World's Largest Prestressed LPG Vessel
• Design • Construction • Marketing

by
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Design-Construction-Marketing Highlights of

World’s Largest Prestressed LPG Floating Vessel

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Synopsis
The world’s largest precast prestressed concrete floating liquefied petroleum gas (LPG) facility is described. Criteria for design and construction of the 375,000-barrel floating facility are given. Construction procedures and prestressing methodology are discussed. Problems related to the development and marketing of prestressed concrete for marine construction, and prospects for future applications of prestressed concrete sea structures are presented.
The world's first large prestressed concrete floating, totally offshore facility for liquefied petroleum gas (LPG), was recently installed at a permanent mooring in Indonesia. Shown in Fig. 1, the 65,000-ton vessel was designed by ABAM Engineers, Inc. and constructed by Concrete Technology Corporation, in Tacoma, Washington. It was then towed 10,000 miles (16,000 km) across the Pacific Ocean to the Ardjuna oil and gas field in the Java Sea (Fig. 2). This field is in an earthquake belt, where the water depths range from 100 to 135 ft (30 to 40 m).

LPG at +45 C (113 F) and pressurized in underwater pipelines is transmitted to the facility for cooling to -45 C (-49 F) and stored in 12 insulated steel tanks whose capacity is 375,000 barrels (30,000 metric tons).

The nearest coast, some 20 miles (approximately 32 km) to the south, is marsh and mud terrain, unsuitable for heavy industrial construction. Although the Java Sea is subjected to gales up to 75 knots (138.9 km/hr), with sea waves reaching 27 ft (8 m), the following factors favored a floating structure:

- Seismic loads on the structure and its complex equipment were avoided.
- Time and cost demands were less than those for land-based construction.
- The total facility, including the hull, tanks, machinery, piping and electrical systems, was constructed at a location near sources of technically-skilled manpower and support industries, making it possible to deliver a complete package.
The following factors favored prestressed concrete for the hull construction:

- Lower initial cost.
- Less maintenance cost, since concrete is corrosion-free in salt water.
- Periodic drydocking for inspection, repair and painting is unnecessary.
- Superior fire resistance.
- No problems associated with cyclic loading and fatigue.

For more than a century, the marine industry has been iron-and-steel oriented. Only during times of plate shortage (the two world wars) has concrete been seriously considered for large ships' hulls. Although a number of concrete ships performed well on the high seas, steel regained its exclusive status when it again became available.
In gaining acceptance for a prestressed concrete floating facility, an early obstacle was removed when the owners received assurance from the American Bureau of Shipping that it would classify the vessel for insurance purposes.

Ship classification societies have served a unique role in the design and construction of sea-going vessels for more than 150 years. Institutions such as Lloyds Registry (British), Bureau Veritas (French), Det Norske Veritas (Norwegian) and the American Bureau of Shipping have formulated “rules” for ship design and construction.

These societies also critically review vessel design for rules compliance as they relate to structural adequacy and seaworthiness. Their “surveyors” carry out detailed inspections, not only during construction but also periodically during the service life of each vessel.

Before a vessel is deemed insurable, the owner must obtain a document from the ship classification society, whose dry-land counterpart would be a combination of institutions like the ACI and AISC for codes, structural, electrical and mechanical engineering firms for design review, building officials for approvals and permits, and inspection agencies for compliance.

Obviously, the ship classification societies have tremendous authority and responsibility in their role of passing judgment on the insurance risks for ships. Over the years, their rules have been largely based on past experience (hindsight), and gradually extrapolated into the future.

Thus, the introduction of prestressed concrete as a hull material posed some unusual problems regarding classification, mainly because it lacked sufficient seagoing experience.

When comparing sea structures to buildings and other land structures, one is immediately impressed with the complexity of loadings endured by ships and other sea structures; not only are the stress magnitudes more difficult to quantify, but also they are further complicated by millions of cycles of stress reversal encountered during service life.

