Intrinsically Safe Cryogenic Cargo Containment System of IHI-SPB LNG Tank

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The recent skyrocketing demand for LNG and deep water gas field development attracted the attention of businesses to floating LNG production, storage, and offloading installations, LNG transportation, and LNG-fueled vessels in the marine and offshore industries. The IHI-SPB cargo containment system has excellent features and is suited to LNG carriers sailing on rough seas and floating LNG units working nonstop, because it has intrinsically safe functions, thanks to its high reliability and structural features, and preparedness in the event of an accident. This paper introduces these safety functions that the IHI-SPB is built with.

1. Introduction

Due to the recent rise in demand for Liquefied Natural Gas (LNG) and deep water gas field development, floating LNG production, storage, and offloading facilities (FLNG facilities) are being developed. An FLNG facility is a floating offshore facility that receives the natural gas produced by an offshore gas field, produces LNG by removing impurities and liquefying it in a plant on the upper deck, cryogenically stores the LNG in tanks at −163°C, and offloads the LNG to LNG carriers. FLNG facilities are large facilities able to process 2 000 000 to 3 000 000 t of LNG yearly, and store 200 000 to 250 000 m^3 of LNG. Typically, an FLNG facility houses 4-5 large-scale LNG tanks that exceed 40 000 m^3 in capacity.

Meanwhile, in order to reduce the environmental load, the development of ships that use LNG for fuel (LNG-fueled ships) is also progressing. Although the fuel tanks are small, with capacities of only several thousand cubic meters, the dangerousness of the on-board LNG remains the same. Consequently, efforts such as the establishment of international regulations on LNG fuel tanks are accelerating in the shipping and naval industries.

2. IHI-SPB LNG tank

There are three types of tanks for cryogenically storing and offloading LNG at sea: ① the membrane type, ② the MOSS type, and ③ the IHI-SPB type. IHI-SPB is an abbreviation for Self-supporting Prismatic shape IMO type B. Of these three types of tanks, the IHI-SPB is the only one developed in Japan. **Figure 1** illustrates the IHI-SPB LNG tank. Japan Marine United Corporation (JMU) holds the IHI-SPB license and is licensing the manufacturing of

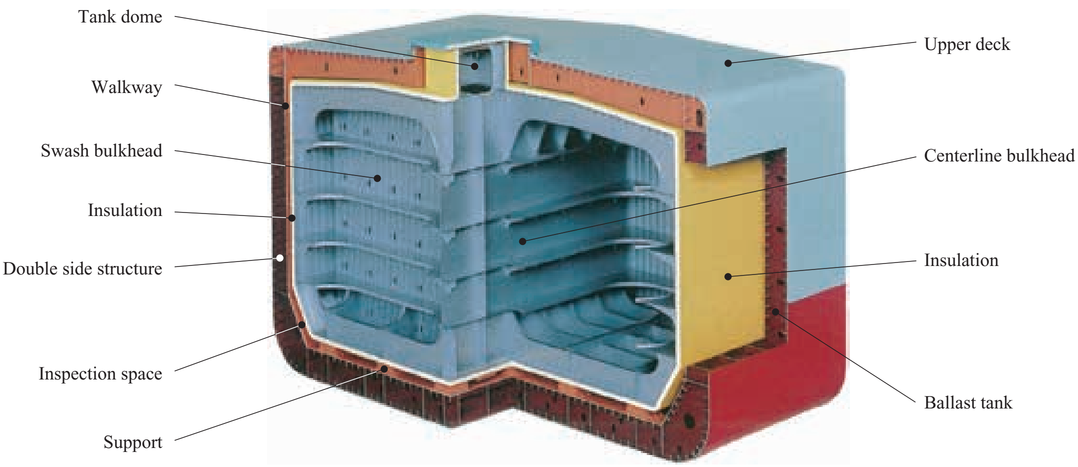

Fig. 1 IHI-SPB LNG tank

tanks to major shipyards in Japan and South Korea.

The IHI-SPB tank's structure is independent from the ship's hull, and it stands supporting itself on top of a reinforced wooden block. For this reason, a tank in the bow of an LNG carrier or the fuel tank of an LNG-fueled ship may be freely shaped to match the hull shape, thereby raising space efficiency. In an FLNG facility, a plant such as an LNG production facility or a reliquefaction plant may be installed on the flat upper deck.

