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Structural Design Criteria for the Safe and Economical Transportation of Liquefied Natural Gas

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ABSTRACT

Major problems in the engineering design of ship structures have emerged from the requirements for specialized vessels to transport liquefied natural gas (LNG).

Transporting the largest volumes of cryogenic cargo ever carried, our vessels will ply but a single trade route, and they must meet strict draft limitations and stringent delivery rate requirements. They must be built and operated to provide an extra margin of safety and a long service life. They must meet or exceed all regulatory requirements.

It has been necessary to develop new designs for structures, and to utilize the latest analytical techniques in order to evaluate and optimize the designs. The techniques include fleet modeling, three dimensional finite analysis and model basin tests.

Quality control is important, especially in design definition and review, material selection and control, and inspection.

Although there has been substantial progress in the design of structures for LNG ships, there is still considerable work to be done.

INTRODUCTION

The marine transportation of liquefied natural gas (LNG), which began in the late 1950's, brought with it major problems in the engineering design of LNG ship structures. New designs had to be developed. Advanced design analysis and testing tools had to be utilized. Construction specifications had to be strengthened.

Although there was considerable progress during the 1960's, the structural design of LNG carriers is still a significant challenge, a matter which would likely be confirmed by just about anyone in the field.

In this paper, we are going to describe the El Paso LNG Company's approach to meeting the challenge. We will review our initial project in the marine transportation of LNG. We will enumerate our basic design parameters. We will describe our basic design criteria. We will explain how we are meeting those criteria. Finally we will look ahead to structural design problems in need of attention in the future.

THE ALGERIA I PROJECT

The El Paso LNG Company entered the LNG business in the late 1960's and on October 1, 1969, the company and Sonatrach, the national oil and gas company of Algeria, reached agreement on a project to import large quantities of LNG into the United States. The volumes are equivalent to one billion cubic feet of natural gas per day. The project is of particular significance because it is the first (and at this writing, the only) importation project to the United States in which baseload requirements will be met with LNG, and it is a pioneering response to the challenge raised by the nation's critical need for energy.

Sonatrach will produce the natural gas from the vast reserves of the Hassi R'Mel field in the Algerian Sahara, and will liquefy the gas at a major new facility near Arzew, a city on Algeria's Mediterranean coast. El Paso will transport the LNG with a fleet of nine 125,000 cubic meter ships, and deliver it to regasification plants at Cove Point, Maryland, on the Chesapeake Bay and at Elba Island, Georgia, not far from Savannah. The volumes carried will comprise the largest quantities of cryogenic cargo ever transported up to this time.

Three of the nine ships are being built by Chantiers de France-Dunkerque, and the cargo tanks are of a Gaz-Transport membrane design. The membrane is constructed of Invar. Three others are being built by Newport News Shipbuilding & Dry Dock Company, and the membrane type cargo tanks were designed by Technigaz and constructed of stainless steel. The final three are being built by Avondale Shipyards, Inc., and the free-standing type cargo tanks were designed by Conch and built of aluminum. (LNG ships utilizing other containment systems may require other considerations not covered in this paper.)

All three classes of ships will have steam turbine propulsion plants. The boilers will burn both bunker fuel and LNG boil-off vapors, a feature which is unique to LNG ships. This feature allows us to utilize the LNG boil-off which would otherwise have to be reliquefied to prevent its release to the atmosphere.

Although the LNG ships are similar in many respects to modern bulk carriers, they are in other respects specialized. Unlike most of the bulk carriers, the LNG ships will ply but a single trade route, one which will impose a strict limitation on draft. They will deliver a specified volume of cargo annually at a specified rate. They are designed to assure an extra margin of safety.

BASIC DESIGN PARAMETERS

The basic parameters for the design of structures were derived from both the conventional considerations and from the specialized requirements for the LNG ships. They include: draft limitations, delivery rate requirements, cargo characteristics and service life requirements.

