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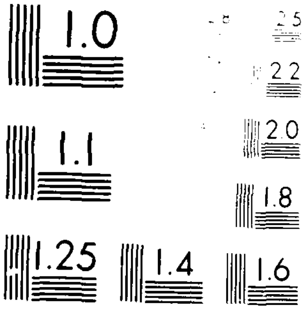
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FEASIBILITY AND PRACTICAL LIMITS FOR THE USE OF LIGHTWEIGHT PRESTRESSED CONCRETE (LWPC) AS A SHIPBUILDING MATERIAL

CONTRACT NO. N00024-81-C-4054

FINAL TECHNICAL REPORT

OCTOBER, 1982

PREPARED FOR :

DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

DEPARTMENT OF THE NAVY
NAVAL SEA SYSTEMS COMMAND
WASHINGTON, D.C. 20362

CONSULTING ENGINEERS

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SECTION I
INTRODUCTION

Purpose and Scope

This report summarizes data which has been developed and collected in order to perform a study of the feasibility of using lightweight prestressed concrete (LWPC) as a shipbuilding material. The Naval Sea Systems Command (NAVSEA) wants to develop alternate materials which are suitable for the construction of functional and cost-effective Navy ships, thus improving the future availability of shipbuilding materials.

This report is the initial effort in the development of LWPC as a suitable shipbuilding material and the identification of applications which are most suitable to the material. Therefore, the historical use and the current state-of-the-art of the material for ship construction is identified. The properties of the material and criteria for the design of LWPC ships are presented as well as considerations regarding the maintainability and repairability of LWPC hulls. In order to focus on suitable applications, LWPC hull concepts have been developed in order to compare costs and capabilities with existing Navy ships.

In addition to making these comparitive studies with state-of-the-art material properties, potentially viable properties have been used to identify the benefits of further research and development of the material.

This effort has focused on conventional reinforced and prestressed concrete which is suitable to the construction of the size of Navy hulls selected by NAVSEA for the comparative studies. Ferrocement, a material suitable to smaller sized vessels, is discussed minimally.

SECTION II

SECTION II

DESCRIPTION OF STEEL HULL BASELINES

2.0 NAVSEA Input Data

NAVSEA has provided input data for five Navy steel hulls. This input has been used as a guide to the development of LWPC hull concepts for comparison of relative capabilities and costs.

Initially NAVSEA selected a typical U.S. destroyer for this purpose. The following data was provided as input for the destroyer:

- Design Specifications
- Longitudinal Strength
- Structural Profiles
- Lines and Molded Offsets
- Deck and Platform Scantlings
- Structural Sections
- Structural Bulkheads
- Weight Data
- Construction Cost Data

The cross sectional arrangement of a midship section of the destroyer is shown in Figure II-1.

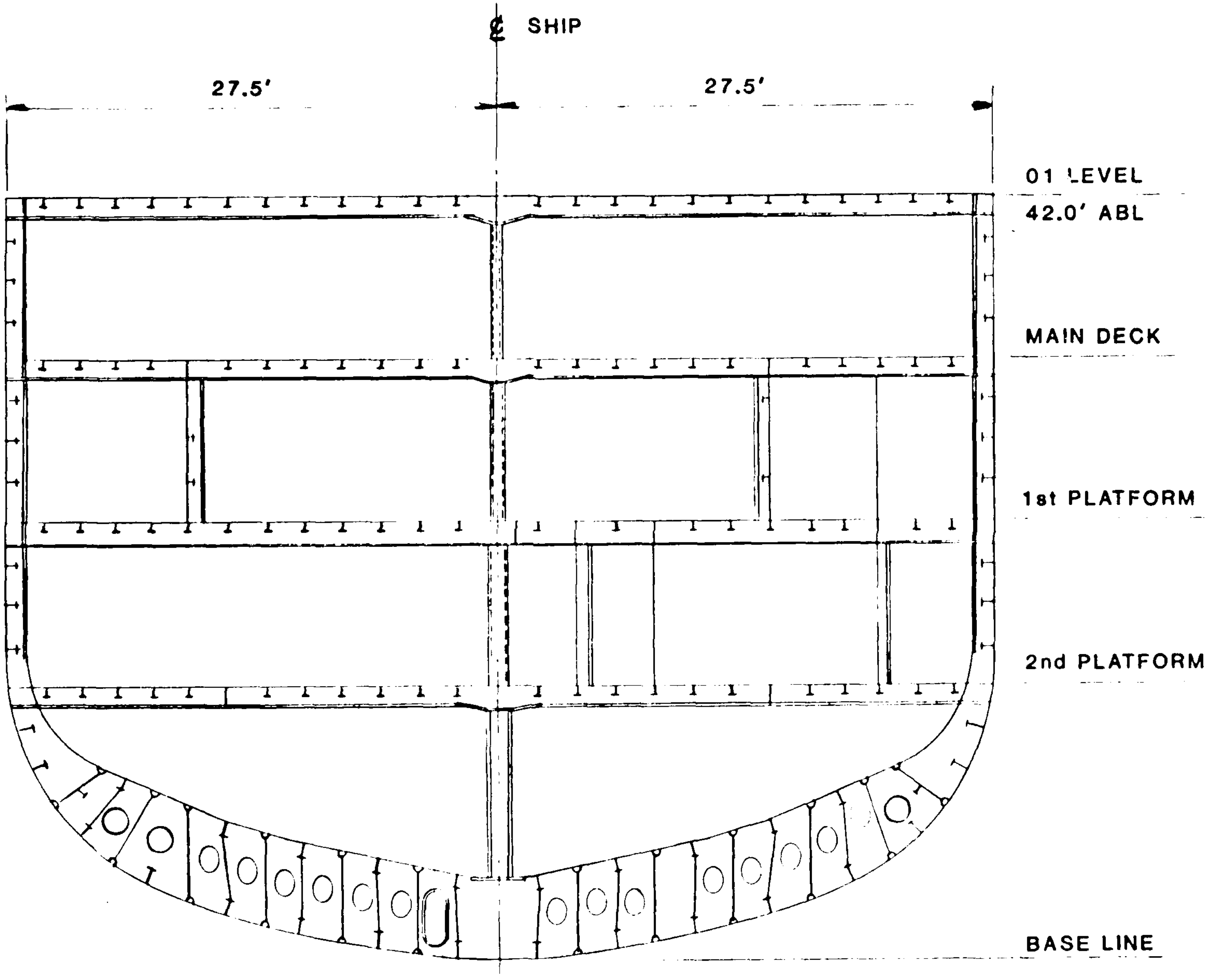
In order to allow further exploration of suitable applications of LWPC for Navy ships, longitudinal strength drawings and structural sections were provided for the remaining hull types. This data was used for investigation of the sensitivity of LWPC hulls to ship size and function.

The characteristics of the input steel hulls are summarized in Table II-1

Hull Type	LBP (Ft)	Beam (Ft)	Depth to Strength Deck (Ft)	Displacement Light (LT)	Full Load Displacement (LT)	Max. Long'l Bending Moment (LT-Ft)	
						Hog	Sag
Destroyer	529	55	42	6,626	8,224	179,205	134,012
AOE	770	106	66	19,000	52,968	960,732	530,694
AOR	640	96	56	12,500	39,840	399,332	480,056
AS	620	82	57	12,770	23,413	491,302	254,051
AD	620	84	67.5	13,600	19,748	361,224	328,866

BASELINE STEEL HULL CHARACTERISTICS

TABLE II-1



STEEL HULL BASELINE - WEB FRAME 284

FIGURE II-1

SECTION III

SECTION III

STRUCTURE AND CONSTRUCTION CONCEPTS FOR LWPC HULLS

3.0 Introduction

Any shipbuilding material has unique considerations which must be recognized for optimum use of the material. This section of the report identifies considerations for cost-effective LWPC hull construction. Additionally, in order to identify relative characteristics of LWPC hulls, concepts have been developed which allow comparison with existing steel hulls. Based upon these comparisons, suitable applications of LWPC as a hull material can be identified. As a result of an investigation of the sensitivities of specific LWPC properties, the benefits of further development of the material are also identified.

3.1 Advantages/Disadvantages of LWPC as a Hull Material

The development of LWPC hull concepts has been based upon consideration of the advantages and disadvantages of the material. LWPC has the following advantages for its use as a shipbuilding material:

o Proven Durability in the Marine Environment -- When properly designed and constructed, concrete hulls provide excellent durability. This is proven by concrete hulls which have been exposed to seawater for greater than 60 years (References 1, 6).

o Low Maintenance -- Due to the durability of the material and its lower susceptibility to corrosion, concrete hulls require much less frequent drydocking than steel hulls. Prestressed concrete barges operating in the Philippines have required no drydocking in their initial 12 years of operation (Reference 2).

o Fire Resistance -- Concrete has proven superiority to unprotected steel in terms of fire resistance.

- Impact and Blast Resistance -- Experience has shown that reinforced and prestressed concrete hulls have withstood impact and blast damage very well (References 2, 3, 4). A study by the Corps of Engineers (Reference 5) provides documentation of satisfactory performance of a reinforced concrete frame subject to blast overpressures.

- Availability of Materials -- Steel for concrete reinforcement is a lower grade than that used for ship construction, and is available in the U.S. Materials used to batch concrete are available in the U.S.

- Behavior in Cold Temperatures -- Concrete exhibits excellent properties in cold temperatures. Reinforcing steel and prestressing strands, subject to uniaxial tension, exhibit little loss of ductility in low temperatures.

- Thermal Conductivity - Concrete has a lower thermal conductivity than steel.

- Vibration Damping -- Concrete has excellent vibration damping properties. Additionally, concrete hulls are more rigid than steel hulls of equal strength resulting in smaller hull deflections.

- Watertightness - Concrete hulls have proven through experience to be watertight.

- Ease of Forming Shapes - Concrete can be formed to complex shapes.

LWPC has the following disadvantages as a shipbuilding material:

- Hull Weight -- As a result of the lower strength-to-weight ratio of concrete as compared to steel, LWPC hulls are heavier than steel hulls.

- Retrofits -- While retrofits can be accomplished in LWPC hulls, they are more easily accomplished with steel construction.

3.2 Considerations for Cost-Effective LWPC Hull Construction

Concrete structures can be constructed using many combinations of cast-in-place concrete and precast concrete elements. Experience has shown many benefits result from the utilization of precast elements in construction. Precast elements are usually fabricated in a horizontal or nearly horizontal orientation, and once the element has gained sufficient strength it is erected into its proper orientation in the structure. Precast concrete construction offers the following advantages:

- Formwork costs are lower for panels constructed with a horizontal orientation. Precast panels which will become vertical walls can be constructed using formwork on only one surface of the element. Additionally, form pressures generated by the fluid concrete mix are reduced by the horizontal orientation.

- Placement of both reinforcement and concrete are greatly simplified. This results in reduced labor costs and allows reliable placement of well-compacted high quality concrete, particularly in thin vertical elements which contain post-tensioning ducts in two directions.

- Curing of concrete components is simplified. Accelerated curing techniques can be readily used with the associated construction schedule benefits.

Optimum construction of precast concrete structures is analogous to an assembly line manufacturing process. Both construction schedule and cost are reduced by the use of repeatable construction details which allow multiple use of construction tooling and increased labor efficiency. The benefits of repeatability are most greatly realized in hull forms with a long parallel middle body. Construction of a number of vessels in a class will also provide benefits of the repeatable use of formwork and other construction tooling.

For applications of LWPC in hulls without a parallel middle body, construction costs may be improved through the use of formwork with panels which can be adjusted to provide a variable geometry. Such formwork has been used to construct curved beams for transit vehicle guidance.

The efficiency of a LWPC hull can be improved through the proper selection of a framing plan. A minimum thickness of concrete plates is dictated by that required to allow placement and protective cover of reinforcing steel and post-tensioning ducts. Framing arrangements should be such that the full strength of these plating elements are utilized. Where large spans are required, the use of curved shells will improve efficiency by taking advantage of the compressive strength of the material.

3.3 LWPC Hull Concepts for Comparisons With Steel Destroyer

In order to allow comparison between an existing steel hull and an "equivalent" LWPC hull, NAVSEA has provided data for several Navy ships. A typical steel destroyer has been used for the baseline comparison, which is discussed in this section. Other hull types have been used to investigate the sensitivity of the material to hull type and function, and are discussed in Section 3.4. The input steel hull characteristics are discussed in Section II.

Comparisons are based upon a conceptual design of a midship section of a LWPC hull with the same molded shape as the steel hull. The framing concepts developed for this comparison use LWPC exterior plating in the hull structure and steel framing for all interior decks and platforms. The use of this "composite" construction benefits from the advantages offered by LWPC and minimizes the extent of the disadvantages of the material. A midship section of the composite hull is shown in Figure III-1.

The sidewall plating resists the hydrostatic pressures by spanning vertically between the decks and platforms. The bottom shell acts as a curved shell supported at the ship centerline by stanchions. A concrete beam is provided at the ship centerline to transfer unbalanced stanchion loads longitudinally along the shell. The 01 level deck plate spans transversely between sidewalls and stanchions at the ship centerline.

The concrete elements are sized to resist hydrostatic pressures and deck loadings as defined in the design specification for the steel destroyer. The plating is post-tensioned vertically and transversely to a level of 800 psi to resist local plate bending loads. Rectangular post-tensioning ducts are required in order to achieve the 6 inch side shell thickness. A concrete strength, f'_c of 6000 psi has been used.

Longitudinal strength of the composite section has been investigated using hogging and sagging moments from the steel destroyer. Longitudinally continuous steel framing in the decks and platforms acts compositely with the concrete shell in resisting longitudinal bending. Longitudinal post-tensioning levels of approximately 1400 psi in the deck and 900 psi in the bottom shell satisfy longitudinal strength criteria of no net tension. Sagging moments result in compressive stresses in the deck which are near the maximum allowable stress.

In order to limit the required longitudinal post-tensioning force it is assumed that the steel framing is not made composite with the concrete shell until longitudinal post-tensioning is complete. Construction details and sequences for the steel framing must allow this. Maximum hogging and sagging stresses in the steel framing elements are less than 11 ksi.

3.3.1 Hull Weight Comparison

A comparison of the hull weight of the steel destroyer hull and the composite LWPC hull has been made in the following manner:

- The weight of the baseline steel hull is estimated from scantlings furnished by NAVSEA. A unit weight of steel per foot of hull length has been determined for a section of the hull near midships.

- A similar unit weight is estimated for the composite LWPC hull. The weight of the interior steel framing is the same as used for components of the baseline steel hull. The weight of the LWPC plating is based upon a concrete density of 130 pcf. This density includes an allowance for reinforcement and water absorption. The weight ratio for this cross-section of the hull is then applied to the total steel hull weight.

This weight comparison is presented in Table III-1. The composite LWPC hull structure weighs twice that of the steel destroyer resulting in a full load displacement which is approximately 50 percent greater than that of the baseline steel hull. This is particularly undesirable for hulls where speed is important. Therefore, the benefits of improvements to the state-of-the-art material properties are presented in Section 3.3.2. Additionally, the suitability of LWPC to other hull types is discussed in Section 3.4.

TABLE III-1. WEIGHT COMPARISON BETWEEN TYPICAL
U.S. DESTROYER AND COMPOSITE LWPC HULL
(concrete density = 130 pcf, f'_c = 130 pcf)

Item	Steel Hull Baseline	Composite LWPC Hull[1]	Weight Ratio
Hull Structure	3,356 LT	6,646 LT	2.04
Systems	3,270	3,270	--
Lightship (w/o Margin)	6,626	10,116	--
Margin	40	665[2]	--
Lightship (w/ Margin)	6,666	10,781	1.62
Loads (Full)	2,340	2,340	--
Full Load Condition	9,006	13,121	1.46

[1] Based upon LWPC with strength, f'_c = 6,000 psi, and density = 130 pcf.

[2] A margin of 10 percent is applied to the composite LWPC hull structure weight.

3.3.2 LWPC Hull Weight Sensitivities

As discussed previously, the primary disadvantage of concrete as a shipbuilding material is the hull weight which results from the relatively low strength-weight ratio of LWPC. Items which can have significant effects on the weight of LWPC hulls are identified below, and where possible, the sensitivity of the hull weight to potential improvements to these items is quantified.

- Concrete Plating Thickness: A minimum possible thickness of LWPC plating is dictated by the amount of concrete cover required for protection of reinforcement and the space required to incorporate reinforcing bars and post-tensioning ducts within the plate.

  For hull types investigated in this study, plating sizes are dictated by strength considerations rather than the minimum thickness. Smaller hulls may experience plating thicknesses which are controlled by reinforcement placing considerations. In these instances, weight penalties may be reduced by the development of smaller post-tensioning systems and investigation of minimum concrete cover requirements.

- Concrete Density: The above comparison of hull weight is based upon a state-of-the-art lightweight concrete with a compressive strength f'_c = 6000 psi and a density of 130 pounds per cubic foot. Structural lightweight concretes have been developed with densities below 100 pcf, however, these concretes have not achieved compressive strengths necessary for application in hull structures. Lower density concretes can potentially be developed to achieve compressive strengths between 6000 psi and 8000 psi. Table III-2 shows a comparison between hull weight of the steel destroyer and the composite LWPC hull using concrete with a density of 100 pcf and a compressive strength, f'_c of 6000 psi.

TABLE III-2. WEIGHT COMPARISON BETWEEN TYPICAL
U.S. DESTROYER AND COMPOSITE LWPC HULL
(concrete density = 100 pcf, f'_c = 6000 psi)

Item	Baseline Steel Hull	Composite LWPC Hull[1]	Weight Ratio
Hull Structure	3,356 LT	5,718 LT	1.70
Full Load Condition	9,006	11,900	1.32

[1] Concrete density = 100 pcf, f'_c = 6,000 psi

- o *Concrete Strength*: *Lightweight concrete with a density of 100 pcf* can potentially be developed with compressive strengths as high as 10,000 psi. Table III-3 shows a comparison between hull weight of the steel destroyer and the composite LWPC hull using concrete with a density of 130 pcf and a compressive strength of 10,000 psi.

TABLE III-3. WEIGHT COMPARISON BETWEEN TYPICAL
U.S. DESTROYER AND COMPOSITE LWPC DESTROYER
(concrete density = 130 pcf, f'_c = 10,000 psi)

	Baseline Steel Hull	Composite LWPC Hull[1]	Weight Ratio
Hull Structure	3,356 LT	5,370 LT	1.60
Full Load Condition	9,006	11,517	1.28

[1] Concrete density = 130 pcf, f'_c = 10,000 psi

- o Fiber Reinforced Concrete (FRC): The incorporation of steel wire or glass fibers into LWPC will improve the ductility of the material and its resistance to impact and blast. Additionally, the use of FRC will increase the tensile and flexural strength of the material. FRC mixes should be developed in order to quantify its benefits to the strength-weight ratio and ductility of LWPC.

3.3.3 Hull Cost Comparison

A comparison between hull construction cost of the composite LWPC hull and the steel destroyer has been made in the following manner:

- NAVSEA has provided cost data for a midship section of a steel hull using mild steel. This data indicates a total hull construction cost of $0.94 per pound in 1980 U.S. dollars. This has been escalated to $1.18 per pound in 1982 U.S. dollars.

- This unit cost has been applied to estimated steel weights for a unit length of the destroyer. This unit cost has also been applied to the internal steel framing in the composite LWPC hull.

- Quantities for concrete shell materials in the composite LWPC have been based upon the conceptual design. Unit prices for concrete construction have been based upon those for similar construction, and have been factored to account for relative construction difficulty. Formwork costs have assumed no parallel middle body in the hull. Formwork costs have assumed reuse due to construction of 20 vessels in the class with typical hull geometry. Concrete costs assume construction by a precast concrete fabricator and costs include a markup of 100 percent for overhead and profit.

A comparison of hull construction costs is presented in Table III-4. This comparison shows that the initial cost of the composite LWPC hull will be approximately 10 percent less than that of the steel destroyer. It should be noted that the unit cost for the steel hull has been based upon a unit price for mild steel and for a section of the hull near midships. It is felt that the more complex hull geometry at other sections of the hull would have a greater affect on the unit cost of steel construction than on that of LWPC construction. Additionally, the extra cost associated with higher strength steel components of the destroyer will increase the cost of the baseline steel hull.

The construction cost benefit of LWPC hull construction would be improved for hull configurations with a long parallel middle body, due to greater benefits of repeatability.

TABLE III-4 - HULL CONSTRUCTION COST COMPARISON
BETWEEN TYPICAL U.S. DESTROYER AND COMPOSITE LWPC HULL

Configuration	Structural Steel	Reinf. Concrete	Total
Baseline Steel Hull	$12,300/ft	--	$12,300/ft
Composite LWPC	$ 5,790/ft	$5,170/ft	$10,960/ft

Note: Costs are for a 1-ft slice near midships of a typical destroyer hull.

3.4 Sensitivity to Hull Type

The weight penalty of LWPC makes the material unsuitable for construction of a destroyer. In order to further investigate the range of Navy ships where LWPC affords potential, additional hull types were selected by NAVSEA for comparison. The particulars of the Navy ships are presented in Section II.

LWPC hull concepts have been developed for comparison with the AOE and the AS hulls. The AOE was selected since it is the longest hull and has the largest displacement. The AS was selected as a smaller hull. Again, the LWPC hull concepts provide the same molded shape as a midship section of the steel hull. Weight comparisons have been based upon use of LWPC for exterior plating and steel for interior decks, platforms and bulkheads.

The thickness of LWPC plating for both hulls is controlled by local plate bending rather than global strength considerations. The investigation indicates that a composite LWPC hull is approximately 2.2 times the weight of either steel hull. By inspection of the AOR and AD hulls, similar weight ratios are expected. Hull weight comparisons are shown in Tables III-5 and III-6.

TABLE III-5. WEIGHT COMPARISON BETWEEN
AOE HULL AND COMPOSITE LWPC HULL
(concrete density = 130 pcf, f'_c = 6000 psi)

Item	AOE Hull	Composite LWPC Hull	Weight Ratio
Hull structure	21.6 LT/ft[1]	46.7 LT/ft	2.16
Lightship	19,000 LT	41,040 LT	
Loads (full)	33,968 LT	33,968 LT	
Full load conditions	52,968 LT	75,008 LT	1.42

[1] Based upon hull weight estimate at STA 11

TABLE III-6. WEIGHT COMPARISON BETWEEN
AS HULL AND COMPOSITE LWPC HULL
(concrete density = 130 pcf, f'_c = 6000 psi)

Item	AOE Hull	Composite LWPC Hull	Weight Ratio
Hull structure	9.9 LT/ft[1]	22.0 LT/ft	2.22
Lightship	12,770 LT	28,094 LT	
Loads (full)	10,643 LT	10,643 LT	
Full load conditions	23,413 LT	38,737 LT	1.65

[1] Based upon hull weight estimate at STA 10

All four hull types investigated in this sensitivity study are used to transport cargo. The increased hull weight for the LWPC hull reduces the cargo capacity of these vessels. The suitability of LWPC hulls for cargo carrying applications will depend upon the life cycle cost of the vessel. This can be determined by a tradeoff between the lower initial costs, lower maintenance costs, and the reduction of dry dock time for a LWPC hull as compared to reduced operating costs associated with the greater cargo capacity and smaller hull weight of a steel hull.

3.5 Construction Methods for LWPC Hull

A construction scenario for a composite LWPC hull is described below, and is presented in Figures III-2 through III-6. This construction procedure is developed to maximize the use of precast concrete elements.

- Precast the Elements -- In order to take advantage of the benefits associated with precast concrete construction, all LWPC elements in the composite hull are precast. Formwork for the bottom shell element is shown in Figure III-2. Elements with significant curvature may require formwork on both surfaces.

- Erect the Precast Elements -- Precast elements are erected in a graving dock facility. Precast elements will require special lifting hardware to control stresses in the precast elements during handling. Elements may be prestressed to facilitate handling. The precast elements are supported and aligned using support frames and braces. Panel sizes will be controlled by the capabilities of cranes at the construction facility. See Figure III-3.

- Form and Place Cast-in-Place Concrete Connections -- Connections between precast shell elements are made using cast-in-place concrete closure pours. See Figure III-4. Reinforcing steel and ducts for post-tensioning tendons are placed in these closure pours. An epoxy bonding agent is used to bond the cast-in-place concrete to the hardened concrete in the precast element.

- Erect Steel Decks/Platforms -- Steel decks and platforms are connected to the LWPC shell using weld plates or other hardware which is cast into the precast concrete elements. See Figure III-5.

- The precast concrete deck plate is supported from the steel decks below while cast-in-place concrete connections are constructed. See Figure III-6.

Once this construction effort has been completed for a portion of the length of the hull the vertical, transverse and circumferential post-tensioning can proceed. Longitudinal post-tensioning cannot begin until construction is completed for the full length of longitudinal tendons.

A portion of the hull construction may be completed while the vessel is floating if dictated by draft limitations at the hull construction facility.

3.6 Specific Construction Details for LWPC Hull

3.6.1 Attachments to LWPC

Connections for the attachment of steel framing, equipment or machinery to LWPC elements can be made with a variety of details. These details fall into two general categories: preplanned connections and retrofit connections. Several connection details for each of these categories are presented in Figures III-7 and III-8. Preplanned connections generally consist of hardware which is embedded in the concrete element in a preplanned location. Connections of this type are presented in Figure III-7. Retrofit connections generally consist of hardware which is attached to the concrete element by drilling or coring into the element. Connections of this type are presented in Figure III-8.

The capacity of these connections are generally dependent upon the length of embedment into the concrete element and the concrete strength. This relationship is shown graphically for headed bolts, studs or bars in Figure III-9.

3.6.2 Non-Magnetic Reinforcement

For certain applications such as mine layers and mine sweepers, the use of non-magnetic materials for hull construction are essential. A potential material for use as a non-magnetic reinforcing and/or prestressing steel is Armco Nitronic 50 stainless steel bar and wire. This material remains non-magnetic even after severe cold working.

Research has been undertaken to study the behavior of fiberglass rods as main reinforcement of concrete elements (reference 7). Testing indicates that strength of such concrete elements is predictable; however, further work is necessary to improve the durability and alkali resistance of fiberglass. The investigation indicates that the strength of fiberglass reinforcement cannot be fully realized due to the low elastic modulus of the material.

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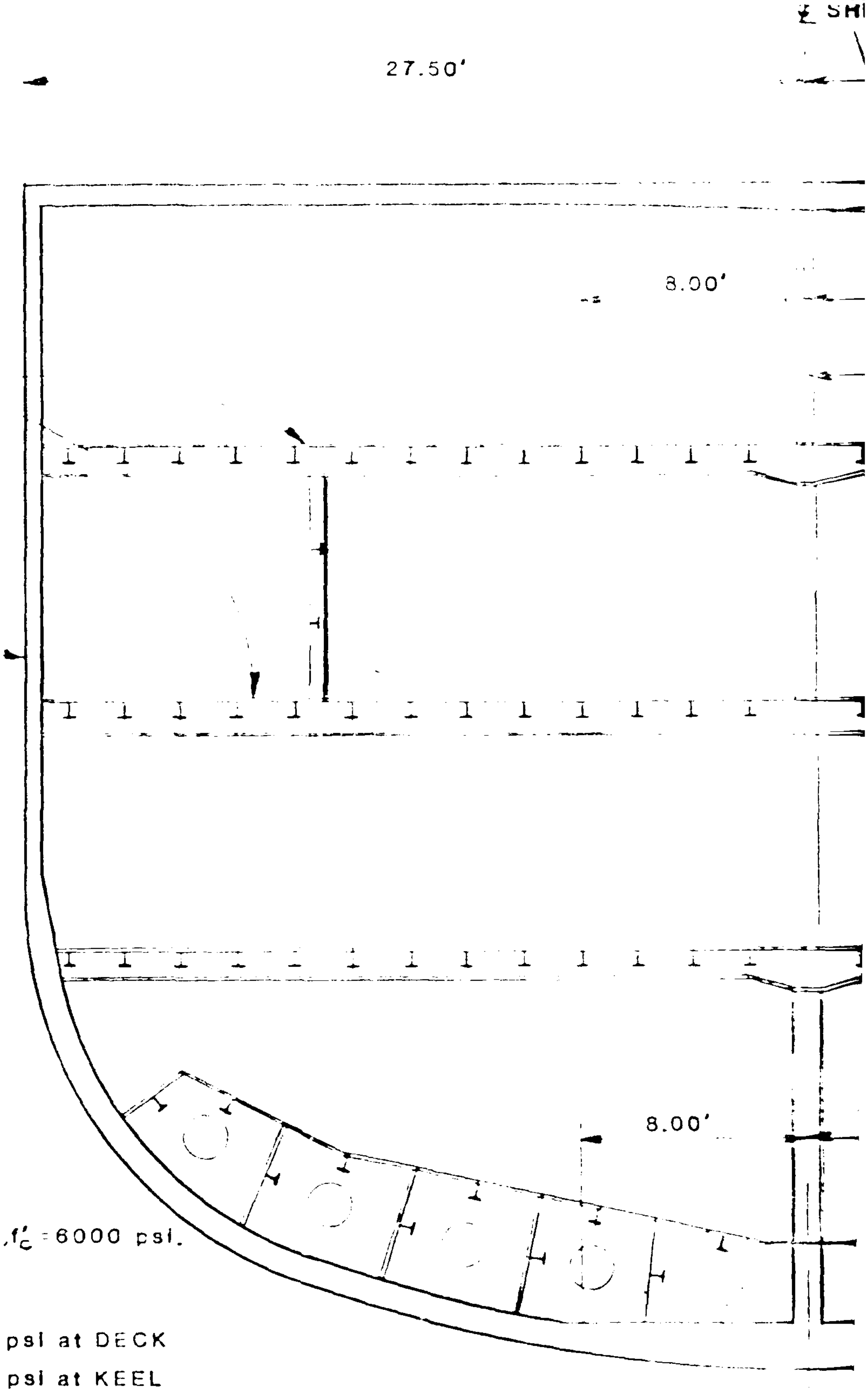


NOTES:

1. CONCRETE STRENTH, f'_c = 6000 psi.

2. PRESTRESS LEVELS;

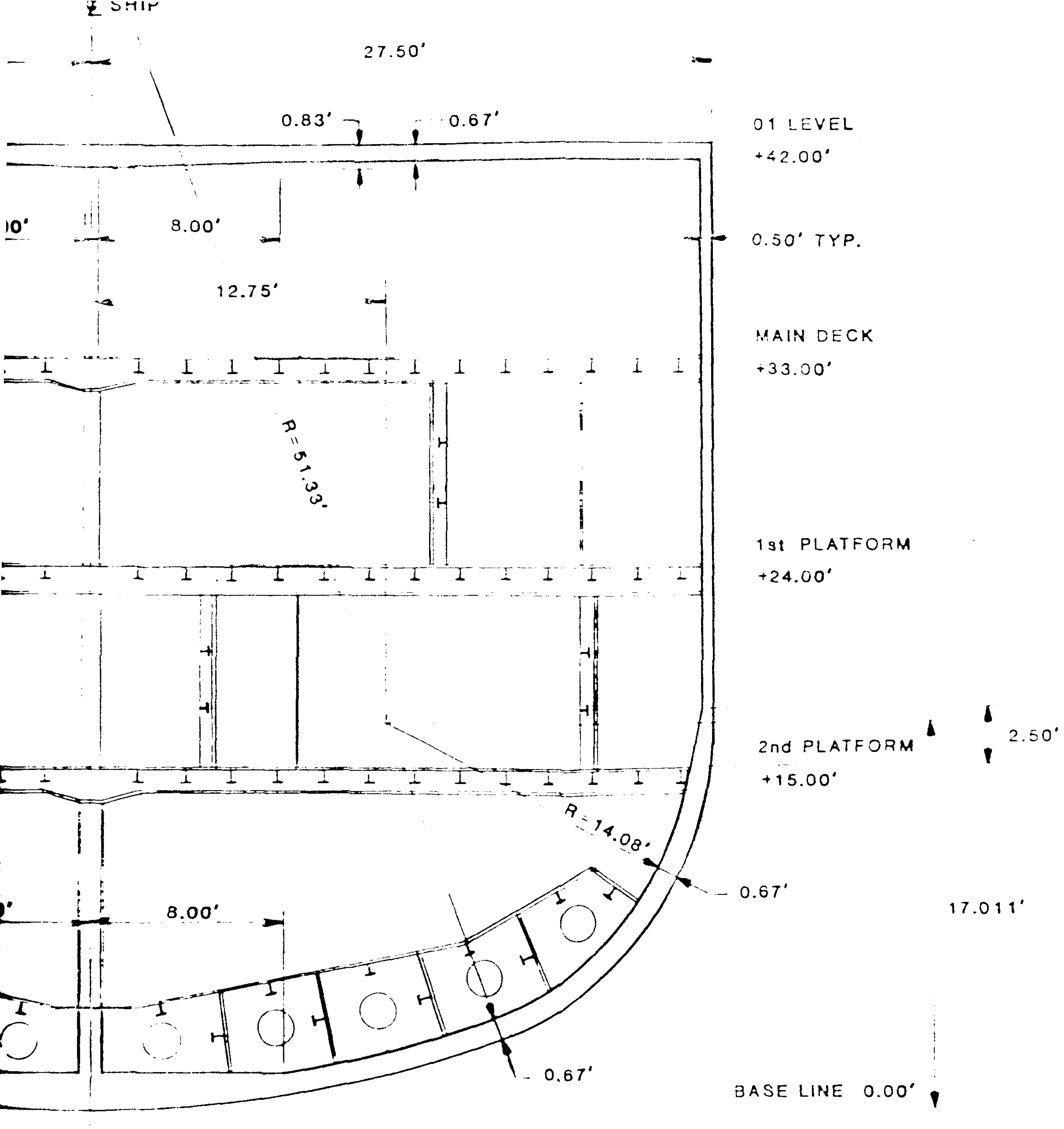
   LONGITUDINAL–1400 psi at DECK

   900 psi at KEEL

   VERTICAL & TRANSVERSE– 800 psi

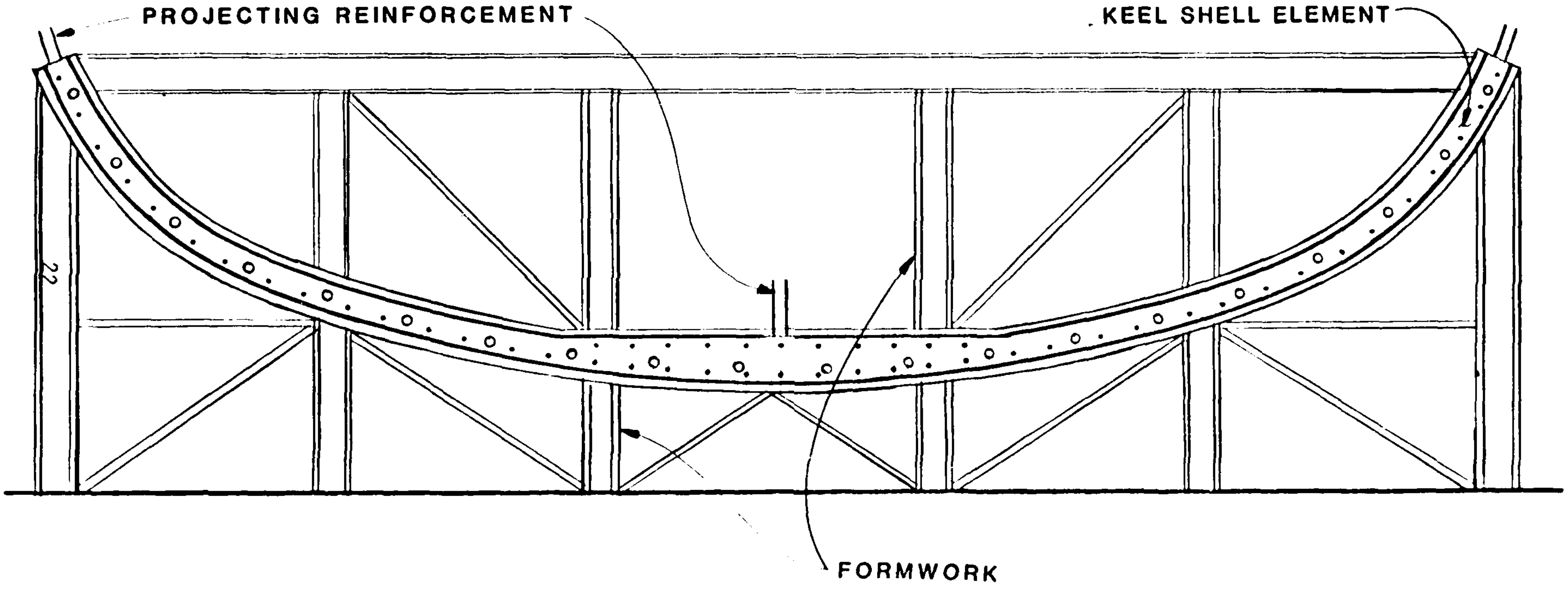
COMPOSITE HULL SE

3/16" = 1'-0"



