The Role of Classification Societies in Design, Operation and Construction of LNG Carriers and Terminals

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Abstract
Class society ABS has been at the forefront of addressing technical issues associated with the next generation of liquefied natural gas (LNG) carriers. Major step changes are taking place in the industry. Most notably, LNG ships are becoming larger, operators are considering partial loading, differing tank designs are available, ship designs are being extended to a 40 year fatigue life, and alternative fuel and propulsion systems are now available. Furthermore, the role of the ship is expanding beyond transport to regasification and offloading offshore.

Class societies exist to promote the security of life, property and the marine environment. This is accomplished by establishing and applying technical standards to the design, construction and survey of marine related facilities. The standards issued by classification societies are known as Rules. The world of classification is changing as we see structures in all ship types that are larger and more complex with a call for emphasis on safety equivalency and flexibility from the traditional prescriptive Rules. This change can be seen particularly with the LNG market sector as operators face the challenges of responding to high market demands for natural gas. Virtually every LNG carrier that has ever been built for international trade has been classed by a major classification society. In 2004 71 LNG carriers were ordered. These carriers will be classed and built to technical standards established by one of the major classifications societies around the world.

Along with LNG vessel developments, the introduction and transition to offshore LNG terminals has called upon class societies to take a comprehensive approach toward the integration of design standards for marine transportation and terminal reception and gas processing facilities. Technical guidance for gravity based or floating offshore LNG terminals has been provided by class societies.

This paper provides an overview of the issues, tools and criteria established from a class society perspective to address the technical issues and standards for the advancement of natural gas transport. It discusses the evolving role of class from a reviewer role developed as an outgrowth necessary for insurers and underwriters to an integral part of the project development process by providing technical guidance at the outset, especially in terms of new and novel concepts for the LNG transportation market.

Introduction
The scope and complexity of many of the new natural gas projects have created a unique opportunity for classification societies to contribute to technical developments across the entire gas transportation chain. The transportation of liquefied natural gas by sea imposes unique demands on the marine industry. A comprehensive understanding of liquefied natural gas characteristics and the sea environment in which the vessel operates is critical as the designs become larger. Historically, the increase in size of LNG carriers has been fairly gradual. LNG ships for many years were in the 133,000m³ to 148,000m³ range. Designs for the new breed of LNG carriers are in the 200,000m³ to 250,000m³ range. This step change in size is significant. The entire design of the ship’s structure and containment system requires evaluation to determine its adequacy to withstand the additional loads.

Combine this technical complexity with the market need for LNG which has dictated that the worldwide LNG market double in size over the next decade, and you have an environment for class societies to become a more integral part of the project development process. Operators are demanding technical advice up front for larger designs and systems to economically and safely transport and offload natural gas.

Drivers for this rapid LNG growth include political concern over the stability of oil supplies, sharply escalating oil prices and evolving demand for a cleaner-burning, more environmentally friendly fuel. Concern over long-term U.S. gas supply; a large number of new supply projects; environmental restrictions on gas flaring; and lower LNG infrastructure costs compared to even a decade ago are also contributors to the LNG growth spurt.

Class societies are responding with guidance for building and classing the vessel, offshore terminals and associated process facilities. And societies have been responsive to the commercial environment by offering designers and operators risk-based alternatives to strict compliance with traditional prescriptive rules.

LNG fleet capacity based on current orderbook will grow by nearly 50 percent in the next four years. (see Figures 1 and 2) The rapidly changing LNG environment alters the worldwide shipping trade patterns from regional to global, creates demand for larger vessels, requires close review of the containment systems and creates the need for LNG terminals to handle the processing and discharge of the gas.
Shipyards with current or recent LNG carrier construction experience are developing designs for the new generation of very large LNG or VLNG carriers and the significant increase in cargo tank size that these designs incorporate. The size of each of these tanks results in increased dynamic loads due to the movement of the LNG inside the tanks. Detailed sloshing analysis to predict the anticipated loads and to determine the required strength of the proposed containment system designs to withstand these loads is a critical element in the decision to order these new large carriers. Some class societies have developed sophisticated analytical tools to determine the impact of LNG movement on the containment systems.

**LNG Vessel Size**

In 1959 the converted LNG carrier, the Methane Pioneer, transported LNG from the United States to England. Then the Methane Princess and Methane Progress built in 1964 were 27,400m$^3$ capacity using the Conch containment system. The first membrane containment ships, the Polar Alaska and Arctic Tokyo, were delivered in 1969 and represented a significant jump in size to 71,500m$^3$. In 1975 the Ben Franklin and El Paso Paul Kayser vessels at 120,000m$^3$ and 125,000m$^3$ respectively delivered into service setting a size standard that was maintained for the next 20 years with only a marginal growth to around 133,000m$^3$.