Draft Limitations

The waters surrounding the Cove Point, Elba Island and Arzew terminals are only about 12.2 meters (40 feet) deep at low tide. This restricted the draft of the LNG ships to 11.00 meters (36 feet), which leaves only 1.2 meters (4 feet) of water beneath the keel for safety.

Delivery Rate Requirements

Contract delivery rate requirements called for the average delivery of the equivalent of one billion cubic feet of natural gas per day. Based on subsequent economic and engineering work to optimize the fleet, the cargo capacity was set at 125,000 cubic meters (876,000 barrels); the ship service speed was set at 18.5 knots, and compartmentation was to be designed to permit simultaneous cargo transfer and ballasting or deballasting in order to compress turnaround time in port.

Cargo Characteristics

The LNG to be transported has a liquid specific gravity of 0.487, less than half that of water, and it has a boiling point at near atmospheric pressure of -162 degrees Centigrade (-260 degrees Fahrenheit), the conditions at which it is transported.

As a liquid, methane is not combustible, but when vaporized and mixed in the proper proportions with air (5 to 15 percent by volume) it will burn. Ignition of a flammable mixture of air and methane in open areas produces a flame with a slow and even burning rate. A methane and air mixture will not explode in an unconfined space. LNG is colorless and odorless.

LNG presents no hazard unless accidentally released from its containment system. Upon release, its greatest hazard is the flammability of the LNG vapor which is generated immediately on contact with ambient temperature surfaces. A cubic meter of LNG equals approximately 600 cubic meters of natural gas at 15.5 degrees Centigrade (60 degrees Fahrenheit) and atmospheric pressure. This significant volumetric reduction permits large quantities of natural gas to be stored and transported economically (as LNG) at near atmospheric pressure in tanks of reasonable size.

The most likely accidental release of LNG from an LNG carrier would occur as a result of a collision between the LNG ship and another large ship. The many ignition sources on both ships (boilers, electrical equipment, etc.) plus the heat and sparking of the collision would ignite the LNG vapor immediately and the resulting fire would burn at the ship.

The low specific gravity influenced the design of scantlings. The cryogenic temperature of the cargo governed selection of materials. The hazardous nature of LNG required a double hull design to help protect the cargo tanks in the event of casualty.

Service Life Requirements

The 25-year service life is required primarily because of the economic considerations. LNG carriers are extremely costly.

From the structural design standpoint, the long service life requirement affects the scantlings design, structural arrangement, the corrosion protection system, provisions for maintenance, and the degree of quality assurance. These are discussed later in the paper.

DESIGN CRITERIA

Once the basic parameters were established, we developed fundamental design criteria. Our designs would meet or exceed the existing requirements of the applicable regulatory bodies. They would be optimized to meet project requirements. They would require high quality to assure a 25-year service life.

Requirements of Regulatory Bodies

The criterion of equaling or exceeding the requirements of regulatory bodies is difficult to meet, primarily because the requirements have been in a state of development for the past several years. The designer has had to do a lot of "wing shooting," frequently basing design decisions on experience and judgment rather than well defined regulations. This situation, of course, raises distinct possibilities for misunderstandings and communication breakdowns, and redoubles the need for design followup to assure compliance with the objective of anticipated regulatory requirements.

As is well known, the overwhelming majority of existing requirements appear in the U. S. Coast Guard regulations. The International Maritime Consultative Organization (IMCO) is presently finalizing its "Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk" (IMCO Gas Code), which will contribute to the establishment of uniform design and construction standards and to the integrity of the world LNG fleet.

From the standpoint of structural design, the requirements can be grouped into five major categories:

1. The structure must be designed to assure "adequate" positive initial stability under all conditions.

2. Two compartment subdivision over the entire length of the ship is required.

3. The distance between shell plating and the cargo containment system must equal or exceed specified minimums.

4. Safety factors, design parameters and testing requirements are defined for the containment system and supporting structure.