ULL SECTION NEAR MIDSHIPS

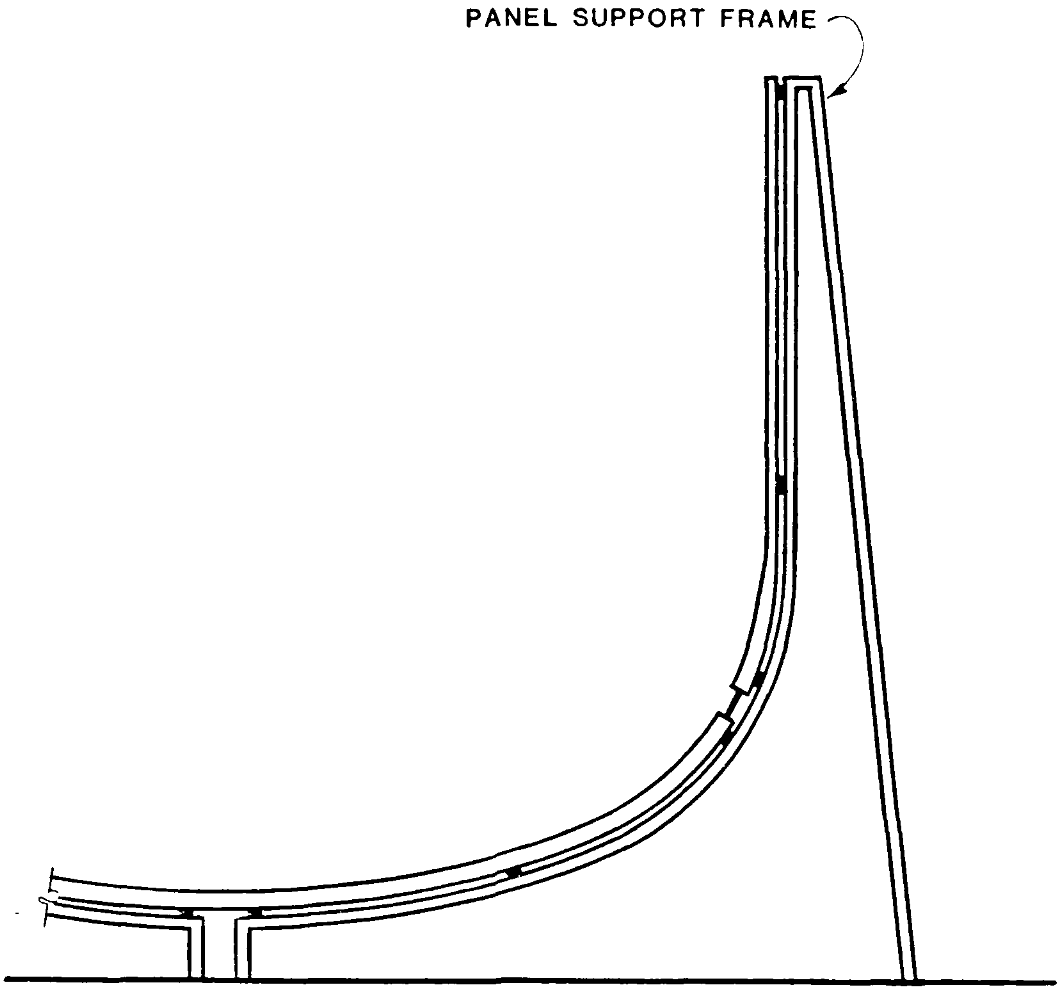
FIGURE III-1



LWPC HULL CONSTRUCTION CONCEPTS

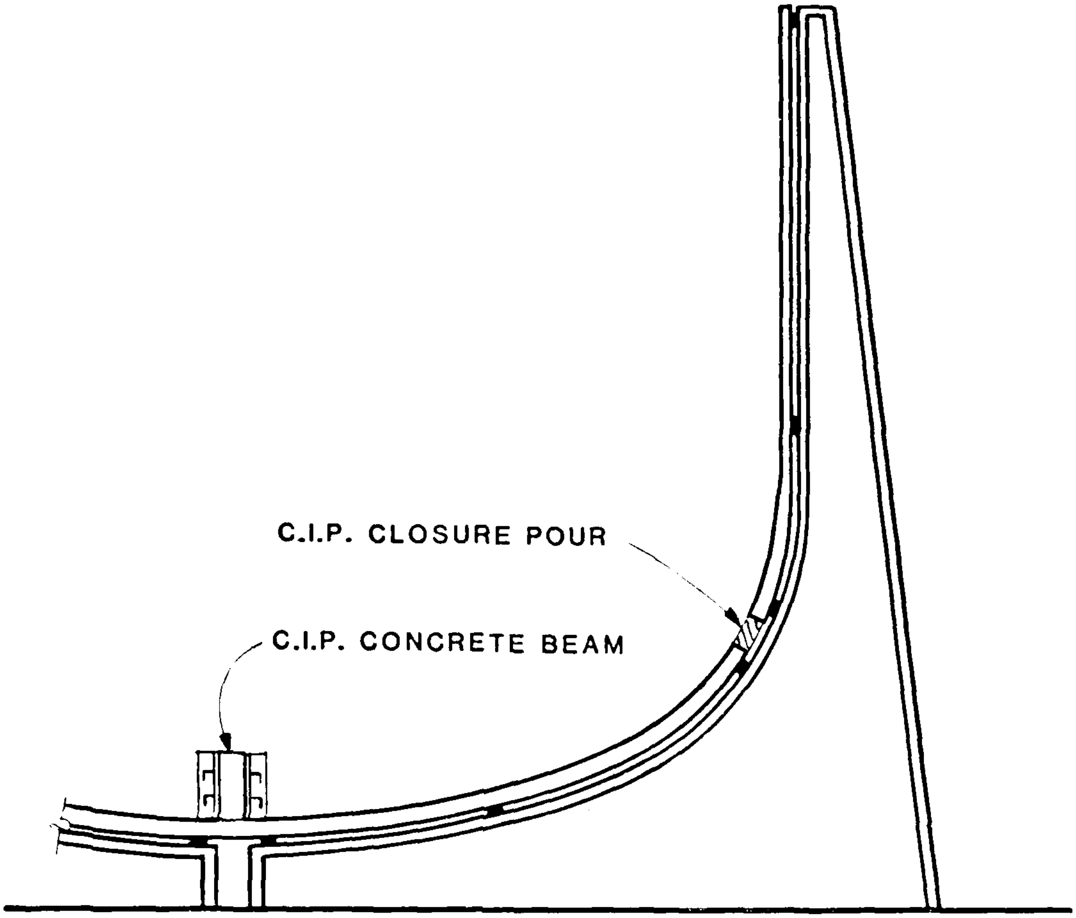
PRECAST ELEMENTS

FIGURE III-2



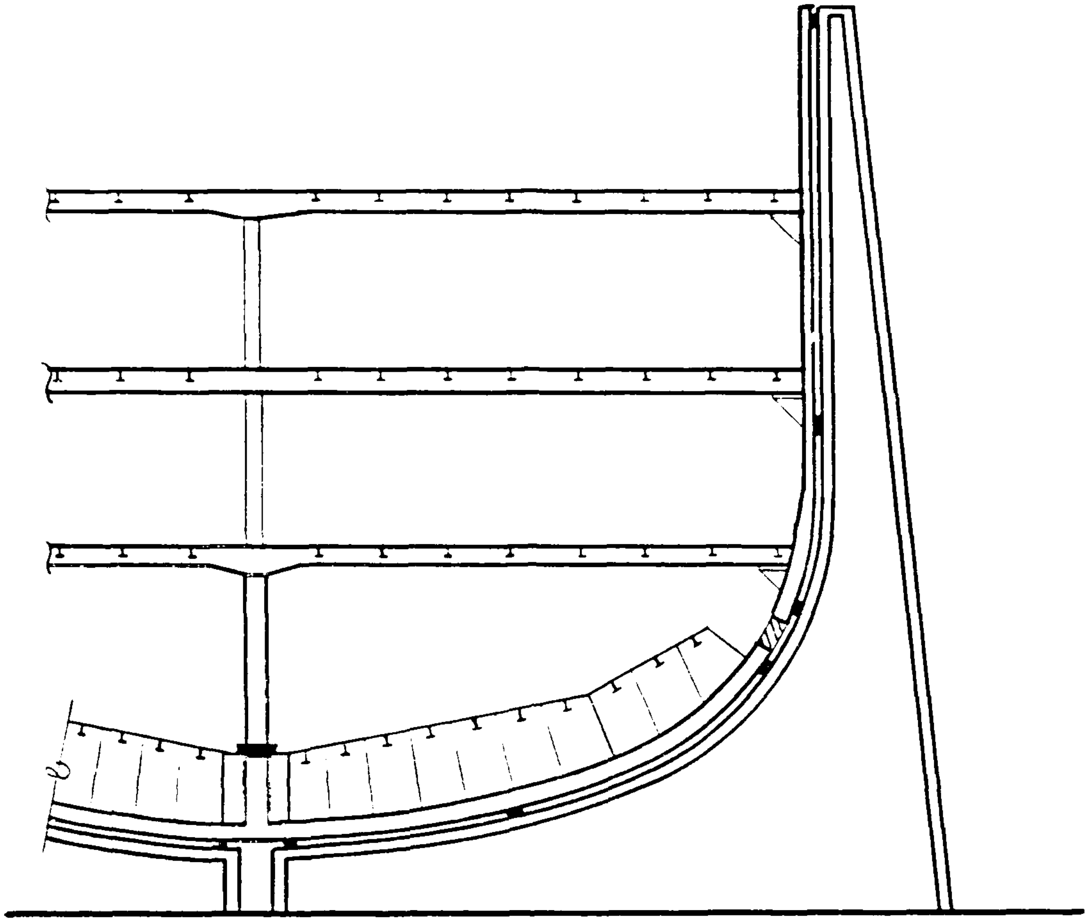
LWPC HULL CONSTRUCTION CONCEPTS
ERECT PRECAST ELEMENTS

FIGURE III-3



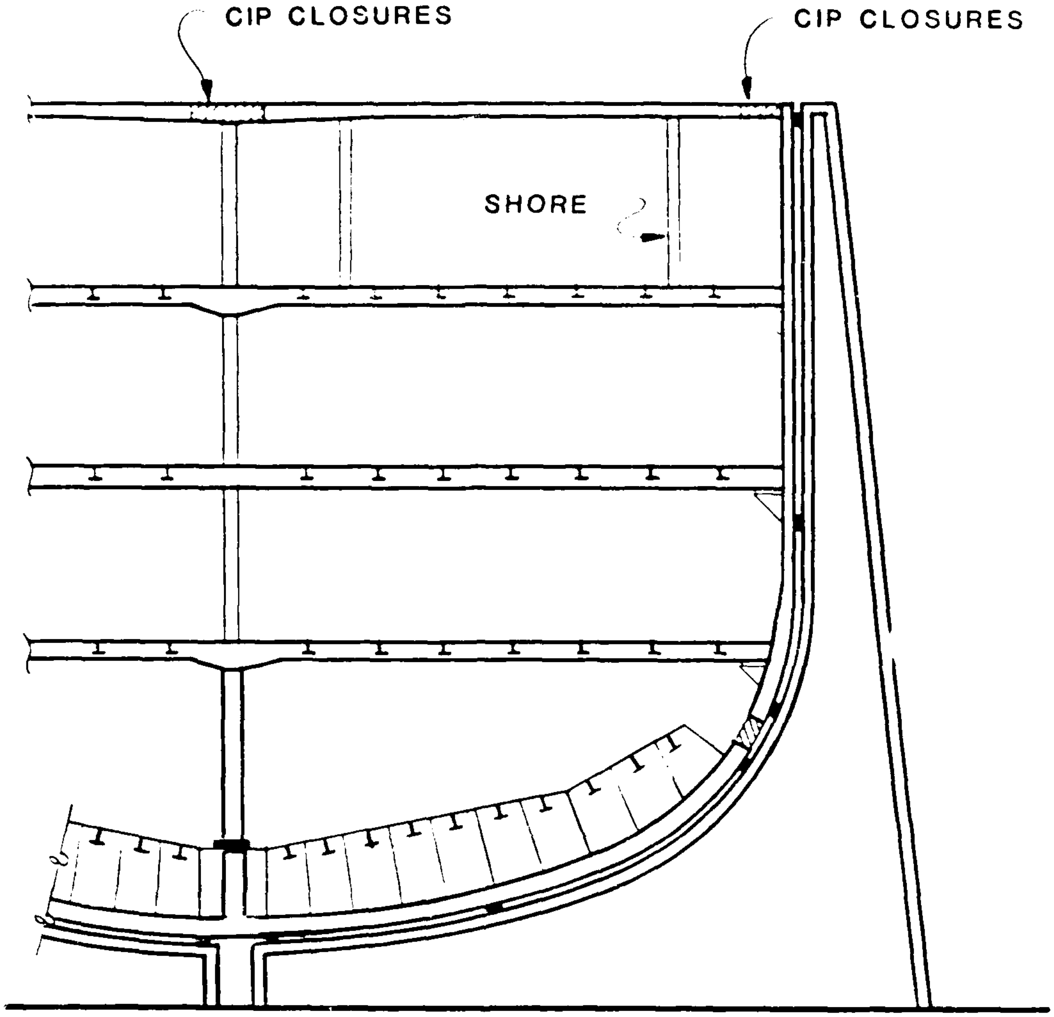
LWPC HULL CONSTRUCTION CONCEPTS
FORM & PLACE CAST-IN-PLACE
CONCRETE CONNECTIONS

FIGURE III-4



LWPC HULL CONSTRUCTION CONCEPTS
ERECT STEEL DECKS / PLATFORMS

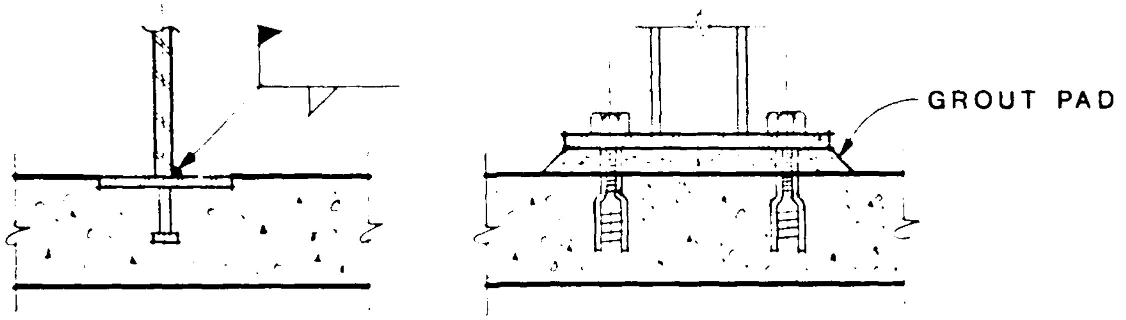
FIGURE III-5



LWPC HULL CONSTRUCTION CONCEPTS

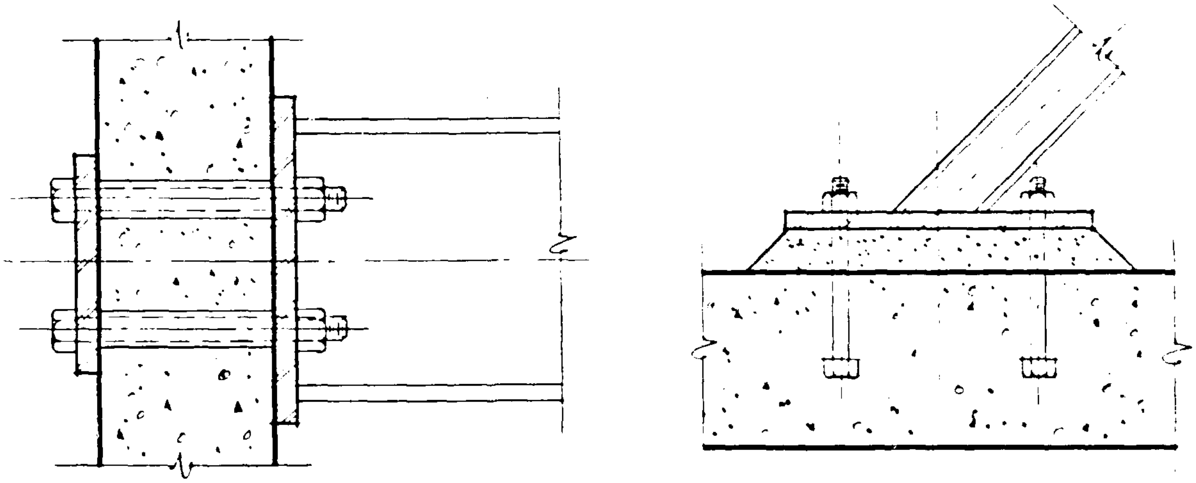
PLACE DECK

FIGURE III-6



WELD PLATE WITH HEADED STUD

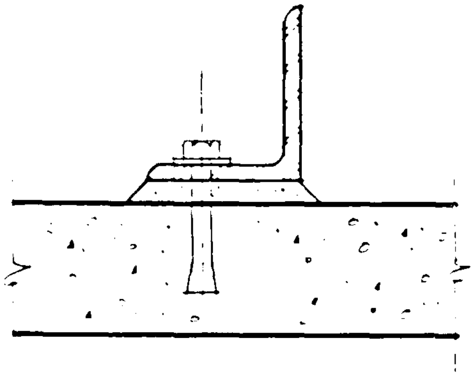
BOLTED CONNECTION-EMBEDDED CONCRETE INSERT



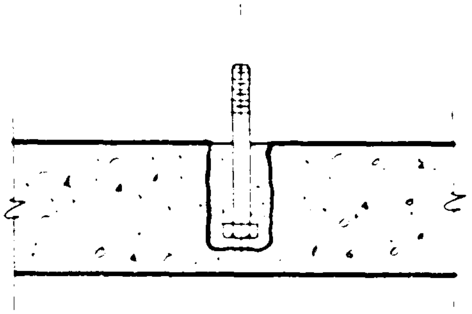
BOLTED CONNECTION-BLOCKOUT THROUGH CONCRETE ELEMENT

BOLTED CONNECTION-EMBEDDED ANCHOR BOLT

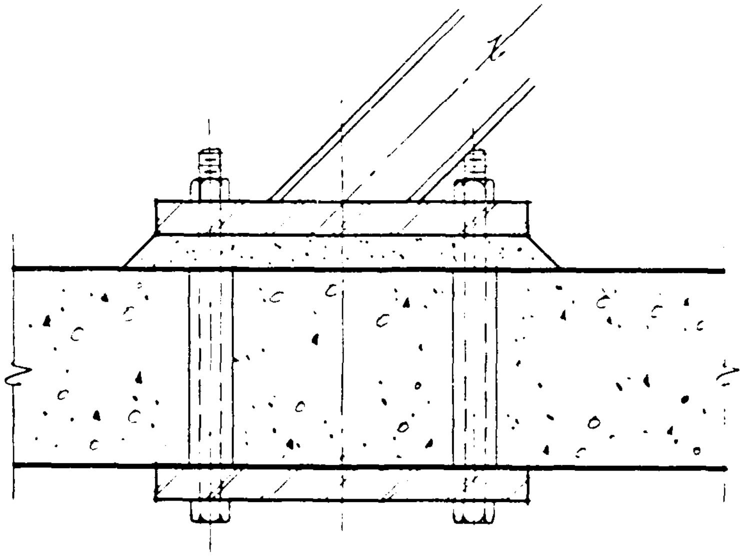
Figure III-7
TYPES OF PREPLANNED CONNECTIONS



DRILLED IN WEDGE ANCHOR

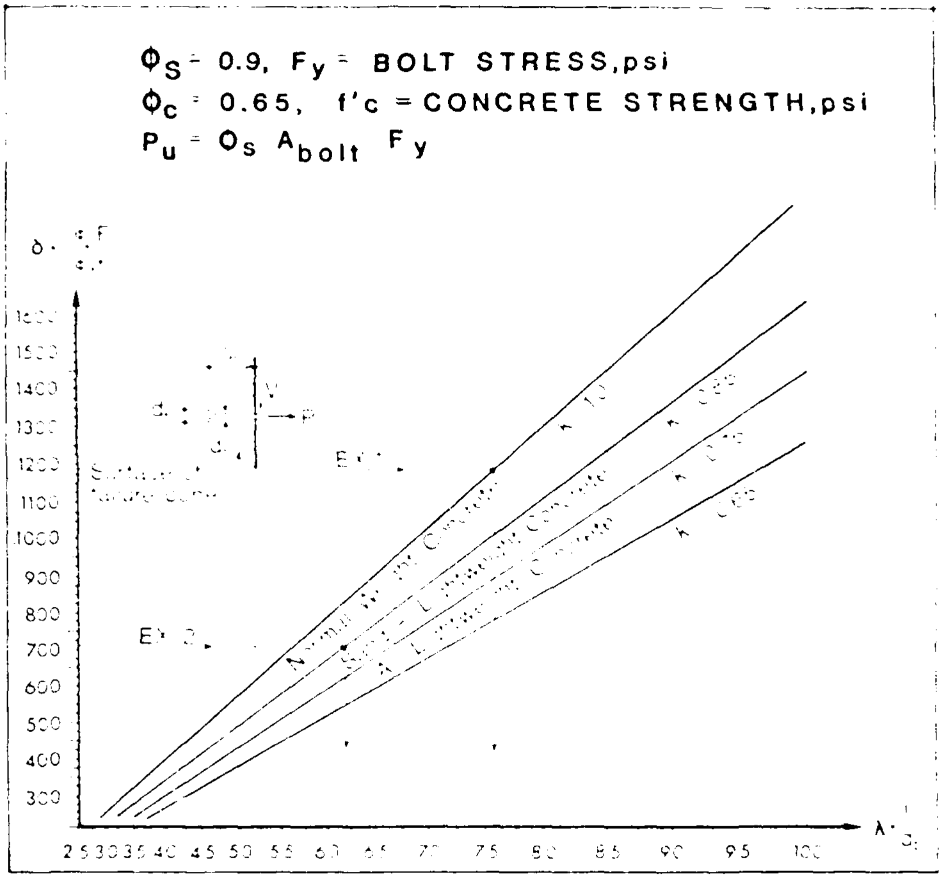


ANCHOR BOLT BONDED INTO FIELD DRILLED HOLE



BOLTS IN CORE DRILLED HOLES

Figure III-8
TYPES OF RETROFIT CONNECTIONS



$\Phi_S = 0.9$, F_y = BOLT STRESS, psi

$\Phi_c = 0.65$, $f'c$ = CONCRETE STRENGTH, psi

$P_u = \Phi_s A_{bolt} F_y$

Figure III-9 HEADED BOLTS, BARS, AND STUDS-ULTIMATE PULLOUT CAPACITY, P_u, FOR FULL CONES AND EMBEDMENT LENGTH, l_e

SECTION IV

SECTION IV

DESIGN CRITERIA FOR LIGHTWEIGHT PRESTRESSED CONCRETE FOR SHIP HULL CONSTRUCTION

4.0 Introduction

The purpose of this section is to provide an instructional narrative concerning recommended design criteria for concrete applied to ship construction. The primary emphasis will be to give the reasoning behind the design criteria, and to make comparisons with the more familiar criteria for steel ships. Basic design stresses and safety factors will be given in this section, but detailed lists of criteria which may be found in the cited references will not be repeated.

Design criteria fall into two major categories: loads and strengths. Loads are determined from principles of naval architecture, and are similar to the loads used in the design of steel vessels. Strengths are determined using established principles developed for dry-land concrete construction. Loads are equated to strengths, with safety factors. The main task of developing criteria for concrete vessels is to establish the proper safety factors for various types of loads, considering also the degree of reliability of the strength equations. This is done by comparing safety factors used in steel ship construction to the safety factors used in steel and concrete construction on dry land.

4.1 The Properties of Concrete as a Structural Material

It is important to understand the properties of concrete, for the properties of the material affect the way in which it is used, and thus determine the appropriate design criteria. Reinforced or prestressed concrete as used in large-scale construction is a composite material which combines the properties of both concrete and steel. There are various degrees or levels of reinforcement, with differing properties of the composite material.

4.1.1 Unreinforced Concrete

The use of unreinforced concrete in ship construction is not contemplated. The properties of unreinforced concrete are given here as a reference point, so that the manner in which reinforcement alters the behavior can be better understood. The most important property of unreinforced concrete is that it is prone to cracking. Unreinforced concrete has good compressive strength but low tensile strength. It is subject to shrinkage. The tensile stresses caused by loads, thermal deformations and shrinkage deformations will almost inevitably cause any large construction of unreinforced concrete to crack in tension. Whereas cracking is something to be positively avoided in steel construction, the cracking of concrete must be accepted as fundamental to its nature.

Concrete is quite useful in compression. Good quality concrete has a compressive strength approximately 1/6 that of mild steel. The elastic modulus, although lower than steel, is fairly high in comparison to its strength, so that a concrete structure is normally stiffer than a comparable steel structure designed to resist the same loads. Concrete creeps slowly under constantly applied loads, producing ultimate deflections of roughly three times the initial elastic deflection. This is often looked upon by engineers as an undesirable property of concrete, because it makes deflections harder to predict. However, it is also a very useful property, for creep relieves stress concentrations.

A very important property of concrete is that of autogenous healing. The chemical reactions that cause plastic concrete to harden or set continue indefinitely in a moist environment. Thus, the concrete continues to gain strength throughout the life of the structure. Very old structures may have strengths 50% to 100% in excess of the strengths originally specified at the time of construction. The presence of continuing chemical reactions also allow the concrete to "heal" itself over a period of time. This property makes concrete relatively immune to fatigue from large numbers of load cycles at low amplitude. Over time, the concrete heals the fatigue damage and thus the fatigue is not cumulative as it is with steel structures. Additionally, if the concrete is finely cracked, the continued chemical reactions will heal the crack in a moist environment, providing the crack is not continuously "worked."

4.1.2 Reinforced Concrete (Reinforced with Mild Steel Bars)

This is the type of concrete that is most widely used in building construction. Mild steel reinforcing bars are embedded in the concrete for the primary purpose of controlling the effects of cracking. It is very important to understand that reinforcing bars are not effective in preventing cracking. Concrete shrinks slightly during curing, and the shrinkage of the concrete causes the embedded reinforcing bars to contract also. This puts a small amount of initial compression in the steel. If an external tension is then applied to a reinforced section, the concrete and steel share the tension in proportion to their moduli of elasticity. At the time the concrete reaches its tensile strength, the tensile stress shared by the steel is about sufficient to cancel out the initial compression; thus the steel stress is about zero at the time the concrete cracks. Therefore, the reinforcement is ineffective in preventing cracking. However, the reinforcement is very important in controlling the behavior of the concrete element after cracking. Reinforcement is used to resist tensile stresses across the crack and may also be used to resist shear stresses across the crack. In reinforced concrete design, it is commonly assumed that all tensile stresses are resisted by reinforcement rather than by the concrete. Reinforcement also limits the width of the crack. The amount of reinforcement and the distribution of reinforcement may be chosen in order to limit cracks to an acceptable width. If the cracks are kept small enough, they do not result in undesirable effects such as corrosion of the reinforcement, for the alkalies in the concrete are able to chemically protect the reinforcement in the presence of small cracks. Concrete design standards for dry-land construction are so chosen as to limit crack widths to about .010 inches in normal construction, although in very corrosive environments, the limit may be about half this.

Reinforced concrete was widely used for ship hull construction during World Wars I and II. Although it is the nature of reinforced concrete to crack, whatever cracking was present in these ships did not adversely affect their watertightness or their performance. In recent years, most large vessels have been constructed of prestressed concrete, which was developed after World War II. Prestressing gives better control of cracking and thus has become favored for use in concrete vessel construction. Nevertheless, it should be emphasized that it is often impractical to prestress for all stresses in all directions, and a prestressed member retains some characteristics of a reinforced member, at least for the minor stresses. There is ample experience to indicate that reinforced concrete is a satisfactory material for ship construction, even though it has largely been superseded by prestressed concrete.

4.1.3 Ferrocement

Ferrocement is a special type of reinforced concrete in which the reinforcement is very finely divided and distributed throughout the concrete. The reinforcement consists of fine wires spaced a maximum of 1/2 inch, and often much less. The behavior of ferrocement is quite different from ordinary reinforced concrete. When tensile loads are applied to a ferrocement section, cracking of the concrete does occur as previously discussed. However, the cracks are effectively arrested by the finely divided reinforcement, and thus the various small cracks between the reinforcing wires do not unite into more continuous cracks as happens with conventionally reinforced concrete. This causes the material to behave as if it were uncracked, even though micro cracks exist. Thus, ferrocement maintains the stiffness and watertightness (at moderate heads) which would be characteristic of uncracked concrete.

Ferrocement is commonly used as a boat building material for small boats. Very thin sections can be made to retain their watertightness because of the special properties of ferrocement. Assembling the small wires and applying the concrete to the assembled wires is a very labor-intensive process. Ferrocement is not widely used for large construction because of the labor requirements. For navy ships, it is unlikely that Ferrocement would be an appropriate choice for construction of the entire ship. There may be certain elements within the ship, however, for which Ferrocement might be an appropriate material.

4.1.4 Prestressed Concrete

Prestressed concrete derives its name from the fact that the steel in the concrete element is prestretched or prestressed in such a manner that precompression is introduced into the concrete prior to the application of external load. This may be done by stretching the steel wires under high tension between fixed abutments prior to casting the concrete around them (pretensioning method). Alternately, the same effect may be accomplished by casting ducts in the concrete, placing steel wires in the ducts, and jacking the wires to high tension after the concrete has hardened (post-tensioning method). Providing the ducts are injected with cement grout after tensioning, the end result of the two methods is essentially the same. The steel is placed under initial tension and the concrete under initial compression, prior to the application of external loads.

Prestressed concrete was originally developed to make possible the use of high-strength steel as concrete reinforcement. If high-strength steel is used as concrete reinforcement without prestressing, the excessive strains associated with high stresses lead to unacceptable crack widths in conventionally reinforced concrete. Therefore, it is essential that when using high-strength steel, the steel be prestretched to remove this excessive strain. The resulting pre-compression in the concrete enables one to design a structure in which the major stresses in the concrete are compressive at all times with external loads causing a fluctuation in the level of compression. Such a structure would theoretically be uncracked throughout its service lifetime. It is important to realize, however, that complex states of stress may exist at the intersection of members and that it is often impractical to prestress in all directions to counteract all secondary tensions. Thus, it should not be assumed that prestressing will *totally eliminate cracking. However, it does greatly reduce the amount* of cracking compared to a reinforced structure, and conventional reinforcing can be used to control, to acceptable levels, what cracking may occur.