Since the IHI-SPB is designed to hold up well to service in rough seas, and does not require extensive labor for maintenance or repairs, the IHI-SPB is highly rated as a system that single-handedly solves the problems of other cargo containment systems.(1) Because of its high reliability and low lifecycle costs, we have received many orders and inquiries regarding use of the IHI-SPB as an LNG storage tank in an FLNG facility. This demand reflects the current climate, in which recent enormous natural disasters and accidents on offshore structures have led to demand for an extremely high level of safety and reliability to eliminate any unforeseen circumstances, as well as to start efforts by society at large, including the LNG production industry, to always be fully prepared. The demand also reflects the need for an intrinsically safe LNG storage tank for cryogenically storing and transporting large quantities of dangerous, highly flammable cargo.

3. IHI-SPB achievements

The IHI-SPB system has a long history, and has been constructed since the early 1980s when the self-supporting prismatic tank technology was established. The IHI-SPB system was installed in the 75 000 m^3 LPG ship "GENKAI MARU" of 1981, the 1 500 m^3 LNG/LEG ship "KAYOH MARU" of 1988, the 87 500 m^3 LNG carriers "Polar Eagle" (see **Fig. 2**)(2) and "Arctic Sun" of 1993, the 54 000 m^3 "Escravos LPG FSO" of 1997,(3) and the 135 000 m^3 "Sanha LPG FPSO" of 2005.(4) Among these, people involved with the IHI-SPB system are particularly attached to the LNG carriers, which navigate a route carrying LNG all the way to the LNG terminal in front of JMU's Yokohama shipyard.

The LNG carriers "Polar Eagle" and "Arctic Sun" are valuable vessels engaged in LNG transport from Kenai Port in Alaska to the Negishi Terminal, and for the past 18 years have navigated the North Pacific route (see **Fig. 3**),(2) the world's harshest trade route with continuously rough seas throughout the winter. Our engineers are always in attendance for regular inspections, whether they are conducted at JMU's own Yokohama shipyard or at another shipyard, and have confirmed that the IHI-SPB LNG tanks have never experienced any trouble for the last 18 years. JMU also possesses valuable detailed inspection logs.

The authors also attended the regular inspection of "Polar Spirit" (formerly "Polar Eagle") that was conducted at a shipyard in Singapore in October 2011. During this inspection, the LNG tank and its support structures and thermal insulation were examined. **Figures 4** and **5** are photographs taken during the inspection, and depict the state of the tank floor structure and supporting structures. The aluminum LNG tank is still in the same good condition at its construction in 1993, offering proof of the high

Fig. 2 "S/S Polar Eagle" (IHI-SPB inside), since 1993

(a) Japan - Alaska route **(b)** Voyage in rough seas

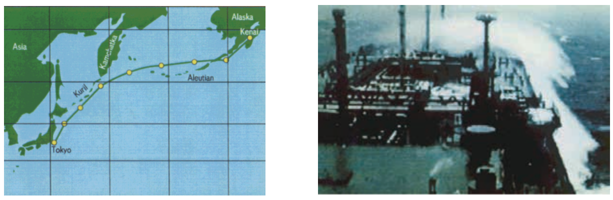

Fig. 3 The world's harshest trade route : Kenai, Alaska – Tokyo, Japan

Fig. 4 IHI-SPB LNG Al tank ("Polar Sprit" 18 years old)

Fig. 5 Supporting structure of IHI-SPB ("Polar Sprit" 18 years old)

reliability of the IHI-SPB tank.

4. Features of the IHI-SPB

One important feature of the IHI-SPB is its high reliability and built-in safety functions. The source of this reliability is in the long history of marine and offshore structures using the IHI-SPB structural framework, and in the fact that its proven stiffened panel structure continues to be used. With the stiffened panel structure, stiffeners support the panels that make up the tank perimeter, and are combined with main supporting members to create a free-standing structure that supports its own weight, the internal liquid, and the reaction force from the tank supports. A large number of LPG ships with tanks of the same structural type are currently in service around the world.

This structure allows structural members to be arranged inside the tank, making it possible to place bulkheads to avoid resonance between the liquid in the tank and the ship motion. The main supporting members inside the tank also have the advantage of inhibiting the motion of the internal liquid, resulting in a safe tank that does not produce sloshing impact loads. Since the structure is strong against both pressure from the liquid inside the tank as well as pressure from external forces, internal/external pressure adjustment of the tank is easy. The tank will not collapse even if water infiltrates the cargo area. Furthermore, since shipyards have much experience with this structure, scaling up and scaling down are easy, making it possible to design and construct tanks of any size, from large-scale FLNG tanks to small-scale fuel tanks.

