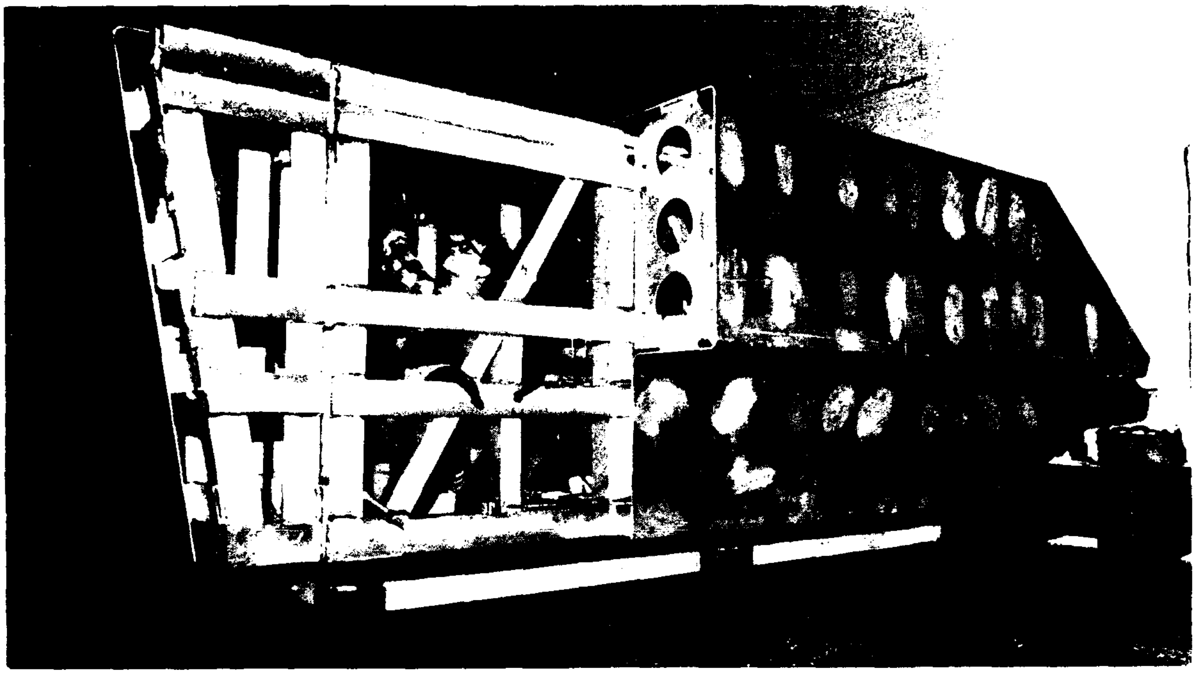


Figure 6-2. Upper Hull Layup Tool

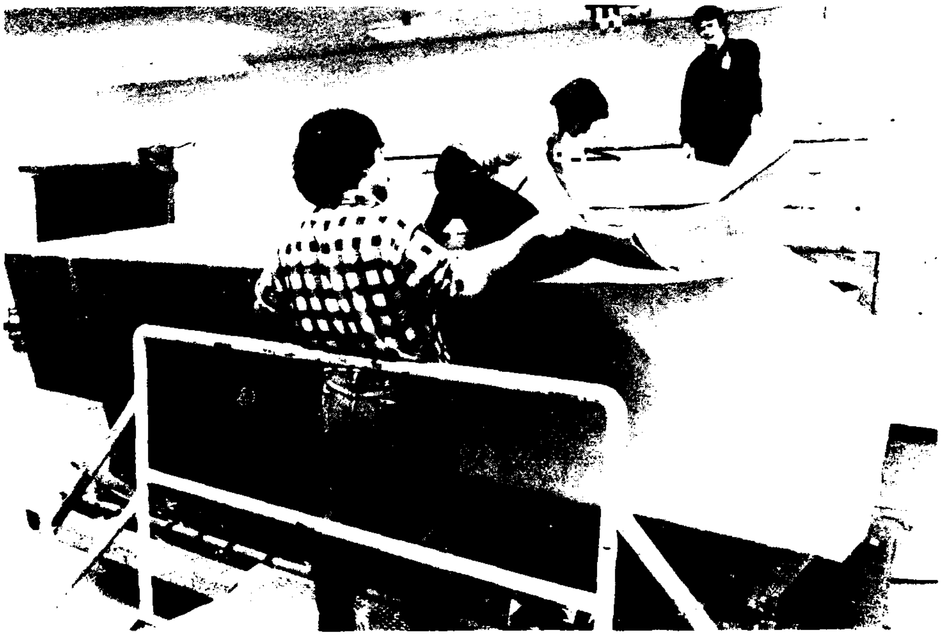


Figure 6-3. Layup of Upper Hull

Table 6-1. Ply Orientation and Prepreg Properties, Hull Laminate

PLY LEVEL	PLY ORIENTATION (Degrees)	ROLL NO.	VOLATILE CONTENT (Wt %)	RESIN SOLIDS CONTENT (Wt %)	RESIN FLOW (Wt %)	GEL TIME (Minutes @ 275°F)
1	0	54	1.2	33.2	12.4	4.8
2	45	54	1.2	33.2	12.4	4.8
3	90	54	1.2	33.2	12.4	4.8
4	0	53	1.2	33.3	13.1	4.8
5	45	53	1.2	33.3	13.1	4.8
6	90	52	1.4	33.6	13.2	4.8
7	0	52	1.4	33.6	13.2	4.8
8	45	51	1.1	32.2	12.3	4.8
9	90	51	1.1	32.2	12.3	4.8
10	0	50	1.2	32.0	10.3	4.8
11	45	50	1.2	32.0	10.3	4.8
12	90	19	1.2	31.5	11.3	4.3
13	0	19	1.2	31.5	11.3	4.3
14	45	20	1.1	32.5	10.9	4.3
15	90	21	1.3	32.1	9.9	4.3
16	0	21	1.3	32.1	9.9	4.3
17	90	21	1.3	32.1	9.9	4.3
18	0	24	1.2	32.7	11.4	4.6
19	0	24	1.2	32.7	11.4	4.6
20	90	27	1.2	32.3	11.7	4.6
21	0	27	1.2	32.3	11.7	4.6
22	90	26	1.1	31.9	11.5	4.6
23	45	25	1.1	31.7	11.8	4.6
24	0	25	1.1	31.7	11.8	4.6
25	90	58	1.2	32.7	11.1	5.0
26	45	58	1.2	32.7	11.1	5.0
27	0	57	1.2	33.1	11.7	5.0
28	90	57	1.2	33.1	11.7	5.0
29	45	61	1.2	32.5	9.9	5.0
30	0	61	1.2	32.5	9.9	5.0
31	90	60	1.1	33.6	10.9	5.0
32	45	60	1.1	33.6	10.9	5.0
33	0	63	1.2	32.0	11.5	5.3
34	90	50	1.2	32.0	10.3	4.8
35	45	65	1.4	31.4	11.1	5.3
36	0	64	1.4	31.8	11.6	5.3

conducted at room temperature. In addition to the debulks at vacuum pressure, one debulk at 100 psi was performed after ply 18 was laid up. This was accomplished by bagging the layup as above and then placing the bagged assembly in an autoclave and pressurizing it to 100 psi for 10 minutes. The above debulking schedule, which is extremely conservative, was selected on the basis of minimizing risk during fabrication of this one-of-a-kind hull. The lay up and debulking were performed by a three-man crew. All pattern development and ply trimming was done by hand adjacent to or on the tool. All joints between pieces of prepreg were staggered a minimum of six inches to avoid weak spots in the laminate.