4.1.5 Reinforced and Prestressed Concrete

Current design standards for dry-land construction require that a structure be classified as either prestressed or reinforced (without prestressing), and different design rules apply to each. There is no commonly used set of design rules that are appropriate to a structure that utilizes a combination of prestressing and reinforcing steel to share the load. However, such a combination may be highly desirable for ship hull construction as will be discussed in Subsection 4.10.

4.2 General Arrangements

4.2.1 Comparison to Steel Properties

Lightweight concrete has a density 1/4 that of steel and a compressive strength 1/6 that of steel. The comparison of compressive strengths can be misleading, however. Steel has the same strength in compression and tension, whereas concrete is only useful in compression. For reversible stresses, such as hogging and sagging, it is the allowable stress range that is significant. The allowable stress range in steel is from 19,000 psi tension to 19,000 psi compression, for a total range of 38,000 psi. In concrete of 6,000 psi strength, the allowable stress range is from 0 to 2,700 psi compression. The total stress range is 2,700 psi, compared to 38,000 psi for steel. This is a ratio of about 1:14. Where plate thicknesses are controlled by hogging and sagging, a concrete plate will be about 14 times the thickness of an equivalent steel plate. In other words, a 10-inch thick concrete plate is about equivalent to a 3/4-inch steel plate.

The fact that concrete plates are so much thicker than steel plates has a significant effect on the structural arrangements. The resistance of a plate to bending (hydrostatic) loads varies as the square of the thickness. Similarly, the critical buckling stress for a plate in compression varies as the square of the thickness. Steel plates require stiffeners at intervals of a few feet, to prevent buckling and local bending from becoming critical. Concrete plates, being approximately 14 times as thick, can be designed with unsupported widths or lengths approximately 14 times that of steel plates. Thus, stiffeners are generally not required, and the concrete plates span directly from bulkhead to bulkhead. If the span between bulkheads is too great, intermediate frames may be used. Also, curved concrete shells may be used to increase the span between bulkheads. These considerations lead to a framing system for a concrete vessel that is generally much simpler than the equivalent steel system. See Figure IV-1 for a comparison of concrete steel framing. Some weight is saved as a result of the deletion of stiffeners. Nevertheless, if the ratio of plate thicknesses is 1:14 and the ratio of density is 1:4, it is obvious that a concrete hull will be heavier than the equivalent steel hull. In practice, a concrete hull normally is between two and three times the weight of a comparable steel hull. There are ways to improve on this, as will be discussed later.

It is usually advantageous to haunch or thicken the plates near the intersection with bulkheads. Local bending stresses are, of course, maximum at this location. Typically, slabs are haunched so that the thickness at the support is between 1.5 and 2.0 times the mid-span thickness.

Shearing stresses are more likely to be critical in concrete than in steel. The shearing strength of steel is about 60% of the tensile strength, whereas the shearing strength of plain concrete is approximately 5% of the compressive strength. The shearing strength of concrete may be improved by the addition of reinforcing and prestressing; nevertheless, shear is of greater concern in concrete than in steel. The use of flat or curved plates without stiffeners allows the entire volume of concrete to be effective in resisting both in-plane shear and out-of-plane shear, whereas in a stiffened plate, the in-plane shear is resisted only by the plate and the out-of-plane shear is resisted only by the stiffeners. Thus, considerations of shear also argue for the use of unstiffened plates and shells.

4.3 Performance Requirements

4.3.1 Strength

Strength is the obvious performance requirement and strength requirements are spelled out in detail below.

4.3.2 Watertightness

Watertightness is obtained primarily by the use of prestressing, although it is feasible to build a watertight vessel without prestressing. If prestressing is not used, particular attention must be paid to the details of any construction joints to obtain watertightness. Construction joints are much less of a problem when prestressing is used to maintain compression across the joint. Nevertheless, if there are any problems with watertightness, they will normally be at construction joints.

4.3.3 Durability

Durability is concerned with resistance to chemical attack of both the concrete and the reinforcing steel. Good durability is obtained primarily by attention to concrete quality as discussed elsewhere in this report. Concrete quality is not only important in protecting the concrete against attack, it is also the most important factor in protecting the steel against attack. The cover (the minimum thickness of concrete between steel and the face of the member) is also of some importance in protection of the steel. Many existing design codes use the specification of minimum cover as the primary means of controlling corrosion of the steel. This is unfortunate, since concrete quality is actually a more important parameter. Excessive cover requirements can lead to excessive weight, which has particularly serious consequences in marine vessels.

4.3.4 Fatigue Resistance

Prestressed concrete is exceptionally resistant to fatigue. Under normal design loadings, the stress in the concrete oscillates within the range of 0 to about 45% of the compressive strength, with the stress being compression at all times. Because of the autogenous healing properties of concrete, concrete has an infinite fatigue life at these stress ranges. The stress range in the steel is the stress range in the concrete multiplied by the ratio of their elastic moduli. This produces a stress range in the steel which is only a few percent of the ultimate strength of the steel. Thus, there is no fatigue problem in the prestressing steel or mild steel.

There is a potential fatigue problem caused by a few cycles of repeated load at very high stress levels,[12] such as in a 100-year storm. This is somewhat analogous to earthquake loads in a dry-land structure. In earthquakes, a few cycles of very high loading may be experienced. At the present time, earthquake design standards applicable to cyclic loads at high stress levels are not directly applicable to marine construction, although future earthquake research results may be. The allowable stresses and safety factors given in this section are designed to prevent low cycle, high load fatigue from being a serious problem. However, unduly conservative results may be produced. The considerations of low cycle, high load fatigue is a research subject which is rapidly evolving at this time.

4.3.5 Impact Resistance

At the present time, very little is available concerning impact resistance of concrete structures. Of course, plate theory may be used to analyze the elastic behavior under point loads, but impact resistance generally involves inelastic behavior under overloads. Some

information has been developed by the Corps of Engineers for use in the design of concrete fortifications, giving the resistance of concrete to various explosives and projectiles. Also, the design of nuclear power plants requires resistance to impact of various missiles which might be generated by explosions or tornadoes, and some useful information may be found here.

The design of concrete structures to resist impact is also a subject which is rapidly evolving at this time. The oil companies are currently considering the design of large concrete structures for use in ice-infested Arctic waters. It is quite probable that extensive research will be conducted in the resistance of concrete to impact loads in the near future.

4.4 Philosophy of Strength Design

4.4.1 Basic Equation

The basic equation of strength design is:

Loads = Strength

Of course, the strength should be greater than the applied loads by an amount called the "safety factor." Different design methods locate the safety factor in different parts of the equation. The traditional design method is called working stress design. In this method, the strength of the material is divided by safety factor to produce an allowable stress. The design equation is thus:

Loads = Strength/Safety Factor

In recent years, ultimate strength design has become popular. In ultimate strength design, the loads are multiplied by safety factor and equated to the strength of the material. Thus, the basic equation is:

Loads x Safety Factor = Strength

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Loads x Safety Factor = Strength

Current concrete codes for dry-land construction utilize a split safety factor in which the bulk of the safety factor is applied to the load side of the equation, but a small "capacity reduction factor," Ø, is applied to the strength side of the equation to allow for variations and material strength. Thus, the design equation is.

Loads x Safety Factor = Strength x Reduction Factor

For concrete ship design, the loads are derived from the principles of naval architecture, and are basically the same as those used in the design of steel ships. A problem sometimes arises in that specifications for steel scantlings do not give the load directly, but rather give requirements for steel area or section modulus as a function of span and depth. These requirements can be back-figured to determine the load on which they were based. However, there are often corrosion allowances or other considerations buried in the equation. Where the loads are explicity stated, such as the trochoidal wave loading of 1.1 times the square root of the length in feet, the same loads may be used for concrete hulls. The strength side of the equation is computed using the principles of dry-land concrete design. The American Concrete Institute (ACI) Building Code[3,4] and other ACI standards are the primary source of this information.

The safety factor must be determined by experience. This experience is with steel ships and with other dry-land concrete construction. Fortunately, the safety factors used in these two types of construction are reasonably compatible.

The ACI code allows reinforced (unprestressed) concrete structures to be designed either by the ultimate strength method or the working stress method. The designer may choose either method, but is not required to use both. For prestressed concrete, however, the code requires that a check be made by both methods. The reason is that in prestressed structures, stress is not proportional to load. Thus, the true design equation is more complex than the very simplified equations given above, which are based on the assumption that stress is proportional to load. In prestressed sea structures, a working stress check is made at a "normal service" load level, and an ultimate strength check is made using loads applicable to an extreme event such as a 100-year storm.

4.5 Types of Stress

Stresses in steel ships are normally classed as one of three types. Primary stress is the stress caused by hull-girder bending. Secondary stress is that due to bending of a stiffener plate combination, and tertiary stresses are those due to hydrostatic or other normal loads on the plating. A similar distinction is made in the case of concrete design.

4.5.1 Primary Stresses

These are normally stresses arising from hog/sag moments which produce overall bending of the hull girder. The important feature of these stresses is that they produce compression or tension throughout the thickness of the hull plating. Such stresses are commonly called membrane stresses in concrete design.

4.5.2 Secondary Stresses

These stresses are much less common in concrete design, for stiffeners are normally not used. However, if a stiffening beam is used, the flexure of the stiffening beam would produce membrane-type stresses in the hull plating which forms a flange of the stiffening beam. Therefore, the allowables for secondary stresses would be the same as for primary.

4.5.3 Tertiary Stresses

These are stresses from hydrostatic or other loads acting perpendicular to the plane of the plate. They are commonly called "plate bending stresses" in concrete design. This type of stress produces tension on one side of the plate and compression on the other.

Membrane (primary) stress can produce tension throughout the thickness of the hull plate whereas plate bending (tertiary) stresses produce tension on only one side of the plate. Thus, the consequences of tensile cracking are quite different for these two types of stress, and different allowables are used. In fact, experience has shown that for plate bending stresses, prestressing is not necessary and that conventionally reinforced concrete will maintain its watertightness under plate bending loads.

4.6 Plate Bending (Tertiary) Loads and Stresses

4.6.1 Loading Diagrams

For preliminary design, hydrostatic loadings may be assumed as shown in Figure IV-2. The maximum waterline is assumed to be at the level of the deck. Alternatively, the maximum waterline may be taken as 1/2 the wave height above the stillwater line. A triangular diagram is used for the hull side, and a uniform pressure of maximum intensity is used across the hull bottom. For final design, more complex rules for determining hydrostatic pressures are given in the Det norske Veritas (DNV)[9] and Nippon Kaiji Kyokai (NKK)[14] rules for steel ships. The American Bureau of Shipping (ABS)[2] rules specify scantling requirements for steel without giving a loading diagram, and are thus not readily translatable into a design requirement for a concrete vessel.

4.6.2 Allowable Stresses for Prestressed Concrete

The allowable stresses for prestressed concrete are as follows:

- For compression $.45\ f'_c$
- For tension $5\ (f'_c)^{0.5}$

The allowable compression stress is the same as in dry-land structures. The allowable tension stress is 2/3 the modulus of rupture, and is slightly less than for dry-land structures. It will normally be found that these allowables lead to a relatively small volume of concrete that is actually in tension, and the great share of the thickness of the plate is in compression.

4.6.3 Factors of Safety

For the hydrostatic loads defined above, a safety factor of 1.7 is used in combination with a Ø (material reduction factor) of 0.9 applied to the strength side of the equation. These factors are the same as those used for live loads in building construction and are similar to the factors of safety in steel ships designed by ABS and other rules.

4.6.4 Damage Conditions

For damage conditions, hydrostatic loads against the interior watertight bulkheads are investigated. Additional pressure on the hull sides and bottom may also arise from the sinkage, heel and trim associated with damage conditions. Plate bending analysis should be done for these hydrostatic loads; however, with a safety factor of 1.3, rather than 1.7. This analysis also uses a Ø factor of 0.9 for flexure. The load factor of 1.3 is comparable to code load factors for extraordinary wind and seismic loadings. Only a strength design check is required for the damage condition.

4.7 Hull Girder Bending Resulting From Hog/Sag Conditions (Primary Stresses)

4.7.1 Loading Conditions

During the life of a vessel, it may be subjected to several types of loading. These include, but are not limited to:

- Construction loads. These are temporary stresses which may occur during construction and launching processes.

- Stillwater bending. This is computed in the usual manner.

- Normal service wave. This is normally taken as the wave loadings given by ABS, Lloyds, DNV, and other rule books.

- Extreme event (100-year storm). If data on extreme loads are available, the structure may be designed for the extreme load also, but with lesser factors of safety.

- Damage conditions.

4.7.2 Levels of Design

The design may be checked for allowable stresses at service load for factor of safety against cracking at service load and factor of safety with the respect to ultimate load. Not all loading conditions require checks at all levels of design, however. See Table IV-1 for the design requirements.

TABLE IV-1
HULL FACTORS OF SAFETY, ALLOWABLE STRESSES

	Allowable Stresses	Factor of Safety Against Cracking	Ultimate Load Factors
Construction Loads	$.6\ f'_c$ (c) $5\ (f'_c)^{0.5}$ (t)	-	1.5
Stillwater + Normal Wave	$.45\ f'_c$ (c) 0 (t)	1.5	1.7
Stillwater + Extreme Event	-	-	1.3
Damage Condition	-	-	1.3

4.7.3 Shear

Shearing stresses may be checked using the methods given in the ACI code. The ACI code calls for checking shear at a distance from the support equal to one-half the depth of the beam. In the case of the hull girder, one-half of the depth is a large distance and it is recommended that shear be checked at the support rather than at d/2 from the support.

The ACI code requires only a shear check for ultimate strength. However, it is recommended that the principal tension at service load also be checked, and that this principal tension at service load should not exceed $4\ (f'_c)^{0.5}$.

4.8 Hull Plating Design

4.8.1 Combinations of Membrane and Bending Stress

In steel design, higher allowables are used for combinations of primary and tertiary stresses. However, this is not recommended for concrete design. Stresses from plate bending and hog/sag membrane stresses should be directly added. The higher allowable tension applicable to plate bending would then be the appropriate allowable stress providing the membrane tension alone does not exceed zero.

Plate bending stresses from hydrostatic loads will have some effect on the capability of the hull sides to resist shear arising from hull girder bending. The interaction of plate bending and membrane shear for concrete design is not well understood and virtually no research data exist at this time. An approach which is believed to be conservative is to determine the reinforcement requirements for plate bending and for shear and to provide reinforcement for the sum of these two requirements.

4.8.2 Buckling Criteria

Buckling of concrete plates is seldom critical, for the thickness ratios dictated by other requirements are generally sufficient to prevent buckling. For a flat plate in which the long dimension is in the same direction as the stress, the critical ratio of the short dimension "b" to the thickness is about 50. Formulae for the buckling of plates may be found in Reference 13. If the short dimension of the plate is in the direction of the compressive stress, the plate may be checked for buckling using the column provisions of the ACI code.

For shells, the critical radius to thickness ratio is about 200 for cylindrical shells loaded in compression parallel to the axis of the cylinder.[6] In practice, it is unlikely that this limit will be exceeded.

4.9 Special Considerations for Lightweight Concrete

The modulus of elasticity of concrete is proportional to the 1.5 power of the density. As a practical matter, lightweight concrete has a modulus of about half that of regular weight concrete. This is a drawback in slender structures, but it is not of great significance in ship design. The critical buckling parameters are reduced approximately in proportion to the square root of the modulus. Thus, for lightweight concrete, the critical buckling parameters are about 70% of those given above.

The tensile strength of lightweight concrete made with regular sand is about 85% that of normal weight concrete of the same compressive strength. For lightweight concrete made with lightweight fines, as well as lightweight coarse aggregate, the tensile strength is 75% that of normal weight. The allowable tensions given previously should be reduced by these percentages when using lightweight concrete. Shear and bond strengths are also related to the tensile strength of concrete. Therefore, shear stresses should be reduced and bond lengths increased by the factors given above.

4.10 Proposed New Limit State Criterion for Prestressed Concrete Vessels Subject to Hog/Sag Bending

4.10.1 Introduction

A new limit state criterion for prestressed concrete vessels subject to hog/sag bending is proposed. The limit state is a stress state in between the conventional working stress and ultimate strength states. It is thought of as a state comparable to that of first yielding in a steel structure. There are three purposes for proposing the new criteria. One is to develop more realistic criteria for the types of bending encountered in hog/sag conditions. The second is to unify criteria for prestressed and nonprestressed reinforced concrete. The third purpose is to allow the utilization of a combination of prestressing and reinforcing to produce a more efficient design.

4.10.2 Review of Present Design Criteria for Hog/Sag Bending

Present criteria for hog/sag bending are twofold: working stress and ultimate strength. The working stress criteria call for limits of zero tension and .45 f'_c compression. This essentially is a fatigue limit, and concrete working within this range has an infinite fatigue life. The second criterion is ultimate strength, which is the breaking strength of a member subjected to a one-time loading in one direction, allowing for whatever inelastic redistribution of stress occurs prior to rupture.

The ultimate strength criterion is not appropriate to hog/sag bending. The nature of hog/sag bending due to wave action is that of a fully reversible stress applied many times at various levels of intensity. Figure IV-3 illustrates a common assumption for the relationship between number of cycles and load intensity experienced in the lifetime of a ship. The total number of cycles of load in the life of a vessel is approximately 10^8. If we plot the maximum load intensity occurring in the lifetime of the vessel on the Y-axis and the logarithm of the number of cycles of load on the X-axis, a straight line defines the number of cycles of various intermediate load levels which might be experienced. It would be inappropriate to equate the maximum load level on the Y-axis to the ultimate strength as determined by conventional procedures. In a ship, not only will the maximum load level be experienced once, but a load level 7/8 of the maximum will be experienced ten times, 3/4 of the maximum 100 times, etc. Loading a concrete structure to 7/8 of its ultimate load 10 times, with fully reversed loading, is a more severe loading than one loading to ultimate. Thus, a new limit state definition is needed to replace the ultimate strength state.

The "design load" specified in ABS and other rules is not the absolute maximum load which might be experienced. Rather, it corresponds to a load which might be experienced 1,000 times, which is approximately 5/8 of the maximum load. See Figure IV-3. It is not necessary to apply the conventional working stress criterion to this level of load, for the working stress criterion defines a stress-state which concrete can experience an infinite number of times. A more liberal limit should be applied to a stress state which might be repeated 1000 times.

4.10.3 Proposed Limit State

The limiting conditions for ultimate strength design are the ultimate strain, .003 in the concrete, and the rupture strain, .035 or more, in the steel. A large amount of inelastic behavior normally takes place prior to reaching these limits. Such behavior cannot be repeated in loading reversals.

For the new limit state criterion, it is proposed to limit both compressive and tensile strain to .002. This limits the concrete stress and strain to a point where the stress-strain curve may have some "rounding," but without gross departure from elastic behavior. For Grade 60 rebar, .002 is the yield strain. For prestressing steel, .002 strain over and above the prestressing level is approximately the yield point of the prestressing steel. Thus, the proposed limit of .002 strain maintains the steel within the elastic range, going just up to yield. For concrete, a parabolic stress-strain curve is assumed using the PCA equations.[16] For the higher strength concrete used in ship construction the stresses in the concrete will always be less than ultimate. Figure IV-4 shows strain conditions for a "balanced" design in which limiting tensile and compressive strains of .002 are reached simultaneously. In most cases, a balanced condition will not exist and either the compressive or tensile limit will control.

Figure IV-5 shows the results of applying the limit state criteria to a typical prestressed concrete hull section, with various levels of prestressing and rebar. The reinforcement was assumed to be uniformly distributed throughout the section. The limit state moment was computed and divided by the section modulus of the concrete cross section, to give an "effective" flexural stress. The breakpoint in the curves shown on Figure IV-5 represent the balanced condition at which tensile and compressive strains reach .002 simultaneously. Note that this balanced condition occurs at a prestress level of about 2,150 psi, whereas by conventional working stress design, the balanced prestressed level would be 1,350 psi. (With the hull prestressed to 1,350 psi, the flexural stress may then be ±1,350 psi, producing the allowables of zero tension and 2,700 psi compression.)

4.10.4 Safety Factors

As previously noted, the load specified by ABS and other rules is not the absolute maximum load which might be experienced in the lifetime of a vessel, but is rather that which would be experienced 1000 times. Inspection of Figure IV-3 shows that the maximum load is 1.625 times this level. Thus, by using the common safety factor of 1.7, the maximum load would be just below the limit state. A ϕ factor of 0.9 is also recommended, to allow for variations in material properties. The overall safety factor is thus 1.7/0.9, or 1.87. Figure IV-4 shows the effective flexural stresses at the limit state. These should be divided by 1.87 to obtain the allowable stresses for use in comparison to ABS or other rules for hog/sag design. Still, the use of limit state design approach can result in considerably greater effective flexural stresses than allowed under working stress design. For instance, with 2,000 psi prestress and 3% rebar, the limit state flexural stress is 5,000 psi. Dividing this by 1.87 produces an "allowable" flexural stress of 2,700 psi, which is twice that allowed by conventional working stress design. Even higher percentages of rebar are feasible with correspondingly higher effective stresses.

4.10.5 Summary

The proposed criterion is more rational than the current criterion for design of reinforced and prestressed concrete hulls for global hogging and sagging stresses. The new criterion is established to provide a more serviceable response of the hull structure to overload. The limit state criterion is more restrictive than current ultimate strength criteria since both tensile and compressive strains are limited to .002. The limit state criterion is more liberal than current working stress criteria as controlled cracking of the concrete is allowed. Thus the criterion allows for much more efficient use of the reinforcing steel. The criterion should be tested in order to assure the proposed strain limits will provide acceptable performance of the hull structure.

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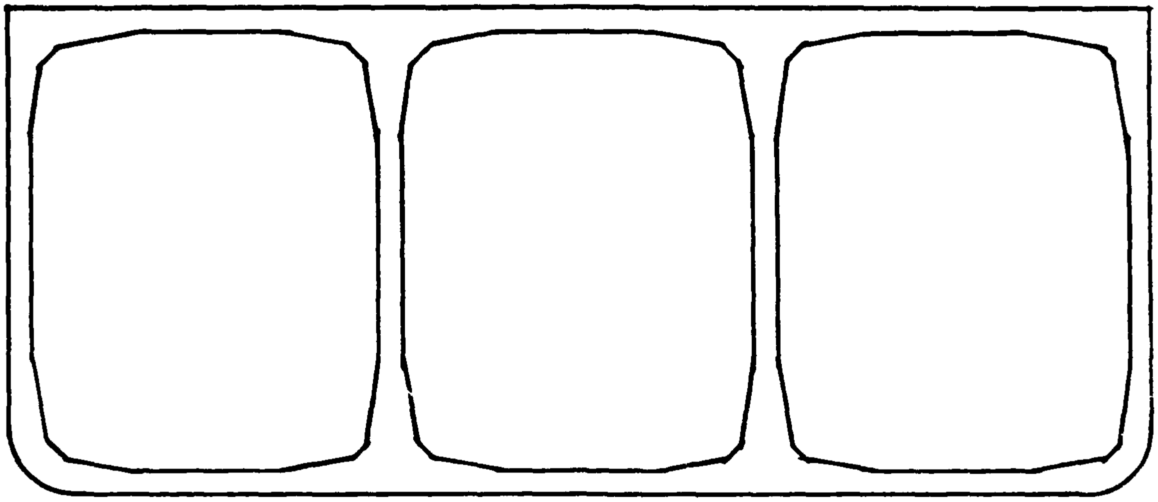
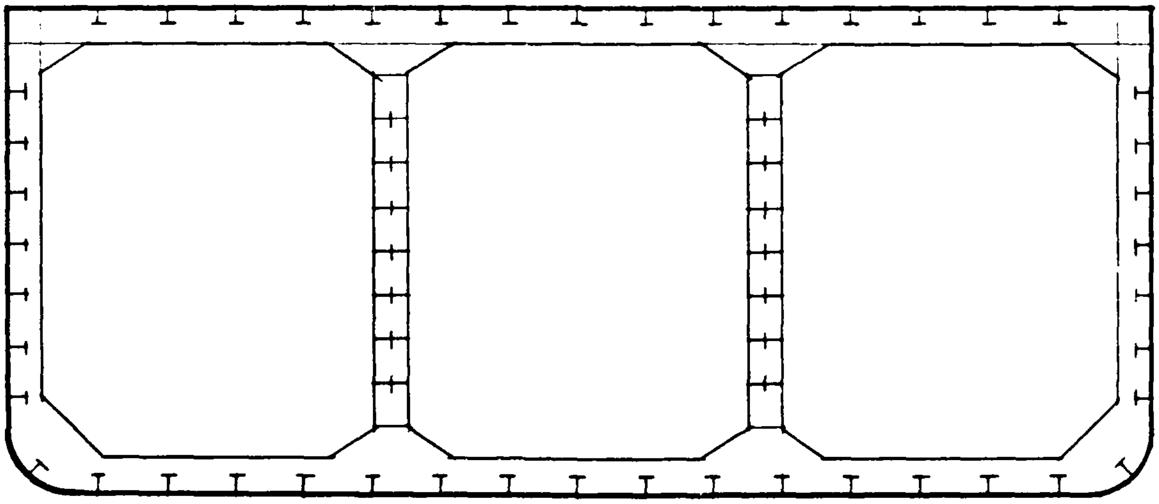


CONCRETE



STEEL

Figure IV-1 COMPARATIVE CROSS-SECTIONS OF CONCRETE AND STEEL HULL

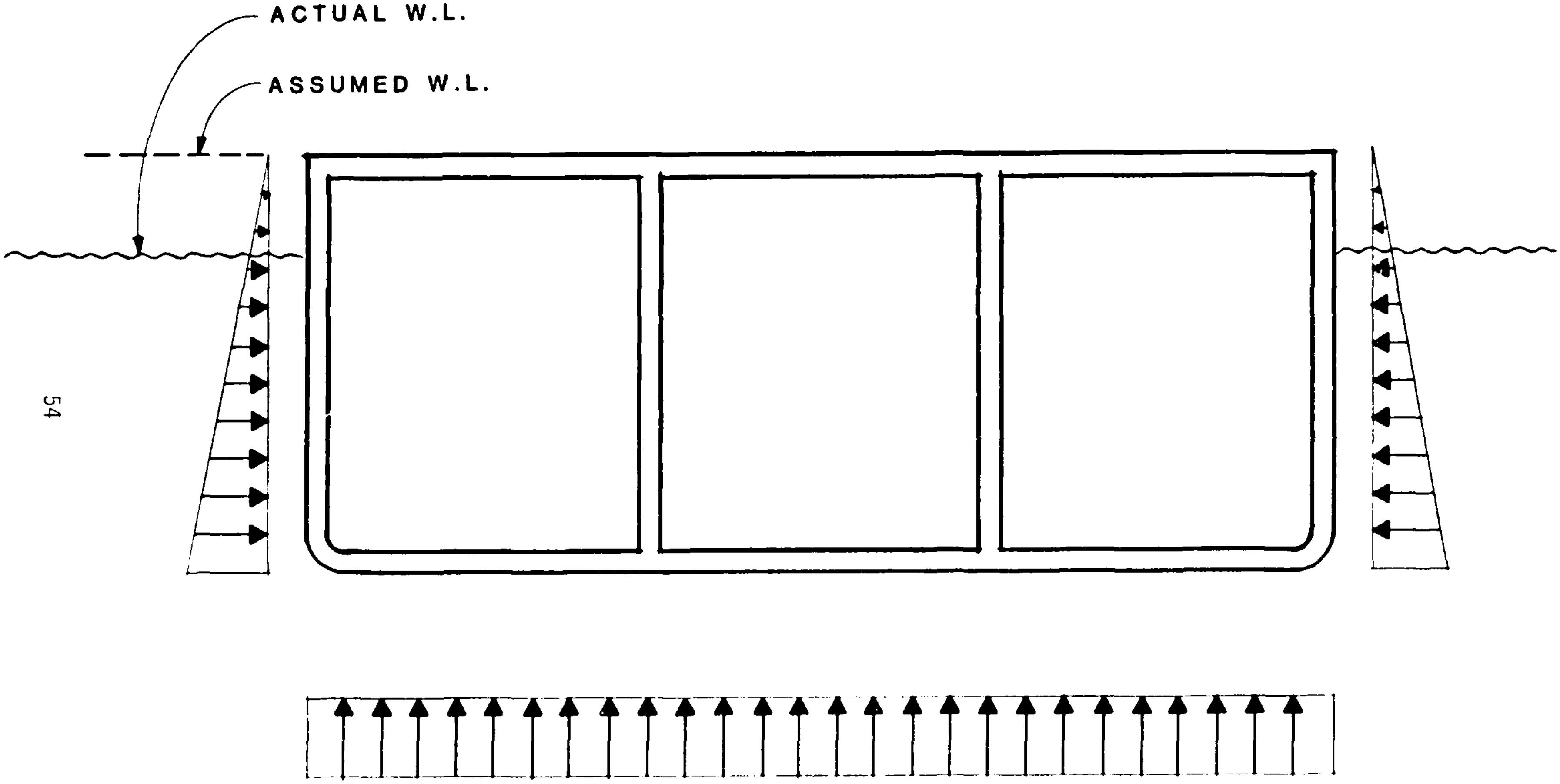


Figure IV-2 HYDROSTATIC LOADS

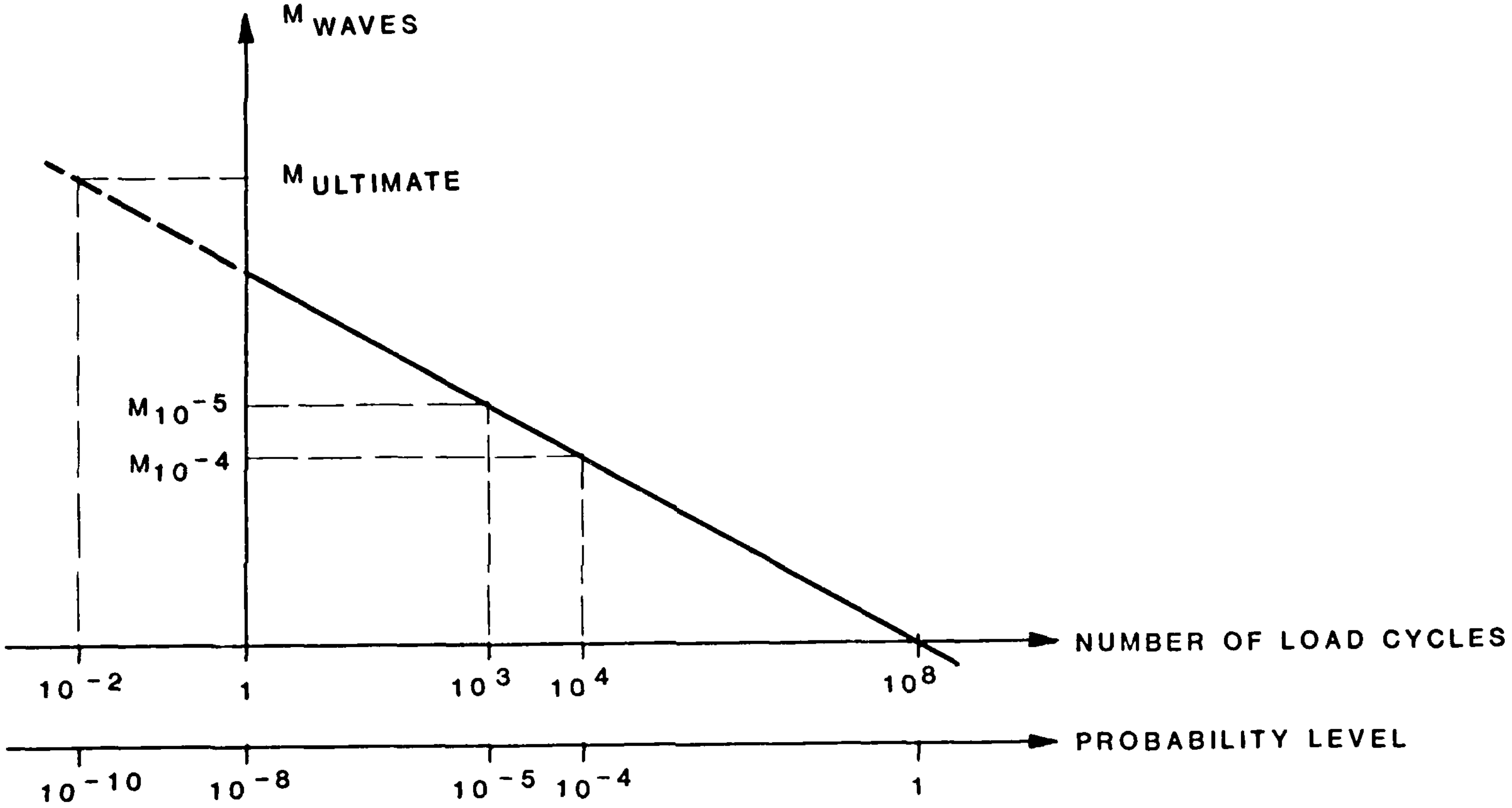
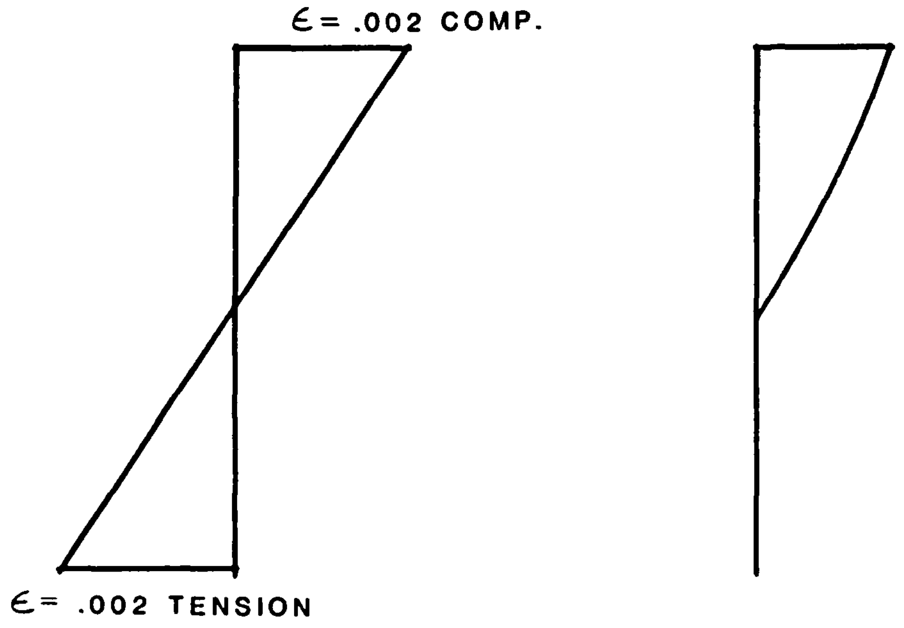