The fact that these two LNG carriers have not been damaged throughout 18 years of service is thanks to the stiffened panel structure, in addition to design based on advanced analysis techniques and precise construction under strict supervision. Since the analysis and construction techniques for the IHI-SPB have already been introduced in other articles,[(2)] this article will introduce the latest computational techniques.

In designing an independent tank, it is important to correctly compute the reaction force of the tank supports. For this reason, as illustrated in **Fig. 6**, a Finite Element Method (FEM) is used. This method models major components including the hull of a ship with a plant on the upper deck, LNG tanks, and the supports bearing the tanks. Non-linear convergent calculation using contact elements between the supports and the tanks is also conducted.

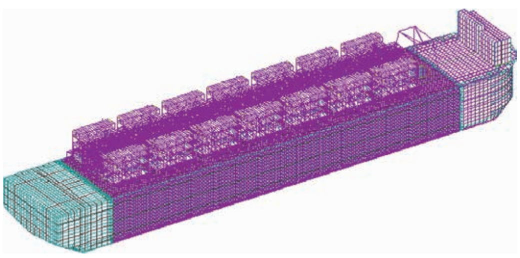

Fig. 6 Whole ship FE model (Hull, tank, and wooden support included)

Furthermore, since an FLNG facility runs continuously for 25-30 years, there are many loading conditions, such as constant variation of the liquid levels, and emptying any one of five tanks for regular inspection.

In order to conduct non-linear convergent calculation for many loads with a large-scale FEM model as described above, JMU's analysis techniques enabling fast and precise numerical analysis are indispensable. Of course, we have developed and are operating a system that automatically conducts the fatigue strength analysis and crack propagation analysis demanded by the international regulations (IGC Code) set by the International Maritime Organization (IMO). The system is able to efficiently carry out leak calculations for verifying the function of the partial secondary barrier in the hypothetical case of crack propagation in the tank and support structures with an LNG leak due to the crack propagation.

Since the IHI-SPB tank has internal structural members, supervision to prevent misalignments during construction and supervision of the precision of elements such as the shapes of welding beads are important. JMU conducts strength evaluations based on a massive amount of real-world performance data, and also takes various measurements during construction.

5. Safety of cargo containment equipment

The built-in safety functions of the IHI-SPB tank come from the type of structure, which includes a main supporting member inside the tank, and the type of tank, which is a free-standing tank independent from the hull structure. The following will introduce several excellent functions that fundamentally avoid potential damage and serious accident risks.

5.1 No sloshing

Sloshing is a phenomenon in which the motion of LNG inside the tank and the motion of the ship resonate, causing the LNG to impact violently against the tank walls. Sloshing occurs when the natural period of the left-and-right motion of the LNG is close to the natural period of the rolling motion of the ship leaning left and right, or alternatively, when the natural period of the front-and-back motion of the LNG inside the tank is close to the natural period of the pitching motion of the ship leaning forward and backward. When sloshing occurs, the motion of LNG inside the tank is extremely large, and a massive impact load is applied to not only the side walls but the front and rear walls of the tank. Sloshing is thus an extremely dangerous phenomenon for an LNG carrier carrying dangerous cargo having a low flash point at very low temperature.

For LNG carriers with a membrane type tank, there have been many reports of trouble caused by sloshing. In 1969, "Polar Alaska" suffered damage at sea with 20% LNG remaining in the tank, and its sister ship "Arctic Tokyo" suffered similar damage in 1971. Additionally, there have been damage reports for "Larbi Ben M'Hidi" in 1978, and more recently, "Catalunya Sprit" in 2006 (ship constructed in 2004), and three Mark III membrane ships in 2008.[(5)]

Every time an incident occurs, countermeasures are proposed in order to avoid sloshing caused by the resonance phenomenon, such as restricting navigation to when the liquid level in the tank is nearly full or nearly empty, or reinforcing the tank walls. To prevent sloshing, liquid inside the tank is typically restricted to 5% or less, or 95% or more.