Between 1995 and 2004 the size of the largest LNG carrier has gradually increased from 153,000m$^3$, the capacity of the Chantiers De l’Atlantique vessel for Gaz de France scheduled for delivery this year, to 216,200m$^3$ with the order of the Q-flex vessels for Qatargas II. Today, shipyards in Korea, Japan and Europe are vying for contracts that are considered for a new generation of very large LNG carriers with cargo capacities up to 250,000m$^3$. (see Figure 3) Gas producers are driving the demand for increased ship size to take advantage of the economies of scale. By increasing the size of the standard LNG carrier from about 145,000m$^3$ to 200,000m$^3$ and even larger, it is estimated that there could be a reduction in transportation costs of as much as 15 percent.

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It should be noted that as early as 1975 designs were proposed with these large capacities. However, it was not until recently, with commercial demand driving the need, that these super size LNG carriers have been given serious consideration. For naval architects developing these designs and marine engineers reviewing the design for classification the significant increase in ship size means the ship’s entire structure and containment system needs very careful evaluation to determine its adequacy to withstand the additional dynamic loads that will be encountered.

**Containment System Critical**

A key aspect of transporting LNG is designing the membrane-type tank and containment systems to withstand the dynamic loads imposed by the sloshing of the cargo within the tanks when the vessel is in a seaway. The high pressures due to liquid surge inside the cargo tanks may damage cargo tank systems and internal tank structures unless adequately addressed at the design stage. (see Figure 4)

![Figure 4](image)

**Figure 4:** Key aspect of transporting LNG is designing the membrane-type tanks to withstand dynamic loads and sloshing of LNG cargo.

Loading restrictions on membrane tanks have been in place for the past 20 years. However, the significant increase in tank size demands further evaluation and analysis to determine appropriate structural criteria for all loading conditions. Additional reinforcement of critical areas, such as the insulation system, high stress areas of the tank structure and the pump tower, which serves as the cargo handling connection to the hull, must be considered.

The high percentage of new orders of membrane systems and proposed new membrane designs are evidence that operators have a clear preference for the operational cost savings offered by the membrane containment system. When coupled with their interest in building in the operational flexibility of handling partial cargoes, it means that a great deal of research has been required to determine appropriate acceptance criteria for these configurations.

This capability opens up new spot trading opportunities for operators. It will permit these larger vessels to make multi-port discharges. And it will also significantly lengthen in-service voyages during which tank levels decline as a result of the gas boil-off. (Note: Independent tank type containment systems such as the spherical tank Moss design and the IHI prismatic designs are not subject to the same sloshing impacts).

Partially-loaded carriers can exhibit high dynamic loads as the low-filling condition produces progressive waves, known as hydraulic jumps. Characteristics unique to LNG, namely low temperature, compressibility of entrapped gas, hydrodynamic interaction between liquid and containment system and dynamic material characteristics challenge the vessel’s strength and may require additional reinforcement of critical areas. These areas are the insulation system, high stress areas within the tank structure and the pump tower. (see Figure 5)
Figure 5: One critical area that may need reinforcement to handle loads is the pump tower which serves as the cargo handling connection to the hull and the base support structure.

Sloshing software has been developed by ABS to analyze the deflections and stresses on membrane-type tank and containment systems. Since membrane systems are connected to the vessel’s hull, as distinct from the free standing spherical and prismatic designs, they place the greatest stresses on the hull structure, particularly on the bulkheads and inner bottom.

ABS has developed structural strength criteria for LNG carriers. Using software such as ABS SafeHull for LNG carriers, the ABS Dynamic Load Approach (DLA) and Spectral Fatigue Analysis programs a design can be comprehensively evaluated against the principal failure modes of buckling, yielding and fatigue.

For ABS a sloshing analysis consists of two phases: identification of critical ship motion conditions and computer simulations of liquid motions in the tank. Computational fluid dynamic (CFD) software codes are input in order to generate equations of liquid motion. The simulation produces instant values of flow velocities, accelerations and pressures in the liquid volume in accordance with the given mesh. (see Figure 6) This data is used for calculation of time histories of pressures at the most vulnerable points of the insulation system, typically located at the filling level. The strength assessment is made based on the sloshing load and impact strength of the containment system.

Figure 6: Computer simulation produces instant values of flow velocities, accelerations and pressures in the liquid volume.