Figure IV-3 STATISTICAL DISTRIBUTION OF WAVE BENDING MOMENTS DURING 20 YEARS



$$f_c = .85f'c\left[\frac{2\epsilon}{\epsilon_o} - \left(\frac{\epsilon}{\epsilon_o}\right)^2\right]$$

WHERE:

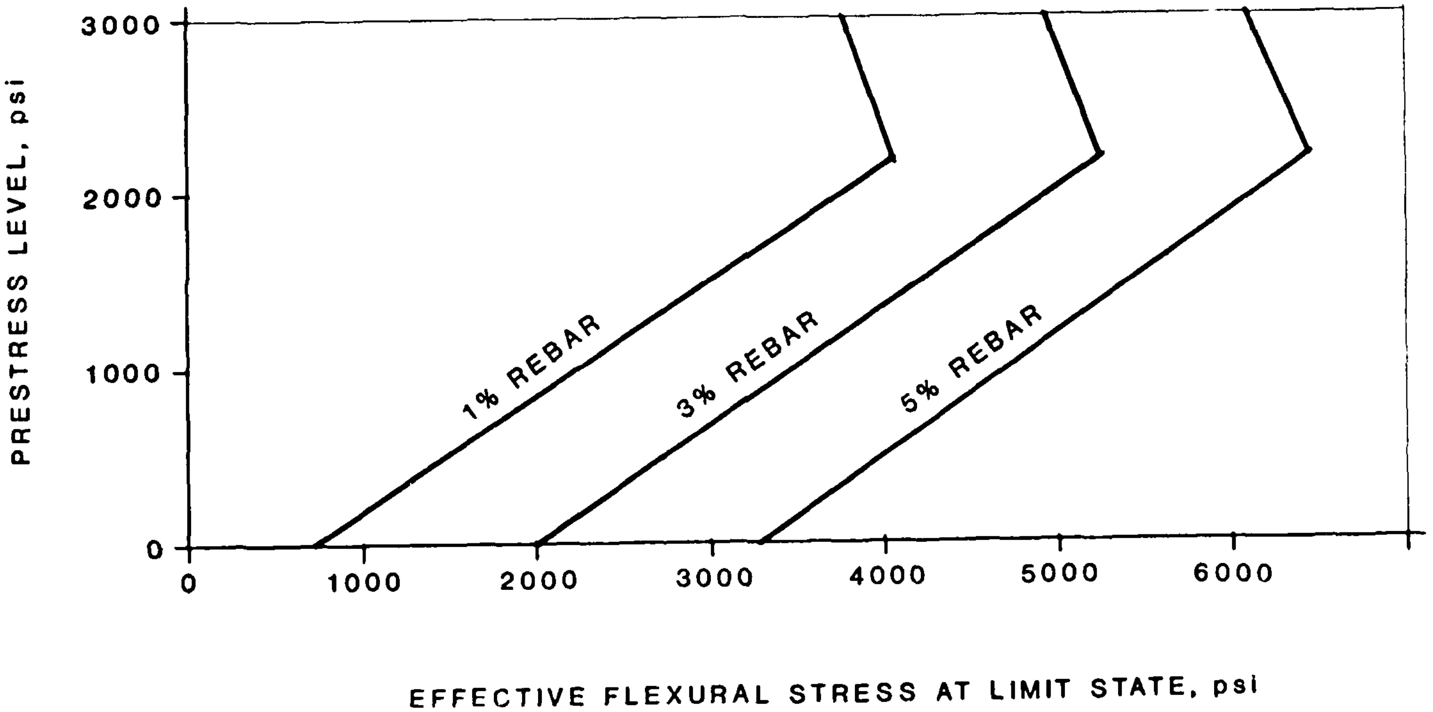
$$\epsilon_o = \frac{1.7f'c}{E_c}$$

$$E_c = 33w^{1.5}\sqrt{f'c}$$

STRAIN

STRESS IN CONCRETE

Figure IV-4 LIMIT STATE



EFFECTIVE FLEXURAL STRESS AT LIMIT STATE
FOR VARIOUS LEVELS OF PRESTRESS AND REBAR

Figure IV-5

SECTION V

SECTION V
HISTORY AND THE CURRENT STATE-OF-THE-ART IN LWPC FOR SHIPS HULLS

5.0 Introduction

As a hull structural material, portland cement concrete has been seriously employed only during two national emergencies.

Although it is one of the oldest and most economical man-made construction materials, its potential for ships' hulls has been seriously limited. Its physical properties vary considerably, depending on the quality of the ingredients and the qualifications of the producer.

In contrast to steel, which is manufactured under controlled conditions and delivered with a mill cerficiate, only the cement constituent of concrete is furnished with a mill certificate.

In addition to portland cement which, when mixed with water, provides the paste or binding agent, the bulk of the concrete material is in the aggregates, most commonly natural sands and gravels, or particles of crushed stone graded into specified sizes. Depending on the density of the stone and concrete mix properties, the specific gravity of ordinary concrete will vary between 2.2 and 2.5. Structural lightweight concretes with specific gravities between 1.6 and 2.0 can be achieved using natural or manufactured lightweight aggregates.

Concrete quality is most commonly measured by its compression strength, usually determined by its resistance to axial load on 6 x 12 inch cylinders. Its tensile strength is sometimes of importance, and usually amounts to around 10% of the compression strength.

Although the quality of the concrete depends on the cement and the soundness of the aggregates, the most important factor influencing it is the ratio of water to cement in the paste.

Concrete construction can be compared to a foundry process, in which fluid material is poured into a mold to solidify. When uncontrolled, construction workers naturally demand wetter concrete and more fluidity to ease the task of filling the mold and consolidating the concrete. Under these conditions, "soupy" concrete flows into place with a minimum of placing and compacting effort, but at the expense of good quality.

In addition to the ratio of water to cement, strength is also related to ratio of cement to aggregate and the age of the concrete in a moist environment (Figure V-1). Tensile strength of concrete, as measured by flexural test beams (commonly known as modulus of rupture), varies in proportion to the square root of the cylinder compression strength.

In most land-based facilities, the working loads on reinforced concrete structures are generally unidirectional and slowly applied. Because of the relatively high self-weight of concrete structures, the live (transient) loads are less than the permanent loads. Even concrete highway bridges are subjected to live loads amounting to less than 30% of the total load.

Only during the past two decades have limit-state or ultimate strength methods been applied to reinforced concrete design. Prior to that time, elastic theory (straight line) philosophy prevailed. Working stresses under full service loads utilized 40 to 50% of the 28-day cylinder compression strength for concrete and 20,000 psi for the reinforcing steel. The tensile strength of the concrete was generally ignored in reinforced concrete design, although for shear, a nominal credit was taken.

Current practice in reinforced and prestressed concrete is based on ultimate srength with load factors. Building codes provide for 1.4 times dead loads plus 1.7 times live loads for ultimate design. In addition to load factors, a further safety provision provides for strength-reduction factors: 0.9 for flexure, 0.85 for shear, and 0.7 for axial loads.

Although plain concrete lacks tensile strength and ductility, it can sustain cyclic compression loads with ease. Compared to metals, where failures of a brittle nature have created serious problems, concrete fatigue tests have indicated endurance of ten million stress cycles, each load cycle at 50% the static strength. Design for fatigue loading in concrete can be facilitated by the use of a modified Goodman diagram, illustrated in Figure V-2.

5.1 Reinforced Concrete Ships

The earliest example of a reinforced concrete boat has been credited to France's J. L. Lambot in 1848, at a time when wood was the only shipbuilding material. It was some 70 years later that serious interest in concrete ships was rekindled.

A Norwegian Civil Engineer, N. K. Fougner, built a coastal freighter, the M. S. Namsenfjord, 200 tons dead weight capacity, completed in 1917 (see Figure V-3). Designed as a dry cargo carrier, she was powered by a Bolinder crude oil engine of 80 B.H.P. The Namsenfjord, on her builder's trails, reached a speed of 7.5 knots.

Fougner's success led to a second contract for construction of the 1000-D.W.T. M. S. Askelad whose length, beam, and draft were 176 feet, 31 feet, and 19 feet, respectively. Equipped with twin 320 B.H.P. Bolinder crude oil engines, the Askelad reached a speed of 8-1/2 knots on her trails in August 1918.

Figures V-4 and V-5 show the general arrangement and midship section of the Askelad. Particulars of the Askelad are tabulated in Table V-1. The M. S. Askelad made a number of North Sea crossings and voyages into the Baltic. While proceeding along the French coast in mid-January, 1919, the Askelad went aground on the estuary of the River Saume. She was refloated after having been severely buffeted by heavy seas for two weeks. A hull inspection indicated only minor cracking. She returned to Norway and continued to serve as a cargo ship for several years.

U.S.-Built Concrete Ships -- 1918 Through 1920

The first American reinforced concrete ship, the S. S. Faith, was built in Redwood City, California. Construction commenced in September 1917, and launching took place March 1918. Particulars of the S. S. Faith are tabulated in Table V-2.

TABLE V-1 - PARTICULARS OF THE ASKELAD

	Tons
Weight of reinforced concrete hull	733
Weight of equipment	120
Weight of machinery	31
Displacement, light	884
Deadweight, freeboard 2' 6 1/2"	1,036
Displacement, loaded	1,920
Deadweight/Displacement	0.54

TABLE V-2 - PARTICULARS OF FAITH

Length between perpendiculars	320'-0"
Breadth	44'-6"
Depth	30'-0"
Freeboard, loaded	6'-0"
Load displacement	8,150 tons
Block coefficient	0.835
Engines, triple expansion type	1,700 IHP
Speed	about 10 knots

Shown in Figure V-6, the S. S. Faith is said to have had a hull consisting of 2700 tons of concrete and 520 tons of reinforcing steel. Heavy transverse frames were spaced 16 feet apart. The hull sides and bottom were 4-1/2 inches thick, and the main deck was 3-1/2 inches.

The Faith was launched six weeks after concreting started. Machinery installation and outfitting was completed in only two months, and soon thereafter went into service, transporting dry cargo to Honolulu, then to Chile and New York via the Panama Canal. This was followed by transatlantic voyages, and a round trip to the Mediterranean.

After several voyages to Montevideo and Buenos Aires, the Faith was laid up in New Orleans. Later she was stripped of her machinery. The hull was then towed to Cuba and sunk as a breakwater. Thus ended a notable pioneering effort in concrete shipbuilding and operation, all privately financed and managed. No concrete ships subsequently have equalled the career of the S. S. Faith.

U.S. Shipping Board Program -- 1913 Through 1920

The heavy demand for steel plate for both merchant and naval vessels during World War I stimulated interest in reinforced concrete ships. Reinforcing bars, cement, and aggregate were in good supply, which argued in favor of a substantial U.S. reinforced concrete ship program.

Fougner's Norwegian success may have been persuasive in his meetings with the U.S. Shipping Board to discuss the merits of reinforced concrete ships. Soon thereafter the U.S. Shipping Board formed a concrete ship section. Five shipyards were established especially designed for reinforced concrete construction.

The U.S. Shipping Board Emergency Fleet Corporation shipyard contractors are listed in Table V-3.

TABLE V-3. U.S. SHIPPING BOARD EMERGENCY FLEET CORPORATION SHIPYARD CONTRACTORS

Contractor/Location	Ships (Qty/DWT/Type)
San Francisco Shipbuilding Company Oakland, California	2-7500 DWT Oil Tankers 1-7500 DWT Cargo Ship
Pacific Marine & Construction Company San Diego, California	2-7500 DWT Oil Tankers
Fred T. Ley & Company Mobile, Alabama	2-7500 DWT Oil Tankers 1-7500 DWT Cargo Ship
A. Bentley & Sons Company Jacksonville, Florida	2-7500 DWT Oil Tankers
Liberty Shipbuilding Company Wilmington, N.C.	2-3500 DWT Cargo Ships

The concrete ship program mounted a substantial effort in structural engineering research and experimental work for the development of artificial lightweight aggregates, mainly expanded shales, which led to successful reduction of the concrete density from 150 to 115 lbs per cubic foot, and a compression strength of 4000 psi. The weight saving represented a gain of nearly 1000 tons cargo capacity in the 7500-ton ships.

The 7500-ton cargo ships of the World War I program were the largest concrete ships built -- a record which remains today. Unfortunately, they were not completed until long after the end of the war and were not placed in transoceanic service.

The U.S. Maritime Commission Concrete Ship Program -- 1941 Through 1945

The steel plate shortage in mid-1941 prompted the U.S. Maritime Commission to embark on a reinforced concrete barge program which led to a decision to construct two tankers and five dry cargo barges, the principal features tabulated in Table V-3.

After the U.S. entry into the war, the program was expanded from 15 concrete hulls to a total of 65. The hull lines closely resembled those for conventional steel ships (Figure V-7). Construction commenced in 1942, but initial deliveries were slow, mainly due to lack of experience and ability to combine the art of shipbuilding with the technology of concrete. Concurrently with the Maritime Commission program, the U.S. Army ordered 24 dry cargo lighters, designated B5J. The Maritime Commission ships, oil tankers (B7A1 and B7A2) and dry cargo ships (C1SD1 and B7D1) were traditional ship hull forms (Figure V-7). The Army lighters had a blunt bow and a scow-like stern (Figure V-8).

The hull structures followed the 1918 practice, utilizing lightweight aggregate concrete, but the specified concrete strength was raised to 5000 psi, permitting a maximum working stress of 2250 psi. The concrete's tensile strength was not utilized in the design, although tests of the concrete consistently indicated values of 500 psi and more. In order to utilize butt welding of the rebars, a medium carbon 40,000 psi structural grade) steel was specified. Following the 1918 practice, a very conservative (12,000 psi) working stress was specified for all reinforcing steel below the waterline.

To verify calculated stresses in the hull structure, strain gage tests were conducted on waterborne hulls in still water. Controlled filling of selected compartments with measured quantities of water made it possible to introduce known hogging and sagging bending moments. Strain gages on reinforcing bars indicated that measured stresses in the hull structure were only about 50% of the theoretical value. Although tension stresses in the concrete on the order of 700 psi were observed, no cracks were found, leading to the conclusion that the heavy concentration of reinforcing steel evidently supressed the cracking tendency observed in tests of plain concrete.

TABLE V-4

PRINCIPAL FEATURES OF THE U.S. CONCRETE SHIP PROGRAM OF WORLD WAR II

Design Type	B7A1	B7A2	C1SD1	B7D1	B5BJ
Cargo	Oil	Oil	Dry	Dry	Dry
Length O.A., ft	366	375	366	366	265
Molded depth, ft	35	38	35	35	17.5
Molded beam, ft	54	56	54	54	48
Maximum draft, ft	26.25	28.50	27.25	26.25	12.75
Displacement, tons	10,940	12,890	11,370	10,970	4,000
Long'l. bulkheads	2	1	None	None	2
Trans. bulkheads	10	10	10	10	5
Bale capacity, c.f.	325,000	354,000	282,000	292,000	183,000
Deck thickness, in.	4	4.75	5.50	5/6.25	7
Side thickness, in.	4.25	4.5/5	6.5	6	8
Bottom thickness, in.	5	5	6.5	7	8
Framing system	Long'l	Trans.	Long'l	Trans.	None
Block coefficient	0.77	0.79	0.77	0.77	0.86
DWT/Displacement	0.53	0.50	0.47	0.53	0.42
Reinforcing steel, long. tons	1,360	1,520	1,120	1,004	430
Concrete, cu yds	2,940	3,200	2,890	2,440	1,500
Number built	11	22	24	20	27

5.2 Prestressed Concrete Ship Hulls

Unlike the monolithic character of all-welded steel ship's hulls, where a brittle fracture could spread with catastrophic consequences, prestressed concrete distributes tensile forces over a multiplicity of small diameter wires. The high-tensile steel under uniaxial stress, working in concert with precompressed concrete, behaves very satisfactorily even at very low temperatures. In fact, concrete strengths rise with decreasing temperature -- a characteristic of value for Arctic environments.

Prestressed concrete is naturally most efficient when a system of steady loads can be counteracted by built-in prestress forces. For ship hulls subjected to alternate tension-compression stresses such as hogging and sagging, prestressing may be applied, but the compression strength of the concrete must be considerably higher than that for structures subjected to single direction loads.

During World War II, two prestressed concrete vessels were built. One, a landing craft (tank), was built by Roger Corbetta (Figure V-9). The other was a barge of similar construction. The vessels were constructed using open-ended precast cells with 3/4 inch walls. The landing craft was said to have made a number of landings in rough surf with satisfactory results.

5.3 ARCO LPG Facility

A few very heavy prestressed concrete sea structures have been built for petroleum production offshore. Perhaps one of the major examples of a prestressed concrete floating sea structure is the Atlantic Richfield LPG facility, the Arjuna Sakti, located in the Java Sea (Figure V-10).

The hull section (Figure V-11) is essentially a three-cell box girder, 461 ft long, 136 ft beam, and 56 ft molded depth. The vessel is permanently attached to a single buoy mooring, collecting liquid petroleum gas through underwater pipelines. The gas is liquified by cooling to -50°F and stored in insulated tanks for later transfer to tanker ships. The general arrangement of the facility is shown in Figure V-12. Figure V-13 shows framing plans and a structural profile of the facility.

The hull bottom consists of three cylindrical barrel shells whose shape most efficiently functions to resist 3600 psf hydrostatic pressure, and also reduces the vertical span for side shell pressure.

To minimize the transverse bending moments in the deck, Y-shaped sides and Y-shaped longitudinal bulkheads were introduced. This configuration eliminated the necessity for transverse ribs and longitudinal stiffeners of the type used with steel hull construction.

The bottom shell is stiffened by the four tank saddles and diaphragms at the bow, stern and the midships bulkhead. The spacing of these stiffening elements forces the side shell and deck plating to span primarily in the transverse direction.

To the resist the longitudinal bending caused by the global distribution of weights acting downward and buoyancy forces acting upward the hull functions as a multicell box girder, in which the fore and aft global bending stresses and shears are accommodated unencumbered by the local stresses due to hydrostatic pressures against the bottom shell. Moreover, transverse local bending stresses in the side shell and deck are not directly additive to the global load stresses.

The development of design criteria for the hull structure took into account the loadings for ships applicable to steel vessels of comparable dimensions, as required by the rules of the American Bureau of Shipping. Longitudinal hull girder bending stress limits were established for (1) delivery voyage; (2) Normal service in the Java Sea; and (3) the 100-year storm.

The assumed wave heights and stress limits are given in Table V-4.

TABLE V-5

ARCO LPG FACILITY, WAVE HEIGHTS AND STRESS LIMITS

Sea Conditions	Delivery Voyage	Normal Service	100-Year Storm
Wave Height	23 ft	11 ft	27 ft
Max. Allowed Stress	Zero Tension 0.45 f'_c compr.	Zero Tension 0.45 f'_c compr.	-- --
Cracking load factor	1.65	2.00	--
Ultimate load factors:			
Required	2.0	2.6	1.3
Actual	2.1	3.5	2.0

In the case of local bending due to hydrostatic pressure, a tension of $5\,(f'_c)^{0.5}$ was permitted, in recognition of the fact that, in plate bending, the cracks would not penetrate into the tendons, which were encased in steel tubes filled with grout.

In addition to the stresses under service conditions, stresses during construction were analyzed to insure the hull integrity during launching and subsequent construction afloat.

Also, a special analysis was made to determine the rate of roll of the vessel, and its effect on the tank foundations and certain items of equipment. Moreover, a special case of damaged stability was investigated for the case of a collision and flooding of a below-deck compartment.

It was found that the vessel can survive a collision with one compartment fully flooded. In this case, however, the vessel would heel to a 25-degree angle.

The ARCO facility was constructed using normal weight concrete with a density (including reinforcement) of approximately 160 pounds per cubic foot and a design compressive strength, f'_c, of 6000 psi. Strength test records kept during construction showed a strength exceeding 9000 psi was achieved. Hull weight data is presented in Table V-5.

The hull construction scheme is shown in Figures V-14 through V-19. Bottom shell elements were precast in steel forms using match casting techniques. Each element was reinforced and provided with ducts for both longitudinal and transverse tendons. The 40-ton bottom shell members were placed on precast concrete supports (Figure V-14). During assembly of the shell segments, each joint was coated with epoxy adhesive, after which the segment was then promptly stressed to its neighbor by means of Dywidag high-tensile thread bars.

Following immediately after erection of the bottom shell came the construction of the vertical sides and longitudinal bulkhead with cast-in-place concrete (Fig. V-15). The transverse tendon ducts projecting from the bottom segments were coupled with those in the vertical sections. Prior to closing the form, a coating of epoxy adhesive was applied to the hardened concrete joint surface, and shortly thereafter, the new concrete was cast against it.

Erection of bottom shell segments, followed by cast-in-place vertical shells and longitudinal bulkheads, proceeded on a vertical front in a routine manner. The only exception was for a change in detail at the tank saddles (Fig. V-16) and at the midship section, where vertical precast elements were introduced for the amidship bulkheads.

A 45-degree rake to the bottom shell at the forward end was provided to reduce towing resistance on the 10,000-mile delivery voyage.

Concreting of the lower 40 feet of the hull and erection of the end shell members made the hull ready for launching. All longitudinal tendons which were located below waterline were stressed prior to launch. Sufficient vertical and transverse post-tensioning was completed to resist temporary stresses during the completion of hull construction.

TABLE V-6
ARCO LPG FACILITY -- WEIGHT SUMMARY

Item		Weight (L.T.)
Basic Hull (41.5 T/foot)		18,992
Bow		638
Stern		1,002
Midship Bulkhead		1,026
Below Deck Saddles		1,808
Above Deck Saddles		1,032
Permanent Ballast		738
	Subtotal	25,236
LPG Storage Tank Empty		3,840
Accommodations Module		577
Aft Refrigeration Platform		775
Stern Catwalks and Saltwater Pumps		38
Deck Mounted Equipment and Foundations		626
Piping and Supports		328
Miscellaneous		83
Displacement - Light		31,503
Cargo (375,000 BBL.)		34,720
Displacement - Fully Loaded		66,223
Draft Light		22 Ft
Draft Loaded		42 Ft

The dock was then flooded and opened, and with the aid of tugs, the hull was moved to the outfitting pier.

Concurrently with hull construction work on the tanks, refrigeration and electrical plant and crew's housing structure was under way nearby. The fabrication and insulation of the 12 tanks was an operation of the same order of magnitude as the hull construction. The 400-ton tanks were lowered into the hull by a pair of stiff-leg derricks installed especially for this purpose (Fig. V-17). Each tank was seated on end-grain cedar pads built into the concrete saddles, and then securely strapped down. The tanks at -45 C (-49°F) were thus insulated from the concrete. In addition, the tanks were insulated with a heavy layer of butyl-covered polyurethane material.

After tank placement, the upper portion of the hull was cast in place utilizing movable steel forms (Fig. V-18). Starting at the after end the concreting progressed forward, using the same techniques for tendon alignment and epoxy bonding at the construction joints.

When the concreting of the upper hull and deck structure had reached midship, erection of the upper-tier tank saddles commenced. These heavily reinforced elements were precast on their side and post-tensioned with U-shaped tendons. The 1200-kip final force in the circular path provided the desired safeguard against cracking during tilt-up and erection of the saddle element. After placement on deck, additional tendons were installed and post-tensioned for the connection to the hull.

Upper hull post-tensioning followed closely behind the concreting. Horizontal tendons stressed the deck and bulkheads, both fore and aft and athwartships. U-shaped tendons anchored in the deck were stressed simultaneously at both ends, providing transverse compression to the longitudinal bulkheads, side shells and bottom shell elements.

As deck construction progressed, the above deck tanks were erected (Fig. V-19). Additionally, the vessel was outfitted with a 600-ton accommodations module for the 50-man crew and the necessary process equipment for refrigeration and handling of the LPG cargo. When completed, the vessel was towed to the Java Sea, a 100-day, 10,000-mile voyage.

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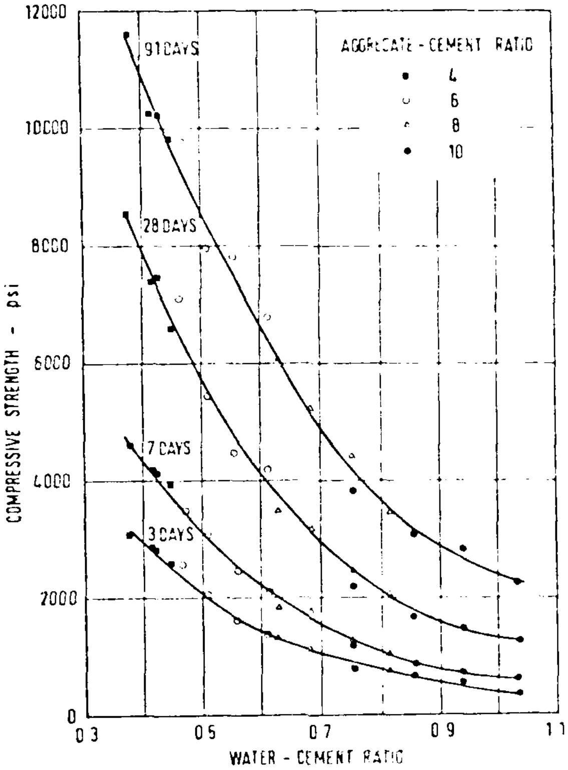


Fig. V-1. Compressive strength as a function of water-cement, aggregate-cement and age.

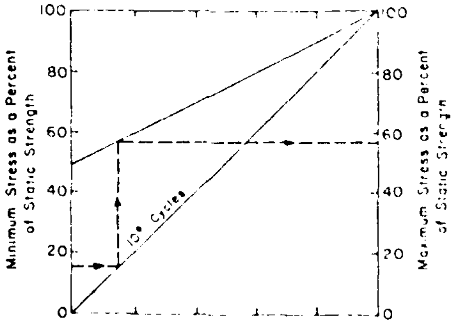


Fig. V-2. Fatigue strength of plain concrete in tension, compression, or flexure.

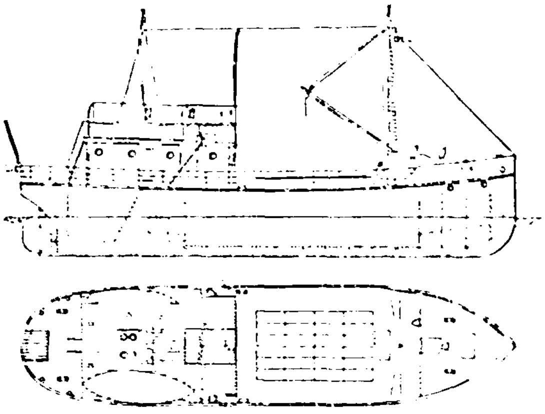


Fig. V-3. M.S. Namsenfjord.

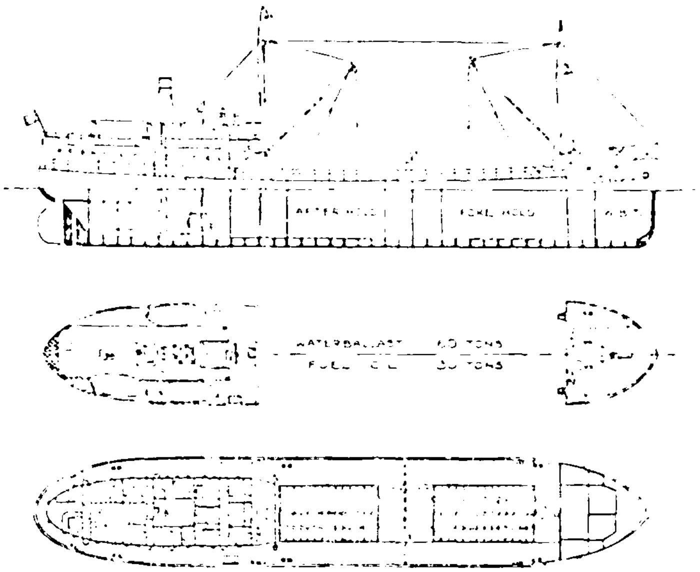


Fig. V-4. M.S. Askelad, general arrangement.

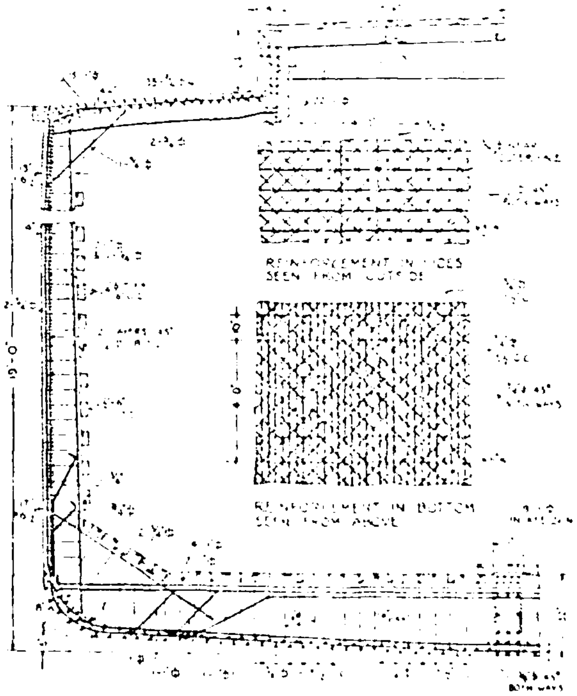


Fig. V-5. Midship section M.S. Askelad.

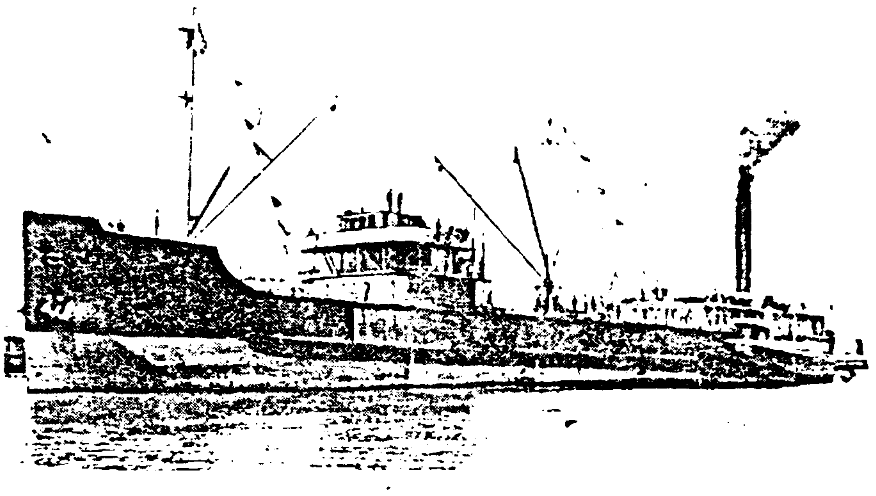


Fig. V-6. S.S. Faith, first U.S. concrete steamship.