5. Standards for structural steel grades and testing for various design temperatures are defined.

It appears that uncertainties regarding requirements of regulatory bodies will be alleviated to a large degree in the near future. The Chemical Transportation Industry Advisory Committee (CTIAC) task group which was formed to advice the U. S. Coast Guard on regulations for gas carriers has largely finished its work. The work has been coordinated with the IMCO effort. Following passage through the U. S. Coast Guard rulemaking procedure, the work will be incorporated into the Code of Federal Regulations. The incorporation of the provisions of the IMCO Gas Code in the Code of Federal Regulations by the U. S. Coast Guard will produce the most advanced and comprehensive regulations available for LNG ships.

Design Optimization

The criterion of optimizing the design was met by exhaustive engineering studies, model tests and advanced analytical techniques. These methods for design development will be discussed more fully at a later point.

The optimization of the design was of particular importance because of the specialized nature of the LNG ships. The process led to a hull design quite different from that of comparable oil tankers. The length-to-depth ratio, for instance, is roughly 9.9 for the LNG ship compared with about 13.8 for a typical oil tanker (Figure I).

Service Life Requirements

The criterion of designing and building a ship for a service life of 25 years is met in three basic ways. Specifications are developed for full ABS scantlings and for corrosion protection systems; extra design provisions are made for maintenance and reliability; and although it is not a design function in a strict sense, every effort is taken to strengthen design review and quality control throughout construction. These measures will be discussed more fully at a later point.

EL PASO DESIGN APPROACH

It is well understood that the structural design of a ship—especially a new type of ship—is an extraordinarily complex business. It is not within the scope of this paper to describe our design work in detail, but rather to offer an overview through a brief review of several major areas: design development and verification, material selection, compartmentation design, ballast tank drainage provisions, personnel access provisions and corrosion control.

Design Development and Verification

Three basic techniques are of instrumental importance to our work in design development and verification. These include three dimensional finite element analysis, model tests and engineering studies.

Three dimensional finite element analysis is performed both for the main hull girder and for the after body of the ship. For the main girder, the analysis must encompass sufficient length to assure reliable answers. This amounts to at least two cargo tank lengths. The objective is to establish stress levels and hull girder deflections. This was required in order to ensure structural adequacy and compatibility between the hull structure and the containment system.

There are numerous instances in which the analysis has led to alterations in structural design. For instance, on each of our three designs, the strength of the hull girder was increased beyond regulatory requirements to ensure that deflection levels were maintained within an acceptable range as specified by the containment system license.

For the ships equipped with the Conch cargo containment system, heavier plates were required in the lower inner hull knuckle, and an access opening was deleted between stringers No. 4 and 5 (Figure II) at each transverse web. Investigation revealed that similar areas had experienced cracking on earlier LNG carriers, which had been designed without the benefit of three dimen-

Fig. 1 . COMPARISON OF LNG CARRIER AND OIL TANKER

	LNG Carrier (Avondale)	Oil Tanker (Typical)
Cargo Capacity	125,000 m^3	125,000 m^3
Deadweight Tonnage	63,000 LT	110,000 LT
Overall Length	284.0 m	274.0 m
Beam	42.8 m	39.6 m
Depth	28.6 m	19.8 m
Draft	11.0 m	15.2 m
Block Coefficient	0.74	0.82
SHP	41,000	23,000
Service Speed	18.5 Kts	16.0 Kts
Hull Structure	Double Skin	Single Skin
Structural Materials	Selected Materials Resistant to Cryogenic Temp.	No Materials Resistant to Cryogenic Temp.

sional finite element analysis. There are many other examples in which alterations have been made. In some instances, increasing scantlings, in other cases, reducing scantlings.

For the after body, the analysis encompasses all structure aft of the mid-span of the aft cargo tank, and includes the deckhouse. The objectives are to verify structural integrity, establish vibration levels and determine deflection values associated with the shafting and main engine foundation system. Again a variety of significant design alterations have resulted from these analyses.