The completed layup was prepared for curing by placing one layer of nylon tear ply, one layer of Mauchberg bleeder ply, and a nylon film autoclave bag on the outer surface. The bag was sealed to the tool just below the layup. The layup and tool were instrumented with 12 thermocouples to monitor temperatures during cure. Two vacuum fittings were connected to the bag, one in the center of the aft end, the other in the center of the roof. The bagged upper hull layup is shown in Figure 6-4. A vacuum of 26 torr was pulled on the bag, the assembly was placed in the autoclave, pressurized to 100 psig, and heated to 250°F. The part was cured for two hours at 250°F and cooled to 150°F before removal from the autoclave. The internal part temperatures were measured by thermocouples embedded in the center of the layup (ply level 18) on the roof and aft end. These measurements are particularly significant because they show the amount of exothermic heating occurring during cure. Temperatures in the center of the laminate rose about 45°F above the desired cure temperature. This level of exothermic heating is considered acceptable and will not cause any degradation of the finished laminate. The cured upper hull layup is shown in Figure 6-5.

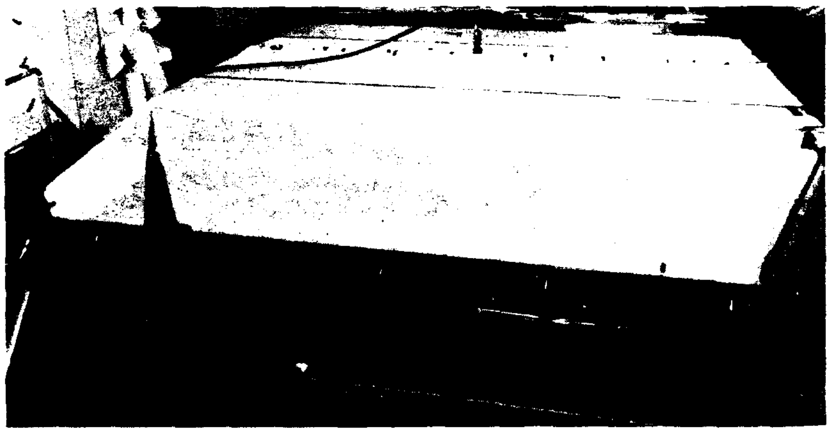


Figure 6-4. Upper Hull Layup Bagged and Ready for Autoclave Cure

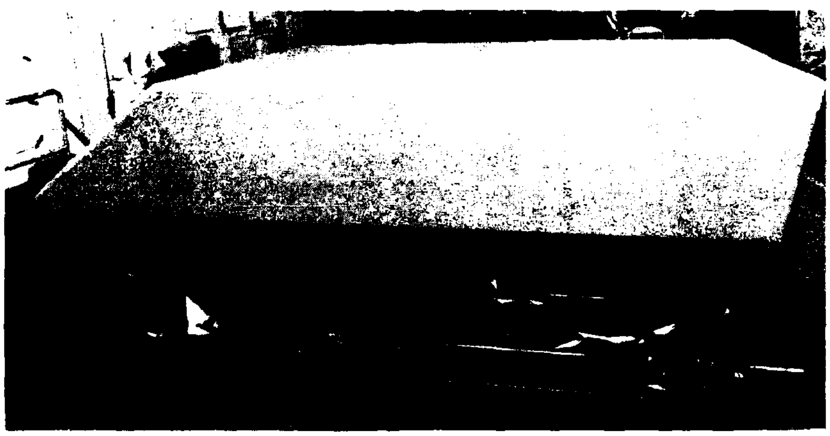


Figure 6-5. Cured upper hull layup

Once the 36-ply laminate was cured, the tool was removed and the laminate was rough trimmed.

The cured upper hull was nondistructively inspected twice using pulse-echo A-Scan with a 1 MHz, 3/4-inch diameter ultrasonic transducer. The 36-ply hull was laid out in a 6 inch by 6 inch grid pattern, labeled, and photographed (see Figure 6-6). Each square was scanned using water as a couplant. The instrument was set up using a piece of trim with 3/8 inch diameter flat bottom holes, 0.25 and 0.50 inch deep as a standard. Both of these defects were readily visible. The criteria for notation of an anomaly were an observation of an intermediate reflection or a loss of the back wall reflection. This inspection process was repeated for the 18 ply doubler after it was cured. The anomalies observed are outlined in Figure 6-7. The only visual anomolies in the hull after trim were a slight bridging condition in the sponson radius and a rough interior surface. This later condition was attributed to air leaks in the layup tool.

Figure 6-6. Grid used for NDI Reference

The roof doubler was laid up next. This was accomplished directly on the inside of the cured 36-ply laminate. First, the nylon tear ply was removed from the area of the laminate to be covered by the doubler to provide a clean surface for bonding. Then one ply of FM 125-5 adhesive film was laid up over the prepared surface. Finally, 18 plies of preimpregnated woven roving were laid up to form the doubler. The ply sequence and prepreg properties of the doubler material are given in Table 6-2. The doubler was autoclave bagged and cured in a manner similar to that used for the main hull lay up except that in this case the cured hull served as the tool. Because there were no trim areas on the doubler laminate, temperature was monitored using surface rather than embedded themocouples on the lay up. No exothermic heating of the laminate during cure was observed. Once again the laminate was laid out in a grid pattern and inspected ultrasonically. No anomolies were found in the doubler laminate.

Trim lines for the upper hull edges and openings were laid out on the cured part by hand. The part was trimmed to the lines using a portable circular saw fitted with a carbide tipped blade, and a saber saw with a silicon carbide grit coated blade.