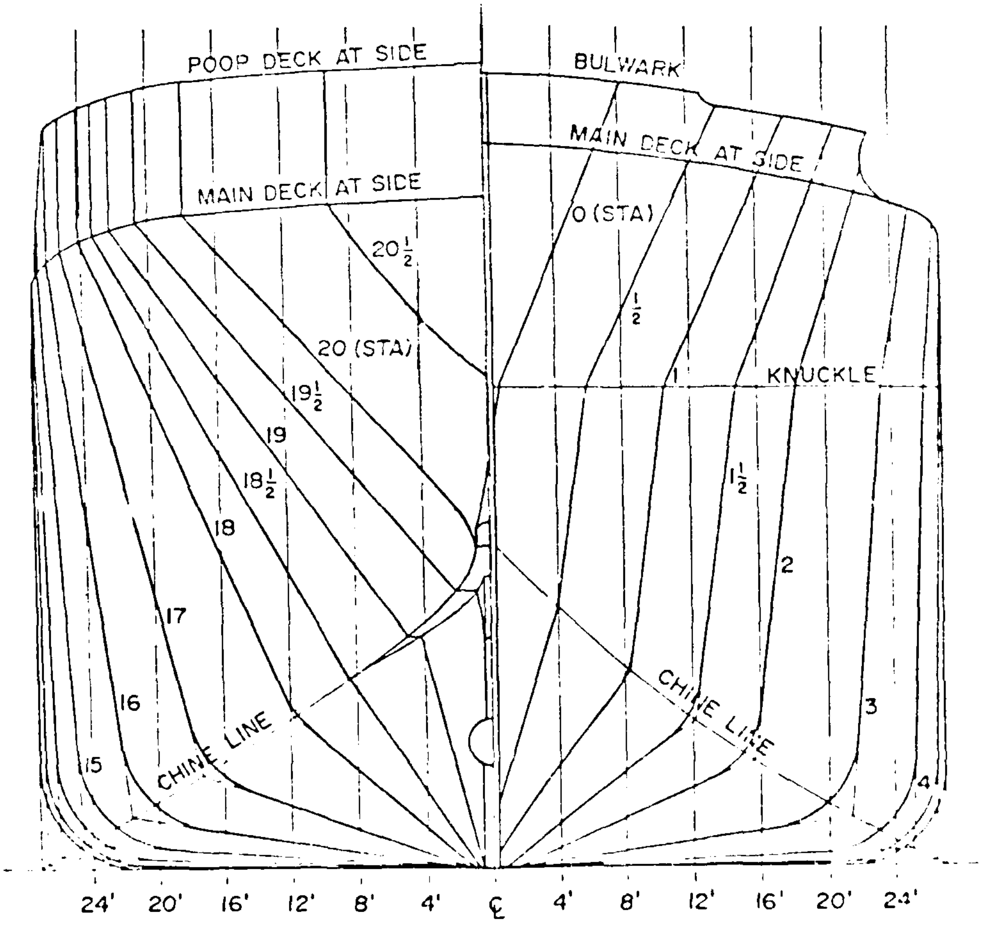


Fig. V-7. Body plan, typical U.S. Maritime Commission concrete hull.

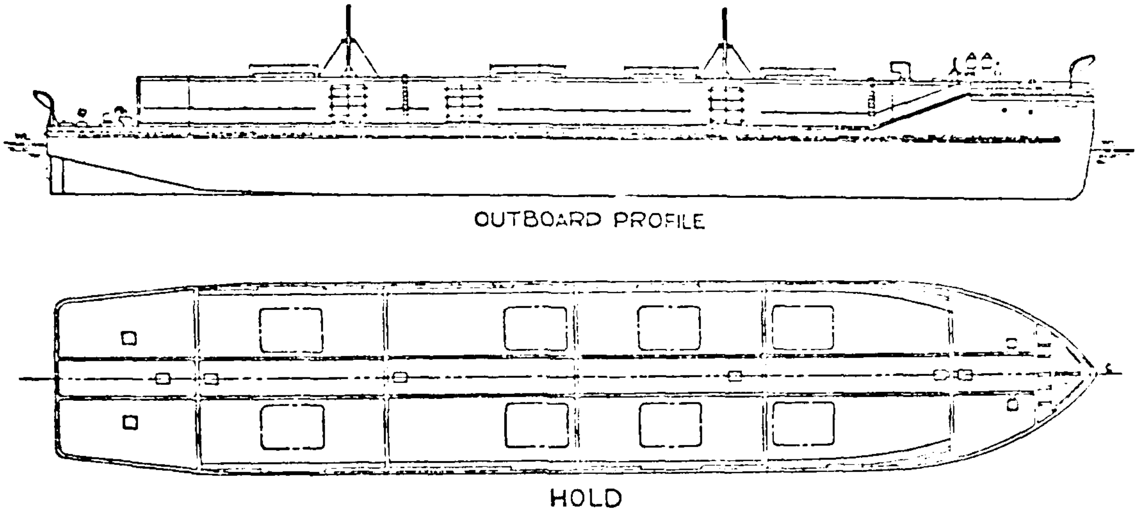


Fig. V-8. U.S. Army concrete cargo lighter.

Fig. V-9. Navy landing craft, prestressed concrete.

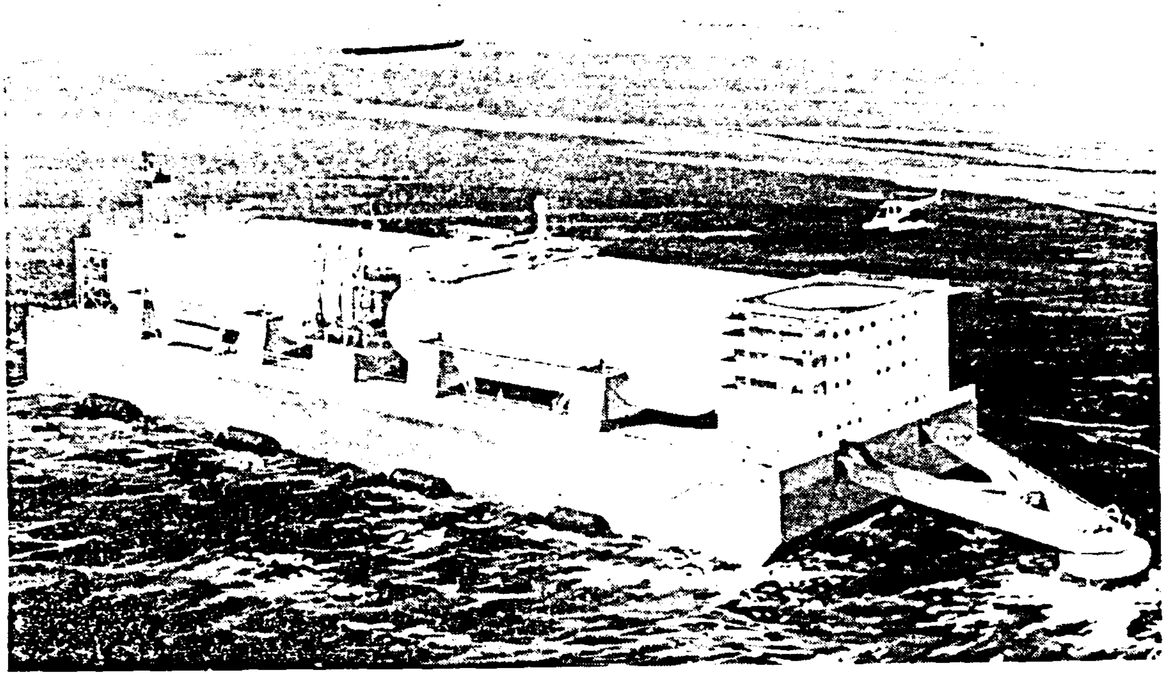
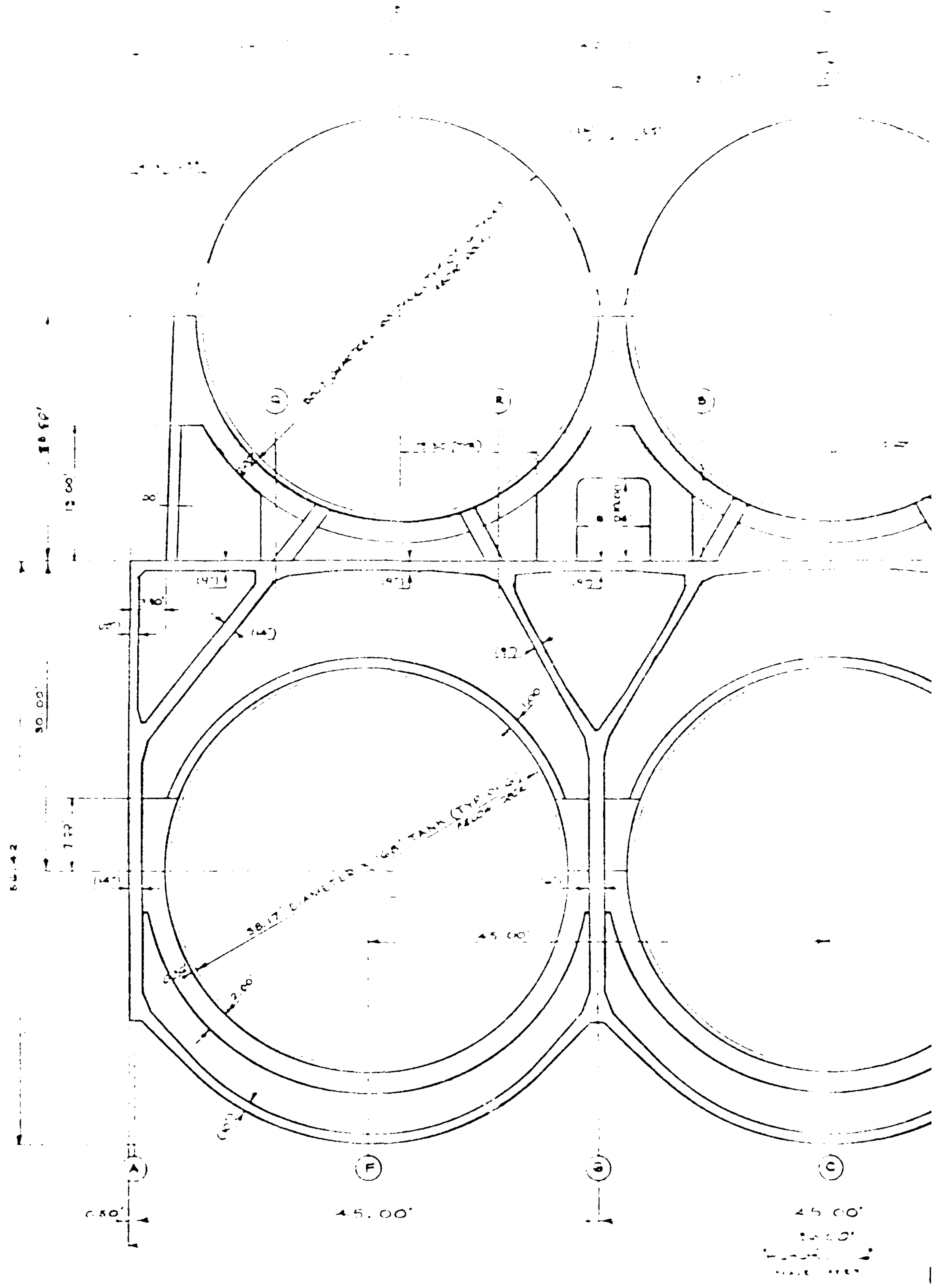


Fig. V-10. Atlantic Richfield Company LPG facility on station in the Java Sea.



12.00'
30.00'
7.33
(.47)
(.97)
1.00
(.92)
2.00
38.17' DIAMETER X 60' TANK (TYP. OF 6)
45.00'
A
F
G
C
D
R
B
0.80'
45.00'
45.00'

AD-A122 954 FEASIBILITY AND PRACTICAL LIMITS FOR THE USE OF
LIGHTWEIGHT PRESTRESSED CONCRETE (LWPC) AS A
SHIPBUILDING MATERIAL(U) ABAM ENGINEERS INC TACOMA WA
UNCLASSIFIED OCT 82 N00024-81-C-4054 F/G 13/10 NL

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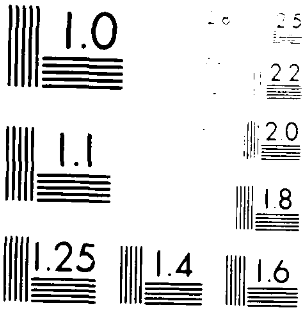
1.0
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2.2
1.1
2.0
1.8
1.25
1.4
1.6

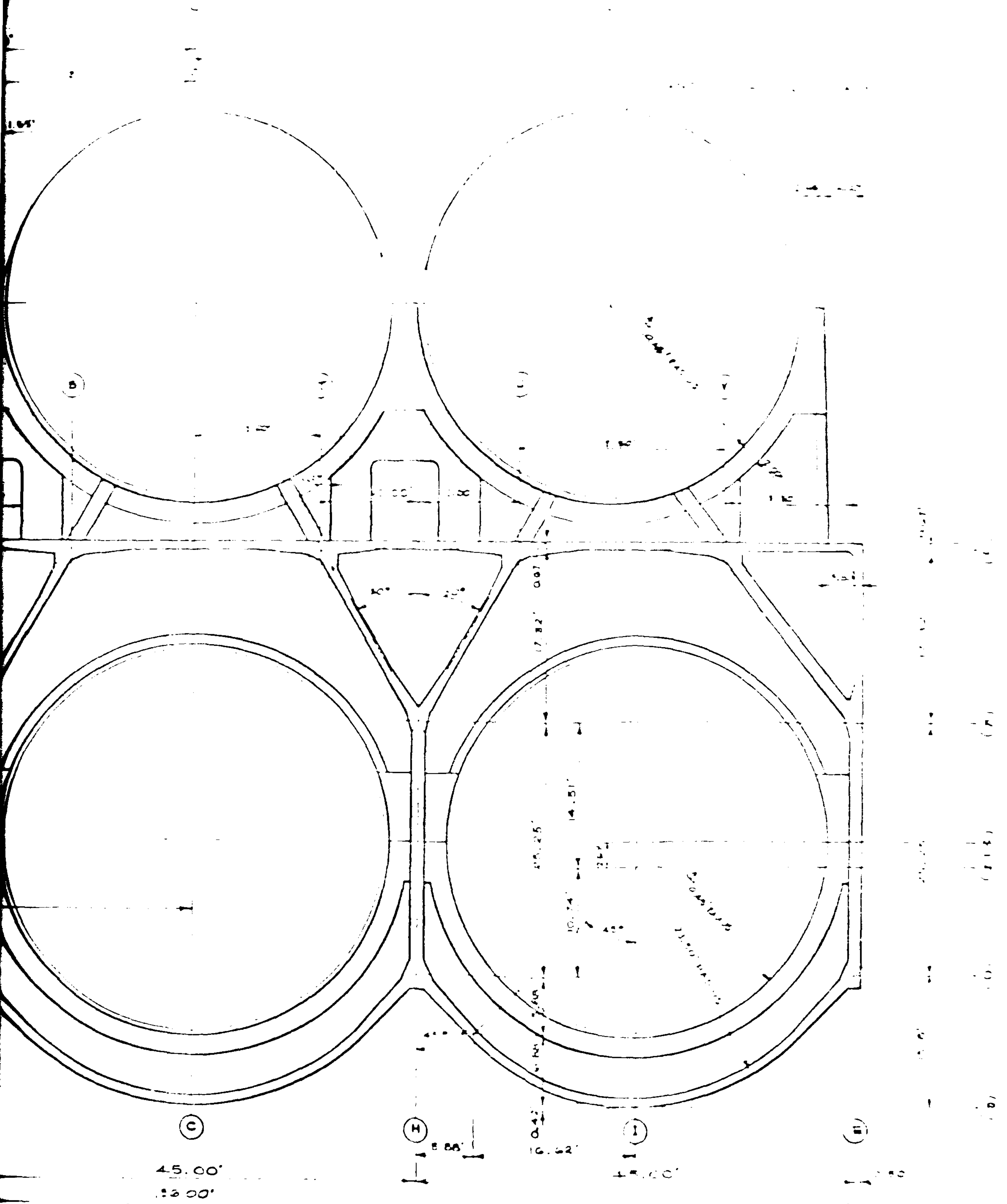
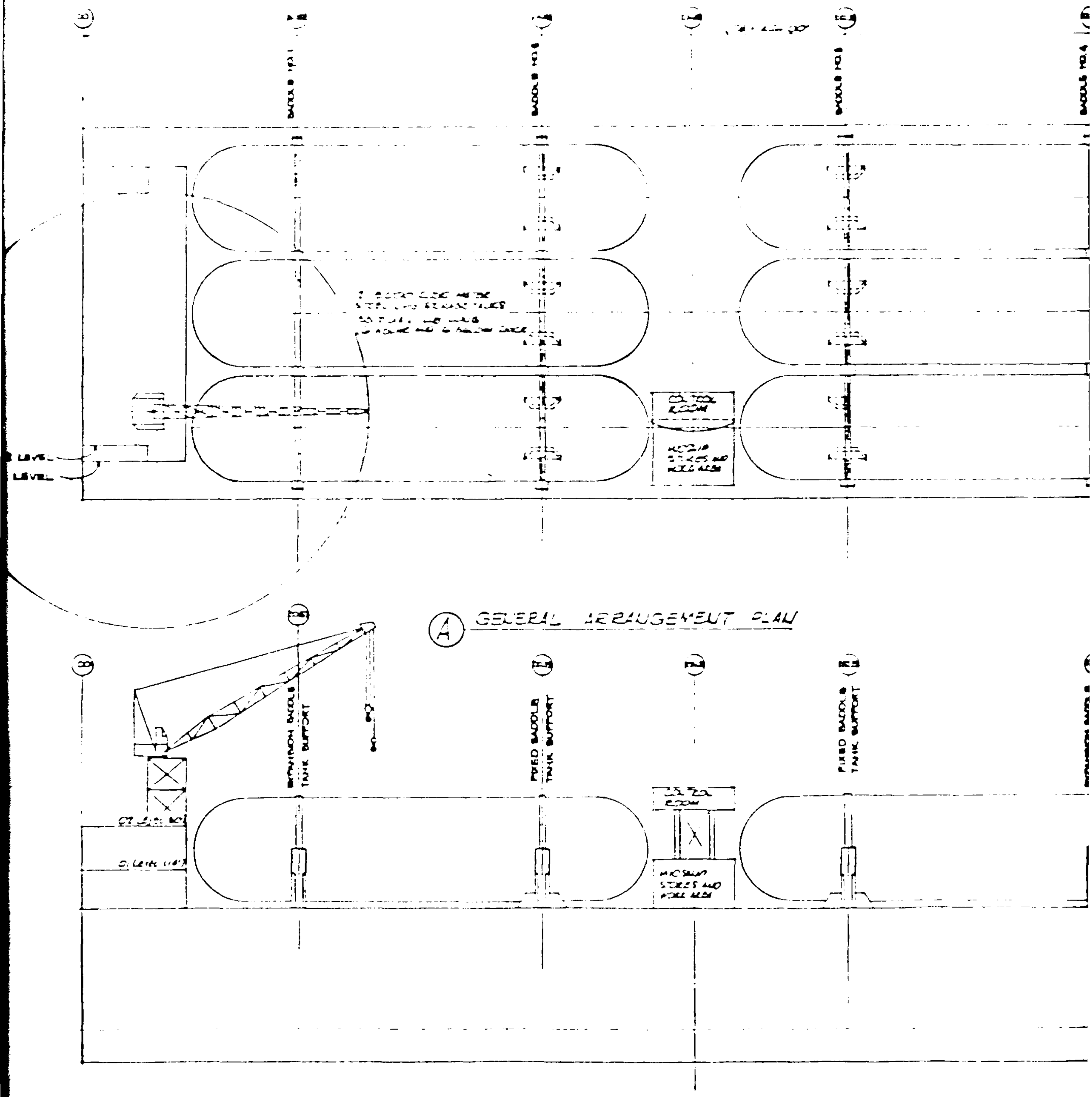


Figure V-11 ARCO LPG FACILITY-HULL SECTION



Ⓐ GENERAL ARRANGEMENT PLAN

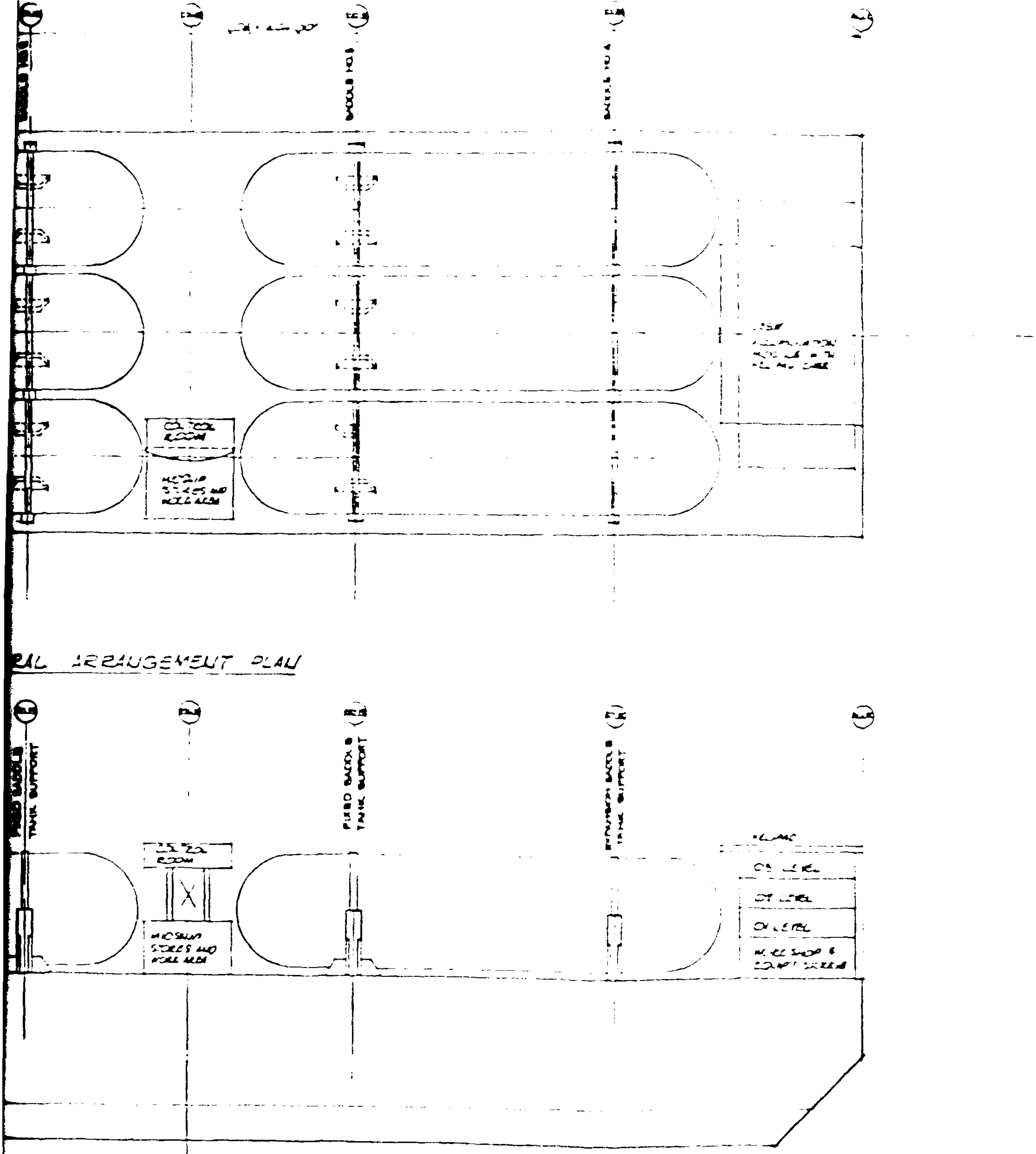
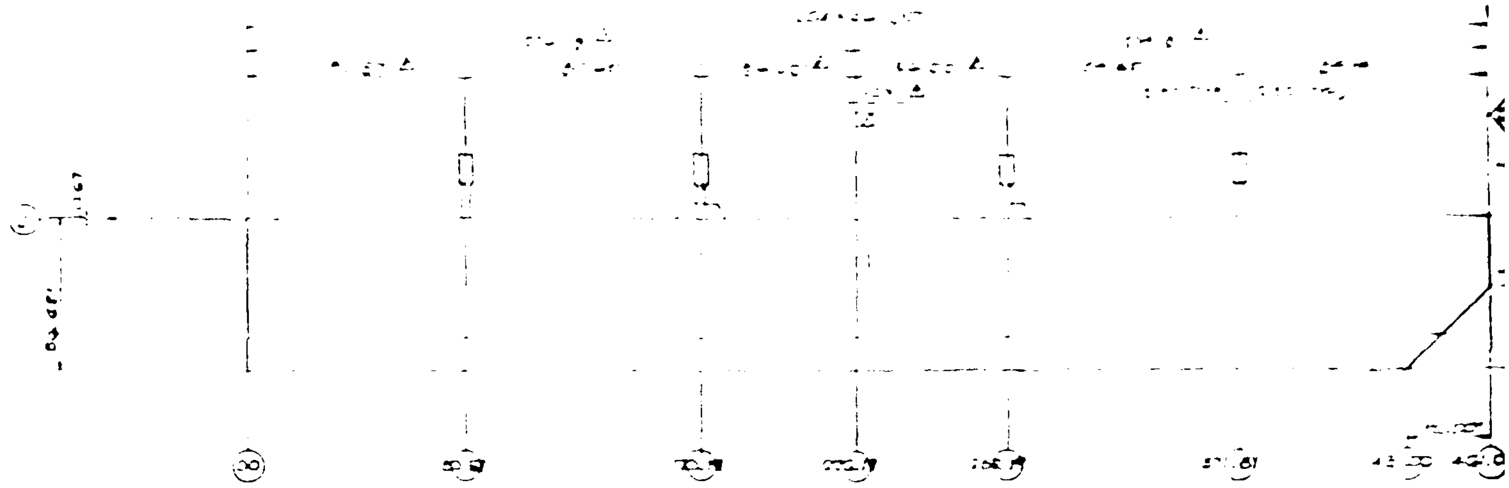
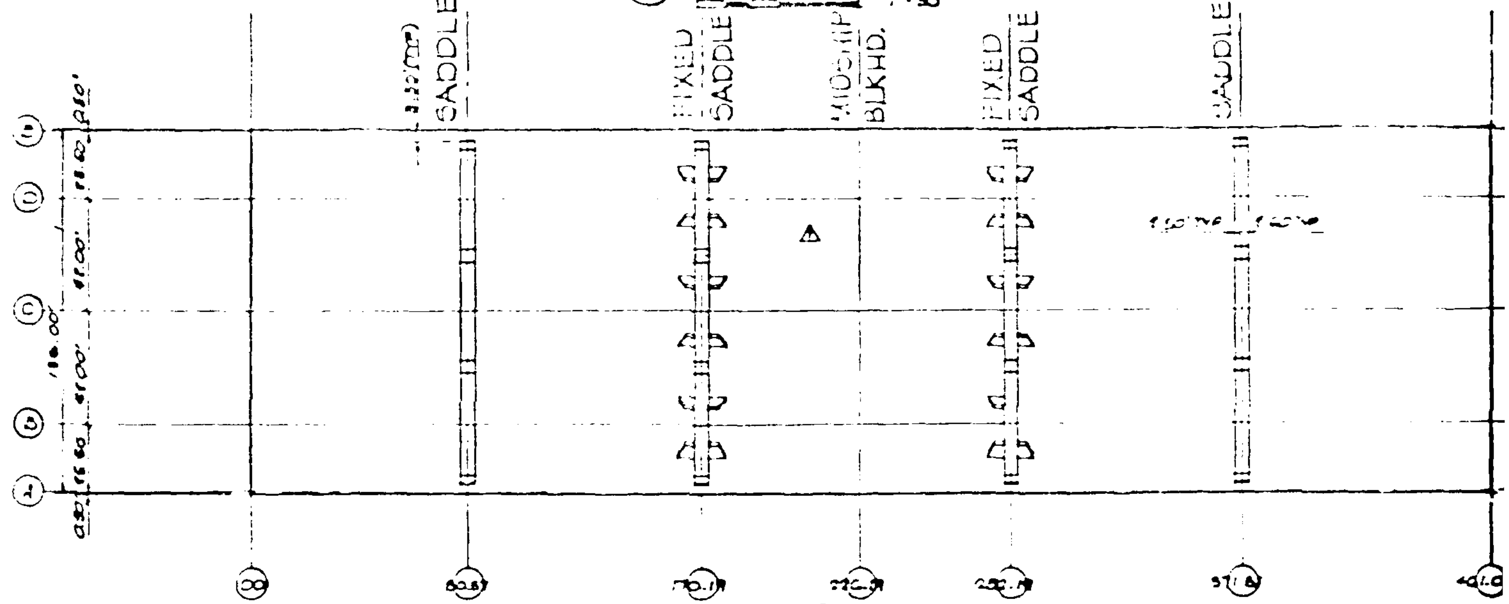


Figure V-12
ARCO LPG FACILITY-
GENERAL ARRANGEMENT



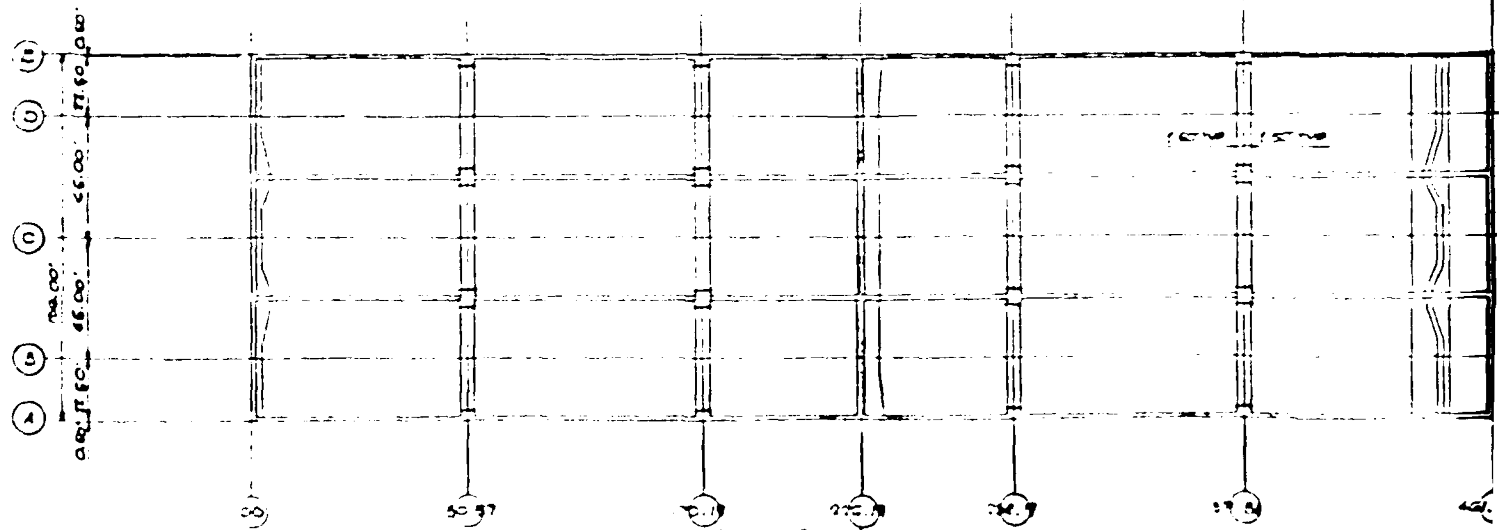
Ⓐ STARBOARD PROFILE

1"=30'



Ⓑ DECK PLAN

1"=30'



Ⓒ HULL PLAN

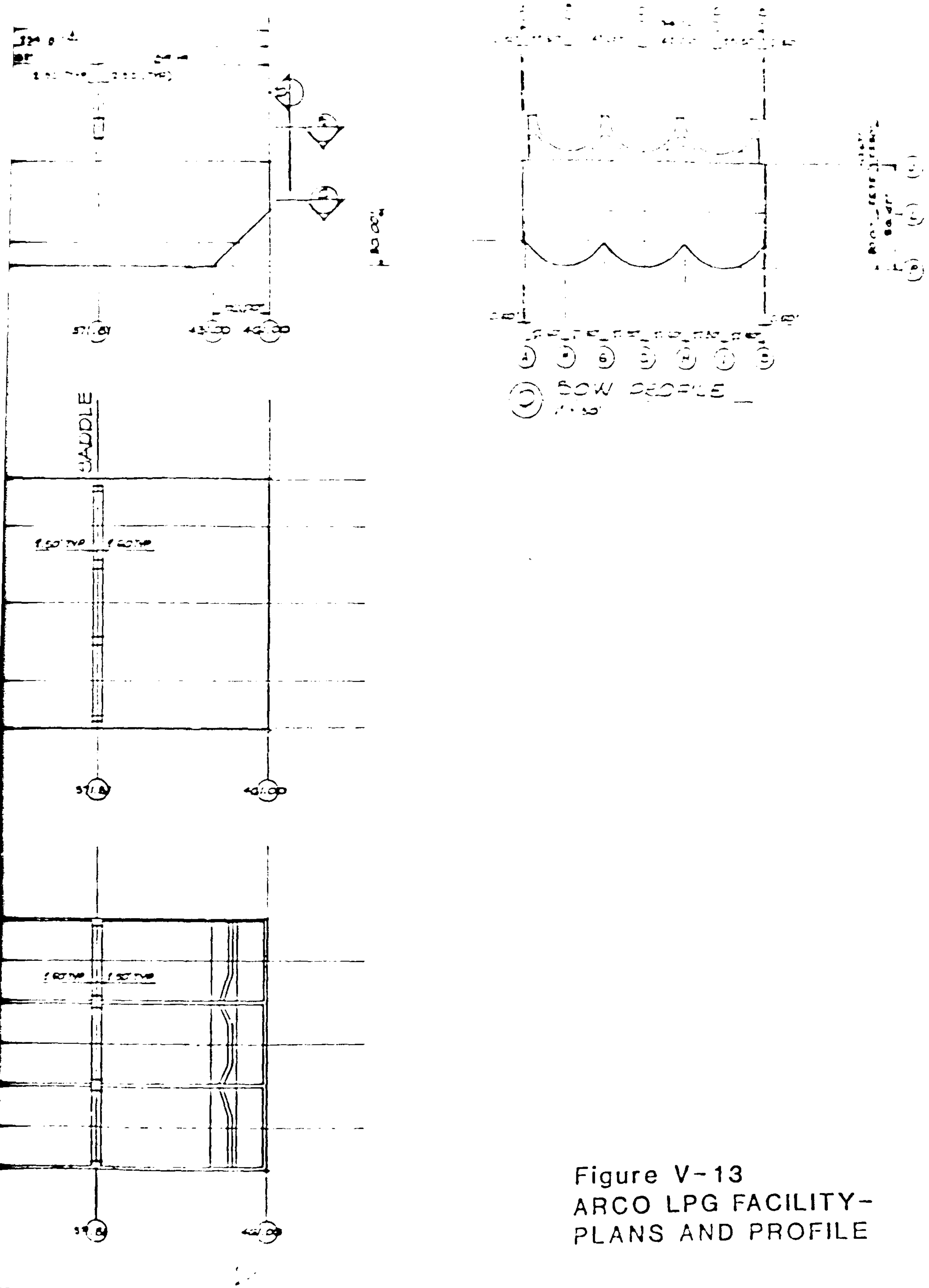
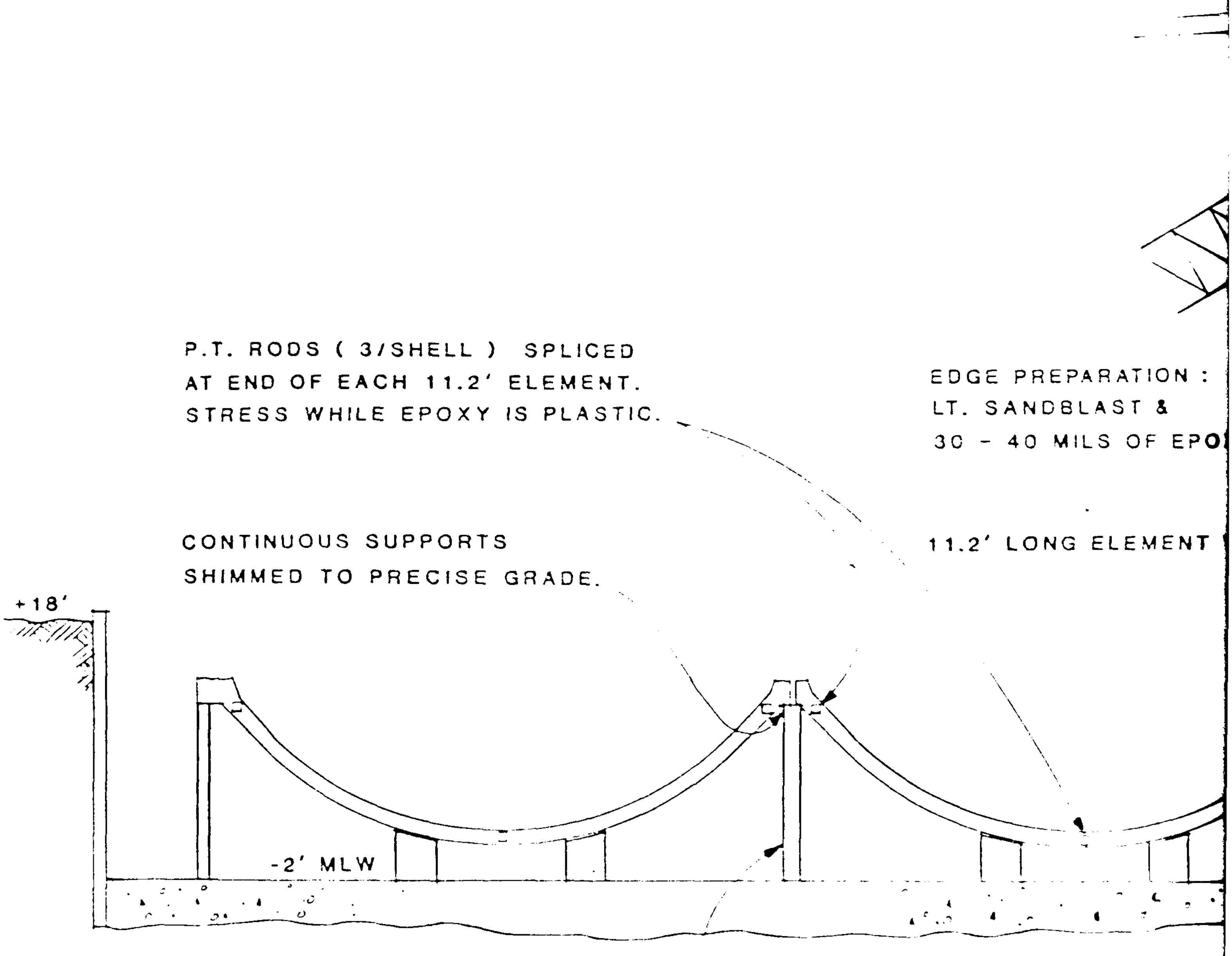


Figure V-13
ARCO LPG FACILITY-
PLANS AND PROFILE



P.T. RODS (3/SHELL) SPLICED
AT END OF EACH 11.2' ELEMENT.
STRESS WHILE EPOXY IS PLASTIC.