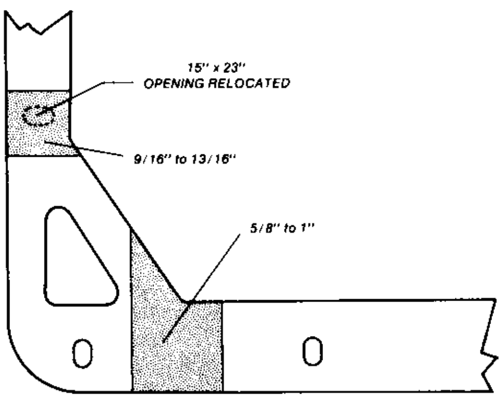

Fig. II. STRUCTURAL MATERIAL, DESIGN ALTERATION

We conducted an extensive model basin test program in 1970 and 1971 to evaluate three types of hull configurations: conventional stern, a bulbous or hogner stern and an open stern with a single strut. The objectives were to optimize propulsion efficiency and to reduce alternating vibratory responses. This was especially important because of the draft restrictions and high shaft horsepower requirements. Self-propulsion tests, wake distribution tests, propeller optimization tests, strut flow tests, cavitation tests, maneuvering tests and seakeeping tests were all carried out to evaluate the designs.

As a result of the tests, open stern configurations were selected for the France-Dunkerque and Newport News ships. Data had indicated that vibratory input due to the uniform wake pattern would be reduced with this design, allowing higher shaft horsepowers to be utilized.

A modified bulbous type stern was selected for the Avondale vessels. Additional model basin tests conducted in 1973 indicated that a satisfactory vibratory response could be expected, and that the propulsion efficiency would be higher, thus achieving our design goal at a lower cost. The designs of our other two classes of ships were too advanced to incorporate the modified bulbous stern, thus the open stern was retained.

The model basin tests, which included runs in a vacuum tank, were of an advanced nature. Although we are confident of the results, the data have not been verified by actual experience, and we therefore intend to instrument the first ship from each yard in order to confirm our predictions. This may well be the subject of a later paper.

In addition to three dimensional finite element analysis and model tests, numerous engineering studies of localized design features have been done. They include, for instance, structural keys on Conch tank design, hatch openings for the dome tops, local panel structure in the stern, propeller struts, shafting and shafting supports, main engine foundations and transition structures. The objective was to recognize potential problems and to solve them before they actually arose. Several design changes have resulted from this work.

We also have had to pay particular attention to thermal stresses imposed on the hull girder and localized areas. These are a function of the type of cargo system, and are additional to the stresses imposed by bending, shear, etc.

The dynamic loading imposed by the sloshing of LNG has been another area of concern. Various programs in Europe and the United States have attempted to model the sloshing to obtain scaling criteria for pressure data for use in the design of containment systems and hull support structure, but there is still considerable work to be done. Without reliable internal dynamic loading values, the design loads for the containment support system and the hull structure cannot be scientifically designed. Sloshing considerations also reflect on the partial loading of the cargo tanks. For certain designs, specific partial loading levels must be avoided because of high stresses imposed by sloshing.

Material Selection

The problem of material selection arises from the well known fact that mild steel becomes increasingly less notch tough as its temperature decreases. As a result, alloys of molybdenum manganese and nickel and the appropriate heat treatment have to be utilized to ensure that the steel will not fail in areas on the inner hull where the temperature gets as low as -50 degrees Centigrade.

For a midship section of a vessel containing a free-standing cargo tank design, typical grades of steel for the inner hull might include: B, C, CN, CS, (MOD.) and ASTM-A 537 Grade B (MOD.). These grades meet the regulations of the ABS rules of 1973. The "MOD" in the grade CS (MOD.) indicates a requirement for the testing to ABS Grade E standards. The "MOD" in ASTM-A 537 Grade B (MOD.) indicates that carbon content is limited to 0.18 percent of the total.