On the other hand, for the ship operators to want to navigate at intermediate liquid levels is very natural. There are many reasons for this, ① ship operators may desire to unload cargo at multiple ports, ② once the temperature is raised in a tank transporting LNG at the extremely low temperature of −163°C, lowering the temperature back down takes time, and thus a ship operator may want to leave a small amount of LNG in the tank and navigate without raising the temperature, and ③ ship operators may want to use Boil-Off Gas (BOG) as fuel.

Furthermore, in an FLNG facility, the cycle of producing and storing LNG and then offloading LNG to a shuttle tanker every week is repeated 24 hours a day, 365 days a year for 25 to 30 years nonstop, and thus the liquid level inside the tank is always changing from full to empty.

In addition, shuttle tankers and LNG-fueled ships similarly demand safety against sloshing. Since FLNG facilities are installed in the open ocean, the weather may change drastically while offloading LNG. If such an event occurs, the shuttle tanker quickly moves away from the FLNG, and either remains in the rough seas with an intermediate liquid level, or retreats to safe waters. For this reason, being able to navigate in bad weather at intermediate liquid levels, or in other words, a shuttle tanker that produces no sloshing, is demanded. Moreover, since LNG-fueled ships consume LNG during a voyage, navigating at intermediate liquid levels is unavoidable.

Given these circumstances, anti-sloshing countermeasures are indispensable for the safe operation of FLNG facilities, the safe operation of shuttle tankers and LNG-fueled ships.

Since the IHI-SPB tank has internal structural members, the natural period of LNG inside the tank can be freely adjusted. For example, the tank may be divided into four sections using centerline bulkheads and swash bulkheads dividing the tank front-to-back, and designed so that the natural period of LNG inside the tank does not correspond with the natural period of the ship motion so that sloshing does not occur. This is a typical technique in ordinary ships, and provides the same proven functionality as the swash bulkheads in oil tankers.

Figure 7 illustrates an example comparing the motion of liquid inside a tank depending on the presence or absence of bulkheads and structural members inside the tank.(6) This comparison was obtained by calculating three-dimensional liquid motion using FLOW-3D. **Figure 7** demonstrates that because of the bulkheads inside the tank, resonance is avoided, and the motion of the liquid is calm. Additionally, the main supporting member inside the tank illustrated in **Fig. 7-(a)** provides resistance to the internal liquid motion, and thus also has the advantage of minimizing motion of the liquid due to ship motion.

Since impact loads caused by sloshing lead to tank wall damage and leakage of LNG, which is highly flammable and stored at very low temperatures, preventing such impact loads from occurring is of the utmost importance. For this reason, levels for indicating the various degrees of safety against sloshing have been devised. **Table 1** illustrates safety levels against sloshing.

(1) Level-I: SLOSH (1)

Natural period resonance is avoided at all liquid levels, so sloshing will not occur. The natural period of LNG inside the tank and motion-induced pressure have been confirmed by numerical computation, and the natural period is amply separated from the period of the ship motion. Structural strength for the liquid pressure has been confirmed.

For FLNG facilities and LNG-fueled ships in which

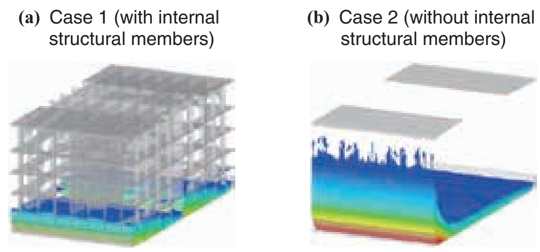

Fig. 7 Example of liquid motion analysis in rolling motion(6)

Table 1 Safety level against sloshing

	Safety Level Notation	Cargo Liquid Resonance	Cargo Liquid Level Restriction Range	Liquid Motion Analysis	CCS Reinforcement	Emergency Release LNG Hose to Shuttle
SAFE	Level-I SLOSH (1)	No Resonance	No Cargo Liquid Level Restriction	Performed	Not necessary	Available
	Level-II SLOSH (2)	No Resonance, Liquid Motion Analysis is not performed. CSR-T (OIL)				
	Level-III SLOSH (3)	Resonance in Designated Liquid Level	75% - Full Allowed	Performed	Reinforced Specially	Specially Considered with Risk Analysis
DANGER	Level-IV SLOSH (4)	Resonance	Only Full (higher than 95%) or Empty (lower than 5%) Allowed	Not performed	Reinforced Specially	Not Allowed

the liquid level changes constantly, achieving Level-I is necessary. Level-I is also required for LNG carriers when operating as a shuttle tanker for an FLNG facility, when navigating at intermediate LNG levels, and when unloading at multiple ports.