EDGE PREPARATION :
LT. SANDBLAST &
30 - 40 MILS OF EPO

CONTINUOUS SUPPORTS
SHIMMED TO PRECISE GRADE.

11.2' LONG ELEMENT

PRECAST WALLS
TO SUPPORT KEEL SHELL

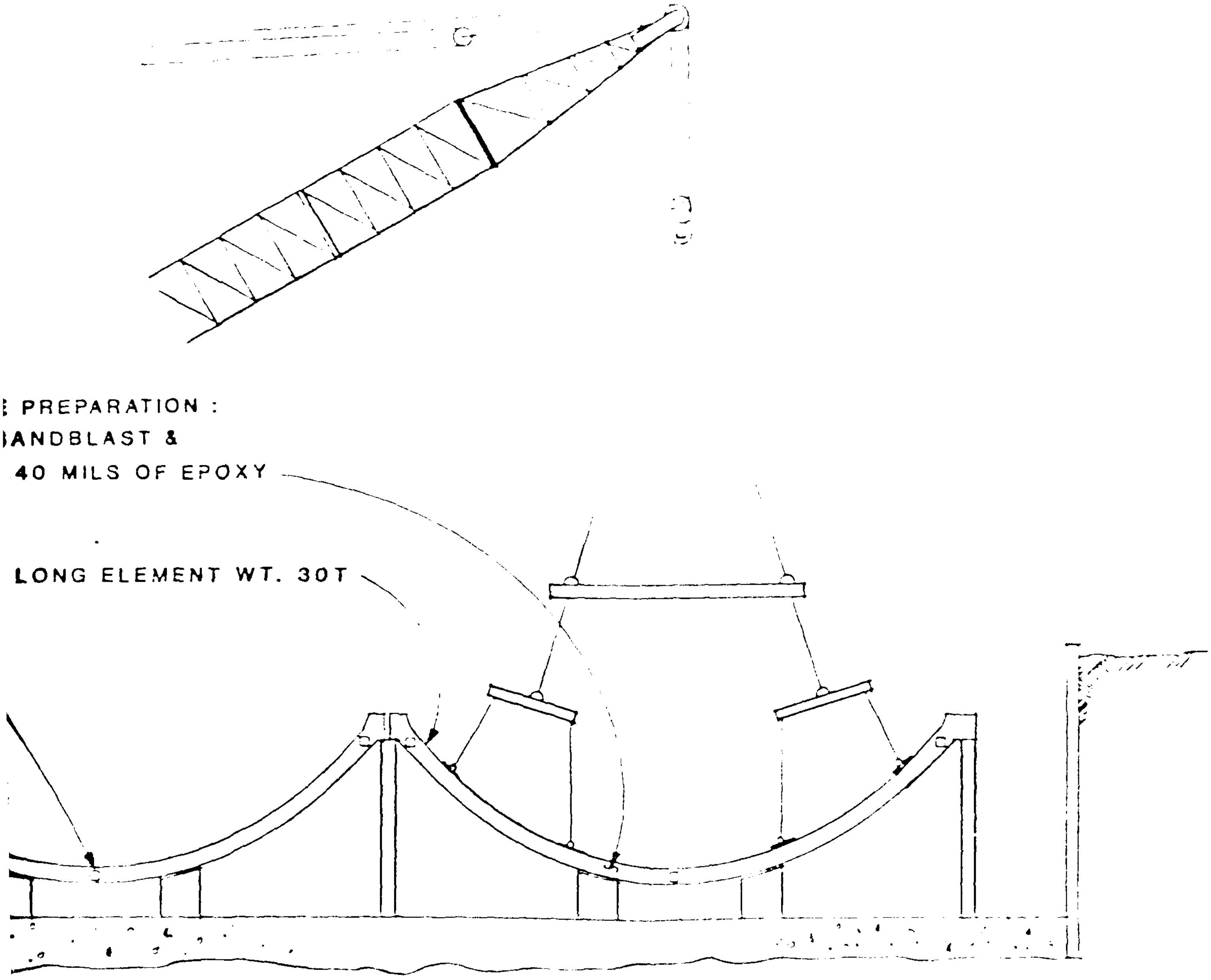
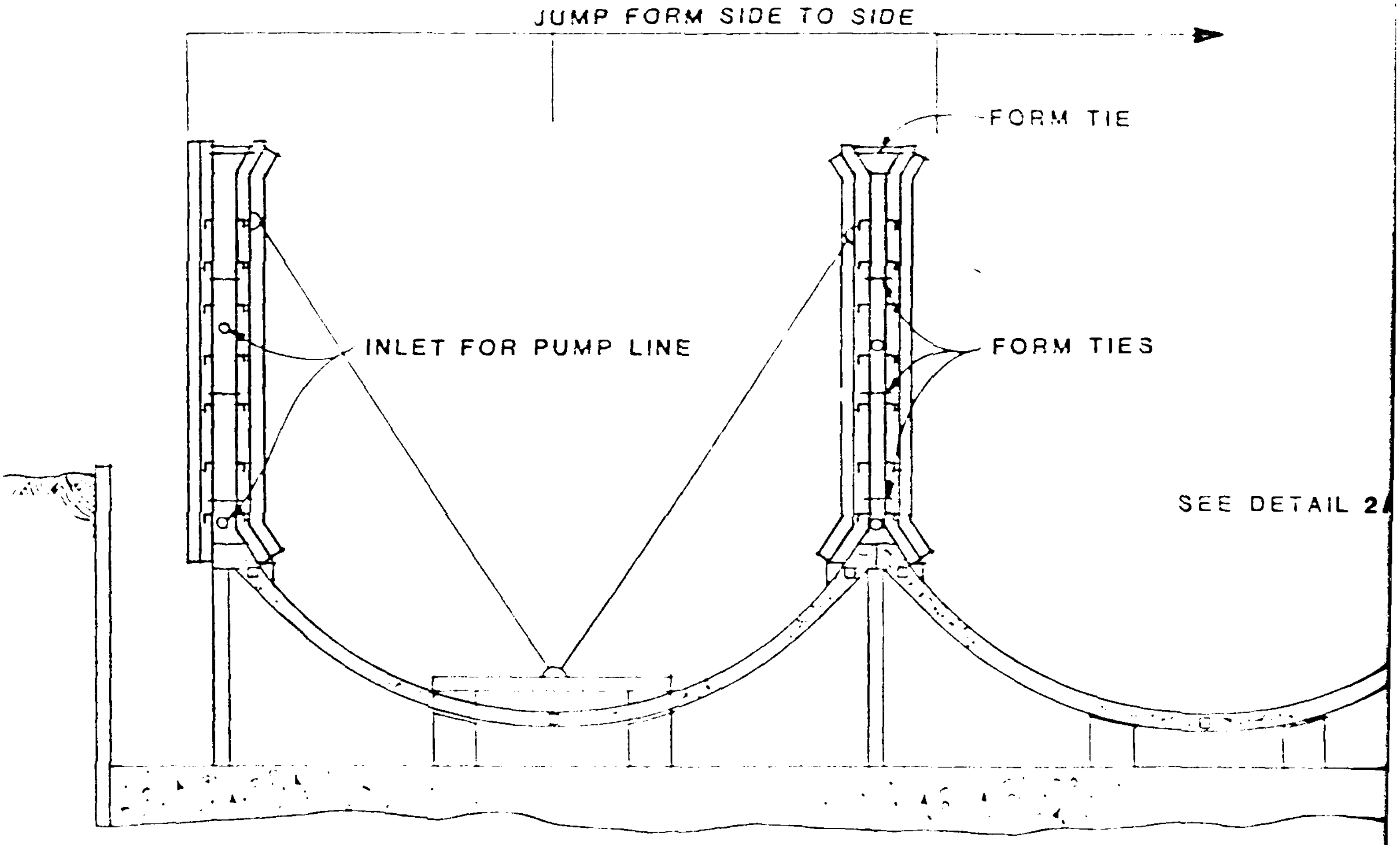


Figure V-14 ERECT PRECAST KEEL ELEMENTS


SPLI
SEC
LAP
LON
180
TRA
JUMP FORM SIDE TO SIDE
FORM TIE
INLET FOR PUMP LINE
FORM TIES
SEE DETAIL 2

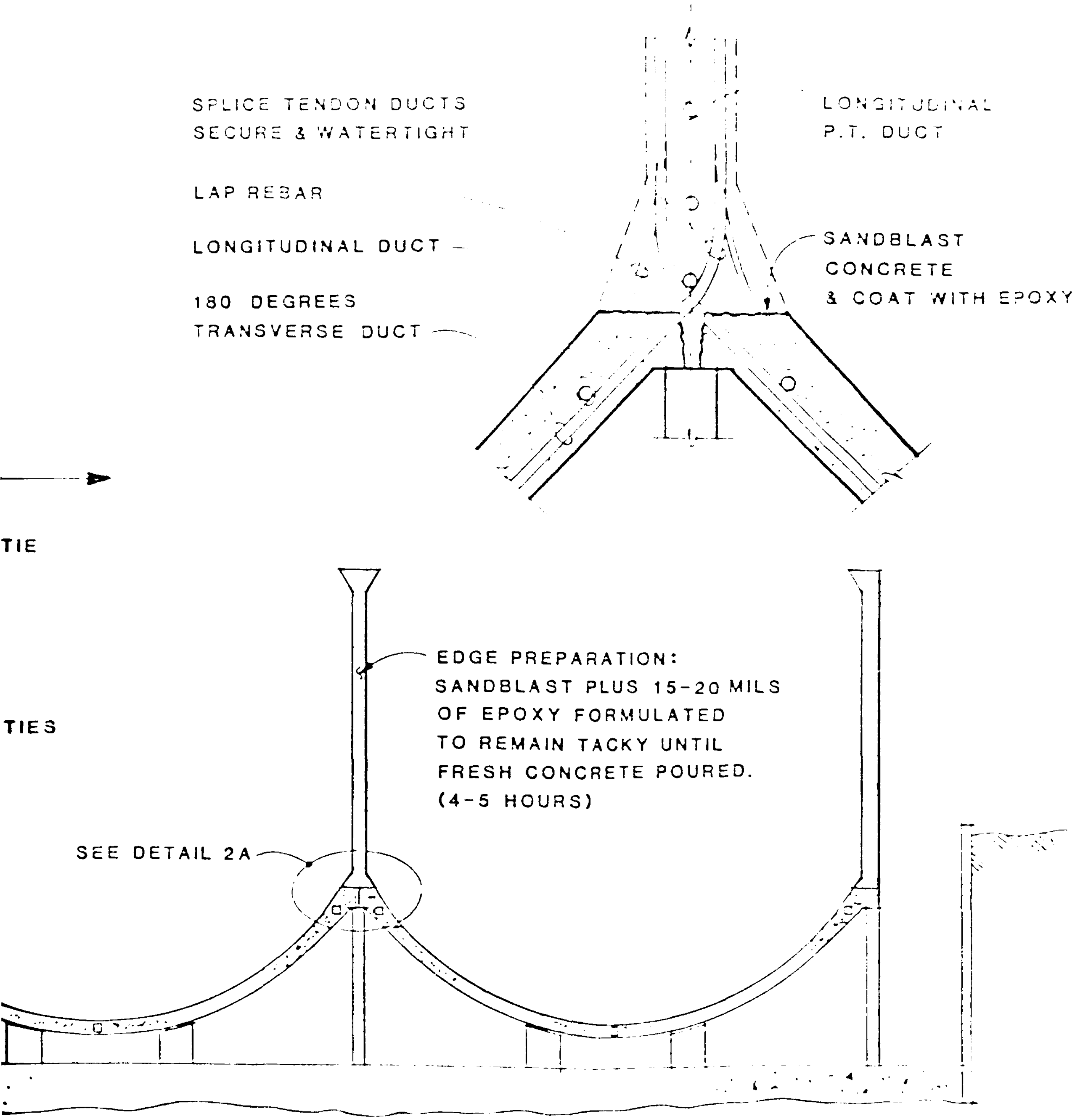
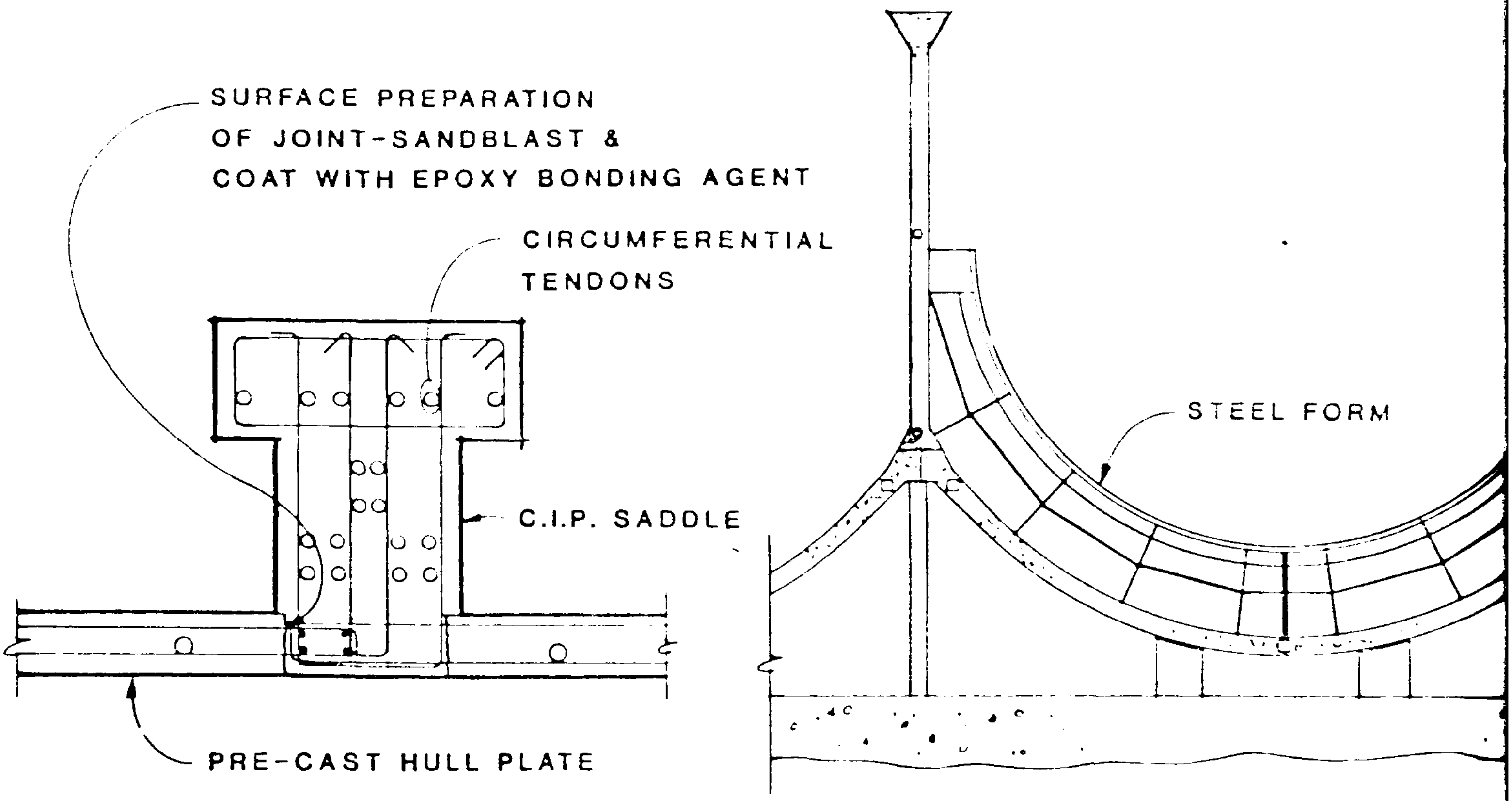


Figure V-15 CONSTRUCT CAST-IN-PLACE BULKHEADS



SECTION THRU SADDLE CONSTRUCTION
3/8" = 1'-0"

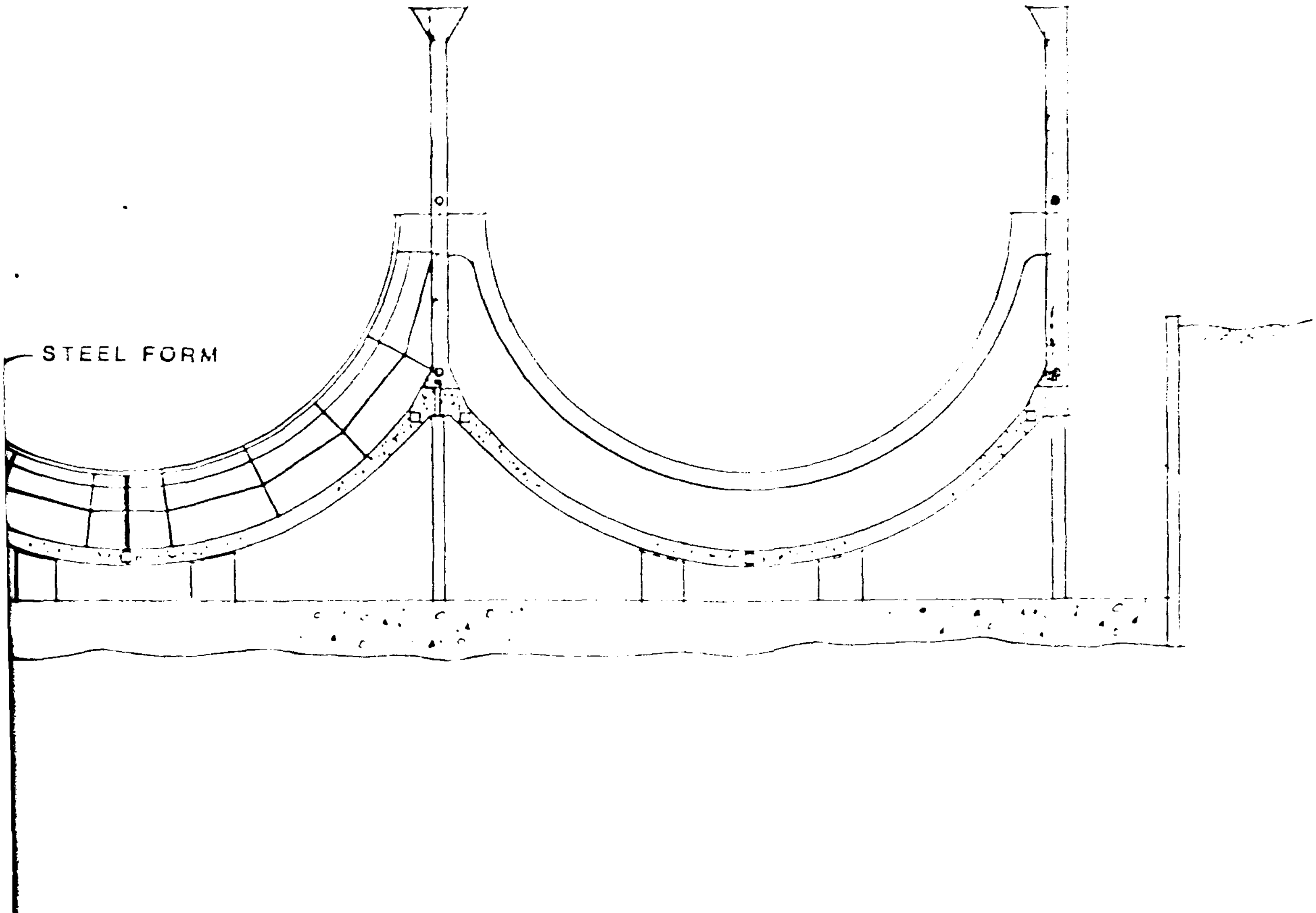
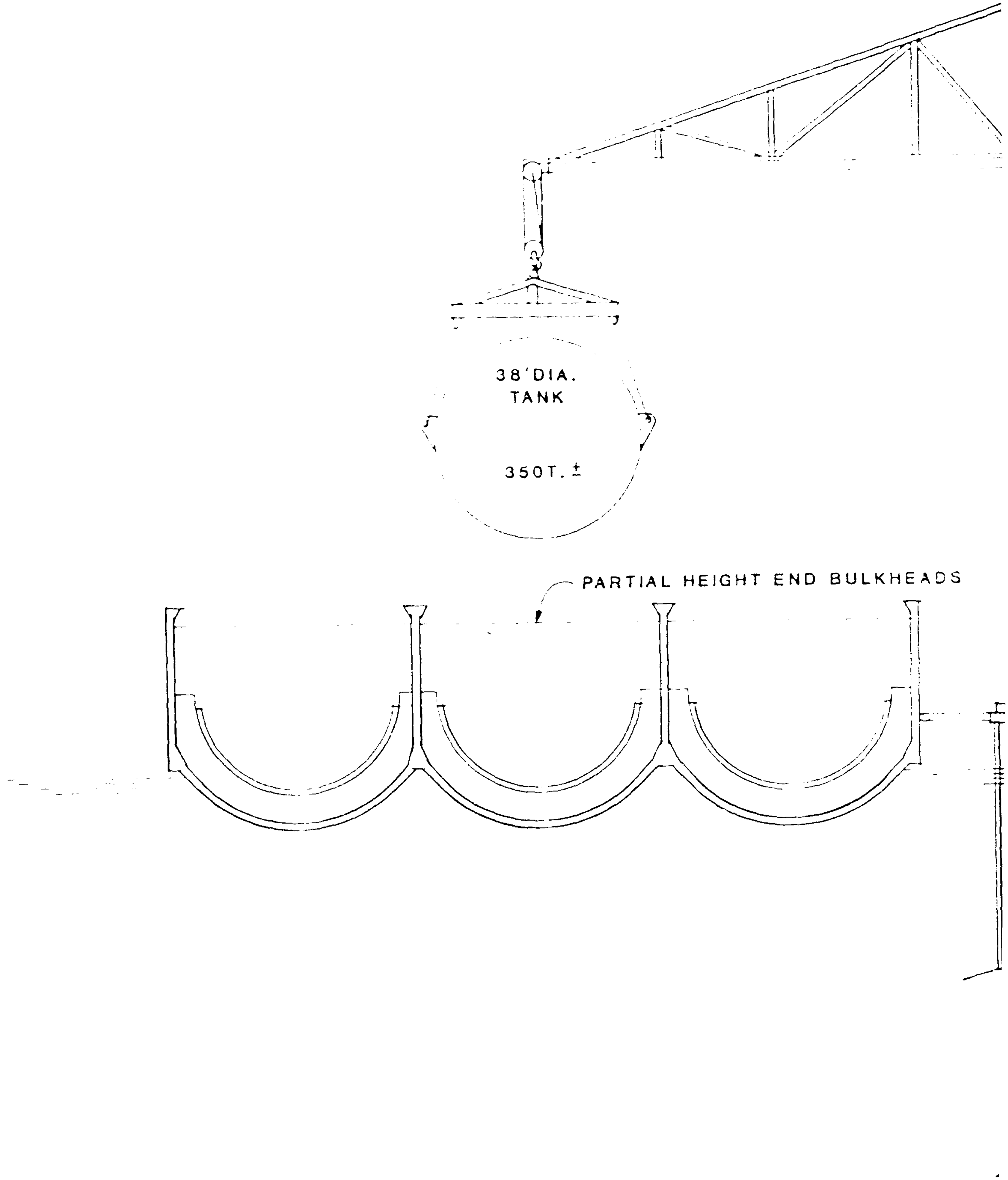


Figure V-16 CONSTRUCT
CAST-IN-PLACE TANK
SADDLES


38'DIA.
TANK
350T.±
PARTIAL HEIGHT END BULKHEADS

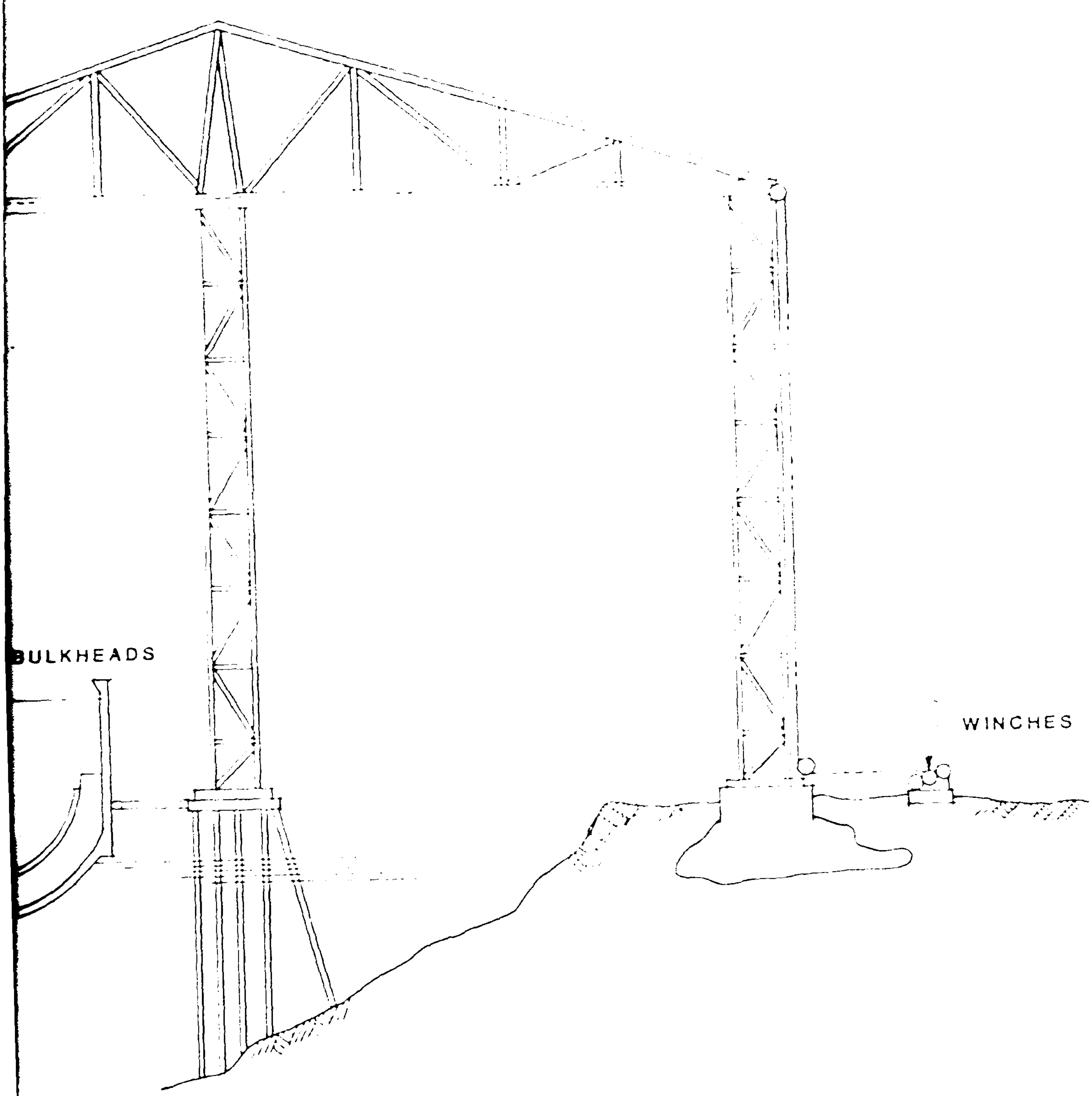
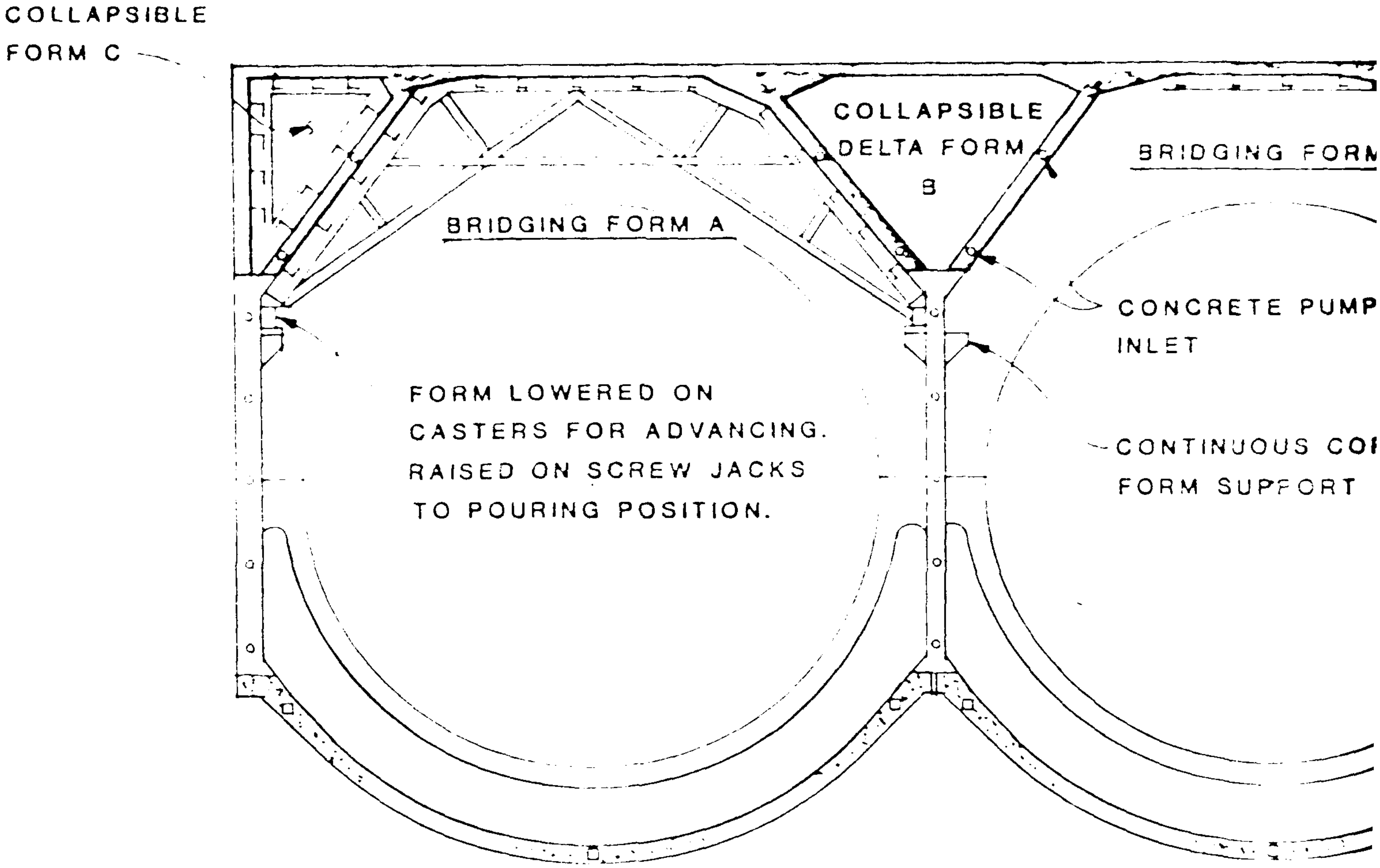


Figure V-17 ERECT
BELOW DECK TANKS



FORM LOWERED ON CASTERS FOR ADVANCING. RAISED ON SCREW JACKS TO POURING POSITION.

