Features of the Latest LNG Carriers Sailing into Low-Temperature Environments

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Ship owners, gas suppliers and shipbuilders are now actively negotiating on the construction and purchase of LNG carriers capable of sailing in ice-bound seaways. The LNG carriers built to sail in the low-temperature ice-bound seas of cold districts require special engineering for their structures, main engines, propellers and shafts, and outfittings. Mitsubishi Heavy Industries, Ltd. (MHI) has established reasonable designs and specifications for actual shipbuilding through projects for cold districts. This paper introduces the main points of the characteristic design. We have also studied specifications, materials, and issues such as plant selection in anticipation of building ships to sail through even lower-temperature environments in the future. From now we will press ahead in our projects for cold districts by capitalizing on the experiences and findings we have garnered so far.

1. Introduction

Recent expansions in the global demand for natural gas have opened up a new chapter of gas field development in cold districts. Ship owners, gas suppliers and shipbuilders are actively negotiating the business of LNG carriers capable of sailing in ice-bound seaways. Many future demands are anticipated. The Russia project is the core of focus. Classification Societies, ship owners, and shipyards are studying winterization for LNG carriers. The diverse environmental conditions in cold districts and the exacting design and specification requirements for suitable and economic performance in seaway environments make this task demanding. The low-temperatures of the ice-bound seas through which these LNG vessels are to sail require special measures for the hull structure, the main engine, the propellers and shafts, and the outfittings. All of these measures have large impacts on the cost and performance of the vessels. Work in earlier projects for Norway, Russia, etc. has helped MHI collect knowledge of LNG carriers based on the specifications for cold districts. This paper introduces the main design points applied to the construction of LNG carriers for cold districts. We also describe concepts and strategies for practical design with an eye toward lower-temperature environments in the future.

2. Features of the state-of-the-art LNG carriers for cold districts (Sakhalin Project)

2.1 Design conditions

The Sakhalin 2 project is the first project for the export of LNG from Russia. Natural gas is mined in the north-eastern district of Sakhalin, transported via a land pipeline to the Prigorodnoye Terminal in Aniva Bay of south Sakhalin, liquefied, and exported as LNG.

May through September are the summer season for the Prigorodnoye Terminal, while October through April are the winter season. The average air temperature in winter is about −9°C. On very rare occasions, however, the temperature drops to −23°C or below. A layer of ice forms during the “ice season.” The ice season typically lasts from the middle of January through the beginning of April. The thickness of the ice is less than 70 cm. Normally it ranges from about 10 to 30 cm. The shipping route for LNG carriers, an expanse of water of about 50 miles from the La Perouse Strait to Aniva Bay, is usually covered with sea ice. The LNG carriers entering and leaving port at the Prigorodnoye Terminal are escorted by icebreakers, sailing in the lead of the ice formed (**Fig. 1**).

To enter port at Prigorodnoye Terminal in winter season, a vessel must be confirmed to meet the following four requirements against the ice and low temperature.

(1) Ice Certificate

The Ice Certificate, a document issued by an institute approved by the Russian authorities, certifies that a ship is capable of sailing in ice sea. Each certificate describes safe speeds for the vessel in different thicknesses of ice, safe distances to the escort icebreaker, and the navigable curvature of the vessel. Vessel suitability for operation in low temperatures of Aniva Bay is also assessed.

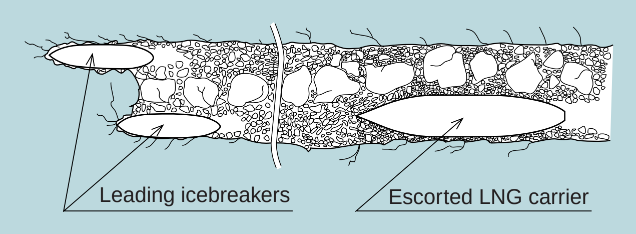

Fig. 1 Navigation in an ice channel

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(2) Certificate of Engine Power

The Certificate of Engine Power, a document issued by an institute approved by the Russian authorities, certifies the suitability of the main engine power of a vessel. Each certificate confirms that the main engine can produce a vessel speed of 4 knots or more in ice 60 cm thick following in the lead created by icebreakers. The propeller and propeller tip immersion are also assessed.

(3) An increased propeller blade thickness (equivalent to the Russian Maritime Register's LU2) and a propeller tip immersion of 70 cm or more

(4) Specifications suitable for operation at −25°C.

2.2 Main particulars

The main particulars are as shown below. A shallower draught design improves compatibility with the terminals. The susceptibility to environmental changes in cold districts necessitates various adjustments in design, including the adoption of double hulls for the fuel tank and the acquisition of environmental notation (EP, BWMP).

2.3 Arrangement

The arrangement of this LNG carrier is outlined in **Fig. 2**. It is a MOSS spherical type 4-tank vessel with a double-hull fuel oil tank arranged in the forward section and another tank of the same design at side of the engine room. The fresh water tanks also have a double hull construction, in order to prevent freezing. The aft mooring deck is equipped with a helicopter winching for pilots onboard.

2.4 Structure

Structural design against ice load is generally carried out in accordance with the applicable sea area regulation (Ice Class Rule). The Finnish-Swedish Ice Class Rule, for example, is applied to ships sailing in the Baltic Sea. For approval to pass through the Russian sea area, however, a vessel need not comply with the Ice Class Rule, but instead must satisfy the requirements of a direct strength analysis conducted under admissible speed conditions. The underlying idea is described as the "ice passport concept." Evaluations based on this concept take account of the actual design strength of the ship and the ice loads reflecting the hull form.

In designing this LNG carrier, MHI observed the ice passport concept. Though we bore no obligation to apply the Ice Class Rule, we decided to adopt grade 1B of the Finnish-Swedish Ice Class Rule, a design criteria reasonable for the applicable shipping route (Sakhalin sea area). We obtained the Ice Certificate after the design drawings were examined by the CNIIMF (Central Marine Research and Design Institute), a Russian Institute. **Figure 3** shows the flow of the design series.