Failures in steel ship structures due to fatigue and stress concentrations have caused the maritime authorities many traumatic experiences. It is only natural that they would take a cautious approach to a brittle, low-tensile-strength material like concrete which is susceptible to cracking. But unlike steel plating, the cracks in prestressed concrete close with the passing of peak loads.

The proposal for the prestressed concrete vessel was made to the owners, a group of American companies and Pertamina, the Indonesia State-owned oil company, with the Atlantic-Richfield Company as the operator.

<table>
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<th>Design Considerations</th>
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<td>The following functional requirements governed the design of the prestressed concrete hull:</td>
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<td>(a) Liquefaction by refrigeration of 18,000 barrels of petroleum gas per day.</td>
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<td>(b) Storage capacity of 375,000 barrels of LPG.</td>
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<td>(c) A complete installation of electric power plant, refrigeration, piping, and instrumentation.</td>
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<td>(d) Complete accommodations for a 50-man crew.</td>
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<td>(e) Crane service for maintenance.</td>
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<td>(f) Life boats and heliport.</td>
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The optimum geometry for LPG storage was determined to be 12 cylindrical tanks with hemispherical ends, and with a 38-ft (11.6-m) diameter and an overall length of 168 ft (51.2 m). With these dimensions, an arrangement with six tanks below and six tanks above deck was adopted. Allowing for the electric power and refrigeration plant abaft the tanks, the crew's accommodations forward, the overall dimensions were established:

- Length: 461 ft (140.5 m)
- Beam: 136 ft (41.5 m)
- Depth: 56.5 ft (17.2 m)

The hull section was then developed to satisfy functional requirements, along with strength and vessel stability. For strength, the hull was required to satisfy two principal loading conditions:

1. Local loads against the shell from hydrostatic pressure heads up to 50 ft (16 m).
2. Global loading on the total hull functioning as a box girder poised on waves up to 27 ft (8.25 m) high and 461 ft (140.5 m) long (equal to the length of the hull).

The hull bottom naturally evolved into three cylindrical barrel shells (Fig. 3) whose shape efficiently functions to resist a 3,000 psf (14.6 T/m²) 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 trans-
verse ribs and longitudinal stiffeners of the type used with steel hull construction.

To resist the longitudinal bending caused by the various combinations 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 accommodating unencumbered by the local 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 1:

Note that zero tension in the concrete was stipulated for the delivery voyage and for normal service at the mooring in the Java Sea. A conservative policy was adopted regarding allowable tension in the concrete under longitudinal hull bending. This resulted in the ultimate load factors given in Table 1.

In the case of local bending due to hydrostatic pressure, a tension of $5\sqrt{f_c'}$ 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.

When compared with established shipyards, equipped with building ways and graving docks, Concrete Technology Corporation had only one

<table>
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<th>Table 1. Assumed Wave Heights and Stress Limits, ARCO Facility.</th>
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<td>Sea Conditions</td>
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<td>Wave height</td>
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<td>Max. allowed stress</td>
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<tr>
<td>Cracking load factor</td>
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<td>Ultimate load factors: Required</td>
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<td>Actual</td>
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thing in common, a site located on
deep industrial waterway. Conse-
quently, upon receipt of notice to pro-
earrowceed, a graving dock 500 ft (152.5 m)
in length and 160 ft (47.8 m) wide had
to be constructed.

Providing for a launching draft of 13
ft (3.96 m) concurrently with the grav-
ing dock construction, detail design of
the concrete hull and production tool-
ing was underway (Fig. 4).

Fig. 4. Graving dock and delivery of 40-
ton bottom hull segment.

Construction

The hull construction scheme is
shown in Fig. 5. The hull bottom is
made of precast concrete shell
segments, (a), which are delivered to
the graving dock, (b). Vertical side
shell and longitudinal bulkheads are
cast in place, (c). The partially
completed hull is launched, (d). When
afloat, the lower six tanks are
installed, (e), and remaining hull
concrete is cast in place, (f).