Generally the selection of steel grades for structural plating and shapes is guided by temperature levels derived from an approved three dimensional heat flow analysis, but as a safety margin, the temperatures we have actually used are 10 degrees Centigrade (18 degrees Fahrenheit) below those indicated by the analysis. The allowance reflects our lack of complete confidence in the analytical technique due to lack of analytical confirming data from actual operations.

In addition, we have taken a more conservative approach than required in our assumptions of ambient conditions. A comparison of the assumed ambient conditions used in our analysis and those required by codes is given in the following:

	Assumed Values	IMCO Code Values
Air Temp	-20°C (-4°F)	5°C (41°F)
Water Temp	-2°C (28°F)	0°C (32°F)
Wind	5 Kts	–
Water Current	0.5 Kts	–

The variety of materials utilized leads to complex material control problems. In this typical midship section (Figure III), for example, six steel grades are used. Every precaution must be taken to assure that the correct grade is appropriately located. Gross errors would almost certainly be discovered during the initial cooldown, but should a steel suitable for -10 degrees Centigrade (14 degrees Fahrenheit) be located where it will be exposed to a temperature of -20 degrees Centigrade (-4 degrees Fahrenheit), the problem is far more subtle. Considerable time could elapse before the error surfaced, and major damage could be done to the containment system or to the hull girder, depending on the location and extent of the improper application.

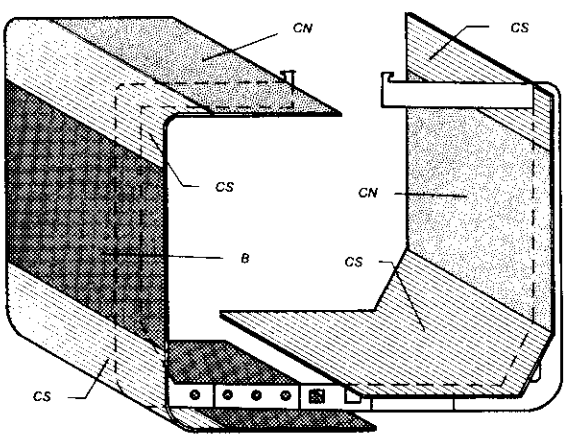

Fig. III. STRUCTURAL MATERIALS ARRANGEMENT CONCH CONTAINMENT SYSTEM

As a part of the quality control, it is essential that low temperature steels be submitted to destructive metallurgical testing to ensure compliance with chemical content and the Charpy V-Notch specifications. This is especially important because steel mills as a rule produce these grades of low temperature steels at infrequent intervals.

To strengthen our design data base for future work, we will provide additional instrumentation and recording equipment for a typical cargo tank on the first vessel delivered by each yard, and we will acquire data necessary for a more detailed picture of temperature gradients. We will compare these data with results derived from the heat flow analyses so we can evaluate the technique. We expect this to lead us to improved techniques for selecting structural materials for future generations of LNG ships.

Compartment Design

We designed compartmentation within our double hulled vessels to meet three major objectives.

First it is arranged to permit simultaneous cargo transfer and ballasting or deballasting. This reduces the time required for port turnaround, which must be accomplished within 15 hours if delivery rates are to be maintained. During this time, 125,000 cubic meters of LNG are transferred, and some 60,000 metric tons of saltwater ballast is either taken on or discharged. This is in addition to the usual storing, bunkering and port operations.

Second the compartmentation is designed to permit operations to proceed without overstressing the hull girder.

Third the compartmentation must meet stringent requirements on trim, stability and subdivision. The requirements are imposed not only by regulatory bodies, but also by operating restrictions, for instance, the draft limitations within terminal waters.

Compartmentation arrangement is developed during several iterations of the design process. During each iteration, all parameters are checked for compliance with the desired objective. The result is a compartmentation arrangement which meets all design requirements.