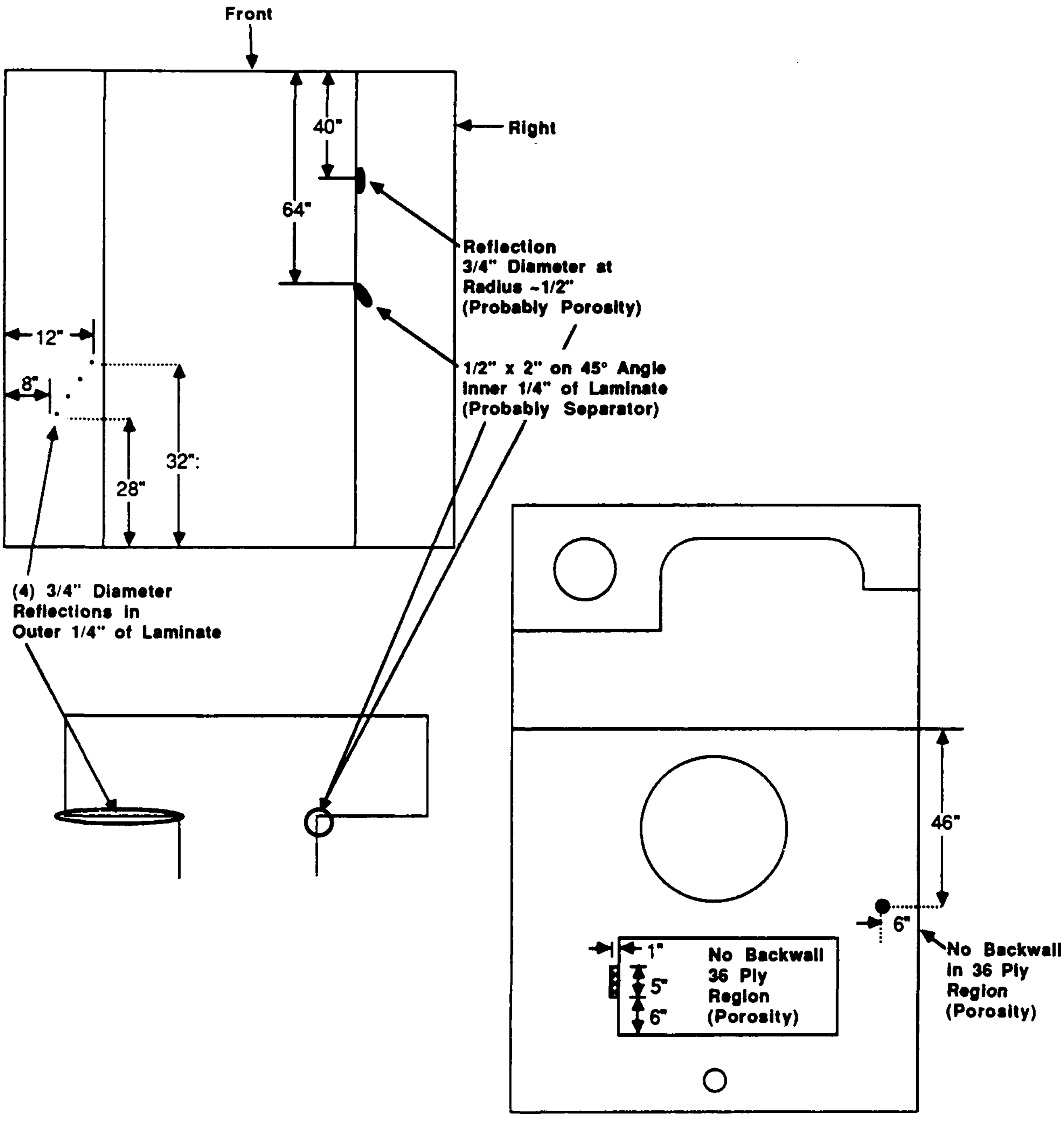


Figure 6-7. Ultra Sonic Indications of Anomalies

Table 6-2. Ply Orientation and Prepreg Properties, Doubler Laminate

MATERIAL DATA						
PLY LEVEL	PLY ORIENTATION (Degrees)	ROLL NO.	VOLATILE CONTENT (Wt %)	RESIN SOLIDS CONTENT (Wt %)	RESIN FLOW (Wt %)	GEL TIME (Minutes @ 275°F)
37	0	11	0.70	32.3	11.0	4.2
38	45	64	1.4	31.8	11.6	5.3
39	90	64	1.4	31.8	11.6	5.3
40	0	64	1.4	31.8	11.6	5.3
41	45	64	1.4	31.8	11.6	5.3
42	90	12	0.9	31.9	11.2	4.2
43	0	12	0.9	31.9	11.2	4.2
44	90	12	0.9	31.9	11.2	4.2
45	0	12	0.9	31.9	11.2	4.2
46	0	72	1.0	33.6	10.7	5.0
47	90	72	1.0	33.6	10.7	5.0
48	0	72	1.0	33.6	10.7	5.0
49	90	72	1.0	33.6	10.7	5.0
50	45	10	0.7	30.7	11.8	4.2
51	0	10	0.7	30.7	11.8	4.2
52	90	10	0.7	30.7	11.8	4.2
53	45	10	0.7	30.7	11.8	4.2
54	0	10	0.7	30.7	11.8	4.2

Destructive inspection were run on trim from the hull as follows:

- Visual examination: The edges of samples cut from edge trim, the ramp cut out, and the ventilator cut out were polished and examined under a low power (30X) microscope. Very low levels of porosity were observed. The ultrasonic indication at the edge of the cargo hatch was verified as porosity by examination of the cut edge.

- Laminate Analysis: Resin content, fiber volume and void content determinations were run on samples taken from the ramp cut out. Resin content was determined by ignition loss (ASTM D2584), and other properties were calculated using actual laminate density and vendor data for constituent properties. The results of 31.6 weight percent resin, 1.5 volume percent voids and 51.7 percent fiber volume showed acceptable laminate quality. Individual test results are provided in Table 6-3.

- To verify the vendor data on prepreg materials, an in-house pregreg analysis was done on four rolls from each phase of the 36-ply layup, and one from the doubler layup. The results are in Table 6-4. Martin Marietta's test results for resin solids and volatile contents were slightly lower than the vendors. Both sets of results were within specification.

Table 6-3. Cured Laminate Resin Content and Void Content

(Samples from Ramp Cutout)				
SAMPLE	SPECIFIC GRAVITY	FIBER VOLUME (VOL %)	RESIN CONTENT (WT %)	VOID CONTENT (VOL %)
1	1.93	51.7%	31.7%	1.2%
2	1.92	51.4%	31.7%	1.8%
3	1.93	51.9%	31.4%	1.5%
Avg.	1.93	51.7%	31.6%	1.5%
Req'd			25% - 35%	<2.0%

Table 6-4. Prepreg Properties

(FIBERITE 7701/24 oz WOVEN ROVING, BATCH 6171)			
ROLL NO.	RESIN CONTENT (Wt %)	FIBER AREAL WEIGHT (oz/sq yd)	VOLATILE CONTENT (WT %)
20	33.1	24.5	0.73
50	-	-	0.46
52	31.2	24.4	0.35
64	30.6	24.4	0.37
65	30.0	24.6	0.34

- **Flexural Strength: Specimens for laminate flexural strength tests were cut from material taken from the ramp opening. The specimens, 16 inches long by one inch wide, were cut in the zero degree direction. They were tested using four point loading with a 12-inch span and 4 inches between loading points. The results are shown in table 6-5. The average ultimate flexural strength of 64.7 Ksi compares favorably to the 62.1 Ksi previously measured on samples from a 3/4-inch thick laboratory laminate, and is well above the 44.2 Ksi measured on a 1/4-inch thick laminate during design allowables testing. The flexural strength expected on the basis of SQ5 computer code predictions utilizing laminate properties was 59.5 Ksi.**

Table 6-5. Flexural Strength Test Results

	THICKNESS (in.)	WIDTH (in.)	LOAD (lbs)	STRESS (ksi)
1	.900	.991	4094	61.2
2	.896	.988	4474	67.7
3	.888	1.049	4518	65.5
4	.887	1.054	4452	64.4
Avg.				64.7

6.3 Lower Hull Fabrication

The aluminum lower hull was fabricated using conventional techniques. The 5083 plate was cut to size and the edges were chamfered as required. The welded joints in the lower hull were patterned after the corresponding joints of the standard M113A1 hull. Once the plates were chamfered, they were set up by hand on acorn tables and welded using standard gas metal arc welding procedures. After the welded assembly was complete, it was set up on a horizontal boring mill and finish machined. At this point, the lower hull was complete except for the motor mounts, transmission mounts and ramp hinge points. All welds were performed by certified welders and the welds were subjected to visual inspection. The complete lower hull is shown in Figure 6-8.

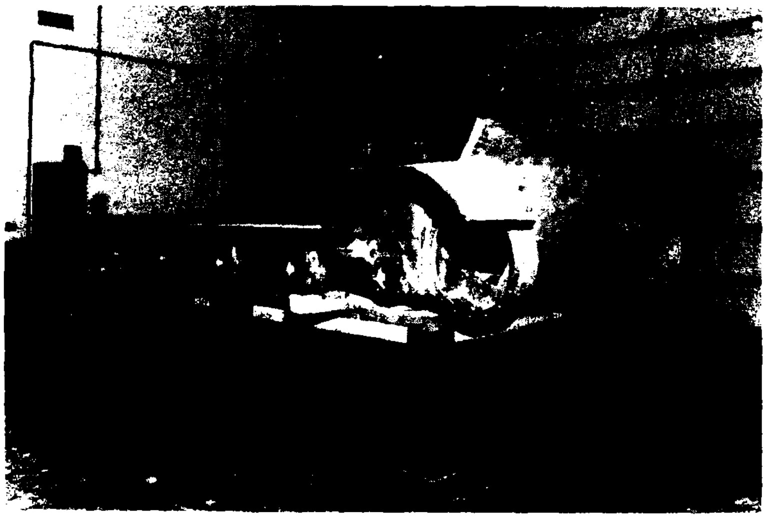


Figure 6-8. Aluminum Lower Hull

6.4 Hull Joining

The upper and lower hulls were joined by means of a bonded, bolted lap joint. The initial step in joining the hull sections was to lower the upper hull onto the lower hull. During the initial fit-up it was observed that residual stresses in the GRP upper hull had caused it to distort locally when it was trimmed and the various openings were cut into it. These distortions resulted in mismatches between the upper and lower hulls when they were mated. When the forward roof beam and the hatch/door frames were installed and clamped in place, the mismatches were eliminated and a good fit resulted (Figure 6-9). Once the fit-up was verified, the hull pieces were separated, the lower hull was grit blasted, and the surfaces that would mate with the upper hull were brush treated with Iridite 14-2. Next, the hull pieces were mated again and EA 9330 adhesive was injected between all faying surfaces. The lower edges of the joint were sealed with round rubber stock to prevent the adhesive from draining out from the joint. The adhesive was allowed to cure 16 hours at room temperature.