(2) Level-II: SLOSH (2)

The natural period of the liquid is confirmed to be amply separated from the natural period of the ship motion in vessels such as tankers that have swash bulkheads placed in them according to a simple formula defined in the regulations. Excessive load due to sloshing will not be produced.

(3) Level-III: SLOSH (3)

In order to prevent resonance between the liquid motion and ship motion as much as possible, restrictions are imposed on the level of LNG in the tank, and the tank periphery is reinforced against impact pressure caused by liquid motion.

LNG loading/unloading is possible in a harbor with minimal waves, and navigating in open waters is allowed at liquid levels that avoid resonance.

Reinforcement provides strength sufficient against pressures caused by liquid motion, while also being countermeasures against damage incidents.

However, there are reports that it is difficult to estimate massive impact pressures when the ship and the liquid inside the tank are resonating, and further elucidation is urgently needed for factors such as the hydroelastic response against structures, the force pulling away from the membrane due to negative pressure produced immediately after collision with the wall surface, and the rise in local load when protrusions or other objects exist.

(4) Level-IV: SLOSH (4)

Loading/unloading LNG at the pier is possible in a harbor with minimal waves. Navigation in open waters is allowed only with the tank full or empty.

5.2 Easy inspection and maintenance

The IHI-SPB tank has an internal horizontal girder, allowing for free access to the tank interior without having to erect scaffolding. Locations of relatively high stress points are specified for regular inspection, and the internal structure allows these locations to be reached and inspected.

On the outer side of the tank, a space approximately 1 m wide between the insulation covering the tank and the hull structure is prepared, and inspection walkways are installed in this space (**Fig. 8**). By enabling inspection on both the inside and the outside of the tank, leakage points can be easily discovered in the unlikely case that cracks were to form and LNG leak out of the tank.

In addition to the ease of inspecting the support structures and insulation, maintenance and inspection of the inner hull is also easy. **Figure 9** illustrates the inspection space between the hull and the IHI-SPB tank. Typically, the intersection between the double bottom and the double side structure of the hull is regularly inspected on both sides of the hold and ballast tanks, irrespective of ship type, and may be considered a weak point in the hull that is of interest to not only the ship owner, but also shipyards and classification societies. Since the IHI-SPB tank provides inspection space between the tank and hull, inspection of such locations is possible, and the presence or absence of tiny ballast water leaks due to age and other factors can be confirmed.

Fig. 8 Walkway between inner hull and tank outside insulation

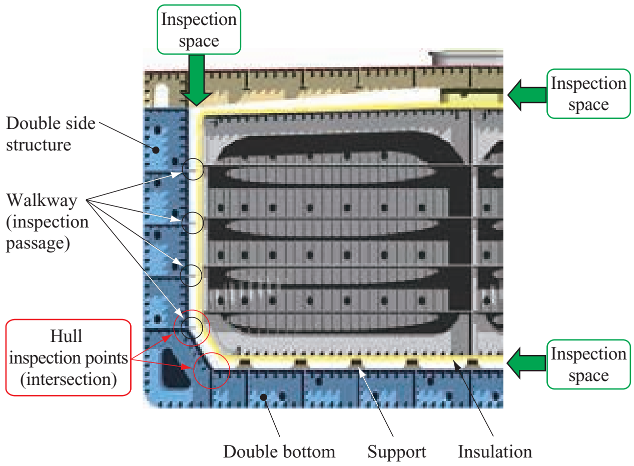

Fig. 9 Inspection space between hull and IHI-SPB tank

The operating expenses (OPEX) of the IHI-SPB tank are generally limited to such inspection expenses. Since additional expenses such as installation fees for scaffolding to reach the entire inner tank surface, maintenance and repair fees, and long-term docking fees in order to search for leakage points do not occur, the OPEX of the IHI-SPB tank is low.

5.3 Collision/flooding strength

With FLNG facilities, since equipment/food/crew are supplied to them by supply ships and LNG offloading onto shuttle tankers occur frequently, the dangers of accidental contact have been recognized for some time.[(3)] Shuttle tankers that connect to FLNG facilities are large-scale LNG carriers with transport capacities of 135 000 m^3 or 175 000 m^3, and thus it is required that even if a collision were to happen, it will not lead to collapse of the LNG storage facilities or LNG leakage. The IHI-SPB tank is strong enough to withstand 0.25 G of collision acceleration from the front or back. On the sides, the IHI-SPB tank is designed to have sufficient strength against a transverse acceleration of 0.5 G corresponding to a maximum tilt angle of 30 degrees. Consequently, the IHI-SPB tank possesses sufficient strength against collisions from the side.