Ships sailing in cold districts must be designed not only with sufficient strength against ice, but also adequate material strength (brittle strength) at low temperatures. The design temperature (LMDAT) in the applicable sea area ranges from −10 to −15°C. The upper value in this range, −10°C, is the design temperature assumed in the classification rule for a normal ship. To withstand temperatures below −10°C, D grade steel is applied to the material for the shell plating above the water plane (A grade steel is applied for normal ships).

For the general hull we conducted a fatigue analysis in order to meet the high specifications required for the ocean

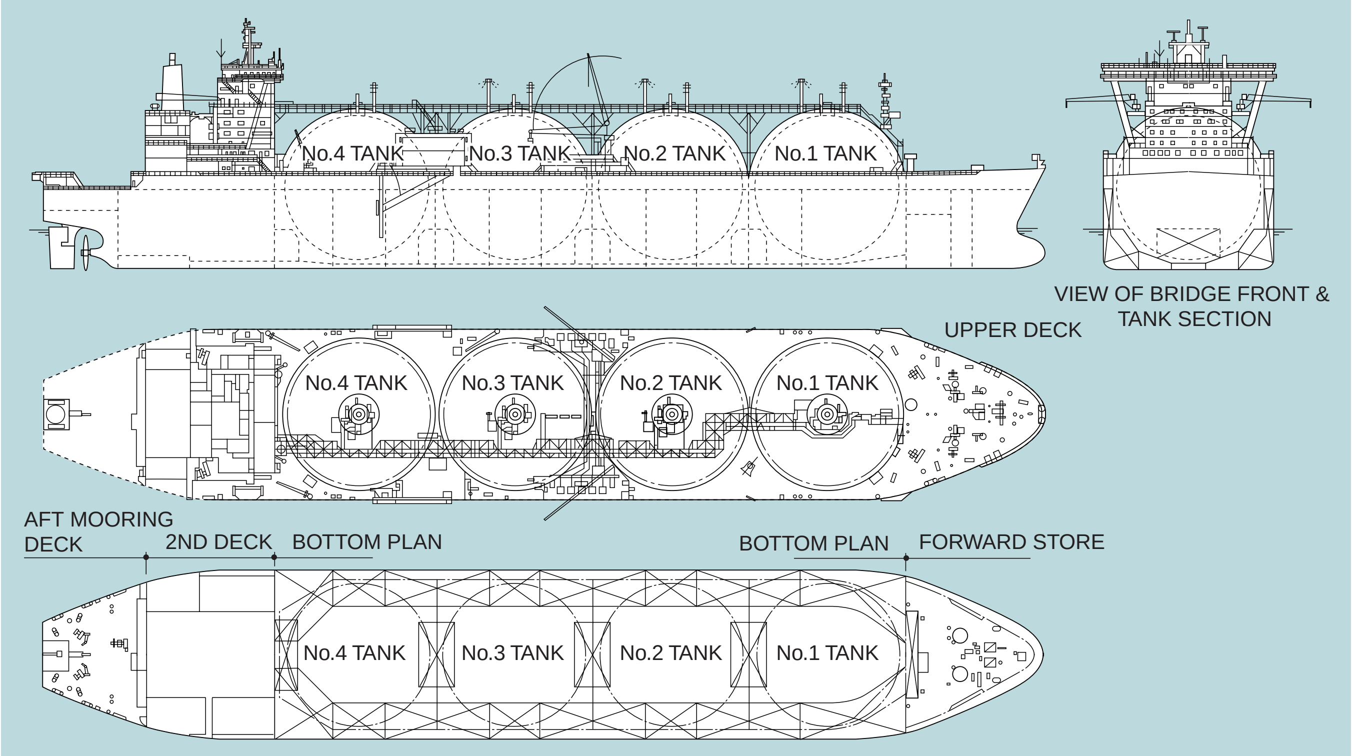


Fig. 2 General arrangement of the LNG carrier for Sakhalin Project

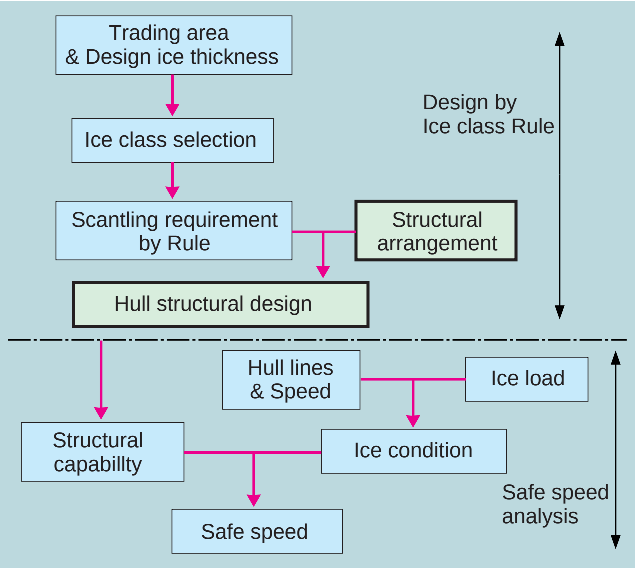


Fig. 3 Design flow for structural design against ice load

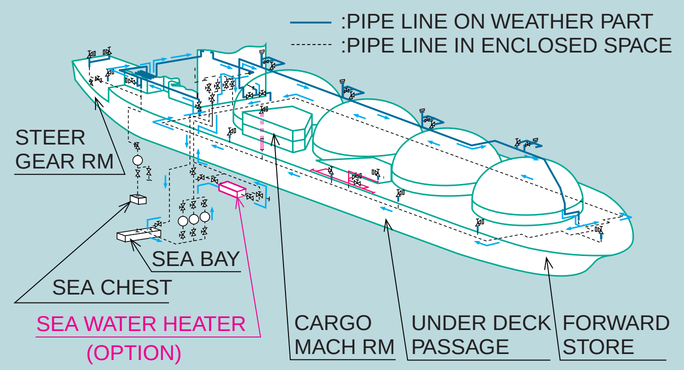


Fig. 4 Circulating system for Fire Hydrant line

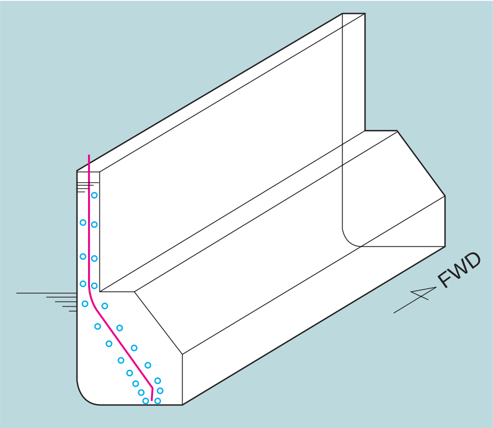


Fig. 5 Ballast tank air-bubbling system

wave conditions in the applicable sea area and for natural conservation in the northern sea area. Through this activity we obtained the LR FDA notation.

2.5 Winterization

The following is a list of the principal events and phenomena to be considered for the assurance of safety and reliability in cold districts, together with the applicable countermeasures to be taken in this LNG carrier.

- Embrittlement of materials: Use of proper materials
- Freeze-up of the seawater and fresh water lines: Drying up
- Freeze-up of the firefighting line: Constant pressurized circulation
- Freeze-up of the ballast tank: Air bubbling
- Accretion of ice to decks and structures: Heating, protection cover, ice melting by steam blow
- Blockage of the sea chest by ice: Adoption of sea bay
- Increase in the viscosity of the lubricating oil and hydraulic oil: Use of low-viscosity oil
- Dew condensation of control air/general service air: Use of dry air
- Damage due to contact with ice: Ice paint on shell plating

The next section introduces countermeasures to be taken against freeze-up of the firefighting line, freeze-up of the ballast tank, and blockage of the sea chest, as examples of winterization.

(1) Countermeasures against freeze-up of the firefighting line

The primary countermeasure against freeze-up of the seawater and fresh water lines (including the firefighting line) in most vessels is to keep the lines empty and dry. A drain valve is installed in each area for this purpose. The standard practice in LNG carriers, however, is to keep the firefighting line pressurized during loading, to enable immediate firefighting activities. This requires a countermeasure against freeze-up other than drying. In this LNG carrier, pressurized seawater is continuously circulated through the firefighting line to prevent freeze-up, as shown in **Fig. 4**. The seawater is taken in from the sea, pumped into the firefighting line by the firefighting pump, fed through the flying passage, forward area, and underdeck passage, sent into the engine room, and finally released into the sea bay. This LNG carrier is also equipped with a seawater heater in the engine room to comply with requests for improved safety from customers.