Propulsion For Next Generation LNG Carriers

Most LNG carriers have a design speed of between 19.5 and 21 knots. The new generation of large ships will be designed to operate within this same speed range. This will require an increase in propulsion horsepower. Although existing carriers have used gas boil-off to run steam turbine plants, it is most likely that the new generation of very large carriers, over 200,000m$^3$ will be fully diesel powered as this will offer operating economies. This propulsion choice is illustrated in the case of the Q-flex vessel design. An on-board reliquefaction plant will return cargo boil off to the tanks.

However, for vessels in the existing size range of around 150,000m$^3$, there is growing interest in dual fuel propulsion plants that use more efficient internal dual fuel combustion engines with diesel electric propulsion. Gaz de France made LNG history as the first vessel to utilize a dual-fuel propulsion system. The expected benefits are lower fuel consumption, larger cargo capacity, lower emissions and higher operational flexibility. This propulsion design configuration led class societies to look at providing guidance for installation of these systems. In 2003 ABS released a Guide for Design and Installation of Dual Fuel Engines for those seeking alternatives to steam propulsion for their carriers.
The machinery arrangements seen on the drawing boards are numerous: two direct driven main diesel engines and a reliquefaction plant; diesel engine or gas turbine driven generators with one propulsion shafting system and a reliquefaction plant; diesel engine or gas turbine driven generators with two propulsion shafting systems and a reliquefaction plant; or a diesel engine or gas turbine driven generators with two azimuthing thrusters and a reliquefaction plant. The most favored arrangement by the shipyards and the owners at this time for a single screw vessel appears to be one that consists of four sets of dual fuel diesel generators supplying power to the propulsion motors. For designs greater than about 175,000m³ the preference seems to be twin slow speed diesels driving twin screws with a reliquefaction plant to consume all of the boil off.

The need to move to more efficient internal dual fuel combustion engines with diesel electric propulsion or a combination of one or more slow speed engines with a reliquefaction plant is proven technology but just now being incorporated into the design of large LNG carriers on order. Therefore, there is limited in-service data to provide a historical look at the issue of vibration during operations to observe its impact on LNG containment insulation.

Vibration research conducted by ABS in a cooperative program with a leading Korean shipbuilder, is examining any vibratory influence from the propulsion to the containment systems. More specifically, the study in process is focusing on the membrane insulation system and the mastic attachment between the inner hull plating and plywood back layer. (see Figure 7)

The study is addressing the question of what effect vibration has on the containment insulation material such as plywood, foam or material like epoxy resin. Diesel engine vibration on membrane systems, particularly in terms of structural resonance interacting with membrane resonance, is an important factor in operational safety. Researchers are determining if the vibration can be expected to damage the containment system by studying the global and local vibration levels on selected locations inside the adjacent cargo hold of the engine room.

The stress levels in the containment system at plywood, foam and mastics have been determined to verify the adequacy of the containment system. The natural frequency of the insulation system has been investigated for the potential resonance due to the excitation induced by the engine and fluctuating propeller forces. Data currently being generated from this study is the most advanced look at the subject of engine vibration on a LNG carrier’s containment insulation.

**Dynamic Structural Analysis to Study Insulation System Strength**

In the past assessing insulation strength was conducted in a quasi-static way. Now with larger vessels, hydro elasticity and visco elasticity must be taken into consideration. Currently a dynamic structural analysis approach to reviewing the insulation’s strength is taking place by ABS in collaboration with the University of Illinois. Employing sophisticated computer modeling and experimental material impact tests, ABS is validating dynamic structural analysis methodology for strength assessment. Along with this research a joint study with leading Korean shipbuilders and Gaztransport & Technigaz (GTT) to examine two membrane types, MK III and No 96, for their strength assessment is underway. (see Figures 8 and 9)
A numerical and experimental scheme has been developed to evaluate the impact strength of the containment system. The scheme consists of a hydro-viscoelastic analysis for fracture and buckling investigation of the insulation materials. The dynamic structural analysis considers the fluid-structure interaction during the vibratory motion of the composite structure of the containment system. Dynamic material properties of the foam and plywood are being tested at the University of Illinois.

Full scale drop tests have been conducted on the insulation systems of both the Mark III and No 96 membrane types to determine the impact strength and failure mode threshold. Both wet drop tests and dry drop tests have been conducted to test the shock absorption of the insulation in both water and on hard surface.

Details from the dry drop test by GTT and water drop test by Samsung Heavy Industries (SHI) for the Mark III system examined the hydro elasticity, corrugation membrane cushioning, structural damping and failure mode of the insulation system. In a dry drop test of the No 96 system by Daewoo Shipbuilding & Marine Engineering (DSME), the impact load was increased until containment or boxes were collapsed. The buckling mode of the side panel of insulation system has been detected as a failure mode and the effect of perlite insulation material to the dynamic strength was studied.