Once the adhesive was cured, holes for the bolts were drilled using a Quackenbush Model 444 power feed drill. The holes were located by means of a template. A total of 500 3/8-inch diameter holes were drilled for the main joint. Next, the bearing plates were located over the hole pattern and the main joint bolts were installed. The bearing plates were dip Iridited and their faying surfaces were covered with EA 9330 prior to installation. All fasteners were coated with zinc chromate primer and installed wet. All main joint bolts were torqued to 20 foot-pounds.

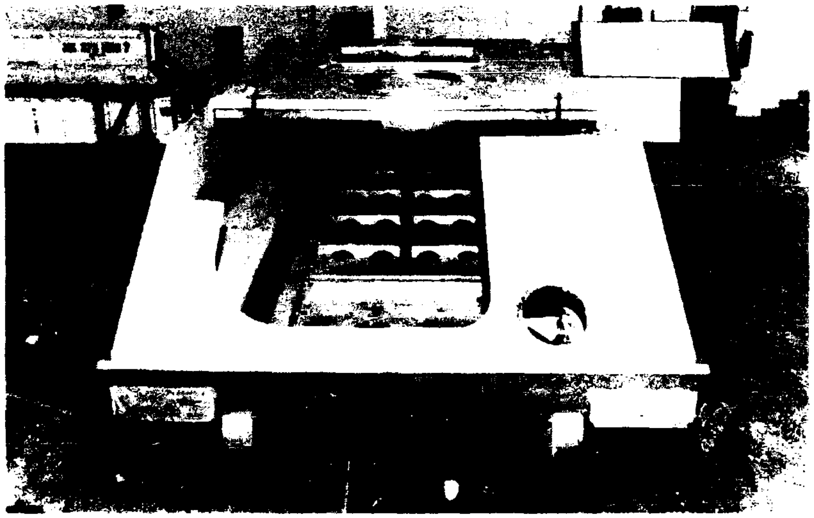


Figure 6-9. Upper and Lower Hull Fit-Up

6.5 Hull Assembly

The hatch and door frames were installed in a manner similar to that used for the main joint. The aluminum frames were degreased and treated with Iridite 14-2. The faying surfaces of the GRP were prepared by peeling off the nylon tear ply. The faying surfaces of both parts were coated with EA 9330 adhesive, the frames were installed, clamped in place and the adhesive was allowed to cure at room temperature. Next, holes were drilled for bolts. The bolt holes were hand drilled using pilot holes in the frames as guidance. Finally, the bearing plates and bolts were installed and torqued to 20 foot-pounds.

Next, heavily loaded brackets needed for equipment attached to the upper hull were installed. These consisted of brackets for the fuel tank, seats, driver's controls and other brackets that could be heavily loaded in service. The general procedure was to drill through holes in the hull and bolt and bond the brackets in place in a manner similar to that used for the hatch rings.

The next item installed was the engine bulkhead. The bulkhead was built up of formed 1/4-inch thick aluminum plate. It was essentially identical to the standard M113 bulkhead. The bulkhead was attached by welding it to the aluminum lower hull, driver's hatch plate and roof beam. In areas where it contacted the GRP upper hull, the bulkhead was riveted to aluminum angles, which were bolted to the hull. All mechanical attachment areas were sealed with MIL-S-8802 sealant to ensure that engine compartment gases would not leak into the crew compartment. The final interior installations were lightly loaded items such as the interior lights, fire extinguishers, battery box, etc. Attachments were made by using expanding threaded inserts installed into holes drilled into the GRP laminate.

Next, the vertical edge guard fenders and the track shroud attachment bars were installed. The edge guards were attached using expanding threaded inserts in holes drilled into the GRP, while the track shroud mounting strips used custom made through hull nuts. The fenders were attached using bolts and a combination of the above inserts. The hull is shown during assembly in Figures 6-10 and 6-11.

At this point, the hull was complete except for the ceramic tiles and the edge closeouts around the periphery of the tile covered areas.

6.6 Tile Installation

Three variations of the basic ceramic armor were installed on the hull:

- On the left (driver's) side and front, tiles with a 0.030-inch thick aluminum coversheet were used

- On the right (engine) side, no coversheet was used and the tiles were covered with an abrasion resistant urethane elastomer layer about 1/16-inch thick

On the rear of the hull, the two rectangular areas above the fenders were covered with tiles and 0.030-inch thick aluminum coversheets using 3M's VHB pressure sensitive adhesive tape in place of the baseline urethane adhesive.

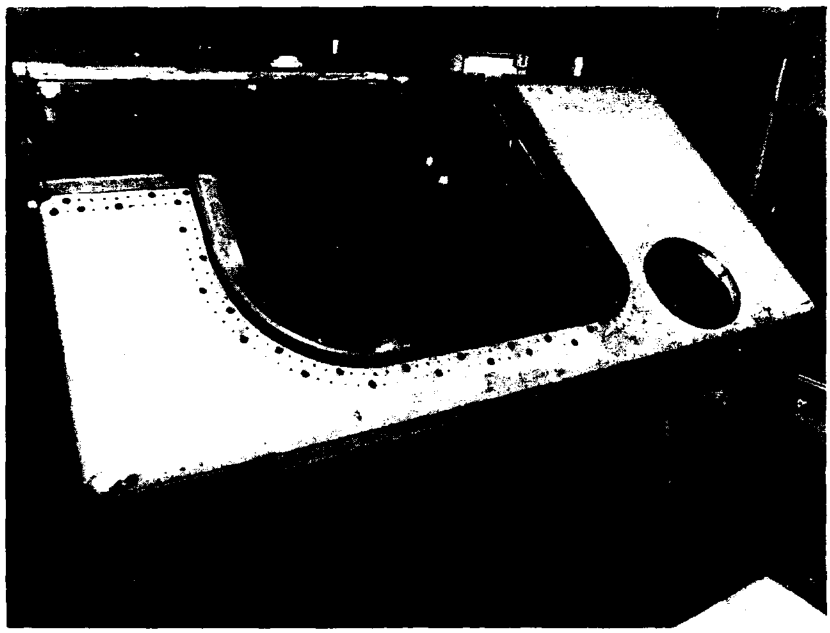


Figure 6-10. Front View of Hull During Assembly

Figure 6-11. Side View of Hull During Assembly

For the baseline case, tile bonding and coversheet bonding were accomplished in the same process. The surfaces of the GRP laminate were prepared for bonding by removing the nylon tear ply. The aluminum coversheet was prepared by a sodium dichromate/sulfuric acid etch and the tiles were cleaned by vapor degreasing. The aluminum and tiles were tiles were primed with Furane 88060 primer. Precured urethane elastomer spacers 0.063-inch thick were bonded to the top, bottom, and sides of each tile to control tile-to-GRP, tile-to-tile and tile-to-cover bondline thickness. Prior to bonding, temporary aluminum dams were placed along the edges of the sides and front, not already framed by edge guards, to form a contained area into which adhesive would be poured. The hull was then rotated so the area to be bonded was horizontal. The tile bonding was accomplished in three separate operations, one for each side and one for the front. The first step of the bonding process was to pour an excess of mixed Uralane 8089 adhesive into the dammed area. The tiles were then pressed into the uncured adhesive until they bottomed out on the spacers, Figure 6-12. Then, on the left side and front, an aluminum coversheet was placed over the tiles and pressed down until it contacted the spacers on top of the tiles. Excess adhesive was scraped away and the assembly was allowed to cure 16 hours at room temperature. On the right side of the hull no coversheet was installed at this stage; excess adhesive was scraped away to expose the tiles. After the adhesive had cured on the right side a cover of abrasion resistant urethane elastomer was applied by airless spraying. The material was applied in 0.10-inch coats with a drying time of 20 minutes between coats. The final cure was 16 hours at room temperature.