(2) Countermeasures against freeze-up of the ballast tank

The first step to take as a countermeasure against freeze-up of the ballast tank is to verify if a ballast water freeze-up occurs within the required low-temperature environment (the verification procedure is described later, in section 3.3). The verification performed for this LNG carrier confirmed that the risk of freeze-up is quite small. Even so, we decided to redouble safety and ensure reasonable specifications by adopting the additional countermeasure of air bubbling, as shown in **Fig. 5**. A continuous spouting of air bubbles up from the bottom of the ballast tank effectively prevents blockage of the tank. The force of the air bubbles can be expected to break up ice as it forms. The bubbles also help to melt the ice by bringing up the warmer seawater from the bottom of the tank.

(3) Countermeasures against blockage of the sea chest

Sailing in water passages between ice pieces at low speed leaves a vessel vulnerable to two important problems: excessive cooling due to the extremely low temperature of the sweater (−2°C or lower) and the blockage of the cooling seawater system by pieces of crushed ice. The design for this LNG carrier adopts an ice sea chest and sea bay method (**Fig. 6**). This system re-circulates cooling seawater and maintains the water temperature at or above the permissible value using exhaust heat from the engine section and excess boil-off gas (BOG) as sources of heat.

3. Next-generation LNG carriers sailing in cold districts

3.1 Level of winterization

(1) General

Cold district environments vary greatly, just as they do in the Arctic and Antarctic. In some areas with extremely low temperatures, a thick layer of ice covers the ocean surface throughout the year. Other areas are less amenable to seawater ice, as the temperatures only fall below freezing for short periods during the wintertime.

LNG carriers are designed for operation under vastly different conditions. Some are designed to sail in cold districts throughout the wintertime. Others, vessels built for long-distance trade, experience cold climates near their thermal ports. There are also large differences in the ways operators approach their work. Some prefer to economize by relying on the experience of veteran crews in cold environments without doing much to winterize the vessels themselves. Others make every effort to winterize their vessels in order to reduce workflows and protect their crews. These differences in usage environments, styles of operation, approaches of operators, and so forth make it difficult to stipulate reasonable specifications for cold districts. Overall, however, a vessel that sails through cold districts more frequently is believed to be placed at a higher risk. The main threats are damages to the hull and outfittings (**Fig. 7**).

LNG carriers now operate very safely in normal environments. Our next task is to realize comparable levels of safety in cold district environments. Another point to consider, in selecting the main engine, is the heightened sensitivity of natural environments in cold districts.