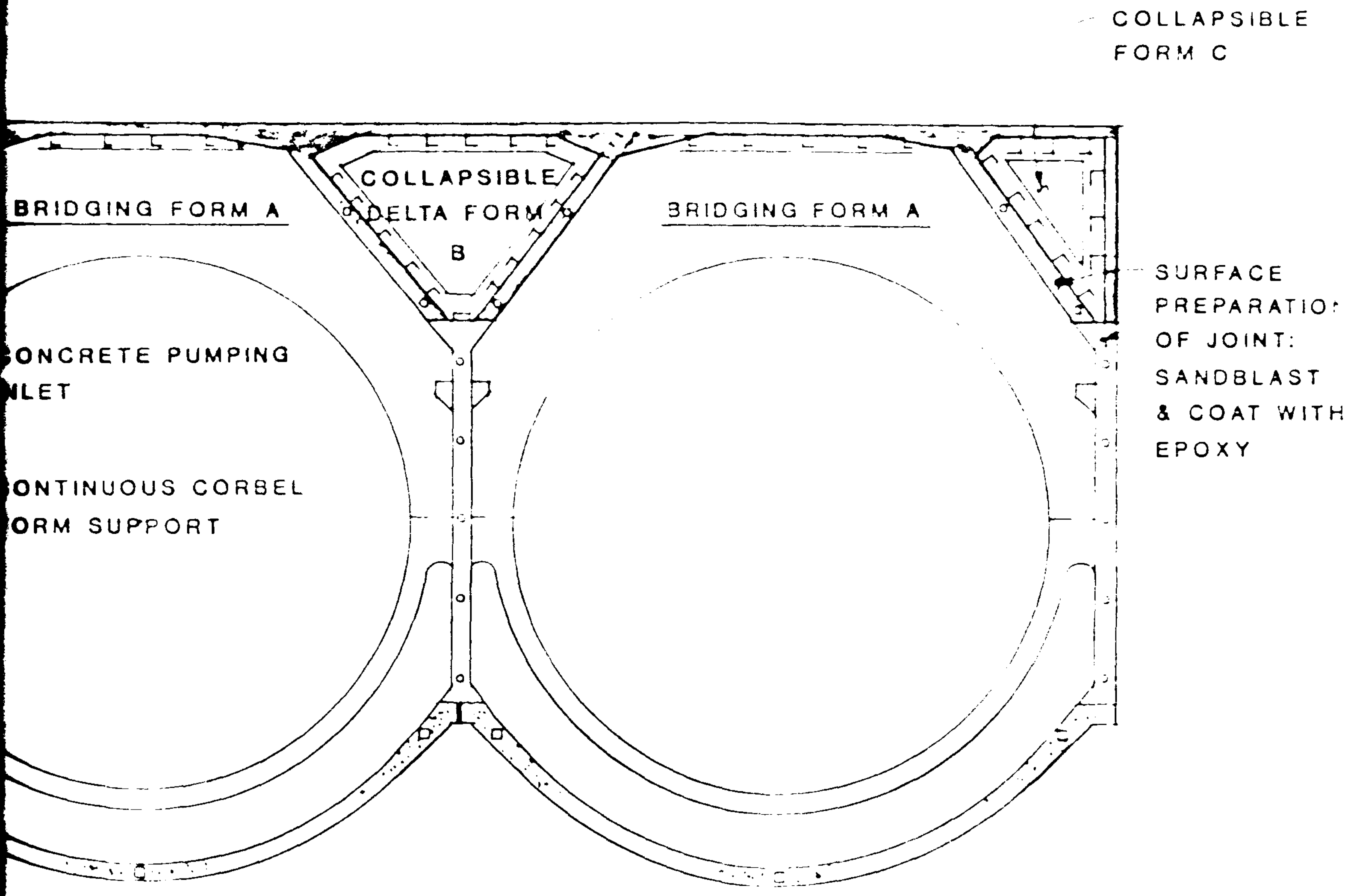
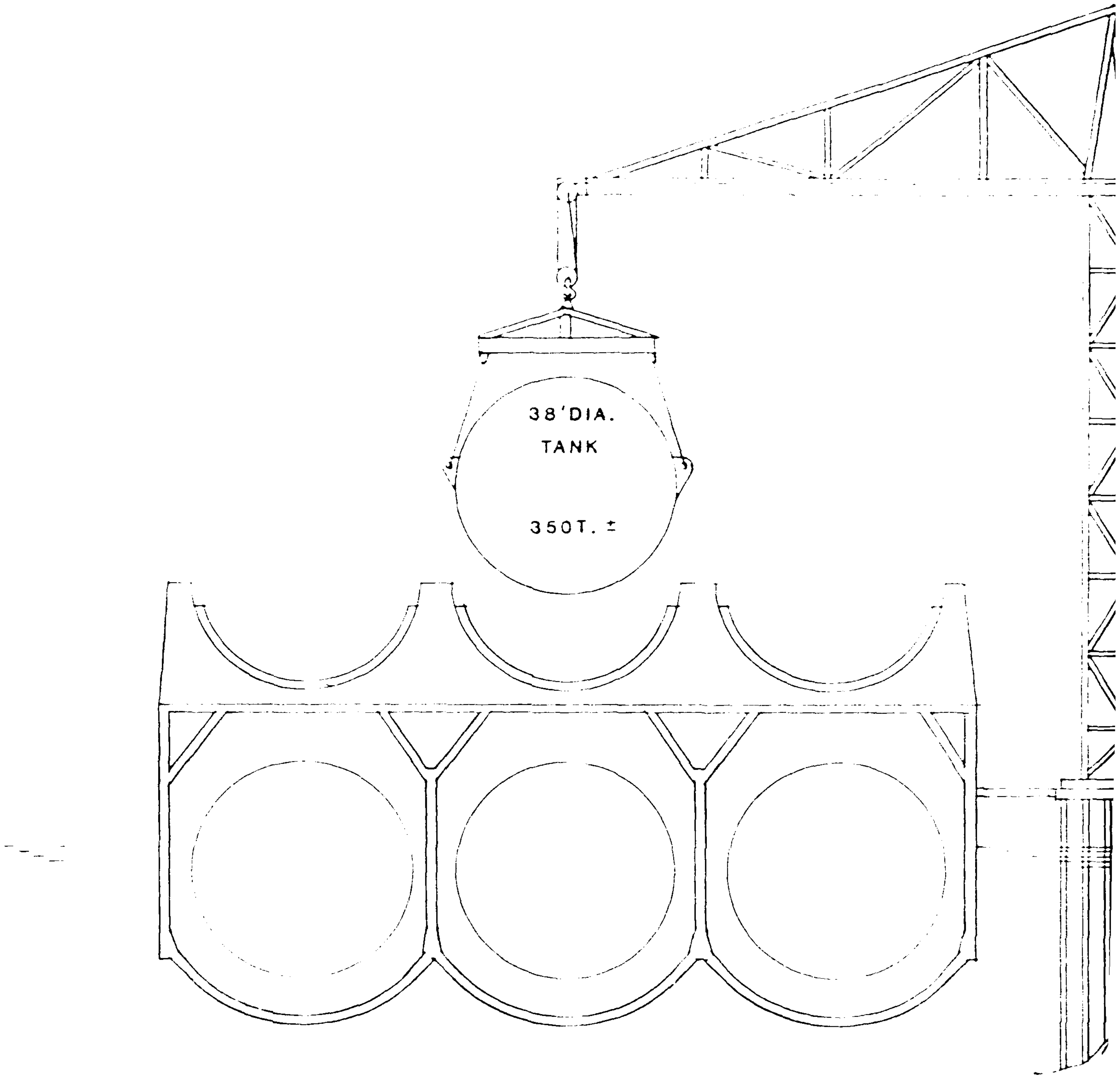


Figure V-18 CONSTRUCT CAST-IN-PLACE DECK


38'DIA.
TANK
350T. ±

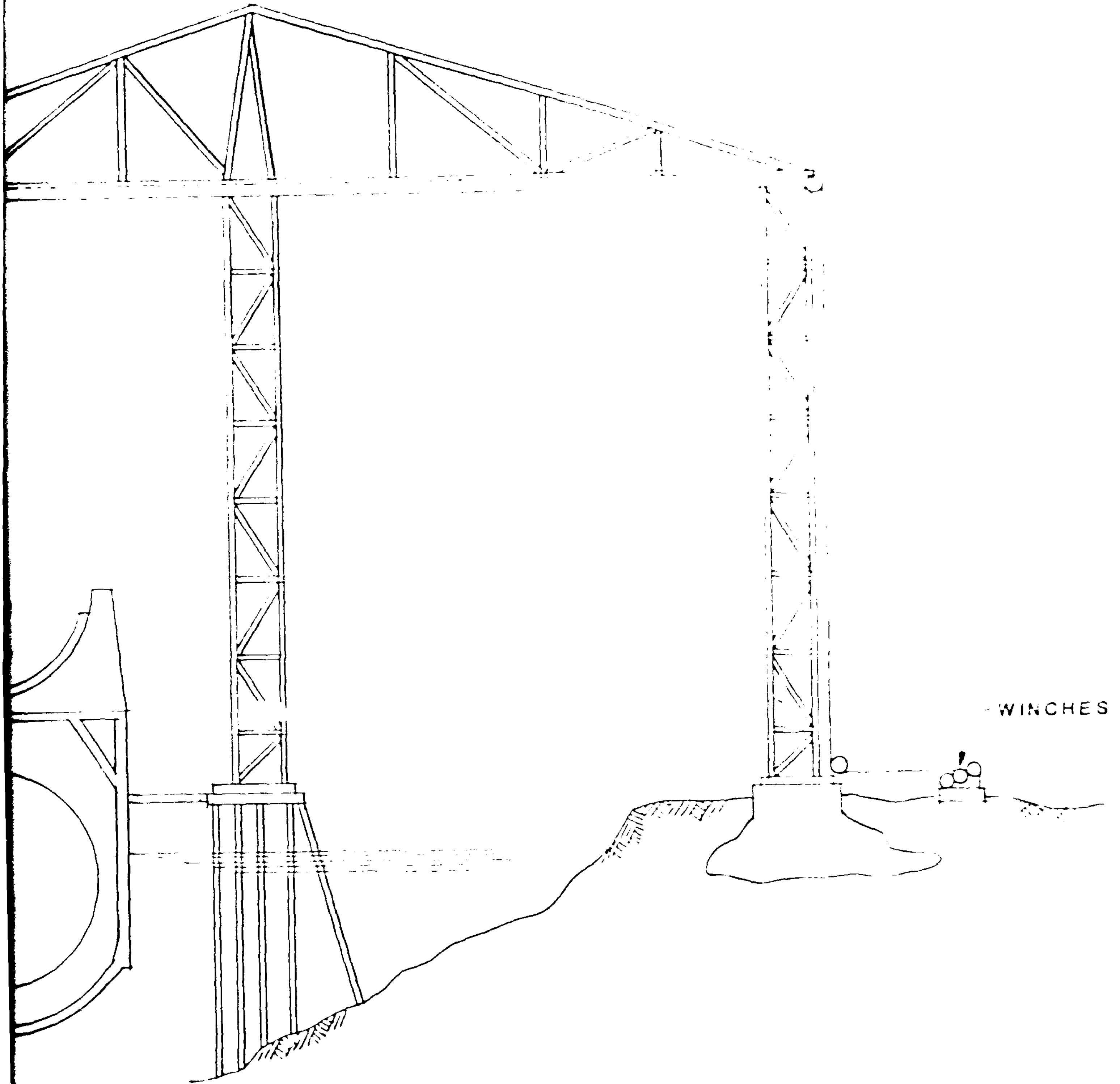


Figure V-19 ERECT ABOVE DECK TANKS

SECTION VI

SECTION VI

CAPABILITIES OF LWPC USED FOR SHIP CONSTRUCTION

6.0 Introduction and Terminology

The discussion which follows will address the current state-of-the-art capabilities and limitations of lightweight concretes used for marine structural applications. Particular focus will be placed on the marine uses of LWC rather than more conventional uses. This discussion will develop the composition of LWC, its precedent for use and potentials for future use. Additionally, the properties of the material which are important for use in the design of LWPC hulls are discussed. A limited technical bibliography of lightweight concrete technology is included to acquaint the reader with the depth of knowledge available regarding this material. This bibliography represents only a fraction of the data available on this subject. Hence, this report will not attempt to fully school the reader on LWC technology, but rather to provide a concise overview of LWC applications related to marine vessel design and construction.

As a prelude to the discussions which follow, it is necessary at this point to clearly define the terminology which will be used extensively herein.

- Structural Concrete - A high quality, heterogeneous matrix of aggregate. cement, water and admixtures which when combined and cured in a predetermined manner, produce a structural material possessing predictable elastic properties and load carrying capacity. Structural concretes are set apart from other concretes used primarily for sound and temperature insulation and for purely architectural purposes.

- Density - Typically defined as the oven-dried or air-dried density of concrete specimens. Because of marine construction techniques and ship exposure to seawater, it will be appropriate to discuss the saturated density of the concrete as it plays a role in vessel mass, vessel draft and concrete materials properties which may vary from those determined from oven-dry or air-dry samples. For this discussion, the symbol γ_c(sat) will be used to express the saturated density of the concrete (less reinforcement).

- Compressive Strength - For the purposes of this discussion, all references to compressive strength of concrete will be as per the definition provided by ACI 318-77 (Reference 45), in that the common expression of compressive strength is the specific 28-day design compressive strength of the concrete. The symbol used for this definition is f'_c and represents the statistical compressive strength of samples cast and cured for 28 days under actual construction conditions. A clear distinction should always be drawn between f'_c values and values obtained under well-controlled laboratory conditions. Values of f'_c can be as much as 15% to 25% lower than select samples tested under laboratory conditions.

Structural lightweight concrete is the name of a category of concretes having a γ_c(sat) = 100-130 pcf and associated f'_c values between 3,000 to 6,000 psi. This is the category of concrete to which this document draws focus. Normal weight structural concretes are characterized by γ_c(sat) = 145-165 pcf and design compressive strengths up to 9,000-10,000 psi and higher. There exists an additional family of structural lightweight concretes which have a density range γ_c(sat) = 75 to 95 pcf and strengths as high as 5,500 psi. Development of these "hybrid" mix designs is relatively recent, and full optimization of their characteristics has not been completed. Such mixes are generally laboratory specific, have little precedent in the construction industry, and tend to be costly compared to more traditional structural lightweight concretes. Future demand for such products should speed research activities to result in a more thorough understanding, and hopefully a more economical assessment, of high strength, very low density concretes. In any event, the emphasis of this document will address state-of-the-art structural lightweight concretes having design strengths up to 6,000 psi. Potential material capabilities are discussed in Section 6.5.

6.1 Composition of Structural Lightweight Concrete

Virtually all structural grade concretes are composed of various gradation aggregates (coarse, medium, fine), Portland cement, water and various chemical admixtures. Structural lightweight concrete gains its density reduction with regard to normal weight concrete by replacing part or all of the natural hard rock aggregates with lower density lightweight aggregates. Chemical admixtures are added to "alloy" the concrete to achieve improved durability of the hardened concrete or to impart improved handling characteristics to the fresh concrete at the construction site.

Lightweight aggregates are grouped into three categories:

- Natural materials such as pumice, lava, scoria, volcanic materials and porous limestone.
- Natural materials which require further processing to reduce density, such as expanded clay, shale or slate.
- Industrial by-products such as sintered pulverized fuel ash (fly ash), sintered slate and colliery waste, and expanded blast furnace slag.

Natural materials which do not require further processing are available in limited quantities only in select areas of the world. Hence, processed materials provide the maximum source capability for producing high quality, lightweight structural concretes, and constitute the focus of the remainder of this discussion on lightweight aggregates.

The manufacture of expanded shale, clay or slate involves the applications of heat to the highly siliceous raw material. The heating causes expansion of the gases which are trapped within the raw material. The release and entrapment of gases cause the raw material to expand, thus producing an aggregate with a considerably lower specific gravity. This is accomplished by two manufacturing processes· the rotary kiln or the sintering process.

In the rotary kiln process, the raw material is crushed and introduced at the upper end of a kiln similar to the type used in the Portland cement industry. Hot air or gases are passed in the opposite direction and the raw material is heated to about 2000^{0}F. In the sintering process, crushed raw material is mixed with pulverized fuel and burnt over travelling grates. Crushing of the manufactured aggregate produces a coarse surface texture and more permeable aggregate. These conditions adversely effect the workability and strength of the lightweight concrete and may lead to additional shrinkage cracking. Therefore, crushing of aggregate after manufacture should be minimized.

The other primary constituent of structural concrete other than potable mixing water is the Portland cement paste. Common practice in the marine concrete industry today is to specify either Type II (modified) Portland cement or Type III high early strength Portland cement. Type II is selected because of its low chemical reactivity with the aggregates in seawater, and Type III is chosen because its high early strength will generally produce lower total volume changes in prestressed structures than would normal type cements (I or II).

Admixtures are frequently used to provide resistance to the deleterious effects of freezing and thawing (air-entrainment) or to make the concrete more plastic, retard the initial set, accelerate the final set and possibly to reduce the amount of required mixing water. Air-entraining admixtures are recommended when it is anticipated that the structure will be subject to repeated freezing and thawing cycles after the structure is complete and in service. The admixtures for the fresh concrete are used to achieve economy of precasting, prestressing and overall field construction, and generally have no effect on the properties of the cured concrete structure.

6.2 Precedents for Use

Among the earliest marine applications of lightweight concrete was the construction of reinforced concrete ships and barges for use in World Wars I and II. Expanded shale aggregates were used to produce lightweight concrete for these ships.

Dry concrete densities of 119 pcf and 28-day compressive strengths exceeding 5,000 psi were achieved by the concrete used in the construction of the U.S.S. Selma in 1919. After three years of service transporting crude oil, the Selma, a reinforced, non-prestressed vessel, ran aground in Galveston Bay, resulting in a large crack near the bow. Because no one would guarantee a repair of the crack, she was intentionally sunk to act as a breakwater in Galveston Bay.

The hull of the Selma was inspected in 1953. Testing of core samples showed the compressive strength of the hull exceeded 8,000 psi. There was no evidence of concrete deterioration in the hull. While the concrete cover on the reinforcing steel was only 5/8-inch, no evidence of pitting of the bars was evident, even in the splash zone. The concrete mix used in the construction of the Selma had a water-cement ratio of 0.49, although the quantity of cement was very high at 1,034 pounds per cubic yard. More recent inspections of the Selma indicate continued durability of the material.

Among other examples of marine applications of lightweight concrete are the San Francisco-Oakland Bay Bridge, built in the 1930's, a floating drydock built recently in Genoa, Italy, and caissons for Dome Petroleum's Tarsiut project in the Canadian Beaufort Sea, which was completed in 1981. The Tarsiut project will provide valuable experience regarding the behavior of lightweight concrete in the Arctic.

Further discussion of the historical use of LWPC for ship construction is included in Section V of this report.

6.3 Properties of State-of-the-Art Structural Lightweight Concrete

6.3.1 Density

The density of lightweight concrete and the compressive strength of the concrete are generally related. In order to achieve higher compressive strengths, the concrete densities are commonly in the upper range of lightweight concrete density.

In compacted structural lightweight concretes, approximately 70% of the volume is taken up by the aggregates. Hence, the particle density of the aggregate is the primary factor influencing concrete density. For lightweight aggregates, the particle density is dependent upon particle size. Therefore a reduction in the maximum coarse aggregate particle size will generally result in an increase in density while also increasing concrete strength. Therefore, natural sand is often used as a fine aggregate in the mix. This results in a more economical mix design due to the reduced water demand for a given workability; however, the resulting density is greater than that possible with a concrete with lightweight fines.

High strength lightweight concretes exist today which have oven-dry densities in the 90 to 120 pcf range. The saturated density range of such mixes used for marine applications may find a limit at 100 to 135 pcf. Should air-entraining admixtures be used to improve the cold weather durability of such concretes, the expected density range may reduce respectively to 95 to 130 pcf, with an accompanying loss of design compressive strength and slight modifications to the elastic properties of the mix. As will be noted in the following discussion, such modifications to the elastic properties are not necessarily deleterious and may, in fact, enhance the structural performance of the concrete.

6.3.2 Strength

In general, because of the reduced strength of lightweight aggregates as compared to normal hard rock counterparts, it is generally expected that the lightweight concrete mix, when cured, would always possess strength properties lower than normal weight concretes. This is only true in part. Since the concrete "mix" consists of aggregates, cement paste, water and admixtures, and because the aggregates are actually inclusions in the concrete matrix, the performance of the matrix is dependent upon not only the physical strength of each constituent, but also the relative elastic properties of each constituent.

A heterogeneous concrete matrix fails by cracking within the matrix, and the nature of the failure is influenced by the matrix deformation characteristics such as modulus of elasticity and Poisson's Ratio. Lightweight aggregates produce lower stress concentrations within the matrix and can therefore significantly compensate for reduced aggregate strength with regard to matrix cracking. It is therefore not unreasonable to produce lightweight concretes with exceptionally high compressive strengths (6000 to 7000 psi) with present state of the art tecnnology, and attention is being directed today for development of lightweight concretes having design compressive strengths perhaps as high as 9000 to 10000 psi.

The shear strength of concrete is related to the biaxial or tri-axial stress state where one of the principle stresses is tensile. Shear strength and tensile strength is generally related to the compressive strength of the concrete, as directed in ACI 318-77 (Reference 45). Specific criteria for the design of LWPC hulls is discussed in Section IV of this report.

6.3.3 Deformation Characteristics

The modulus of elasticity for lightweight concrete in compression, E_c, is less than that for normal weight concrete of equivalent design compressive strength. For high strength structural lightweight concrete (100 to 120 pcf), E_c is estimated to be 50% to 60% of that for equivalent hard rock, normal weight concrete. This will tend to increase deflections of a loaded member, but stresses caused by shrinkage and thermal effects will be lower. In addition, low modulus lightweight concrete should exhibit lower coefficients of thermal conductivity and thermal expansion than normal weight concrete and should therefore have improved resistance to thermal cracking. Also, the lower E_c value should allow the lightweight concrete structure to absorb more elastic energy than normal weight counterparts.

The modulus of elasticity can be calculated by the equation $E_c = 33w^{1.5}(f'_c)^{0.5}$, where w is the unit weight of concrete (pcf) and

f'_c is the compressive strength (psi). Poisson's ratio for structural lightweight concretes will range between 0.22 and 0.24.

6.3.4 Durability Characteristics

Marine concretes, both normal weight and lightweight, must be durable as a material exposed to a variety of severe environmental and functional conditions. If the vessel is to have virtually unlimited use, the lightweight concrete must exhibit good durability characteristics when subject to prolonged seawater exposure and possible marine growth, to various types of abrasion, and to freeze-thaw cycles. Mechanisms of concrete damage and deterioration and the important considerations for durable LWPC are discussed in Sections 7.1 and 7.2 of this report.

The proper design of concrete mix components and the proper placement of the concrete in order to assure a dense concrete is probably the most important requirement to reduce the permeability of the concrete thus and to assure a durable concrete structure. The following guidelines must be followed to assure this:

- Portland cement shall be Type II or III and shall have a maximum tricalcium aluminate (C_3A) content of 8 percent.
- Concrete shall have a maximum water-cement ratio of 0.44 by weight and preferentially shall be below 0.40.
- The concrete shall be air entrained to include an air content between 3 percent and 5 percent.
- All aggregates shall have a history of producing durable concretes.

It is possible to further reduce the permeability of a concrete surface and therefore improve the durability of the concrete through the use of a surface sealer. Such sealers contain dissolved solids which penetrate the voids in the concrete surface and then crystalize. Such materials have proven successful in increasing the durablity of bridge decks and parking garage decks which are subject to the corrosive environment of de-icing salts. It should be noted that such sealers are not permanent and may require repeated applications during the life of the structure.

6.3.5 Absorption Characteristics

The amount of moisture absorbed by lightweight concrete is an important consideration for the determination of the effective draft of lightweight concrete ships. Studies by the Navy (Reference 46) indicate the magnitude of seawater absorption of lightweight concrete. The quality of the cement paste and proper concrete consolidation are important factors in limiting the water absorption by concrete.

6.3.6 Creep and Shrinkage

Concrete is a composite material in which stable aggregates are suspended in a matrix which can be expected to change volume with time, moisture content, and applied stress. The volume change of the concrete will be less than that of the matrix due to the rigidity of the aggregates. Hence, the overall volumetric change should be a function of aggregate stiffness and the quantity and distribution of aggregates in the concrete.

Lightweight coarse aggregates have about 32% voids. The smaller or finer lightweight aggregates have a higher relative density. The disparity in densities is accompanied by a disparity in elastic moduli. Therefore it is expected that creep of lightweight concrete should be greater than for normal weight concrete.

Lightweight concrete has a drying shrinkage of up to twice the mean shrinkage of high density concrete. If the concrete remains saturated, such differences will be mitigated and little difference should be noted for drying shrinkage of lightweight and normal weight concretes in marine structures.

Specific creep and shrinkage characteristics will be highly material dependent and highly dependent upon concrete mix components. Such characteristics can and should be determined by test and the data supplied to the design engineer to assure proper consideration in the reinforcing steel design and the design for prestressing and post-tensioning.

6.3.7 Fatigue Performance

Concrete does not appear to have a fatigue limit (i.e. a fatigue strength at an infinite number of cycles) except when stress reversals occur. The application of prestressing to concrete tends to minimize stress reversals. Thus, if stresses are maintained within the fatigue strength of concrete, an unlimited number of load cycles can be resisted. The fatigue strength of concrete in both compression and flexure is approximately 55-65 percent of the static strength. Allowable concrete compressive stresses for loadings which can be experienced frequently are 45 percent of the compressive strength (see Section IV). This service level loading is selected such that only limited cycles of loads with a higher intensity are experienced. Further discussion of the fatigue resistance of reinforced and prestressed concrete is included in Section 4.3.4.

6.3.8 Thermal Properties

The porous nature and low density of lightweight aggregates tends to make the thermal conductivity and coefficient of thermal expansion of lightweight concrete smaller than those of normal weight concretes. The magnitudes will be dependent upon concrete mix components; however the thermal conductivity of saturated lightweight concrete is on the order of 0.7-1.0 BTU-ft/hr-ft^2 - Deg. F. Conductivity is reduced by approximately a factor of two for air dry lightweight concrete. The coefficient of thermal expansion of lightweight concrete is also concrete specific, however it is on the order of magintidue of $5X10^{-6}$ per Deg. F.

6.3.9 Fire Resistance

Concrete structures have shown excellent resistance to fire damage as compared to other materials. Concrete structures have been able to maintain load carrying capacity for relatively long periods of time while experiencing only superficial surface damage. Lightweight concretes behave better than normal weight concretes due to their lower thermal conductivity. Further discussion of the fire resistance of LWPC is included in Section 7.1.2.

6.3.10 Machine Foundations

Concrete elements provide good vibration damping characteristics due to their mass and due to the fact that concrete elements are generally much stiffer than steel elements of equal strength.

6.4 Availability of Lightweight Aggregates

The manufacture of lightweight aggregate is energy intensive. Increasing energy costs as well as the recent downturn in the economy has forced many manufacturers of lightweight aggregate out of business. Regardless, there is a ready supply of lightweight aggregate to meet current demands and many manufacturers are planning for expanded capacity in the event of increased demand. The interest in lightweight concrete for offshore oil structures will likely lead to expansion of the industry in the near future.

6.5 Potential LWPC Properties

As discussed previously, a family of structural lightweight concretes exists with saturated densities between 75 and 95 pcf. In order to achieve this concrete density, low density materials must be used for both coarse and fine aggregates. Concretes of this density were developed for construction of a scale model LWPC cold water pipe for the OTEC program. These concretes achieved compressive strengths, f'_c, in excess of 5000 psi. This concrete used low density expanded clay materials for both coarse and fine aggregate. Research is currently underway to develop concretes of this density in Europe.

In order to improve the viability of LWPC for ships, it is felt that concretes of this density range should be developed with strengths exceeding 6000 psi. This will involve an extensive development program to thoroughly define all properties necessary for design with this material. This program must begin with an investigation of potential materials which can be used to achieve this density, thus assuring the commercial availability of the necessary raw material for the cost-effective manufacture of the lightweight aggregate.

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SECTION VII

SECTION VII

REPAIRABILITY AND MAINTAINABILITY OF LWPC HULLS

7.0 Introduction

The development of epoxy resins, polymer mortars, fast-setting hydraulic mortars and new bonding agents has made it possible to repair and maintain reinforced and prestressed concrete marine structures under most conditions. Repairs may be performed by unskilled personnel aboard marine structures following instructions and guidelines issued by manufacturers of these repair materials. Tools required for repair are not extraordinary and can be easily carried on the structure.

Few special problems occur with the use of lightweight concrete in the marine environment. Lightweight concrete hulls subjected to accidental or incidental abrasion from hard objects may require more maintenance than normal weight concrete or steel hulls. If for some reason, a large section of a lightweight concrete hull needs replacement, the availability of a suitable lightweight aggregate for repairs may be troublesome. Lightweight concrete is sometimes more difficult to mix and place than normal weight concrete.

On the other hand, lightweight concrete has several advantages over normal weight concrete in marine structures in addition to the weight factor. It has superior resistance to microcracking (i.e., very fine cracks around and sometimes between aggregate particles created by inner stresses) because of better aggregate-to-paste bond and also, the elastic modulis of lightweight aggregates and cement paste are similar, causing fewer microcracks.

Lighweight concrete has a high ultimate strain capacity because of its high strength to elastic modulus ratio. This may result in fewer cracks.

Other benefits from the lightweight aggregate particles themselves are (a) the particles normally exhibit some pozzolanic behavior resulting in increasing strength and bond over a long term, and (b) water is slowly released from the pores of lightweight particles providing a good curing medium as well as lower permeability.

7.1 Mechanisms of Damage and Deterioration

The mechanisms and description of damage and deterioration to concrete hulls can be listed in the following categories.

7.1.1 Impact From Other Vessels and Falling Objects

The extent of damage from impact can range from small surface spalls to a sizeable hole punched through the hull plate or deck. The ability of concrete to resist impact is dependent on its toughness. Toughness varies with the quality of concrete and the type and amount of reinforcement or prestress in the hull. Concrete can be designed to have excellent impact resistance.

7.1.2 Fire Damage

Prestressed concrete can sustain its ability to perform during and after fires of relatively long duration. Fires introduce high temperature gradients in concrete causing the hot surface layers to delaminate and spall from the cooler interior. Cracks may be formed at unreinforced joints, in areas of weak or porous concrete or in the planes of reinforcing bars.

Lightweight concrete is more resistant to fire than normal weight concrete because of a lesser tendency to spall due to the greater resistance of heat transmission in lightweight concrete. Lightweight concrete loses a lower percentage of its strength at high temperatures than does normal weight.

7.1.3 Explosion and Implosion

The resistance of concrete to over-pressures resulting from explosions, as well as the nature of damage resulting from these over-pressures, has been studied by the U. S. Corps of Engineers. Prestressed concrete offers superior resistance to explosive loadings because of its greater tensile strength (enhanced by lighweight concrete, also). Damage from explosions are localized and range from surface spalls to gaping holes.