Furthermore, as illustrated in **Fig. 9**, since the tank is self-supporting, the double hull structure (double bottom and double side structure) and the tank do not share a boundary, and thus the tank is not directly affected even in the case of a collision accident in which a shuttle tanker breaks all the way in to the inner side of the double hull structure, as well as incidents such as ballast water leaks due to tiny cracks, or deformation of the steel plate, for example.

Obviously, the IHI-SPB tank is strong against pressure from inside the tank as it is used to carry LNG, but it is also strong against pressure from outside the tank. For this reason, no special effort is needed to adjust the pressure difference inside and outside the tank. Pressure adjustment can be conducted simply with safety valves installed on the tank and the hold.

The IHI-SPB is a system able to withstand the pressure of seawater flooding the hold, and is equipped with Anti-Floating (AF) chocks that support the tank when it would otherwise float. As a result, cargo can be retained for a fixed period of time during flooding. Furthermore, Emergency Cargo Transfer (ECT) of LNG to another tank in a non-flooded compartment is possible.

Figure 10 illustrates a cross-section of an FLNG facility with flooding in the hold, while **Fig. 11** illustrates an example of FE analysis of the tank in the flooded hold. **Figure 11** shows the deformed state of the tank when seawater floods the hold; the water level has reached the draft level of the hull, and the tank is floating due to the resulting buoyancy. A strength evaluation is conducted for this state of a flooded hold.

5.4 Safety during blackout

When the IHI-SPB tank is installed there is space between the inner hull and the tank, which is filled with dry air or nitrogen gas during operation. Also, since the tank is only supported by reinforced plywood blocks placed on top of steel stools on the hull structure (see **Fig. 5**), the paths

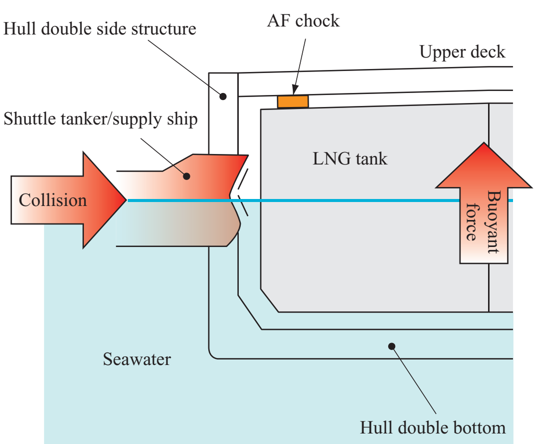

Fig. 10 Cross-section of FLNG in flooded condition

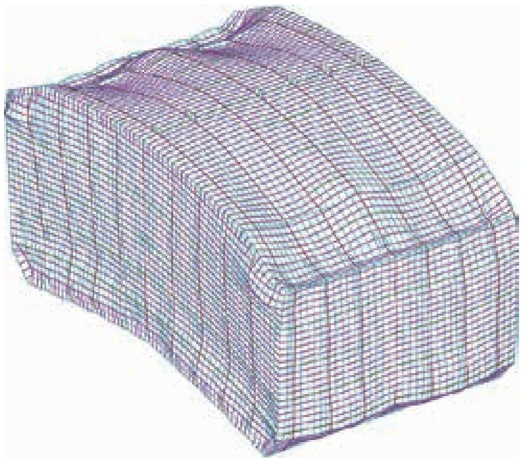

Fig. 11 FE analysis of flooded hull condition

through which heat is conducted are very small in number and being plywood, the thermal insulation capability is high. For this reason, it is not necessary to install a heating device to prevent temperature drops in the hull structural members surrounding the LNG tank.

The hull structural members surrounding the tank are made of steels suited to their designed temperature obtained by thermal conduction calculations. The fracture toughness, which is the ability of steel plates to resist brittle cracking, falls in low temperature environments, and thus by selecting higher-grade steel as the temperature decreases, it is possible to prevent serious accidents such as hull break-up due to brittle cracking.