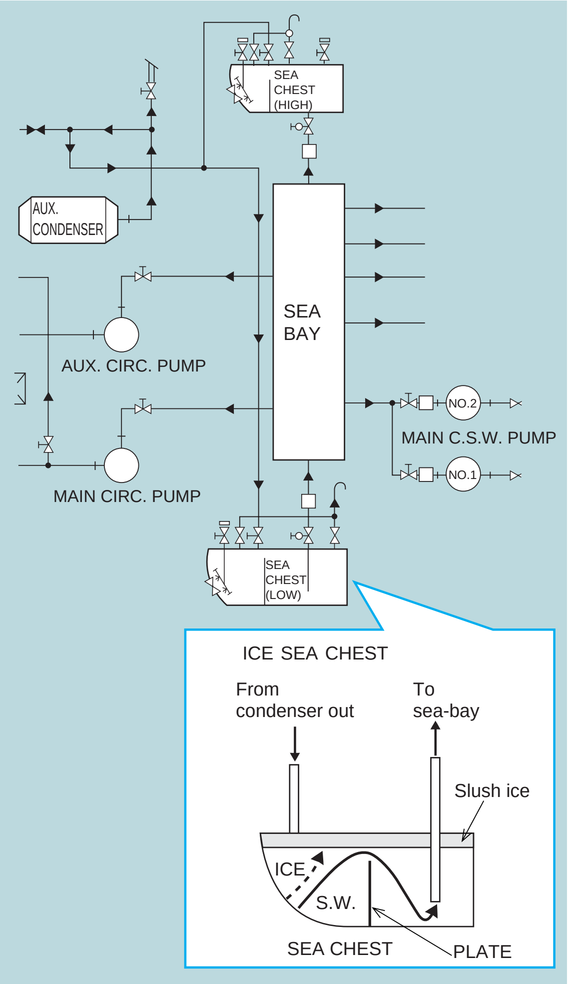


Fig. 6 Ice sea chest

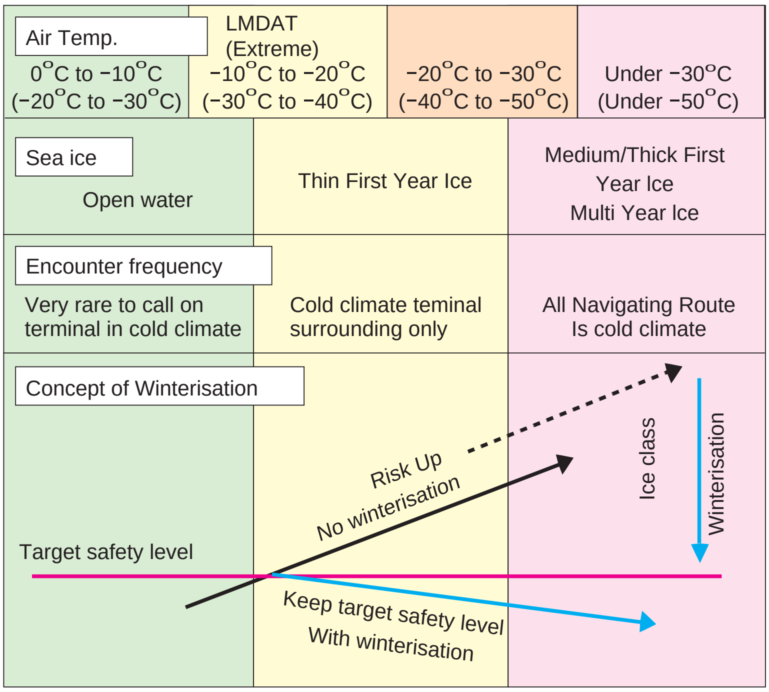


Fig. 7 Concept of winterization

(2) Design temperature

Air temperatures of course vary, and the calculated values for average air temperatures will change when different methods for statistical processing are applied. For this reason, the design temperature must be clearly defined when considering winterization. When selecting hull structure steel grades, for example, the Classification Society includes what it refers to as the "Lowest Mean Daily Average Temperature (LMDAT)" in its definition for the design temperature (**Fig. 8**).

The various definitions shown below apply to the design temperatures for the functions of air conditioners, the main engine, and so forth.

- LMDAT shown above
- Extreme Temperature: Lowest temperature that a ship can be expected to encounter in its lifetime. By definition, this is approximately 20°C lower than the LMDAT. The Extreme Temperature condition is assumed to persist for only a short period.
- Russian Industrial Standard based on the occurrence frequency definition.
- Absolute Minimum Temperature: Peak value of lowest temperature over an assumed period of 100 years.

In some cases, the Extreme Temperature is requested as the design temperature for certain equipment. It would be somewhat excessive, however, to consider the Extreme Temperature in the designs for all equipment of less than foremost importance. It may be adequate, in some cases, to adopt an intermediate value between the Extreme Temperature and LMDAT.

The realistic and ultimately essential approach is to correctly understand the temperature definition from the outset and to consider the importance of the equipment in determining the design temperatures.

(3) Categories of winterization

The levels of winterization are roughly classified into the three categories shown below, in consideration of the form of operation and environments (**Fig. 9**).

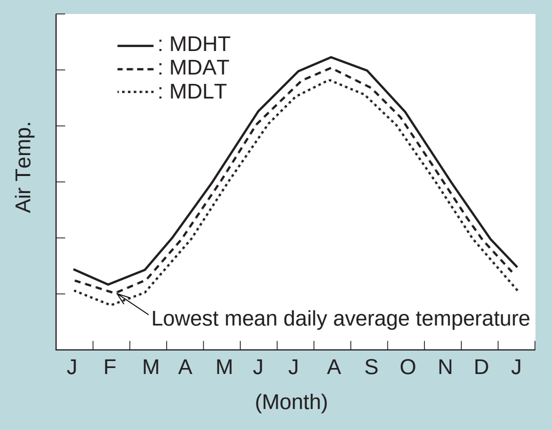


Fig. 8 Design temperature definitions

(a) Normal ships with minimum winterization

Existing ships sailing in the Baltic Sea and LNG carriers for Norway Snohvit Project fall under this category. This category corresponds to an atmospheric temperature of about 0 to −10°C in LMDAT and −20 to −30°C in Extreme Temperature. Normal steel grade should be applicable. Economic and maintenance considerations limit the level of winterization applied.

(b) Ships with practical winterization

Ships assumed to sail in atmospheric temperatures of about −10 to −20°C in LMDAT and about −30 to −40°C in Extreme Temperature fall under this category. These ships are built with ice reinforcement to minimize damages to the hull, and practical and reasonable winterization is applied to maintain the functions of equipment at low temperatures. Ships in this class are positioned between normal ships and ships capable of sailing in polar regions (described later). The level of winterization applied to these ships varies considerably, usually in accordance with the customer's preferences and priorities. Gas fields are scattered throughout the arctic region of Russia and Norway. Ships with practical winterization are thought to be capable of calling on many of the LNG bases in cold districts, including those planned for the future.