7.1.4 Weakness in Construction or Design

If concrete for exposure to a marine environment is not manufactured or designed with a low water-cement ratio (0.44 maximum and preferably less than 0.40) it will deteriorate or lead to corrosion of reinforcement as described in the following categories. Localized areas of poor compaction or low quality concrete can cause a cancerous growth of deterioration into adjacent good quality areas.

Inadequate design strength of a prestressed concrete hull resulting in cracks may lead to damage from corrosion or deterioration that otherwise may not occur.

7.1.5 Corrosion of Reinforcing and Prestressing Steel

Concrete normally provides excellent corrosion protection around reinforcement due to its high alkalinity (pH of about 12.5). Chlorides from salt water can destroy this alkaline protection if allowed to penetrate to the steel by loss of resistivity of concrete (i.e., lower pH). Oxygen from the atmosphere or dissolved in water in the splash or tidal zone of the hull will then lead to corrosion if it, too, penetrates to the reinforcement. The corrosion byproducts occupy more volume in the concrete and eventually can cause cracks or delamination of concrete from steel. Serious corrosion damage to reinforcement may or may not be evident on the surface of concrete depending on several factors.

Prestressing steel in concrete hulls generally has multiple protective layers surrounding it: (1) the concrete cover between outer hull and post-tensionsing duct, (2) the duct itself, generally galvanized steel, (3) the highly alkaline cement grout in the duct around prestressing steel, and (4) mill coatings applied during manufacture of prestressing steel.

Post-tensioning ducts not completely filled with grout or ungrouted ducts eliminate an important safeguard and lead to the most common source of corrosion of prestressing steel.

Steel in reinforced and/or prestressed concrete completely and permanently submerged at some depth (5-15 ft) in water will not corrode at any appreciable rate.

7.1.6 Deterioration of Concrete in Seawater

(See Fig. VII-1, from Ref. 1.) Sulfates and chlorides of magnesium and sodium are the most aggressive naturally - occurring compounds in seawater. The mechanism of their attack on concrete is complex but generally involves chemical decomposition of hydrated aluminates and calcium hydroxide in concrete. The attack is usually accompanied by an expansion and subsequent cracking or spalling.

Long-term tests at Treat Island, Maine, by the U. S. Corps of Engineers led to some of the rules for designing and specifying concrete in a marine environment. It was thought until recent years that high cement content and cement with a low tricalcium aluminate content were the most important factors for good durability. However, the latest research at that site and others indicates that low water-cement ratio and the use of pozzolans are probably more important.

Pozzolans such as fly ash and silica fume react with free lime or calcium hydroxide in the concrete and prevent chemical attack.

Chemical decomposition of concrete occurs almost entirely in the cement paste and results in loss of binding capcity. Coarse aggregate particles become exposed and the loss of concrete surface can continue.

7.1.7 Environmental Considerations

Extreme cold or hot climates can have detrimental effects on concrete ships from two different deterioration mechanisms. Concrete in a freezing environment can suffer damage from being subjected to many freeze-thaw cycles. The damage is particularly acute in the splash or tidal zone where more freeze-thaw cycles occur. The proper design of concrete to resist this kind of distress is well-documented.

Concrete in hot climates is subject to greater damage from chemical attack than in cool or cold climates because the chemical reactions described earlier are greatly accelerated by heat.

The lighweight concrete ships considered in this report would likely be exposed to both hot and cold climates and should be designed to resist freeze-thaw conditions as well as saltwater attack.

7.1.8 Marine Growth

Concrete of the quality to be used in marine structures is not vulnerable to attack by marine borers or other marine creatures. The growth of barnacles on stationary or seldom-moved marine structures takes place rapidly but this growth is slow and of little concern except for loss of speed and freeboard on moving ships.

7.2 Considerations for Durable LWPC

7.2.1 Lightweight Concrete Durability

The most important quality for durable concrete in seawater is impermeability. Recent findings show that permeability of concrete in seawater decreases whereas in fresh water it remains nearly constant. This phenomenon is due to chemical reactions between ions in the seawater and hydrated cement producing crystallized products that precipitate and fill the pores near the surface with magnesium hydroxide otherwise known as brucite.

Permeability is dependent almost solely on the quality of the binding cement paste and not on the porosity of aggregates. Thus, a lightweight concrete with good quality paste (i.e., low water-cement ratio) will be as impermeable as normal weight concrete with an equal water-cement ratio. In fact, the permeability of lightweight concrete may be lower because of fewer micro-cracks. (See Figs. VII-2 and VII-3, from Ref. 1)

7.2.2 Corrosion Protection

Concrete cover over reinforcing steel should provide the most effective corrosion protection. The thickness of cover necessary to do this is controversial because it is more dependent on the quality of this concrete than the thickness.

In recent years, techniques for applying epoxy coatings on rebar have been developed and the process is now commonly done by many suppliers. Many state road authorities are specifying epoxy-coated rebar for floating bridges and bridge decks. The epoxy is applied as a powder and then put into electrostatic ovens. Rebar may be bent after this application without harming the coating. Research is currently being done by many agencies on the use of calcium nitrite as a corrosion-inhibiting admixture in concrete. Results to date look promising and some governmental bodies are trying it in bridge decks.

Cathodic protection of reinforcing steel is undesirable because the electrolytic state of the steel may change with time and reverse the polarity causing rebar or prestressing steel to act as an anode. Sacrificial anode protection may be desirable for steel embedments, inserts and other metals used in ships.

7.2.3 Prevention of Marine Growth

Concrete attracts marine growth and, if allowed to accumulate, is difficult to remove by ordinary scraping means with divers. Therefore, it is desirable to consider use of antifouling systems.

The U. S. Navy Civil Engineering Laboratory has extensively studied antifoulants on and in concrete for marine structures. They tested cuprous oxide and TBTO added as dry ingredients to concrete. Another internal application involved impregnating the lightweight aggregate with liquid toxicants. None of these treatments were very successful or cost effective.

It has been determined that antifouling coatings such as used on steel hulls perform well on concrete. Coatings should penetrate the concrete surface sufficiently so that they are leached out and released along with the marine growth. This may be hard to achieve on concrete which is made to be impermeable, but it is thought that a light sandblasting of the concrete surface should suffice.

The two successful antifouling coatings tested by the Navy Civil Engineering Laboratory were proprietary products. One contained organotin-polysiloxane and the other was a TBTO - impregnated elastomer.

7.3 Materials for Repair

7.3.1 Concrete Materials

Many maintenance and repair functions on concrete ships can be done with commonly available concrete materials.

- Portland cement - Cement should be a Type II or III (ASTM types) cement with a C_3A content of less than 8%. Bagged cement should be rotated frequently and stored in a dry place to prevent lumps.

- Aggregates - Readily available normal weight sand and gravel or limestone can be used for small repairs. Small-sized (1/2-inch minus) lightweight coarse aggregate may be necessary for replacing large sections of a hull. In all cases, the aggregates should have a history of producing durable concrete structures.

- Admixtures - Water-reducing admixtures should be used when mixing quantities over one cubic yard for repairs.

7.3.2 Rapid Setting Hydraulic Mortars

Many new polymeric, rapid-setting mortars are available. Most of these come conveniently packaged with all materials needed for repair. The shelf life of the polymeric, prepackaged mortar is usually much longer than that of portland cement in bags. The binder is often a polyester or acrylic liquid.

These materials are advantageously used where quick, thin, patches must be applied above or below the water line.

Rapid-setting mortars, either cementitious or polymeric can also be used as water plugs to stop ingress of water while repairs are made.

7.3.3 Epoxy Resin

Epoxies are rapidly developing as the most commonly-used bonding material or protective coating for concrete repair and maintenance. Epoxy formulations are available for applying on wet surfaces, concrete below water and under freezing conditions. Low viscosity epoxies can be pressure-injected into cracks as narrow as 0.004". Epoxy gels or pastes are available for patching thin areas or for use as a coating on concrete or steel.

Epoxy coatings are commonly used to protect splash zones but should not be used in lieu of good quality concrete. Any scratches or holes in the coating will expose concrete to seawater in a localized area and result in higher concentrations of the aggressive sulfates or chlorides in that area.

7.3.4 Aluminous Cement (Such as Cement Fondu)

High alumina cement offers better corrosion protection than does portland cement. It also has much faster strength gain, normally achieving its ultimate strength in 24 hours. A small amount of an accelerator, lithium carbonate, can be used with it to reduce the setting time to as little as 1 or 2 minutes after mixing. This has obvious advantages under emergency conditions at sea.

High alumina cement must be mixed with a water-cement ratio of less than 0.40 to prevent it from converting (losing strength) in warm or hot temperatures. It is a much more expensive and less available material than portland cement.

7.3.5 Urethane Foams

Recently, urethane foams have been used successfully to stop leaks through cracked or porous concrete walls. The liquid material can be sprayed at low to moderate pressure into holes or cracks where it will expand to many times its original volume. Bentonite has been used in this manner for many years, but it has poor resistance to seawater whereas urethane is said to be unaffected.

7.3.6 Latex

Latex bonding agents can be used for bonding new concrete to old where higher - cost epoxies are not needed. Latex can also be incorporated into portland cement mortars for improving toughness, tensile strength and freeze-thaw durability.

7.4 Planning for Repairs

Proper planning must be preceded by an evaluation of the damage or need for maintenance. If routine periodic inspections are made, this evaluation becomes a part of the analysis of inspection reports and the rate of deterioration can be monitored.

Fortunately, most distress in prestressed concrete structures becomes evident on the surface before failure occurs. Honeycombed or porous surfaces may indicate a compaction problem, discoloration may indicate loss of cement paste during placement of concrete and rust stains, indicating corrosion or cracks, signal a potential problem.

The availability of proper materials and trained labor to make repairs often determines when, where and how repairs will be made. Some repairs will require divers and underwater equipment not available at the time. It is assumed that maintenance crews on board a concrete ship would be knowledgeable of most of the repair methods that are described later. With few exceptions, repairs can be done with unskilled labor, at least on a temporary basis until permanent repairs are possible under better conditions.

The choice of repairing under "wet" conditions or "dry" is often made by necessity. Normally, better quality repair work is possible if the area can be made dry by surrounding it with a caisson or by dry-docking the entire ship. However, excellent repairs to leaking hulls can be made from the inside of a hull without divers. Materials described earlier make it possible to stop leaks while surfaces are readied for repair. Forms made from ordinary plywood or synthetic materials can be used to dam areas for repair without going outside the hull.

7.5 Repair Methods

Most repairs on concrete ships can be made with classical dry-land construction techniques. The following sections highlight some of these methods.

7.5.1 Concrete or Mortar Replacement

Damaged or deteriorated areas of a hull which require more than about one cubic foot of replacement material should normally be replaced with a high grade concrete mixture. If the area is large and requires more than, say one cubic yard, consideration should be given to using lightweight aggregate as in the original hull construction. Otherwise, normal weight concrete with a water-cement ratio of 0.40 or less and a maximum aggregate size of 1/2" or less can be used.

After the surface has been prepared (see later section), large areas are formed with plywood, wired to rebar with stainless wire or bolted to adjacent concrete surfaces, or formed with synthetic materials (e.g., nylon, fiberglass, reinforced plastics) and filled with concrete. Forms can be vibrated externally or a narrow opening may be left to insert an internal vibrator.

Small areas may be dry-packed with a stiff mortar. The depth-diameter ratio of the patch should be at least one to enable proper compaction of the dry pack. Shallow patches with a small area should be made by troweling in a portland cement mortar, epoxy mortar or polymer mortar.

7.5.2 Epoxy Resin and Epoxy Mortar Patching

Epoxies are very useful and convenient for small, thin patches and for filling narrow, deep holes where maximum protection is desired. Compatibility problems between epoxy and the substrate concrete should be considered, however, before large or thick neat epoxy or epoxy mortar patches are attempted.

The physical properties of epoxy and concrete, particularly lightweight concrete, are quite different. Differences in coefficient of thermal expansion, tensile and flexural strength and elastic moduli can introduce stresses between a patch and the substrate concrete that could cause failure of one or both. When one considers temperature changes, alone, in a concrete hull subjected to varying climates, and variations within the hull in one location, it should lead to alternative materials for large patches.

Normally epoxies should not be used where they would be exposed to temperatures above 140°-150°F unless a special epoxy with a high heat deflection temperature is used. Currently these special formulations are limited to about 350°F.

Epoxy resin formulations are available which permit mixing above water but application under water to stop leaks or to patch damaged or deteriorated areas. Often the compatibility concerns discussed above do not apply here because of uniform temperature and stress conditions below the water line.

One of the simplest techniques for underwater application of epoxy on concrete is to spread the epoxy on a piece of fiberglass or stainless mesh and have a diver press it into the prepared surface. The underwater epoxies have a high viscosity similar to a thick grease and will cure and harden at low temperatures (40°F±).

7.5.3 Crack Repairs

Cracks in a concrete ship hull are best repaired by pressure injecting a low viscosity epoxy resin into them. Cracks wider than about 0.012" on the deck or other horizontal surfaces can be repaired by veeing them out to a depth of 1/2"-1" and flowing an epoxy into them by gravity.

Pressure injection is preceded by sealing the crack full length except leaving 1/4"-3/8" wide openings for injection ports. Proprietary processes are available where the epoxy is injected through these openings from a rubber-tipped "gun" which also mixes the epoxy as it passes through it. For small amounts of crack repair or for emergency repairs when one of the above units is unavailable, 1/4" tubing, "Zerk" fittings or one-way polyethelene valves may be used as injection ports. Ordinary grease guns may then be used for pressure injecting. The spacing of the ports should be approximately equal to the depth of the crack. If water is in the cracks, it will be displaced and forced out ahead of the epoxy at ports above the one where injection takes place. As epoxy flows out of the adjacent port, injection stops and the injection port is sealed. Epoxy injection then begins again at the port above.

Cracks in structures underwater have been successfully repaired by the pressure injection process. The procedure is the same as above.

Normally, the curing time for the epoxy is 1-3 days depending on the temperature of the surrounding concrete.

7.5.4 Shotcreting

Shotcrete applications are extensively used for repair of marine structures where dry or damp conditions exist and where qualified applicators are available. Skilled operators are a necessity for all but portable hand-held units which require a minimum of experience. In the shotcrete process, a considerable thickness of concrete may be built up without the use of formwork. The gun-applied concrete is well compacted and can fill tight spaces otherwise hard to reach. The resulting surfaces are generally quite rough and uneven and 15-30% of the applied material is lost through rebound.

Small patches with sufficient depth to confine the applied material may be placed with small pneumatic guns. These are advantageous where a large number of patches are required with a minimum of labor.

Concrete containing short, wire fibers can be successfully applied by shotcreting. Fibrous concrete offers a high degree of toughness where impact or high thermal stresses may occur. Research has shown that the wire fibers do not corrode below the surface of the concrete when immersed in seawater.

7.5.5 Polymer Resin Patching

Several polyester, acrylic and latex prepackaged mortars are available and are excellent for easy mixing and application over small to medium sized areas. Most of these do not require a bonding agent prior to application of the mortar. Some mortars are available which set in 1-2 minutes after application.

For repairs in areas with a depth of over 3", consult the manufacturer to determine if the material is compatible with concrete in large volumes.

7.5.6 Repairs with Jackets

Nylon or fiberglass jackets are frequently used for splash zone or underwater applications to prevent erosion of the repaired area while the concrete is setting and curing. These jackets or flexible forms allow easy forming of complex areas. Concrete is pumped or tremied into the jackets.

7.6 Repair Techinques - Specific Types of Damage

7.6.1 Holes in Hull Plating

Permanent repairs to holes through hull plates are almost by necessity done in dry conditions. Repairs done in submerged areas can usually be sealed temporarily until that area can be taken out of water. (See Fig. VII-4, from Ref. 2)

Most holes caused by punching from impact or explosion would have a conical shape. It is best to retain this shape while preparing the area for repair to allow the patch to have a wedging action. Often the area must be enlarged by removing concrete to expose sufficient post-tensioning ducts and reinforcing steel to allow suitable splices to be made.

After the concrete surface is chipped back and the reinforcement is replaced, the concrete surface should be coated with a long pot life epoxy bonding agent. Forms are then placed and repairs made by the concrete replacement method.

A structural evaluation must be made if prestressed steel is damaged or broken. It may be possible to replace broken prestressing tendons with an externally applied post-tensioned tendon(s).

It is often possible to leave the forms permanently installed or, at least they should remain fixed until the concrete has cured for 7-14 days.

7.6.2 Damage to Framing Members

Reinforced beams or pilasters in a frame are often heavily reinforced and should be structurally analyzed if damaged. It is difficult or inadvisable to replace broken or damaged rebar by welded splices, which necessitates more extensive preparations.

Concrete should be chipped at least 3/4" away from any exposed rebar. If possible, an epoxy bonding agent should be applied to the rebar as well as the substrate concrete before concrete is replaced. The concrete replacement or shotcrete methods work well for these repairs. If cover over reinforcing steel is reduced or questionable, an epoxy sealer or other good quality surface coating should be applied for additional corrosion protection.

7.6.3 Spalled Concrete from Collisions or Impact

Most often these damaged areas are shallow and expose little, if any reinforcement. It is important when preparing the concrete for patching that the edges or shoulders of the damaged area be undercut or, at least, squared to prevent a feathered edge.

A bonding agent should be applied to the lightweight concrete substrate in order to prevent the absorptive lightweight aggregate from creating a starved glue line. Considerations for the choice of the many different patching mortars or materials were listed earlier.

7.6.4 Fire Damage

It is usually difficult to determine the depth of fire-damaged concrete unless non-destructive test methods are used, such as core-drilling and/or ultrasonic testing. Depending on the intensity and duration of the fire, the concrete is seldom damaged beyond the first layer of rebar. This can be determined by first removing this cover area and then testing the inner concrete.

Concrete or steel damaged beyond the outer concrete cover should require a thorough analysis before proceeding with repairs.

The removal and replacement of spalled concrete can be performed as for spalled concrete from collisions or impact.

7.6.5 Chemical Attack from Seawater

This problem can be treated according to the stage of deterioration. If it has been determined that chlorides have significantly penetrated the surface, but no corrosion of steel has occurred, a coating which limits further ingress of saltwater should be applied.

If it can be determined that chlorides have reached the reinforcing layer and exist in a concentration sufficient to lower the alkalinity of the concrete in that area to corrosive level (about 0.3-0.4% chlorides by weight of cement), a surface coating with chloride and oxygen reducing capabilities will provide sufficient protection.

In the more usual case where cracking or deterioration of the concrete is noted, the concrete is chipped back to behind the reinforcement until sound, uncontaminated concrete is reached. The steel should be treated with phosphate and coated with epoxy before the concrete is replaced.

Preparation and completion of the damaged area should proceed as above for spalling from impact. The choice of concrete or patching material should consider one which yields a very dense patch. The area may be further protected by application of a coating, if necessary.

7.7 Maintenance of LWPC Hulls

Routine inspection or monitoring of concrete hulls is highly recommended. Damage or deterioration caught in the embryo stage is much more easily fixed than after serious corrosion or distress occurs.

It is possible to measure active corrosion of steel in concrete by direct measurement of current flow. One side of a voltmeter is connected to an embedded, but partially exposed rebar or prestressing tendon while the other side is connected to a copper sulfate half cell. The half cell is put into contact with the concrete surface at suspect locations. It is now thought that if the potential measures more than 0.30 volts corrosion will occur.

Routine condition surveys of hulls should be made and suspect areas noted and monitored at shorter intervals. If the sign of distress progresses, the concrete should be examined by non-destructive testing to determine the significance of damage.

Provisions should be made in the design and construction of concrete hulls for making easier condition surveys. Rebar could be blocked out in select areas to allow access for a corrosion potential measurement. Walkways, ladders, ledges and other access devices should be included to make close-up inspections possible. Reference markings should be placed around, inside and outside the hull for easy identification of specific locations on the hull.

Most protective coatings applied to concrete need replacement or reapplication after a few years. Maintenance of these coatings should be part of the routine program.

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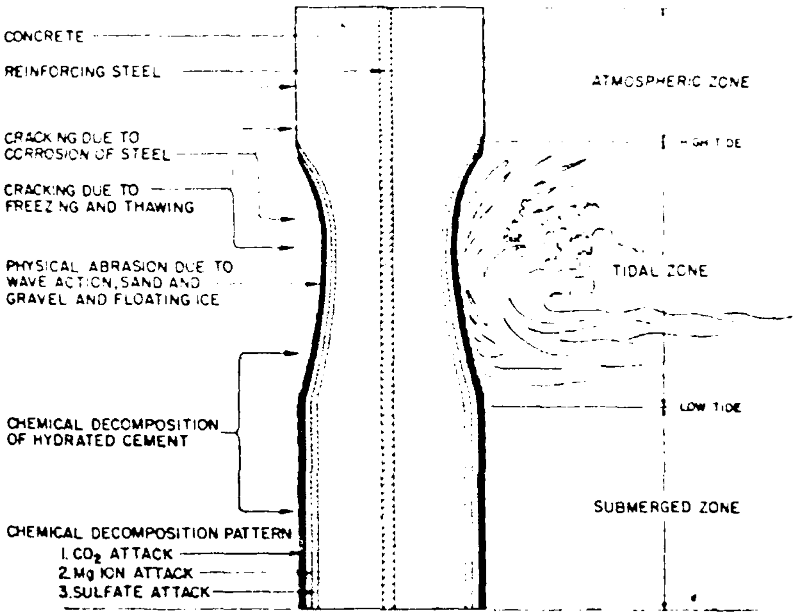

Fig. VII-1. Deterioration of a concrete structure in sea water.

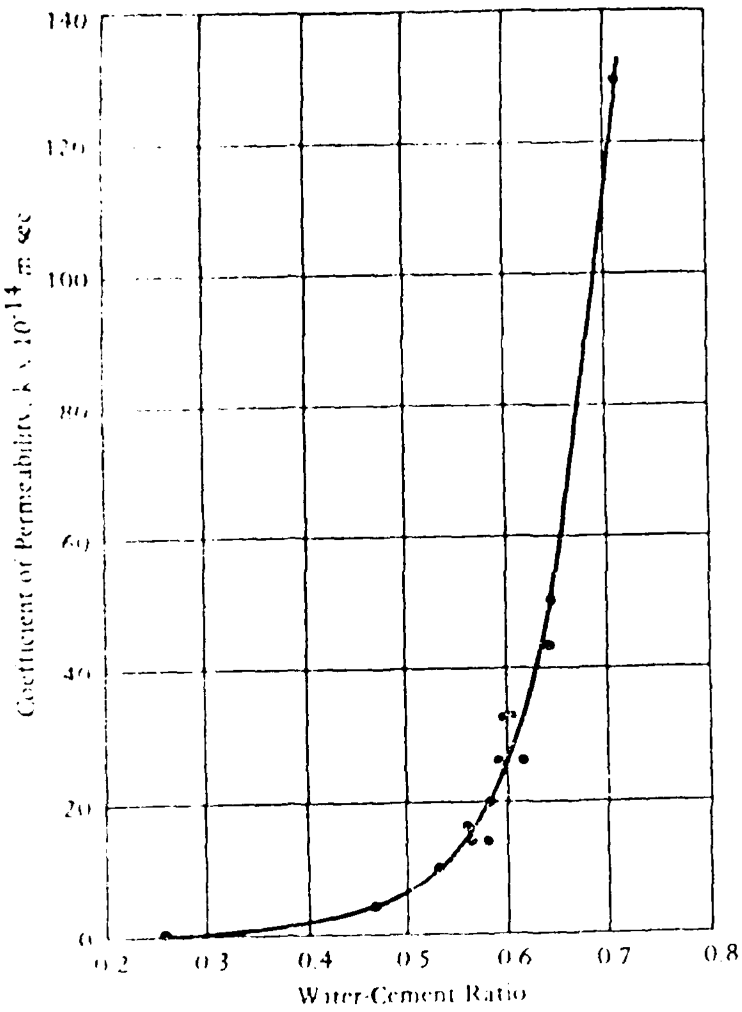

Fig. VII-2. Relation between permeability and water-cement ratio for mature cement pastes (93 percent of cement hydrated).

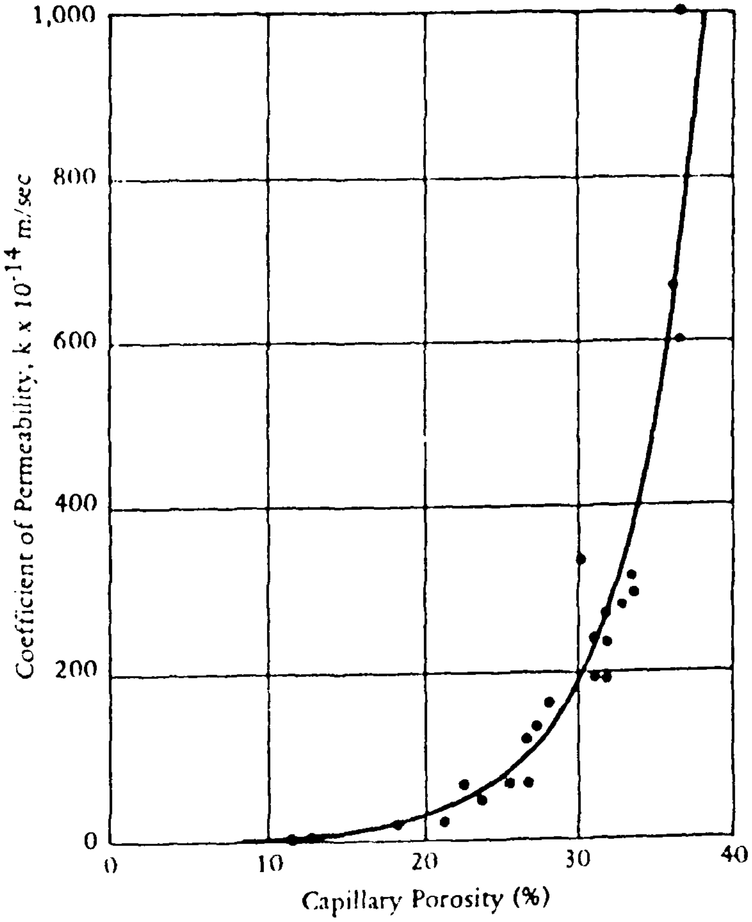

Fig. VII-3. Relation between permeability and capillary porosity of cement paste.

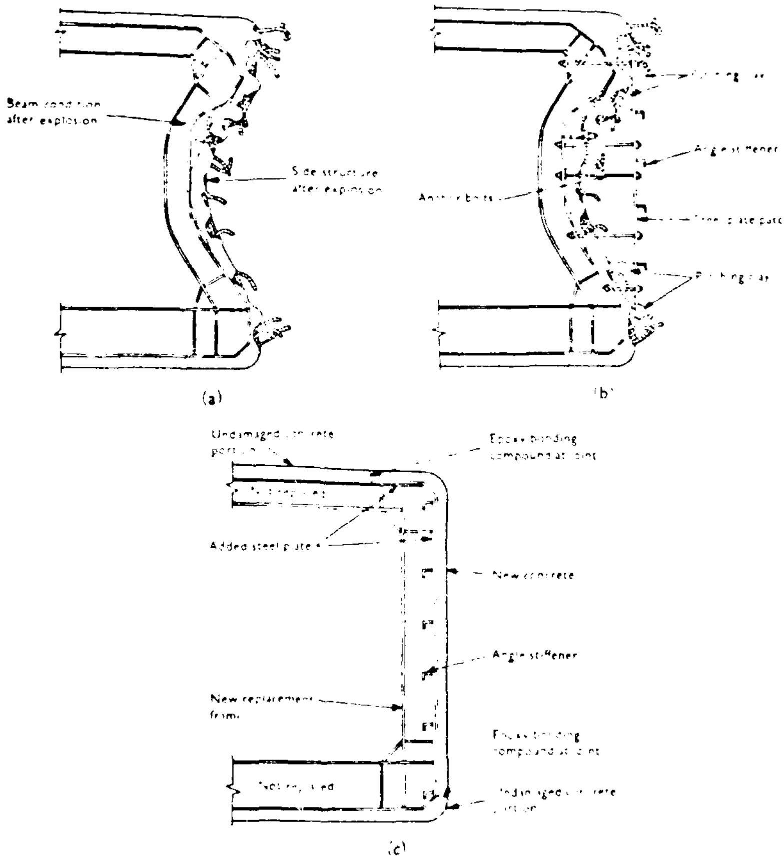

Fig. VII-4. Barge involved in mine explosion incident: (a) condition after explosion; (b) detail of temporary repair; (c) detail of repaired section.

SECTION VIII

SECTION VIII
CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

8.0 Suitable Applications of LWPC

LWPC is a feasible material for constructing ships' hulls. In fact, LWPC offers important advantages for hull construction as compared with current shipbuilding materials, including:

- proven durability and low maintenance;
- resistance to impact and blast;
- fire resistance;
- ductile behavior in cold temperatures; and
- availability of materials.

Comparisons with existing Navy steel ships indicate that LWPC hulls have a hull weight that is approximately twice that of the steel hull. Therefore, suitable applications of LWPC will be for hulls which are insensitive to the increased hull weight.

An investigation of the sensitivity of hull weight to LWPC material properties indicates that this weight ratio between LWPC and steel hulls can be reduced to approach a factor of 1.5 by plausible improvements to LWPC properties.

Comparisons with existing Navy ships also indicate that the initial construction cost of LWPC hulls is less than that of "equivalent" steel hulls. Therefore, reduced efficiency in vessel speed or capacity is offset by lower initial and maintenance costs and reduced vessel downtime for drydocking. Thus it appears the most suitable applications of LWPC as a shipbuilding material may be cargo vessels with a high deadweight/ displacement ratio or vessels which are infrequently moved. Therefore, the hull weight penalty imposed by LWPC will be a small percentage of the overall deadweight tonnage. Additionally, in times of emergency with a shortage of steel plate suitable for ship construction, LWPC will provide a suitable alternate shipbuilding material with domestically available material.

LWPC is suitable to the entire range of hull sizes investigated (see Section II). It appears that LWPC can be applied to both smaller and larger hulls. The weight penalty for LWPC will increase at some point for smaller hulls since plating sizes will be controlled by the minimum thickness to incorporate and protect reinforcement.

Currently, there is an increasing number of LWPC vessels being constructed for application as stationary floating vessels. This family of applications is suitable to deployment as various support vessels for the U.S. Navy. Potential applications of LWPC support vessels are:

- Floating Drydocks
- Floating Docks
- Floating Supply Bases or Shops
- Floating and/or Submerged Fuel Storage Facilities

All of these applications benefit from the advantages of LWPC hull construction with respect to steel construction. Further, applications as stationary facilities or facilities which are occasionally moved overcome the significance of the hull weight penalty. Floating docks, supply bases, and shops may be permanently moored at a deployment site or be mobile to allow quick deployment of these facilities to various sites. Examples of such applications are a floating 100-foot by 700-foot container handling pier for the City of Valdez, Alaska, and the ARCO LPG Facility discussed in Section V. Floating concrete vessels can also be grounded on the sea floor to act as partially or fully submerged structures. This application may be useful as fuel storage facilities. Grounded oil production faclities in the North Sea are examples of this application.

8.1 Recommendations for Research and Development

In order to better define specific properties of LWPC and in order to improve the viability of LWPC as a shipbuilding material, the following research topics are recommended.

8.1.1 Improve LWPC Strength - Weight Ratio

Baseline weight comparisons between LWPC and steel hulls have been based upon state-of-the-art structural lightweight concrete with a density of 130 pcf and a compressive strength of 6000 psi. Potential benefits from reduced density and increased strength have been identified. It is recommended that lightweight concretes be developed with the following characteristics:

Air-Dry Unit Weight	Compressive Strength, f'_c
75- 85 pcf	6000- 8000 psi
105-115 pcf	8000-10000 psi

Additionally, it is recommended that both glass and steel wire fiber reinforced lightweight concretes be developed in order to define their benefits in regard to concrete tensile and flexural strength, and impact and blast resistance.

8.1.2 Define LWPC Durability Requirements

The following research is aimed at better defining the durability of LWPC and developing LWPC design requirements for improved durability.

- Effective concrete cover for steel protection in ship hulls - quality and quantity.
- Acceptable and actual chloride levels in concrete marine structures.

- Critical chloride levels for depassivation of steel in concrete marine structures with different types of cement and cement replacement materials.

- Easy methods for determining corrosive levels of steel reinforcement in concrete ships.

- Oxygen diffusion flow rates for different concrete cover conditions and different cover depths.

- Influence of concrete tensile strength on growth of corrosion products.

- Performance of coatings to reduce chloride and oxygen penetration.

- Effective surface curing conditions for concrete ship hulls.

- Methods of designing and fabricating thin layers of wire fiber reinforced concrete for hull protection.

- Durability of wire-fiber reinforced concrete subjected to stress reversals in saltwater.

- Durability and maintainability of urethane foams for leak stoppages in saltwater.

8.1.3 Test Proposed Longitudinal Strength Design Criteria

A new limit state criterion for longitudinal strength of LWPC vessels has been proposed in Section 4.10 of this report. In order to define steel and concrete strain limits and factors of safety, testing is recommended to investigate the low cycle, high amplitude fatigue behavior of reinforced and prestressed LWPC sections. This testing should be performed under a hydrostatic head in order to model hydraulic effects on opening and closing cracks.

8.1.4 Reduce LWPC Hull Construction Cost

The construction cost of LWPC hulls can be improved by the use of repeatable details. Therefore, vessels with a long parallel middle body will provide a LWPC hull with the lowest initial cost. The efficiency of such hull forms should be investigated.

The construction of hulls without a parallel middle body may be simplified using formwork with panels which can be adjusted to vary its geometry, thus offering potential construction cost and schedule benefits. Adjustable formwork concepts should be developed in order to quantify these benefits.

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