The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk does not allow the use of heating devices to prevent temperature drops in the longitudinal strength members, which are the principal members of the hull structure. Structural arrangements that require heating are disallowed in order to prevent the temperature of major reinforcing members from falling dangerously below the designed temperature when heating is no longer possible during a blackout. Although the installation of heating devices is allowed for transverse watertight bulkheads, the rule to forbid installation of heating equipment for major members is imposed with an understanding of the functions of the hull structural member and its importance.

As illustrated in **Fig. 12**, since the IHI-SPB tank provides inspection space between tank and ship's hull, or in other

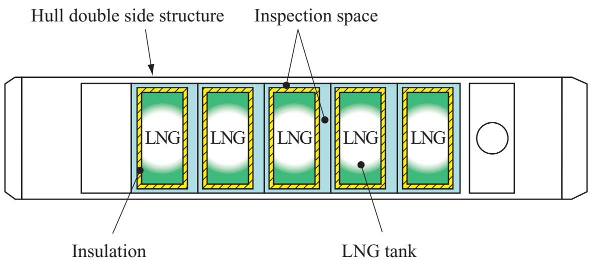

Fig. 12 Tank arrangement with IHI-SPB cargo containment system

words, since it has a structural arrangement independent from the hull, the IHI-SPB tank does not require heating equipment and satisfies the International Code on an ideal level. The IHI-SPB tank is safer, because there is no danger of the temperature of the hull structures falling and the temperature of steel plating falling below the designed temperature even in the event of some malfunction stopping the power supply to a heating device, or a problem with the heating device itself.

6. The future of the IHI-SPB system

6.1 FLNG

The IHI-SPB has been selected for use as LNG storage equipment for FLNG facilities because of its many features, such as no need for sloshing-related loading restrictions, the ability to withstand long-term operation, low lifecycle costs, as well as safety and reliability in the face of unusual oceanic phenomena, collisions, and flooding. In other words, the IHI-SPB is a robust and highly reliable cargo containment system. Currently planned FLNG facilities are large-scale structures 60-65 m wide. Since the IHI-SPB enables the installation of bulkheads that restrict internal liquid motion, large LNG tanks that are 50-57 m wide may be arranged in a single row in the FLNG.

This is in contrast to tank types that do not have internal structural members. Swash bulkheads cannot be provided inside such tanks, and thus the typical FLNG tank arrangement is in two rows, with a longitudinal bulkhead in the center of the FLNG hull.

6.2 LNG fuel tank

The LNG fuel tank of an LNG-fueled ship is small compared to an FLNG tank, with a capacity on the order of several thousand cubic meters. Since LNG is used as fuel, the liquid level decreases constantly over a voyage. For this reason, the tank cannot be restricted to being empty or full of LNG, and thus the IHI-SPB tank which fundamentally does not produce sloshing is chosen for the LNG fuel tank. Furthermore, since tanks can be designed in shapes that closely fit the hull shape or cargo area, it is possible to meet various demands, such as ① the desire to install the tank at a lower position in order to lower the ship's center of gravity, ② the desire to fit the tank in a complex area close to the engine room, and ③ the desire to install the LNG tank in an existing ship. The IHI-SPB tank is very safe, even when the LNG tank is submerged in water due to the impact of a collision or flooding. As a result, the IHI-SPB system is highly rated by shipyards with a high regard for passenger/crew safety and environmental conservation, and we are receiving many inquiries about it.

7. Conclusion

The IHI-SPB tank is a self-supporting prismatic tank with internal structures inside it to make it an intrinsically safe LNG tank with very safe functions built in, such as ① no excessive impact pressure due to sloshing, ② a strong ability to prevent the leakage of LNG from the tank even in the case of a collision with the ship or flooding inside the tank storage area, and ③ no need to worry about malfunctions in heating equipment, since no heating equipment is required.

Additionally, the high reliability has been proven by a long period of real-world operation, and lifecycle costs can be decreased. For this reason, the IHI-SPB is ideal as an LNG tank for FLNG facilities that demand long-term and continuous trouble-free operation, LNG carriers that may navigate in rough seas or with intermediate tank liquid levels, as well as for LNG-fueled ships that navigate by consuming the LNG in their fuel tank.

The companies who are involved with the offshore LNG supply chain, including FLNG facilities, LNG carriers, and LNG-fueled ships, and who are making efforts to be prepared for any situation and to eliminate unforeseen circumstances, recognize and choose the IHI-SPB cargo containment system as an intrinsically safe LNG tank system.

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