(c) Ships with strict winterization

Vessels operating in Arctic regions, including "Polar Class" vessels, may be classified in this category. The polar shipping routes are covered with thick sea ice, and the temperatures fall to very low values. In setting specifications, the top priority should be given to maintaining the integrity of the ship and crews. A specific design concept for this category has yet to be finalized, however. These ships differ greatly from normal merchant vessels in terms of both technology and cost.

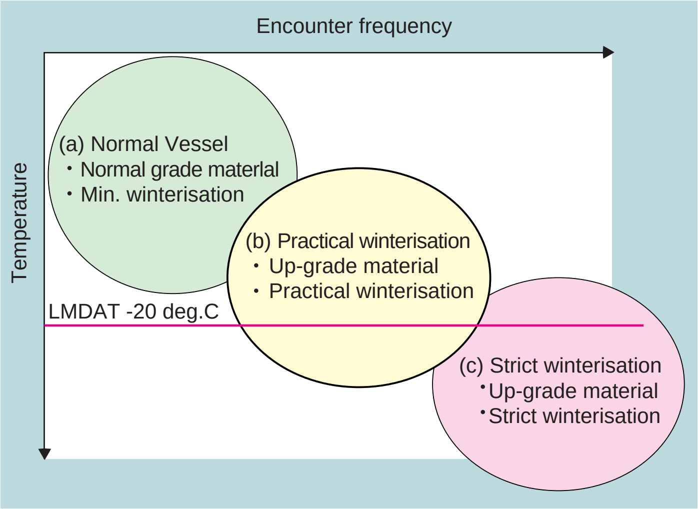


Fig. 9 Categories of winterization

3.2 Hull structure

The ice reinforcement should be designed in accordance with the applicable sea area regulation explained in Section 2.4. While the rule calculations for the same ice class grade are to be used, the actual strength values for completed ships will presumably vary according to the structures of the vessels and practices of the shipyards. To achieve reasonable designs, it will therefore be effective to conduct strength analysis in parallel using both FEM and the designs based on rule calculations. The example shown in **Fig. 10** is based on the relationship between the hull shape (lines) and ice shape. The structural area to be subjected to the maximum ice load is identified, then the strength is assessed on a fine mesh model of the area using the nonlinear analysis code ABAQUS.

The unified rule of the Classification Society (IACS Unified Requirement S6) can conceivably be applied when selecting the steel grades, if the design temperature (LMDAT) is sufficiently low (about –30°C). The temperatures in significant portions of the LNG bases, however, are limited to the order of –10 to –15°C. In such cases, the application of D grade steel to the shell plating is thought to be a reasonable measure as winterization.

In designing LNG carriers for cold districts, it is desirable to apply advanced fatigue analysis in consideration of the relative severity of the marine conditions and public sentiment toward environmental conservation in the northern sea areas. The DILAM (Direct Loading Analysis Method) developed by MHI is effective for this purpose.

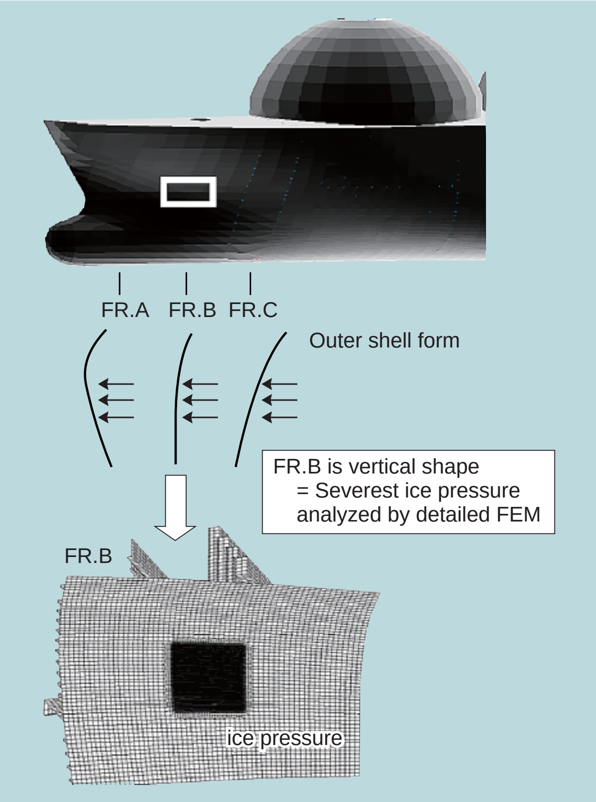


Fig. 10 Structural analysis against ice land by FEM analysis

3.3 Outfittings

When the rules are still being defined for the design of outfittings for ships in accordance with specifications for cold districts, various parties propose specific measures to fulfill the requirements. When designing the outfittings, it is crucial to secure safety, reliability, and a reasonable design all at once in a well and reasonably balanced manner according to the required low-temperature environment. If safety is overstressed, it will be necessary to add more equipment that requires measures against freeze-up (heating device) or to apply more low-temperature materials. This would constitute an increase in wasteful investment. It would be wasteful, for example, to require the constant maintenance of a device that is actually seldom used, or to require the use of an unnecessarily high-grade material during routine replacements due to wear and tear. The first steps to take in ensuring reasonable specifications for cold districts, therefore, are to verify adequate materials and ascertain whether measures against freeze-up are required for a requested low-temperature environment. The following sections describe the phenomenon of ballast tank freeze-up, introduce the procedure for selecting materials for outfittings, and providing examples of verifications.