Ballast Tank Drainage Provisions

Provisions for draining ballast tanks is an important structural design consideration of two reasons. First an unusual amount of silt will be entrained in the water during ballasting because of the shallow depths and muddy bottoms at the terminals; provision must therefore be made for drainage which will allow the majority of the silt to be discharged with the water during deballasting. Second it will be necessary to inspect and possibly repair structures and coatings within the ballast tanks, and the designs must take into account the need to remove muck from the tanks to permit viewing of the structures.

Provisions for drainage are handled during the structural approval process. Care is taken to ensure that proper drainage is provided through all longitudinal and transverse structures with emphasis on adequate size of openings and the flow pattern to the suction connection.

Personnel Access Provisions

The provision of personnel access routes and adequate air circulation through the spaces between the outer hull and the inner hull is complicated by the honeycomb nature of the double hull structure, yet it is essential for two reasons: 1) the need for periodic inspection of the structure for cold spots and watertightness and 2) the requirements for maintenance and repair within the double hull spaces.

In ensuring that proper access provisions are provided, the requirements of the U. S. Coast Guard and OSHA are reviewed to ensure compliance with such things as the number of openings, ladder construction and other safety provisions. Additionally each tank was looked at from an overall circulating pattern to provide safe and convenient access to all areas of the tank. Cutouts in the structure are located for convenient movement from one part of the tank to the next.

Corrosion Control

To help assure a 25-year economic life for our ships, we have incorporated full scantlings with a complete coating system for corrosion inhibition. Technically the full scantlings present no fundamental problems. The coating system is another matter. It represents, in fact, one of our most trying problems.

It is complicated by a number of factors: First there is the sheer quantity involved; the surface area of the ballast tanks alone is some 200,000 square meters (2,100,000 square feet) per ship. Second the coating must be able to withstand extreme temperature variations. On some areas of the inner hull, the temperatures may range from -50 degrees Centigrade (-71 degrees Fahrenheit) to 100 degrees Centigrade (212 degrees Fahrenheit), a span which in itself eliminates certain coating materials. Third coating materials which have little or no solvent must be used because of the honeycomb structure, the limited ventilation and increasingly stringent environmental controls. The problems are compounded because the quality and availability of coatings vary markedly and frequently. In addition, the claims of some coating suppliers cannot be substantiated.

Yet adequate coatings are of critical importance. The time and expense required to recoat complete inner hulls are prohibitive in the extreme. In addition steel replacements would be extremely expensive, primarily because of the honeycombed structural arrangement. It has been estimated that the replacement of a 3x6 meter (10x20 feet) plate on the inner hull and its associated structure would cost some $70,000.

The renewal of the steel requires disruption of the LNG containment system, which is the reason for the high cost.

To solve the problem, we initiated a technical review and material testing program to evaluate available coating materials. Basically the program comprised accelerated weather testing including salt water immersion, salt spray tests, splash zones test and ultraviolet exposure. The end result led to the selection of very high solid content epoxy for the Newport News and Avondale ships and a solvent-free epoxy for the France-Dunkerque ships.

CONSTRUCTION

Because the objectives of the shipbuilder and shipowner do not necessarily agree, either from a technical standpoint or an economic standpoint, it is essential that the position and philosophy of the owner be firmly established at contract signing. The objective of a shipyard is to produce a technically sound design in a manner which best suits its particular production technique and still remains competitive within the industry. The objective of the owner is to purchase a technically sound design which fulfills all technical and operating requirements and is reliable, safe and economical to operate and maintain.

The construction of the ships involves the structural designer in three major areas: design definition, design review and inspection.

Design Definition

Adequate definition of structural designs is one of the most important phases in the construction of a ship. If technical, constructional and operational requirements and constraints are fully appreciated by both the owner and the shipbuilder, then duplication, confusion and disagreement will be minimized. Requirements set by regulatory bodies, the cargo containment system supplier and the owner will be more easily met.

At El Paso we have developed a standard specification which enumerates for the prospective shipbuilder such structural requirements as: required longitudinal structure continuity, minimum plate thickness, structural design concepts to be utilized, local reinforcements, attachments, welding continuity, etc. The basic hull strength requirements and maximum allowable deflections are, of course, dictated by the classification society and the containment system designer. The standard specification is proving to be an exceptionally valuable instrument for design definition.