Figure 6-12. Tile Bonding

The tiles for the aft end of the hull were made up into subassemblies that were then installed on the hull. The first step was to cut a 0.030-inch thick piece of aluminum sheet the size of the area to be covered. The sheet was then vapor degreased and a layer of the VHB adhesive was applied to one side of it. Next, tiles, that had their edges covered with VHB tape, were placed on the VHB tape covered side of the coversheet. When the tile array was complete, the exposed side of the tiles was covered with a layer of VHB tape and the array was pressed in place on the hull.

When the tile installation was complete, aluminum edge protectors were installed over any exposed tile edges. The edge protectors were attached to the hull with number 10 screws and sealed to the tiled surfaces with a fillet of MIL-S-8802 polysulfide sealant.

The bonded tile arrays were inspected visually, ultrasonically, and by tapping. Some blisters were found between the aluminum cover sheets and the tiles on the front and left hand side of the hull. Ultrasonic inspection to confirm the tapping results were run using 10 MHz pulse echo contact testing. The ultrasonic indications confirmed the previous results but were generally 1/2 to 1 inch smaller in size. No tile-to-hull bondline defects were detected in any other area of the hull.

The blisters were repaired by drilling holes through the cover sheets in the blisters and injecting 8089 adhesive into the blistered area and allowing it to cure at room temperature. Inspection after repair showed some debonded areas were still present. Efforts to inject additional adhesive into these areas were not successful. The vehicle was shipped with these debonds present.

The hull was prepared for painting by grit blasting. One coat of zinc chrommate primer was applied to all surfaces. The interior of the hull was finish-coated with epoxy enamel, and the exterior was finished with polyurethane enamel (MIL-C-46168A).

6.7 Equipment Installation

Equipment installations in the composite hull were, with only a few exceptions, identical to those in the standard M113A1. The exceptions were: use of threaded inserts to attach support clips for wiring harnessess to the GRP, the addition of wires to ground electrical equipment attached to GRP, installation of lifting eyes by bolting through the hull, and minor rerouting of the engine compartment fire extinguisher plumbing.

The completed vehicle is shown in Figure 6-13.

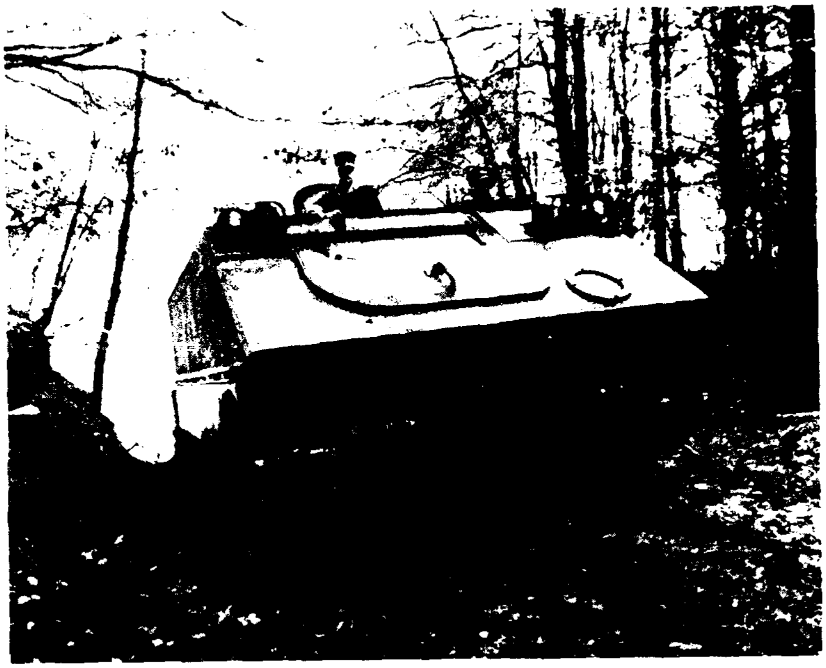


Figure 6-13. Complete Vehicle

7.0 WEIGHT, CENTER OF GRAVITY, AND CENTER OF BUOYANCY

The weight and center of gravity of the GRP M113 vehicle were calculated for combat loaded and lightly loaded conditions. To perform these calculations, a TACOM M113A1 weight summary, dated 10 April 1973, was used as a baseline. The GRP armored hull weight was developed using preliminary design drawings. A detailed weight summary of the items used to calculate the hull weight is shown in Table 7-1. The armored hull structure weight of 9,622 pounds was broken down into an unmodified weight of 3,130 pounds plus the modified composite hull weight of 6,492 pounds. This modified weight was based on a composite cap weight of 2,203 pounds, using nominal thickness side walls of 0.88 inches and a nominal thickness roof of 1.25 inches. The tile weight was 843 pounds and the aluminum structure with fasteners and mounting hardware weighed 3,446 pounds. The hull weight breakdown is summarized in Table 7-2. Using these weights, the combat loaded and curb vehicle weights and CGs are presented in Table 7-3.

Table 7-1. Detailed Weight Summary

Nomenclature	Weight (lb.)
Box frame, hull	323.0
Box frame, hull	323.0
Plate hull-bottom	879.0
Final drive assy	33.0
Final drive assy	33.0
Nose plate lower	228.0
Fender front left	13.0
Fender front right	14.2
Guard tail light	1.9
Stiffener, idle pad	2.1
Stiffener, hull	7.0
Support bumper	7.8
Plate mounting	0.3
Block filler aluminum	0.5
Block filler aluminum	0.6
Block filler aluminum	2.2
Support anchor torsion bar	16.2
Lock filler neck cover	0.05
Bracket filler neck cover	0.40
Strip backup hull	0.07
Strip backup hull	0.18
Strip backup hull	0.04
Cover access engine	16.61
Gasket	0.25
Cover access torsion bar	2.18
Cover access torsion bar	1.43
Gasket	0.25
Strip and pad	0.34
Gusset	0.06

Table 7-1. Detailed Weight Summary (Continued)

Nomenclature	Weight (lb.)
Guard	0.14
Retainer	0.36
Retainer	0.58
Retainer	0.30
Bracket	0.47
Bracket	0.35
Plate	0.59
Guard	3.26
Coaming	3.87
Coaming	2.40
Coaming	0.42
Rear lift eyes	84.78
Front lift eyes	40.50
Lower edge guards	100.80
Upper edge guards	33.46
Vertical edge guards	18.40
Idler gusset plate	4.90
Towing eye plates	14.10
Bump stop gussets	11.14
Box beam modification	87.20
Roof support beam	8.0
Plates, bearing main joint	24.32
Frame-lower	76.55
Support RH side panel	38.71
Plate bearing cargo hatch	6.72
Frame cargo hatch	57.23
Ring support fuel filter	2.64
Support LH side	25.94
Plates-bearing main joints	5.02
Beam top support	106.94
Ring access cover	5.99
Plates--sponson	37.96
Ring-access cover	8.32
Ring support ventilator	4.85
Cover, front access	10.05
Rub strip sponson side	19.22
Rub strip side	19.22
Rub strip-sponson-top	28.74
Rub strip-top	28.74
Frame front access	21.93
Ring support commander's cupola	62.52
Rear cab aluminum plate	110.00
Plate, bearing commander's cupola	1.19
Frame segment ramp L & RS	25.28
Beam rear ramp frame	50.27
Strip mounting track shroud	
L & R side	123.32
Plate drive's hatch	82.25
TOTAL, Aluminum Structure	3307.25

Table 7-1. Detailed Weight Summary (Continued)

Nomenclature	Weight (lb.)
Mounting Provisions (Additional)	
GRP hull to lower hull joint*	100.00
Trim vane	12.00
Driver controls & radio system	4.00
Lighting system	10.00
Fire extinguishers	1.00
Driver's seat	1.00
Commander's seat	1.00
Troop seats	10.00
TOTAL, Mounting Provisions	139.00
GRP hull	2203.00
Tiles on hull	843.00
TOTAL weight of armor	6492.25

*Includes fasteners, adhesive and sealant

Table 7-2. Weight Breakdown - M113 GRP Hull

Item	Weight (lb.)
Aluminum lower hull	2,045.1
Aluminum rings, frames, etc.	1,261.9
Equipment mounting hardware	39.0
Main joint fasteners, adhesive and sealant	100.0
GRP structure	2,203.0
Tiles, adhesive and Cover	843.0
TOTAL GRP hull	6,492.0

Table 7-3. Combat Loaded and Curb Vehicle Weights and CGs

	Weight (lb)	Center of Gravity		
		X	Y	Z
All Aluminum M113A1				
Combat loaded	24,594	83.6	0.04	37.8
Curb weight	21,714	80.9	0.04	37.4
GRP Hull Feasibility Demonstrator				
Combat loaded	24,594	83.0	-0.12	37.2
Curb weight	21,714	80.0	-0.13	36.7

The CG of the GRP hull M113 has shifted forward 0.6 inches and shifted down 0.6 inches. This is because the GRP upper hull is lighter than the existing aluminum upper hull while the lower hull is slightly heavier. This shift of the CG improves the flotation trim slightly.