(1) Ballast tank freeze-up

If the ballast tank is blocked by a freeze-up of water, the pressure in the tank will drop below zero when the water is discharged, possibly destroying the surrounding wall for the tank. One conceivable method to prevent the ballast water from freezing is to heat it with steam. This approach, however, would force the customer to invest in expensive measures to prevent the seawater from corroding the steam pipe, either by using a pipe material with high corrosion resistance from the beginning or by using general steel pipes based on the premise of maintenance during service. The first step to take, therefore, is to verify whether the ballast water freeze-up will result in a required low-temperature environment, and to take measures such as steam heating if there is confirmed to be an actual need to do so. **Fig. 11** shows an example of the simulation calculation performed for ballast water freeze-up.

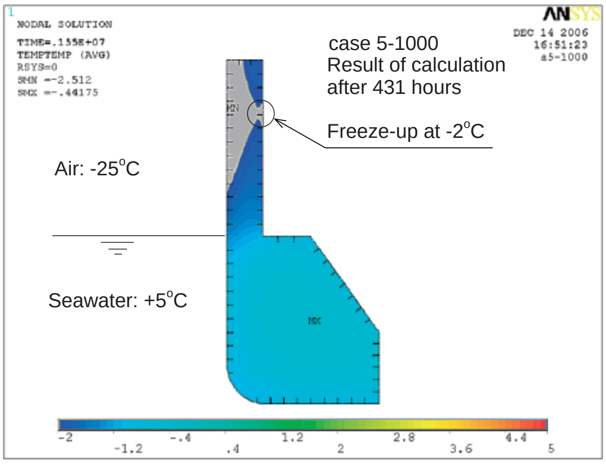


Fig. 11 Estimation of ice formation in Ballast Tank

In this case, a freeze-up occurred after 431 hours (about 18 days). Thus, special measures against freeze-up are not considered necessary for this LNG carrier if the duration of stay of the vessel is well within the 18-day period demonstrated by the test.

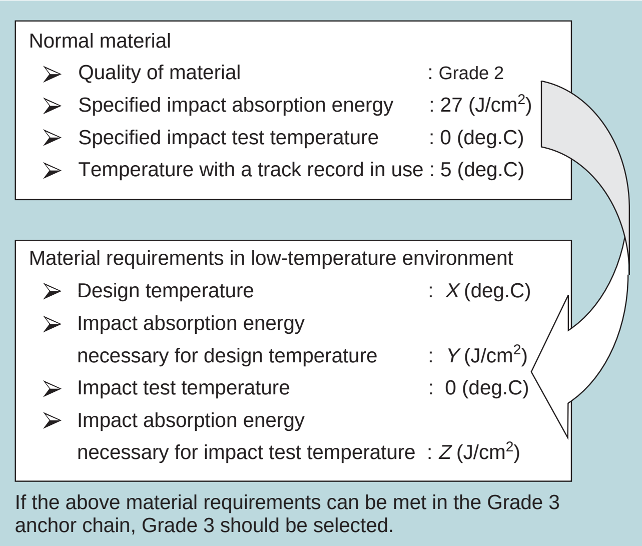
(2) Procedure for selecting materials for outfittings

The unified rule of the Classification Society (IACS Unified Requirement S6) already stipulates the selection criteria for steel grades for the hull in the required low-temperature environments. For outfittings, however, there are no clear provisions. Impact toughness values (V-notch Charpy impact absorption energy) are generally used as the criteria for evaluating materials for low-temperature environments. No technique, however, has been established for stipulating impact toughness values necessary for design temperatures. On the other hand, even ships built to normal specifications routinely carry out loading and sailing safely in low-temperature environments of a certain level. In light of this, the actual strength (reliability) of even normal materials is thought to be capable of withstanding low-temperature environments within limits. We therefore suggest that the actual strength in a low-temperature environment with a track record in use (temperature with a track record in use) be evaluated quantitatively, and that materials be selected in such a way that the same actual strength is achieved in the target low-temperature environment. To put it concretely, the actual strength of a normal material is defined as an impact toughness value for a temperature with a track record in use, based on the fracture-mechanical approach. This enables the selection of a material meeting the same impact toughness value in the target low-temperature environment (design temperature). An example of material selection for an anchor chain is shown in **Fig. 12**.

3.4 Propulsion system

(1) Propulsion plant

The LNG carrier for the Sakhalin Project sails in a lead of ice formed by a leading icebreaker. To succeed at this, an LNG carrier must be driven by a propulsion plant which operates for long hours and navigates at low speeds. Other considerations are the extremely low temperatures of the cooling seawater and the combustion air consumed by the main engine plant. In designing gears and shaft systems, the engineers must also account for higher torques expected when ice gets caught inside.



Normal material

- Quality of material : Grade 2
- Specified impact absorption energy : 27 (J/cm^2)
- Specified impact test temperature : 0 (deg.C)
- Temperature with a track record in use : 5 (deg.C)

Material requirements in low-temperature environment

- Design temperature : X (deg.C)
- Impact absorption energy necessary for design temperature : Y (J/cm^2)
- Impact test temperature : 0 (deg.C)
- Impact absorption energy necessary for impact test temperature : Z (J/cm^2)

If the above material requirements can be met in the Grade 3 anchor chain, Grade 3 should be selected.

Fig. 12 Example of material selection for outfittings (anchor chain)

In this section we compare various plant candidates under the conditions of cold district navigation (**Fig. 13**).

The ultra steam turbine plant (UST) is an advanced steam turbine plant developed by MHI for future use. The thermal efficiency of the UST is about 15% higher than that of the conventional steam turbine. The basic plant configuration is similar to that of the conventional type. The UST, a plant additionally equipped with a shaft inline generator/motor for power generation, can navigate at back-up slow streaming. There are two candidates for electric propulsion (DFE): one is direct drive by low-speed propulsion motors and the other is a combination of a high-speed propulsion motors and a reduction gear. Dual fuel engines are used as a power generation plant in both of the candidates.

For the two candidates of slow-speed diesel engine plant, BOG is re-liquefied or burned in dual fuel auxiliary boilers. The main propulsion system is duplicated to realize the redundancy generally required for LNG carriers. The slow-speed diesel engine is an oil-fired type.