Design Review

The objective of design review is twofold: first, to assure that contractual specifications and owner objectives are met and second, to discover and eliminate design details which might lead to maintenance or safety problems.

There are frequently several design avenues to meeting objectives. Figures IV, V and VI, for instance, are illustrations of midship sections of our three different designs. In each case, the structural arrangement is different, yet all meet our general design objectives.

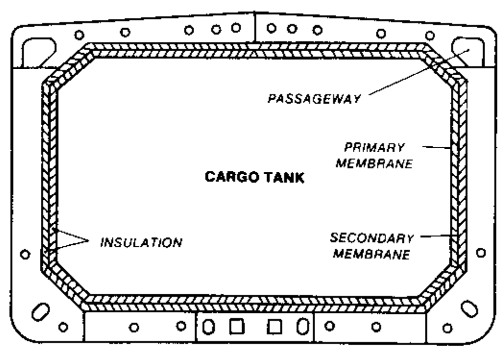

Fig. IV TYPICAL SECTION OF GAZ TRANSPORT MEMBRANE TANK DESIGN

We have uncovered several instances in which designs may be technically adequate, but which require changes in order to avoid "nuisance" problems at a later date. For instance, the type of connection shown on the left in Figure VII, with its through penetration of the flat, is structurally adequate, but it is difficult to weld properly and it is rather susceptible to cracking. Should cracking occur, ballast water could leak into the insulation space behind the containment system, where it would freeze. This would cause distortion of the containment system, and could lead to unscheduled, expensive and time consuming maintenance and repair. Ultimately this design was changed to alleviate the potential problem by eliminating the through penetration of the flat as shown on the right in Figure VII.

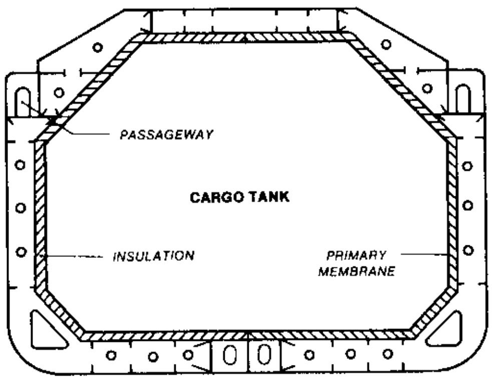

Fig. V. TYPICAL SECTION OF TECHNIGAZ MEMBRANE TANK DESIGN

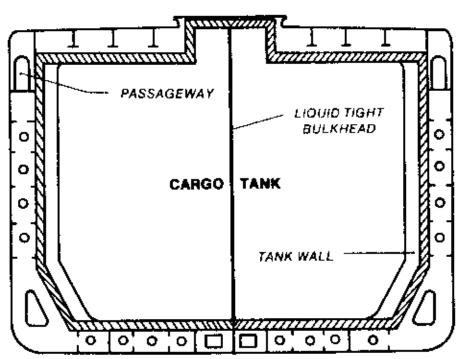

Fig. VI TYPICAL SECTION OF CONCH FREE-STANDING TANK DESIGN

We also try to avoid structural discontinuities, abrupt transitions, intermittent structure and other similar design details because they require more frequent and extensive maintenance. In addition, we avoid designs which would cause stress concentrations, and require provisions of bracketing structure, welding details, welding sequences, etc.

Inspection

Although it is not a function of structural design in the strictest sense, inspection is nevertheless critically important to assuring that the intent of designs is carried out.

As suggested earlier, metallurgical tests of steels and checks of structural members emplacement are essential to make certain that the proper steel grades are used.

It is also essential to require extensive testing of welds on the inner hull to make certain the watertight integrity is maintained. This requires extensive nondestructive testing. Cracks which would amount to no more than a minor problem on a conventional bulk carrier can rapidly become a major problem on an LNG ship.