The research by ABS in collaboration with GTT, University of Illinois and shipbuilders will lead to the development of new classification criteria which will be published in an upcoming ABS Guidance Notes for Strength Assessment of Membrane Type Containment Systems. All class societies are looking at containment and strength assessment issues as the industry demands larger carriers.

**Tank Containment Designs/ Approval In Principle**

Working with energy majors, ABS is providing an Approval In Principle (AIP) for proprietary tank concepts for large LNG carriers.

The AIP process draws upon engineering, testing and risk assessments in order to determine if the concept provides acceptable levels of safety in line with current offshore and marine industry practice. The methodology relies heavily on risk assessment techniques as a way to better understand and anticipate structural and operational issues related to a new or novel concept. ABS is evaluating the overall tank design including an assessment of the tank containment system to the requirements of ABS Rules and the International Gas Code (IGC), a structural strength feasibility study and an analysis of the tank support system.

The impact pressure due to sloshing motion in the cargo tanks is one of the most critical load factors when designing containment systems for LNG carriers. The magnitude, effective area and duration of the impact loads are all important when considering structural response of the containment system. It is also important to examine the spatial and temporal pattern of the impact load in concert with structural response. In conjunction with model tests, ABS developed numerical modeling techniques which were used to examine the sloshing impact load to gauge structure response in these novel tanks.

In one AIP process by ABS a key feature of the unique tank shape was the design reduces free surface area thus reducing the high impact sloshing loads and resonance period in the tank. For the design a four tank scenario was tested for an LNG vessel with 235,000m³. This compares to vessel designs for this size which usually call for five or six tanks.
Comparison and pressure tests were conducted to see if the design was acceptable. The critical ship motion response and sloshing impact conditions were calculated using North Atlantic environment conditions. (see Figure 10)

**Figure 10:** ABS provided an Approval In Principle or AIP to a unique tank design by one energy major looking to reduce free surface area thus reducing the high impact sloshing loads and resonance period in the tank.

The tank design was tested simulating irregular wave conditions and with three different filling levels for the tanks and various ship headings. The test results have so far shown that the loads on the tank for the large LNG carrier are equal to or less than those experienced on a traditionally designed 138,000m³ ship.

ABS analyzed the sloshing effect on the tank membrane with proprietary numerical simulation tools. These two-dimensional (2-D) and three-dimensional (3-D) programs apply North Atlantic wave database information to conduct a direct simulation on a particular LNG vessel. These programs perform complex calculations that predict the dynamic and sloshing pressures acting on the membrane tanks in a seaway.

As another example, AIP was provided by our class society to an operator developing a tank design and carrier consisting of a cylindrical tank with spherical dished ends. (see Figure 11) The 180,000m³ carrier design features five of these large 36m diameter and 40m high cylindrical tanks each holding a volume of 36,000m³ of LNG. The design is intended to minimize the void spaces in the ship’s hull yet still provide full access around the tank for inspections of both the insulation and tank structure. Compared to the traditional spherical LNG tank containment system, the system is expected to increase cargo capacity within the same main hull dimensions by an estimated 25 percent compared to spherical LNG tank systems.
As part of the review process, ABS evaluated the overall tank and vessel design to include: containment system and structural strength feasibility, tank support system, midship section scantlings, stability analysis, hull form and speed calculations, and hydrodynamic analysis for an overall feasibility of the carrier design.

The tank containment system was evaluated to the requirements of ABS Rules and the International Gas Code (IGC). In this particular review process, ABS referred to its Guidance Notes on Review and Approval of Novel Concepts. This document outlines a methodology for requesting classification of a novel design that may have no previous experience in the environment being proposed.

**Offshore LNG Terminals**

Planned increases in LNG movements, combined with a need for safe, cost-effective alternatives to locating LNG terminals in densely populated urban areas, has led to projects for the design, construction and deployment of offshore LNG terminals. *(see Figure 12)*

This concept covers both load terminals, where gas is liquefied, stored and offloaded to LNG carriers, and discharge terminals which receive and store LNG from trading LNG carriers. The receiving terminal may either discharge liquid in a lightering operation or regasify the liquid and discharge the gas by pipeline to shore.

The last five years have seen the number of LNG export terminals double along with the expansion of many existing ones. There are also several new LNG receiving terminals and plans for many more in the US, Europe and Asia. Industry forecasts estimate that at least five and possibly up to 20 terminals could be built in the US alone in the next 10 years, with many planned as offshore installations.