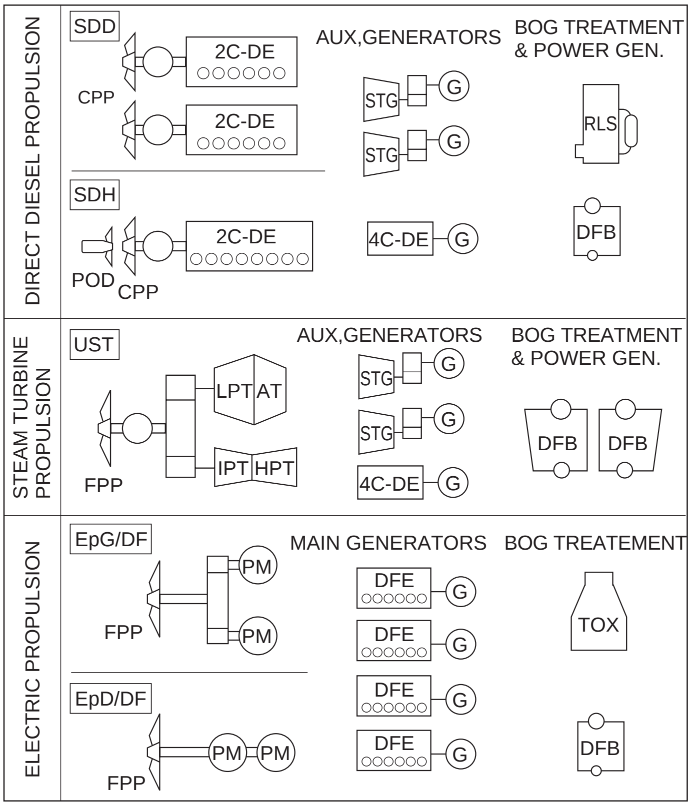


Fig. 13 Propulsion plant options

(2) Ice navigation

Fig. 14 shows the allowable torque range for each propulsion plant. Two torque ranges are applied, in general: a range for plants with a reduction gear and a range for direct drive. Both turbine plants and DFEs with reduction gears are classified within the allowable ranges with gears.

Cases where a turbine ship with a fixed pitch propeller sails in an ice-bound sea with two respective ice thicknesses, 0.6 m and 0.1 m thick, are plotted. Even with the thick ice of 0.6 m, a sufficient margin is available relative to the allowable torque, hence sailing remains possible. When the ice gets thicker, however, or the vessel is assumed to sail by self ice navigation, it may be necessary to adopt a CPP (controllable pitch propeller). With the narrow allowable range of torque for diesel ships, the adoption of CPP is preferred.

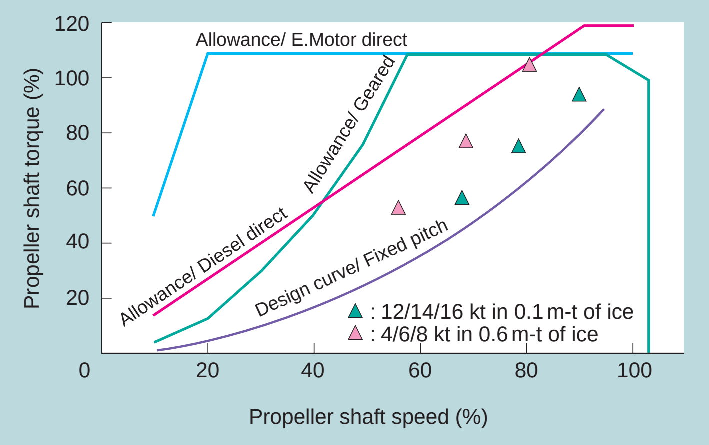


Fig. 14 Allowable torque zone in the navigation zone

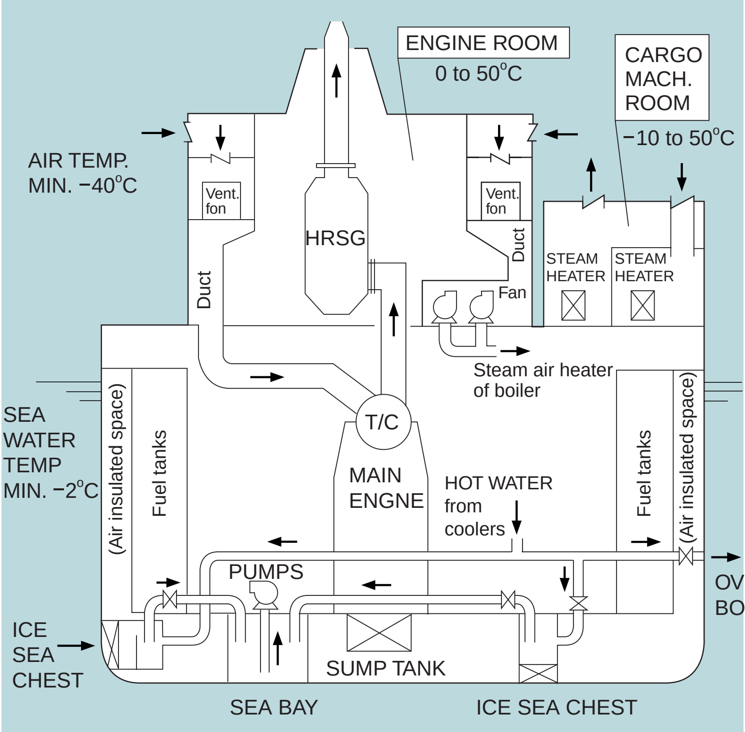


Fig. 15 Conceptual diagram of machinery space with winterization

(3) Winterization

The blockage of the cooling seawater systems due to excessive cooling and broken pieces of ice can be effectively prevented in all of the plants by the ice sea chest and sea bay method, the same method used by the LNG carrier for the Sakhalin Project. For the intake of combustion air for large diesel engines, on the other hand, the preferable method is to suction in the outside air directly. When air is suctioned in from the engine room, a heat source should be used inside the engine room to avoid reductions in the room temperature due to the large amounts of air taken into the room (**Fig. 15**).