If additional ceramic tile armor protection is added in the track channels of the lower hull, the vehicle weight would be increased 307.4 pounds. The corresponding vehicle combat and curb weight would be as listed in Table 7-4.

Table 7-4. GRP Hulled Vehicle Combat and Curb Weights with Track Channel Armor

	Weight (lb)	Center of Gravity		
		X	Y	Z
Full load	24,901	83.1	-0.11	37.0
Curb weight	22,021	80.3	-0.13	36.5

The effect of using minimum versus nominal thickness GRP laminates for the hull was also estimated. These results are shown in Table 7-5.

Table 7-5. GRP Hull Weight vs. Thickness

Side Thickness (In.)	Roof Thickness (In.)	GRP Weight (Lb)	
		Total	Change
0.75 minimum(1)	1.25 nominal(2)	2,203	---
0.75 minimum	1.25 minimum(3)	2,330	+127
0.75 nominal(4)	1.25 nominal	1,986	-217
0.75 nominal	1.25 minimum	2,113	- 90
(1) 0.853 nominal			
(2) 1.129 minimum			
(3) 1.280 nominal			
(4) 0.669 minimum			

The center of buoyancy (CB) was calculated for both the aluminum M113 hull and the GRP M113 hull. Since a comparison of the flotation stability was the desired goal rather than an absolute measure of the stability, simplified models of the aluminum and composite hull were constructed using the Computervision[R] graphics system. The models were representative of the outer moldline of the respective hulls without attachment hardware and running gear. The vehicle waterline and CB were determined by several iterations of rotating the vehicle longitudinally (the lateral water line was assumed to be parallel with the hull) and matching the displaced water weight with the desired vehicle weight. At the same time, the center of buoyancy was lined up with the vehicle center of gravity on a line perpendicular to the waterline. The results of these calculations for the combat loaded and curb weight vehicles are shown in Figures 7-1 through 7-4.

The composite hull is trimmed more nearly level in the water for both the curb weight and combat loaded conditions. This is a result of the larger volume up front on the composite hull caused by the lower angle of the nose plate. Measurement of the distance between the CB and CG indicates that the composite hull will be more stable, with a center of gravity about 1/2 inch further down from the CB for both load conditions.