Economic, safety, environmental and security concerns, coupled with physical constraints at some of the existing shore side terminals, have encouraged the selection of offshore LNG terminals as the most suitable choice for several of these projects. The U.S. Deepwater Ports Act, originally conceived for offshore oil terminals, can help streamline the licensing and approval process for offshore LNG terminals in the United States.

ABS is also providing assistance to the various project teams evaluating offshore terminals, principally through the publication of the ABS *Guide for Building and Classing Offshore LNG Terminals*. This Guide establishes the first classification standards for these proposed installations.
It provides a needed set of safety criteria for those engaged in the development of concepts and designs for these terminals. The Guide addresses both gravity-based and floating terminals. Class notations are clearly defined to effectively describe the function of each LNG configuration.

The document brings together the various applicable ABS Rules and relevant industry codes and standards to give the designer a clear, integrated reference. For instance, API standards are referenced that deal with high pressure gas handling and delineation of gas-dangerous locations on a processing facility, American Concrete Institute as well as Norwegian and British Standards are referenced for concrete structures, and appropriate references are made to the relevant industry standard published by the National Fire Protection Association.

Areas of emphasis within the Guide include terminal structures, hull designs, mooring systems, offloading systems, LNG containment systems, process facilities, and support and safety systems. The new standards address LNG terminal installation, hook-up and commissioning, and surveys during construction, deployment and operation. They also permit designers and operators to consider risk-based alternatives to prescriptive design and survey requirements.

For naval architects and offshore engineers the two key design issues pertaining to offshore terminals are: the relative motion between the terminal and the LNG carrier during cargo handling operations and partial loading of the LNG tanks in an exposed offshore marine environment.

In terms of regasification for LNG a unique concept dubbed the Energy Bridge Deepwater Port, the industry's first offshore LNG terminal in the Gulf of Mexico, some 116 miles offshore Louisiana, called for a class society to review the single-point mooring system (SPM) as the key component for regasification of the LNG on board the LNG vessels. (see Figure 13)

![Figure 13: A submerged turret loading buoy (STLTM). ABS classed the STL, a type of single-point mooring system (SPM), which is an integral component of the industry's first LNG terminal, dubbed the Energy Bridge Deepwater Port.](image)

The terminal will consist of the STL system, a new-build piled platform to support a gas-custody transfer metering station and associated pipelines connecting the STL system to two pipeline grids. The 186-ton unit will allow specially built LNG carriers fitted with onboard re-gasification equipment to transfer gas through the buoy, which is connected to a pipeline end manifold (PLEM) on the seafloor.

The new carriers, known as Energy Bridge™ re-gasification vessels or EBRVs, (see Figure 14) are equipped with a small moonpool to accommodate the STL buoy connection but retain the flexibility to trade as conventional LNG carriers. Two EBRVs are under construction at Daewoo Shipbuilding & Marine Engineering in South Korea. Delivery of the first vessel was scheduled in January 2005. The STL buoy, planned for 298 feet of water, will float at a submerged depth of 90 feet at the top of buoy and is the receiving point for the Energy Bridge concept. Instead of supplying natural gas as a liquid to a shoreside re-gasification plant, the two proposed Energy Bridge carriers, equipped with vaporizers to convert LNG to gas, are intended to supply regasified product directly to the deepwater port facility.
Conclusion

The classification society’s role has changed to become a key player in enabling LNG designers and operators to meet the growing demand for LNG by creating new technical standards to keep pace with the unique demands of the new generation of LNG vessels and offshore terminals.

The capability has been developed to approve designs for a 40 year fatigue life in the North Atlantic and also to approve designs for partial loading of LNG in membrane type containment systems. Other technical initiatives by class societies include establishing standards for dual fuel engines, ongoing studies into the effects of vibration on the hull structure and the membrane containment system of diesel powered LNG carriers, reviewing new tank designs and carriers with no previous existing classification rules by using risk-based alternatives and newly developed technical guidance and the establishment of the first industry standards for the design, construction and maintenance of offshore LNG terminals.

Safety is the critical issue that must be considered as industry considers both a new generation of very large LNG carriers and the relocation of cargo handling facilities from traditional shore-based installations to offshore terminals that may be either floating or gravity based. Industry has successfully dealt with oil and gas processing facilities on Floating Production Storage Units for a number of years. However, the liquefaction and cryogenic storage of LNG offshore is a new arena with specific concerns that must be addressed if it is to be conducted safely.

This transition requires a comprehensive approach toward the handling of LNG, a fully integrated approach that considers production, storage, handling, carriage, discharge and regasification. Although the basic technology for handling and transporting LNG is well established, these new innovations have posed significant technical challenges that ABS and other classification societies are meeting through advanced research and close cooperation with industry.

REFERENCES


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