During the graving dock
construction, bottom shell segments
were match-cast in steel forms (Fig. 6)
and stockpiled. Each element was
reinforced and provided with ducts for
both longitudinal and transverse
tendons. The 40-ton bottom shell

### SIZE OF HULL AND
NUMBER AND DIMENSIONS
OF PRECAST COMPONENTS

#### Size of Structure

Hull dimensions: 461 ft long x
136 ft wide x 56.4 ft diameter
Concrete volume: 12,000 cu yds
Prestressing: 600 miles of 1/2-
in. diameter strand
Weight: 65,000 tons displacement (fully loaded)

#### Number of dimensions of precast components

- Quantity of precast curved shells: 120
  Length: 11 ft 2 in.
  Overall width: 45 ft
  Rise: 13 ft 2 in.
- Midship bulkhead
  Uniform thickness: 1 ft 4 in.
  Twelve precast plates, approximately 40 ft wide and 8 ft high
  Three crescent-shaped plates at keel
- Bow plate
  Three beams: 3 ft thick by 40 ft long, haunched from 6 ft at midspan to 9 ft at ends.
  Twelve plates 40 ft long by 8 ft high with tapered cross section from 18 to 24 in.
  Three crescent-shaped plates at keel.
  Three plates 6 ft high by 40 ft long, pentagon-shaped cross section.
Fig. 5. Construction sequence.

a. Match Castings of Shell Segments

b. Setting of Shells in Graving Dock

c. In-place Casting of Longitudinal Bulkheads, Saddles and Transverse Bulkheads

d. Launching Stage

f. In-place Casting of "Δ" Plates and Deck

g. Placing Deck Tanks and Final Outfitting
Fig. 6. Match-casting, precast concrete bottom shell segments.

Fig. 7. Erection of the bottom shell.

Fig. 8. Formwork for cast-in-place longitudinal bulkhead, and delivery pipeline for pumped concrete.
Fig. 9. Reinforcing steel and ductwork for post-tensioned tendons.

Fig. 10. Bottom shell, longitudinal bulkheads and prestressed concrete saddle tank supports.
Fig. 11. Erection of precast midships bulkheads and construction progress on vertical front.

Fig. 12. Bottom rake construction at forward end.
Fig. 13. Erection of vertical shell element at after end of hull.

Fig. 14. Aerial view of hull readying for launching.

Fig. 15. Float-out of the hull lower section.
Fig. 16. 400-ton steel tank for LPG storage.

Fig. 17. Erection of steel tank into concrete hull.
Fig. 18. Lower tier LPG tanks in place.

Fig. 19. Concreting of upper hull and deck with movable steel forms.
Fig. 20. Stressing of U-shaped vertical tendons.

Fig. 21. Erection of precast saddles for above-deck tanks.

Fig. 22. Completion of upper hull construction, and erection of precast vertical shell closure plates.
Fig. 23. Histogram of 28-day cylinder compression strength tests, hull concrete.

Fig. 24. Electric power plant and refrigeration module in place.
Fig. 25. Departure of the 65,000-ton “Ardjuna Sakti” from Concrete Technology Corporation, on 10,000-mile delivery voyage to Indonesia.

Fig 26. Aerial view of completed vessel being towed to its destination in Indonesia for installation at a permanent mooring.
members were placed on precast concrete supports which, in turn, were supported by prestressed concrete piles (Fig. 7).

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. 8). The transverse tendon ducts projecting from the bottom segments were coupled with those in the vertical sections (Fig. 9). 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. 10) and at the midship section, where vertical precast elements were introduced for the amidship bulkheads (Fig. 11).

A 45-deg rake to the bottom shell at the forward end was provided to reduce towing resistance on the 10,000-mile delivery voyage (Fig. 12).

Concreting of the lower 40 ft (12 m) of the hull and erection of the end shell members (Fig. 13) made the hull ready for launching (Fig. 14).

The dock was then flooded and opened, and with the aid of tugs, the hull was moved to the outfitting pier (Fig. 15).

Concurrently with hull construction work on the tanks, refrigeration and electrical plant and crew’s housing structure was underway nearby. The fabrication and insulation of the 12 tanks was an operation of the same order of magnitude as the hull construction. This work was done by American Bridge Company at the Concrete Technology Corporation site (Fig. 16).