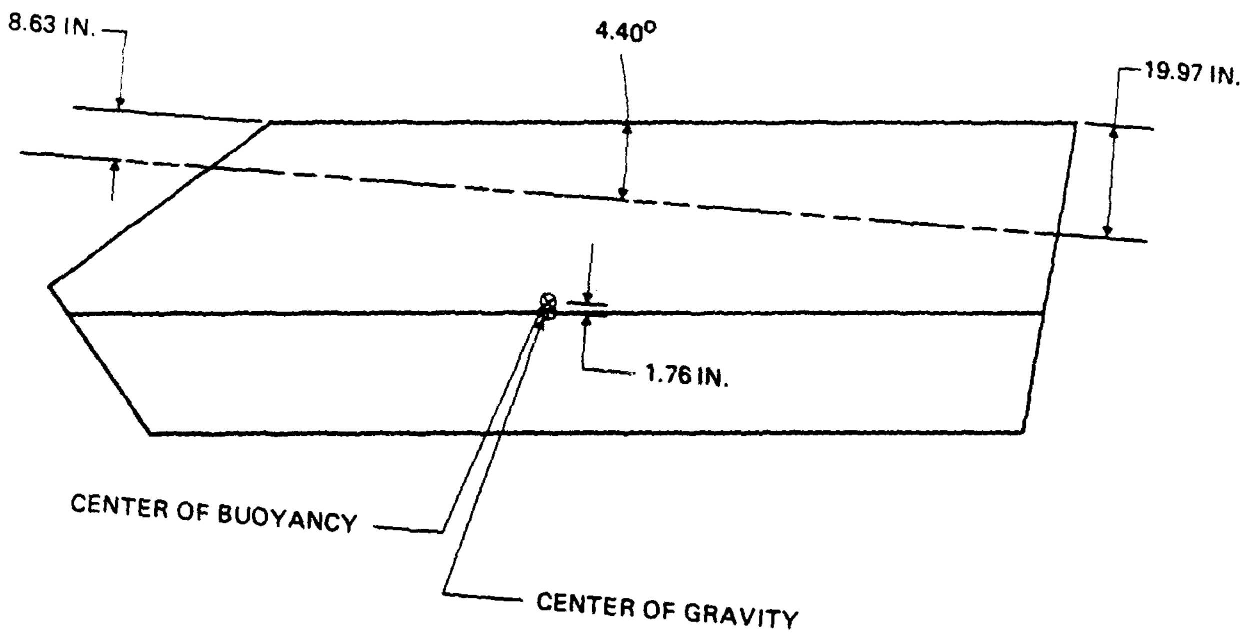


Figure 7-1. Composite Hull Curb Weight

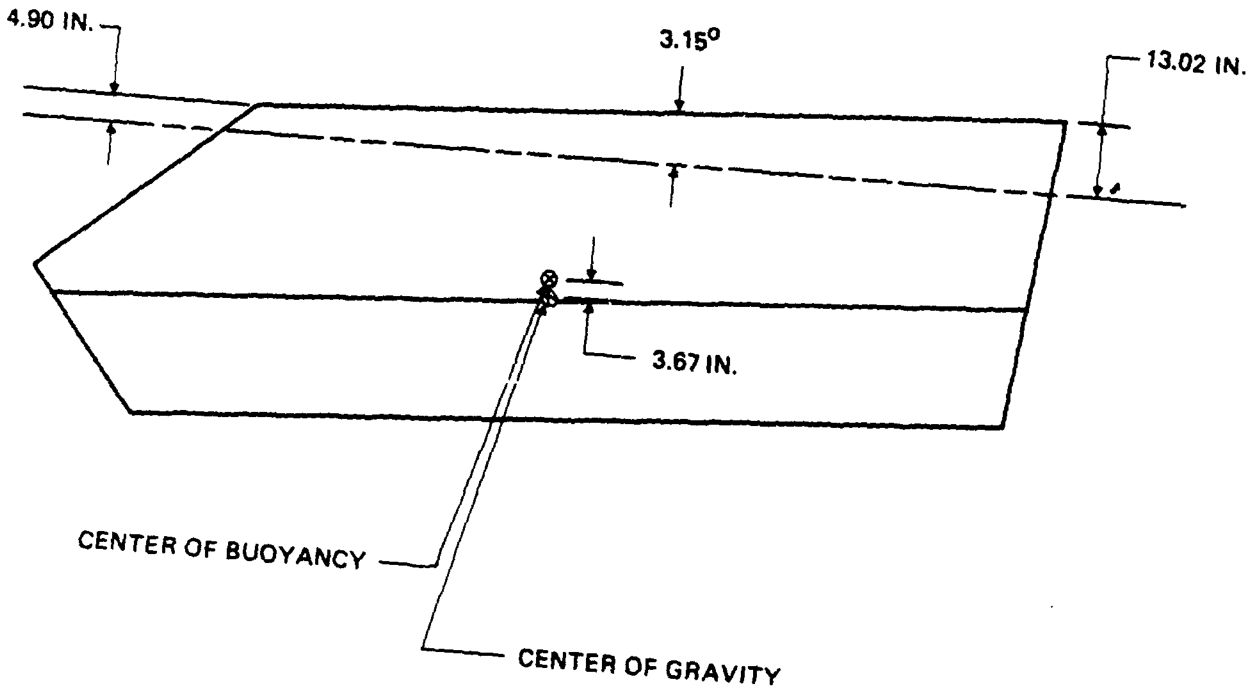


Figure 7-2. Composite Hull Combat Loaded Weight

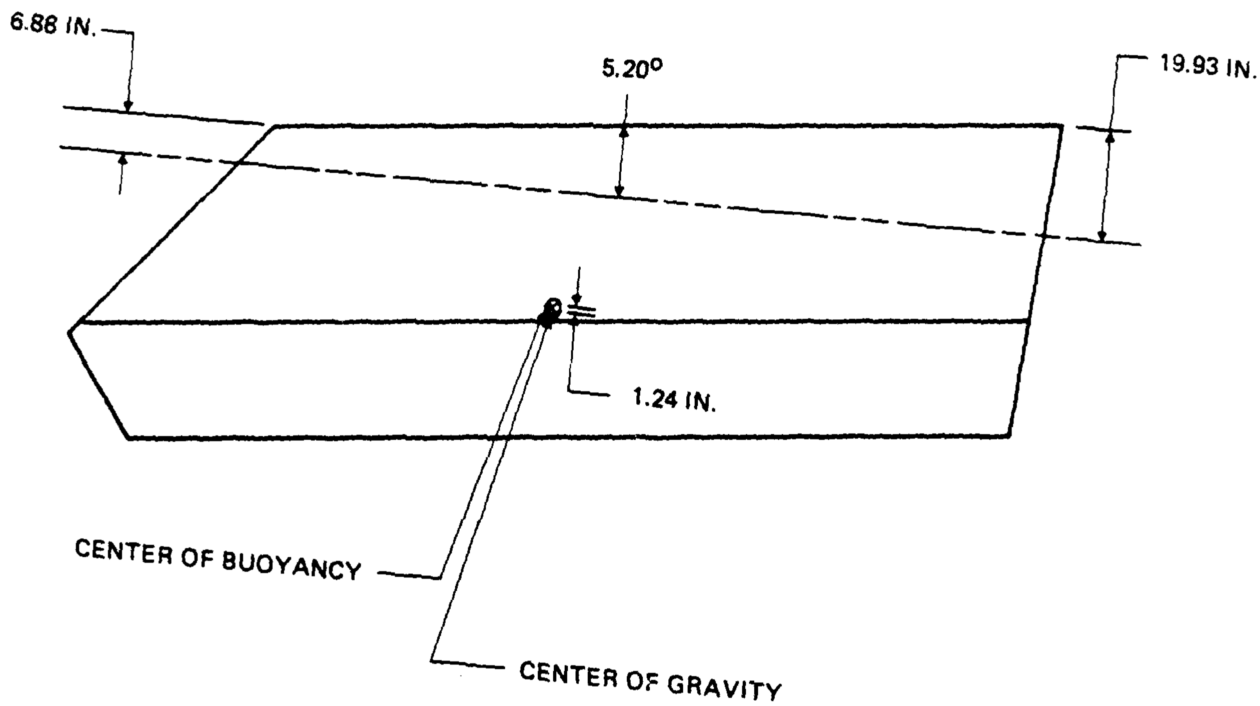


Figure 7-3. Present M113 Curb Weight

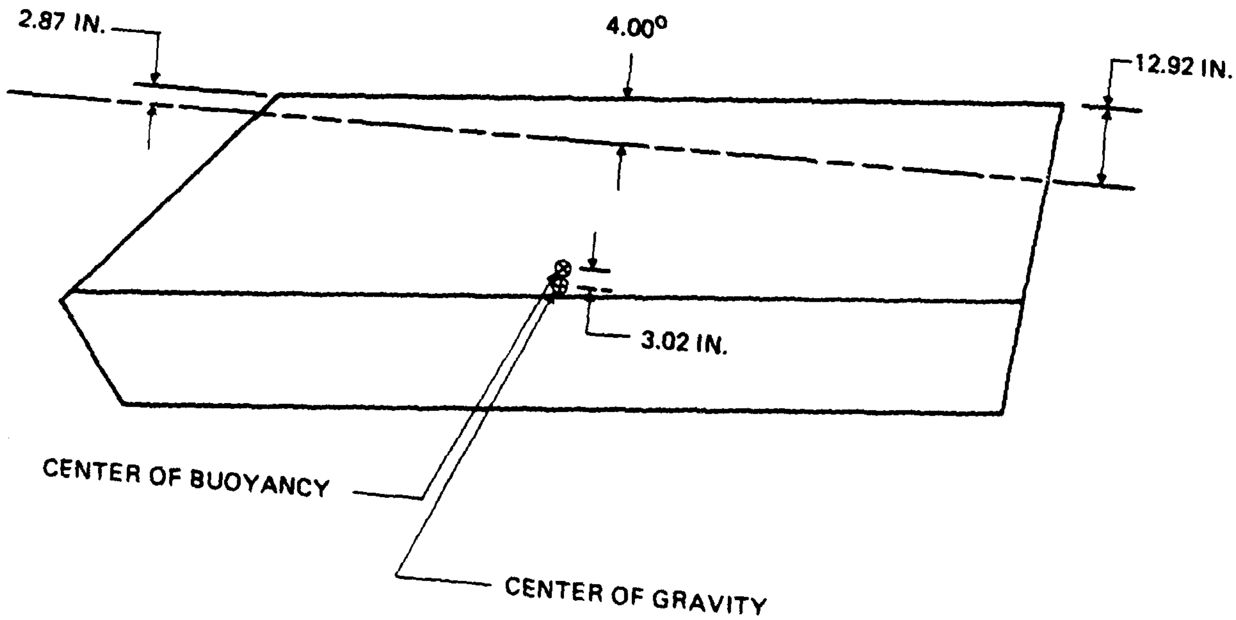


Figure 7-4. Present M113 Combat Loaded Weight

The weight and center of gravity of the GRP hulled vehicle were very close to the predictions made during the design phase. The configuration of the vehicle when it was weighed did not correspond exactly to the curb weight of combat loaded configurations for which the earlier predictions were made. The Phase I predictions were adjusted to the as-delivered configuration using data from the TACOM M113A1 weight summary dated 10 April 1973. The weight and CG predictions are summarized in Table 7-6. Actual weight of the vehicle was determined by placing the vehicle on four scales, one under each forward and aft road wheel. The data recorded are provided in Table 7-7.

Table 7-6. Vehicle Weights and Centers of Gravity

	WEIGHT (LBS)	CENTER OF GRAVITY		
		X	X	Z
All Aluminum M113A1				
Combat Loaded	24,594	83.6	0.0	37.8
Air Drop Configuration	19,345	77.0	1.3	37.4
"As Delivered" Configuration	19,107	77.0	1.8	36.2
GRP Hull Feasibility Demonstrator				
Combat Loaded	24,594	83.0	-0.1	37.2
Air Drop Configuration	19,345	77.1	1.1	36.6
"As Delivered" Configuration	19,107	77.1	1.6	35.4
Measured Values, GRP Hull Feasibility Demonstrator, As Delivered Configuration	19,538	77.0	2.0	N/A

Table 7-7. Vehicle Weight Data

WEIGHTING POINT	MEASURED WEIGHT (LBS)	DISTANCE FROM DRIVE SPROCKET CENTER LINE (IN.)
Left Front Road Wheel	5320	27.2
Left Rear Road Wheel	3985	131.5
Right Front Road Wheel	6035	29.5
Right Rear Road Wheel	4198	133.8

8.0 MANUFACTURING COST STUDY

The cost of manufacturing the GRP hull on a production basis was estimated in the contract proposal, at the completion of che design (Phase I), and at the completion of fabrication (Phase II). All estimates were in 1983 dollars. The estimated costs are summarized in Table 8-1. The basis of the estimates was for the production of 1,000 hulls over a three year period. The Phase I and II estimates assumed fully automated production tooling for all metal working and welding. Manual layup of preimpregnated woven roving and hand laying of ceramic tiles were assumed for the GRP fabrication. Manual production line methods were assumed for assembly. The Phase I estimate was based on the preliminary hull design. For the Phase II estimates, the Phase I estimate was updated based on actual fabrication of the hull. The estimate for the proposal was based on a conceptual design, and costs were estimated parametrically.