Another area of primary concern is the dimensions of the inner hull, which must be controlled to very close tolerances if the containment system is to serve satisfactorily.

In a broad sense, inspection is the final phase of the design process, although design modification (hopefully minor) may sometimes be required as a result of tests and trials or of operational considerations.

FUTURE DEVELOPMENTS

As we mentioned in the beginning, considerable progress has been made in the design of LNG ships over the past 15 years or so, but there is still a lot of research and development to be done.

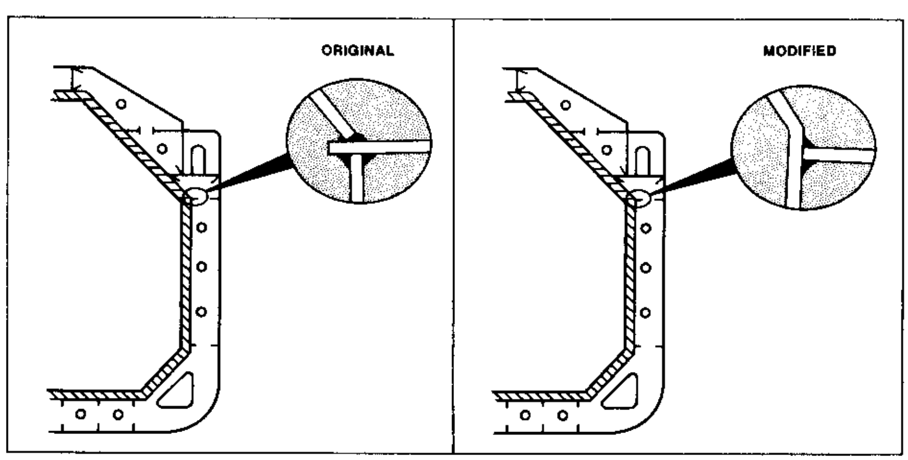

Fig. VII. STRUCTURAL DETAIL, WELDING DESIGN

In particular, we would welcome additional model basin tests to broaden our data base for the design of hull shapes, especially stern configurations.

We would like to see additional research into the dynamic loading imposed by the sloshing of LNG within the cargo tanks. Data derived from model tests and from full scale measurements do not presently correlate very well. Valid data would be useful in the design of future containment systems and hull support structures.

There should be additional research to improve three dimensional heat flow analysis techniques. This would be a major aid in selecting grades of structural steel.

There should be much more development in the effort to control the structural designer's traditional nemesis—corrosion. An economical and effective coating system would be a major contribution.

To solve these problems and others, we strongly encourage classification societies, institutes, shipyards and designers to continue and even increase the research and development which is essential to our technology.

If research and development are to yield practicable design tools, two key parameters must be met. First the cost must not be prohibitive. Naturally sophisticated techniques cannot always be cost competitive with traditional rules of thumb and simplified analytical techniques, and the owner must be willing to incur some design expenses higher than traditional. Still the cost must not be out of reason. Second the time required to utilize new design tools must be compatible with the design schedule. Many of the sophisticated procedures available today cannot be utilized fully because of the time required to obtain answers. As a result, the shipyards and the owner proceed with the design and hope that when the analytical answers become available, they will reveal no major problems. Obviously when serious problems do arise, there is a major disruption of the design process. When marginal problems arise, they normally end up not being solved during design because of the disruptive effect.

The constraints on cost and time may mean that a design tool is less than optimum, but in our opinion, it is better to have an answer which is 90 percent correct and available in time to be utilized rather than an answer which is 95 percent correct but cannot be utilized without disruption to the design schedule and additional cost.

Finally, we encourage fleet operators to make non-proprietary data available to the industry as a whole. The data we acquire from instrumenting our ships as well as from other efforts will be analyzed and reported to the industry. We encourage our colleagues to follow the same approach. We are confident that it will prove of benefit to us all.