Further, it is suitable to equip the turbine plant with dual fuel boilers to cope with the large amounts of steam and hot water required in cold weather compared with conventional ships.

(4) Evaluation of economic efficiency

The amount of fuel consumed is the most important factor for the evaluation of economic efficiency. LNG carriers use multiple fuels (heavy oil, diesel oil, LNG, and BOG) and are expected to navigate at low speeds for long periods in cold districts. Partly as a result of this, simple comparisons of fuel consumption based on the thermal efficiency do not reflect the actual correct conditions. When we compare UST and DFE (**Fig. 16**), for example, the solid line representing the amount of fuel consumed in the fuel gas (BOG) operation shows that DFE has a slightly superior thermal efficiency in the low load area. However, gases unavoidably generated and gasses in amounts lower than the BOG are disposed of as excess gases. Thus, they are not reflected in the fuel consumption difference.

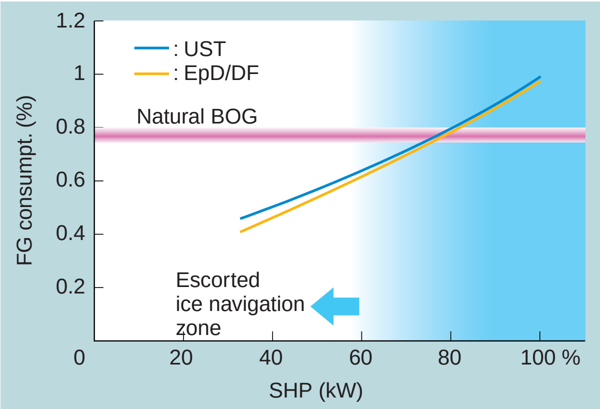


Fig. 16 Amount of fuel gas consumed and natural boil-off gas

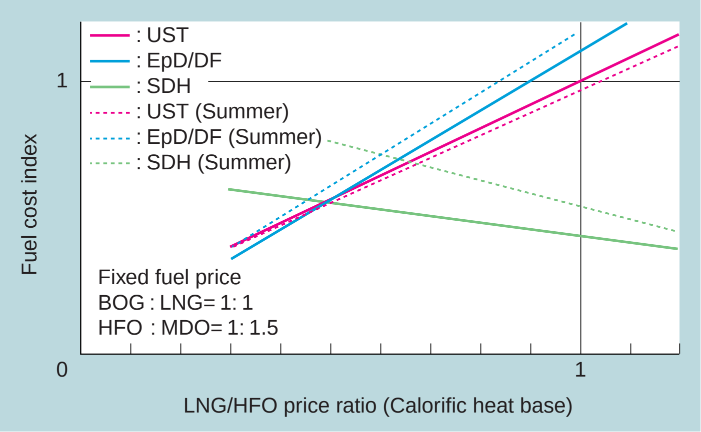


Fig. 17 Evaluation of fuel oil cost

On the other hand, the fuel consumption is largely dependent on the price ratios of LNG and heavy oil. **Fig. 17** shows the price ratios during the winter months (solid line) and summer months (dotted line) when navigation in ice bound seas is expected, assuming transportation from the Baltic Sea in Russia to the coast of North America. The advantage of reliquefaction is noticeable in areas with a high LNG price ratio, and the effect is especially large during winter months when low-speed navigation is frequent and excess gas is generated for longer hours. In the comparison between UST and DFE, on the other hand, there is almost no significant difference in areas with a low LNG price ratio. As the price ratio rises to high levels, however, it becomes more advantageous to use UST, a plant capable of burning BOG with heavy fuel oil.

(5) Environmental friendliness

The environmental friendliness is generally judged by the amounts of CO_2, NOx, and SOx discharged from the propulsion plants. **Figure 18** shows the CO_2 emission during ocean navigation and the NOx emission during operation in harbor, expressed as ratios based on the propulsion power.

The CO_2 emission (and of course the SOx emission, also) can be reduced by using LNG as fuel. The steam turbine or DFE in gas firing (lean burn cycle) mode is superior for the reduction of NOx. Thus, the options for fuel are wide and systems capable of burning gas offer advantages in both fuel consumption and environmental friendliness.

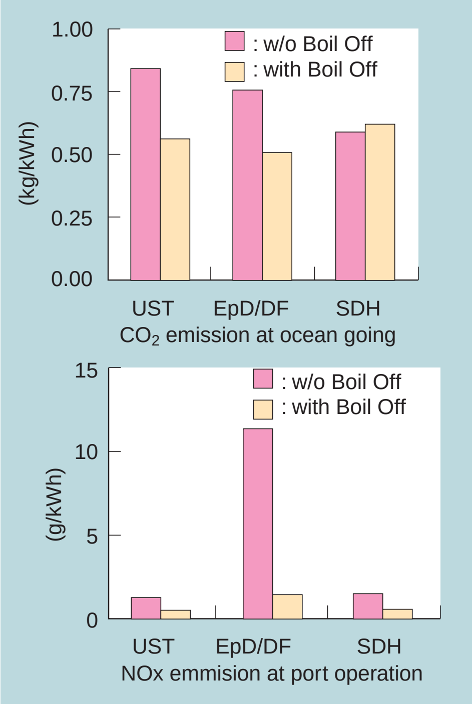


Fig. 18 Evaluation of exhaust gas

4. Conclusion

MHI has accumulated knowledge through projects for Norway and Russia and joint studies with the Russian Institute. With this knowledge, MHI has established designs and specifications (structure, arrangement, anti-icing, de-icing, and so forth) suitable for the construction of actual ships.

MHI continues to study approaches for formulating reasonable specifications, materials, and plant selection for the lower-temperature environments to be navigated in the future. Making the best use of the knowledge it has thus accumulated, MHI plans to continue to work proactively on projects for cold districts.

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