Labor and materials cost for the Phase I and II estimates are summarized in Tables 8-2 and 8-3. The $39 per hour rate used for labor costs is thought to be typical of U.S. fabrication industries. Its derivation is summarized in Table 8-4. The materials costs are vendor estimates, and quantities of materials include trim losses.

The non-recurring cost in Table 8-1 include the cost of special purpose tools and equipment dedicated to a hull production line and up front production planning costs. It does not include general purpose machine tools or autoclaves. The non-recurring cost was based on costs developed during a Martin Marietta proposal effort on the Army/Marine Corps Light Armored Vehicle (LAV) Program.

Table 8-1. Production Cost Estimate - 1000 Units

	Proposal ($K)	Phase I ($K)	Phase II ($K)
Non-recurring	14,800	14,800	14,800
Recurring			
Material:			
Woven Roving Prepreg	11.0 (Woven Roving Prepreg and Adhesive combined)	15.9	11.3
Adhesive		1.6	1.6
Aluminum	7.9	15.5	15.5
Tile	7.7	6.0	6.0
Hardware	7.0 (Hardware and Miscellaneous combined)	4.7	4.7
Miscellaneous		4.2	4.2
Subtotal	33.6	47.9	43.3
Labor:			
Upper Hull	26.0 (Upper Hull and Lower Hull combined)	54.2	24.3
Lower Hull		8.7	8.7
Subtotal	26.0	62.9	33.0
TOTAL	59.6	110.8	76.1

Table 8-2. Estimated Labor Cost Summary

	PHASE I	PHASE II
Upper Hull		
Layup & cure	428 Manhours @ $39 = $16,692	107 Manhours @ $39 = $ 4,181
Trim	153 Manhours @ $39 = 5,967	44 Manhours @ $39 = 1,716
Metal detail part fabrication	132 Manhours @ $39 = 5,148	132 Manhours @ $39 = 5,148
Lower Hull		
Detail part fabrication	22 Manhours @ $39 = 858	22 Manhours @ $39 = 858
Welding and machining	201 Manhours @ $39 = 7,839	201 Manhours @ $39 = 7,839
Assembly		
Hull joining	128 Manhours @ $39 = 4,992	110 Manhours @ $39 = 4,290
Tile, ring & frame installation	550 Manhours @ $39 = 21,450	230 Manhours @ $39 = 8,970
	TOTAL $62,946	$33,002

Table 8-3. Summary of Estimated Materials Cost

	PHASE I		PHASE II	
Woven Roving	3720 lb @ $3.33/lb	$12,388	2639 lb @ $3.33/lb	$ 8,788
Aluminum, Upper Hull	1601 lb @ $2.88/lb	4,612	1601 lb @ $2.88/lb	4,612
Aluminum, Lower	2595 lb @ $2.88/lb	7,468	2595 lb @ $2.88/lb	7,468
Tile	665 lb @ $7.02/lb	4,665	665 lb @ $7.02/lb	4,665
Adhesive	180 lb @ $7.00/lb	1,260	180 lb @ $7.00/lb	1,260
Weld wire		875		875
Paint		100		100
Hardware	From L/M	3,732		3,732
Expendable material		2,256		2,256
		$37,356		$33,756
	5.9% Material Handling	2,204		1,992
		$39,560		$35,748
	10% G&A	3,956		3,575
		$43,516		$39,323
	10% Profit	4,352		3,932
	TOTAL	$47,868		$43,255

Table 8-4. Hourly Rate Derivation

Labor Rate	$ 11.59
Overhead @ 178%	20.64
General & Administrative @ 10%	3.22
Profit @ 10%	3.55
TOTAL	$ 39.00

The Phase II estimate applied a learning curve to the GRP layup and tile installation hours actually required during Phase II fabrication. An 85 percent learning curve was applied to these hours and the cumulative average hours for these operations were calculated. The majority of the drop in estimated manufacturing cost from the Phase I estimate to the Phase II estimate is attributable to the use of these actual labor hours as the basis for the Phase II estimate.

9.0 TEST RESULTS

The vehicle was delivered to the Marine Corps at Camp Pendleton, California for field testing in October 1985. Prior to delivery, the vehicle was run for approximately 10 hours to demonstrate operability, immersed in water to verify its watertight integrity, and instrumented with strain gages at critical locations. Baseline static strains in the hull were measured with the vehicle supported on diagonally opposed road wheels, and with a number one road wheel that bottomed against the top of the track channel.

No problems were experienced with the vehicle during the 10 hours of operation. A small amount of leakage was observed around the ramp when the vehicle was immersed in water. This leakage was considered normal. The measured strains were very low, 0 to 100 micro inches, and consistent with our prediction.

No problems related to the composite hull were observed during one year of field testing at Camp Pendleton. A detailed inspection of the hull was conducted at Camp Pendleton in October 1986. At that time the vehicle had accumulated 159.8 hours (2330 miles) of operation. The inspection revealed the following:

- The polyurethane protective coating used on the right (engine) side of the vehicle showed several gouges in the track channel and a scuff mark of the vehicle side.
- Some of the debonds between the cover sheet and tiles that had been repaired (Section 8.6) prior to delivery had debonded again.
- Ultrasonic indications of porosity found during inspection of the bare hull (Section 6.2) could not be found under field conditions.
- Acid leaking from the battery box had locally removed paint from the GRP. There was no indication of damage to the laminate.

There were no indications of any degradation of the hull during the year of field testing.

10.0 RESEARCH AND DEVELOPMENT PLAN

Research and Development activities required to bring composite hulls to the state of being production items are minimal. The large data base available from the aircraft and marine industries will provide virtually all of the information needed to design and produce a composite hull. Items specifically related to a production composite hull that would be required during a full scale development program are:

- A complete specification of hull performance requirements including loads, environmental, nuclear, and ballistic requirements. Estimated cost $2 million

- Design of a vehicle hull to meet requirements. Estimated cost $1 million

- Qualification of materials, and design for the performance requirements. Estimated cost $0.5 million

- Qualification of a prototype vehicle by field testing in all environments. Estimated cost $5 million

- Production engineering to assure a cost-effective, producible design. Estimated cost $1 million.

11.0 CONCLUSIONS AND RECOMMENDATIONS

On the basis of the Phase I and II efforts it has been concluded that:

1) The selected design is capable of withstanding all defined operational loads without sustaining structural damage or deflecting to a degree that would interfere with operation of the vehicle or its systems and equipment

2) The composite hull has not suffered any degradation in one year of field testing by the Marine Corps

3) High quality woven roving/epoxy laminate having a 70 percent fiber content can be readily fabricated in the required thicknesses

4) The GRP/ceramic tile hull will provide greatly improved ballistic protection at a weight equal to that of the existing aluminum M113A1 hull

5) Design constraints required to make the GRP hull compatible with existing M113A1 hardware and systems imposes a weight penalty on the selected hull design.

It is recommended that:

1) A prototype composite hull for a high water speed armored amphibious vehicle be fabricated and field tested

2) Critical features of the design be verified by structural element tests

3) Additional materials characterization tests be performed

4) The existing M113-based hull be subjected to more severe field environments (For example, tropical and arctic)

5) Field repair of ballistic damage be demonstrated.