The 400-ton tanks were lowered into the hull by a pair of stiff-leg derricks installed especially for this purpose (Fig. 17). Each tank was seated on end-grain cedar pads built into the concrete saddles, and then securely strapped down (Fig. 18).

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. 19). 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 1,200-kip (545 metric ton) final force in the circular path provided the desired safeguard against cracking during tilt-up and erection of the saddle element (Fig. 20). 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 (Fig. 21).

Most tendons consisting of 6-, 8-, and 12-in. 270-kip, seven-wire strands were
stressed and anchored, utilizing the Anderson system. Approximately 600 miles (about 1,000 km) of 1/2-in. 270-kip strand wire was used in the concrete hull structure.

When the concrete deck was completed, the ends were closed in by erection of the precast vertical panels. (Fig. 22).

Quality control of the construction was rigorous and under constant engineering supervision. Special attention was given to the concrete mix, in which a water-cement ratio was held to 0.4 or less.

As can be seen from Fig. 23, an average 28-day cylinder compression strength of 9,800 psi (66 MPa) with a coefficient of variation of 6 percent was achieved.

The mechanical, piping, and electrical installations were subcontracted to firms specializing in services to the marine and petroleum industry. A 500-ton machinery module was preassembled and erected on the after end as a package unit (Fig. 24).

Concurrently, a multistory housing module for a 50-man crew was constructed. It was moved to the edge of a nearby wharf. The hull was nosed into the wharf with tugs, and the 600-ton module was rolled on board and bolted securely to its foundation.

Fig. 25 shows the vessel completed and ready for departure on the 100-day, 10,000-mile (16,000 km) delivery voyage. Aerial shots of the vessel being towed to its destination in Indonesia are shown in Figs. 26 and 27.

### Concluding Remarks

The potential for utilizing prestressed concrete in marine construction is cause for optimism.

Ship classification societies and government regulatory agencies must be persuaded that, when properly designed and constructed under appropriate quality control, prestressed concrete should become a preferred (or at least equally acceptable) material for hull construction.

However, prestressed concrete might not be competitive for hulls carrying cargo on long voyages because the pay-load/total weight or dead weight/displacement, in nautical language ratio is substantially less with concrete hulls compared to steel construction. This was clearly demonstrated with the self-propelled concrete ships built and operated during the periods of 1917-1920 and 1942-1945.

When used as barges or floating structures, mainly on stationary service afloat, the advantages for prestressed concrete versus steel become obvious. Among these advantages, the following must be recognized:

- Lower initial construction cost.
- Superior durability in sea water environment.
- Ductile behavior when severely overloaded.
- Freedom from damage under fatigue-type loads.
- Excellent properties at extremely low (cryogenic) temperatures.
- Superior behavior when exposed to fire.
- Easy to repair when damaged by collision, etc.
- Drydocking at regular intervals for inspection, repair, and maintenance not necessary.
The concrete industry lacks a long, continuous track record for sea-going vessels. Nevertheless, a few examples, some old and some recent, are impressive:

1. A breakwater at Powell River, Canada, consists of 10 concrete ships, one built in 1918 and nine built in 1942-1944. None have been drydocked, nor has any money been spent on maintenance.

2. About 12 years ago Alfred Yee designed and constructed several dry and liquid cargo barges made of pretensioned concrete. These 200-ft (approximately 60 m) barges, with a 200-ton DWT capacity, have performed excellently in the Southeast Asia area during the last 10 years.

3. Several large North Sea oil structures are now in place. Despite severe storms, they have performed well.

Fig. 27. Aerial view of completed vessel being towed to Indonesia.

Credits

Structural Engineer: ABAM Engineers Inc., Tacoma Washington.
General Contractor-Precaster-Prestresser: Concrete Technology Corporation, Tacoma, Washington.
Owner: Atlantic Richfield Indonesia, Inc., and the Pertamina Group, a government-owned Indonesian oil company, Djakarta, Indonesia.
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