Transportation of clean energy at sea
–Mitsubishi LNG carrier, at present and in future–

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1. Introduction

Mitsubishi Heavy Industries, Ltd. (MHI), applying its shipbuilding technology refined through more than a century of experience, has developed, designed and built various types of vessels and floating facilities including cruise ships, liquefied gas carriers, ferries, containerships, crude oil tankers, floating production, storage and off-loading units, submersible research vessels, etc., as illustrated in the photo at the top.

In the field of liquefied gas carriers, MHI constructed in 1962 the world's first fully refrigerated type LPG carrier, and by the end of 2002 it had built forty large LPG carriers and twenty-two large LNG carriers, both of which were the largest number of carriers constructed by a single shipbuilder in the world.

In the field of LNG carriers, since completing its first 125 000-cubic meter class LNG carrier in 1983, MHI has developed and constructed a so-called "second-generation LNG carrier" for the Australian North-West Shelf Project, which was regarded as the last project of the twentieth century. A characteristic of the second-generation LNG carrier is that the freedom of choice of fuel types has been expanded by the application of low boil-off rate (BOR) and forcing vaporizer. This has allowed the economic LNG carriers, and is now the design standard for such carriers.

In recent years, MHI has been continuously offering its epoch-making products through activities such as installation of the world's first onboard reliquefaction plant on an operational LNG carrier, construction of environment-conscious LNG carriers, and development of the largest 145 000-cubic meter class LNG carrier.

Construction of safe, reliable and economic LNG carriers is a matter of great importance. MHI is making every effort to offer the best-suited LNG carriers to satisfy the needs of each customer.

MHI's LNG carriers for the sea transportation of clean energy are introduced in this paper.

2. Yesterday

Since LNG (liquefied natural gas) was introduced into Japan as a clean energy in 1969, imports of LNG to Japan have sharply increased to the current level of about 55 million tons (about 60 per cent of the world's imports). As LNG is an ultra-low temperature (about $-160^{o}C$) liquid-state fuel that is liquefied by condensing the natural gas to about one six-hundredth of its volume, it must be stored in special tanks during transportation. Various special tanks for LNG carriers were developed in the fifties, but spherical tanks and membrane tanks (use of metallic membrane) are today's representative types for the reasons of safety, reliability and economic features.

MHI applied both techniques of spherical tank and membrane tank types to the development of commercial LNG carriers in the seventies.

In 1980, MHI received its initial order for a 125 000-cubic meter class spherical tank type LNG carrier and delivered it to the customer in 1983. With the experience in the execution of this initial order, MHI was able to establish its own design and construction technology for LNG carriers. Furthermore, various improvements have been made for the development of so-called second-generation LNG carriers and, as a result, many large LNG carriers have been built by MHI as a leading shipbuilder. The second-generation LNG carrier is characterized by the following features:

(1) Low BOR has been attained by the development of thermal brake (a special mechanism to suppress the entrance of heat).
(2) Flexibility of choice of the fuel types has been dramatically increased by a combination of low BOR and forcing vaporizer.
(3) Enhancement of structural reliability and reduction of construction costs have been achieved at the same time by improving the structure of the spherical tank cover and flange type pipe tower.
(4) A large four-tank vessel has been developed by MHI for the first time in the world, and the design concept

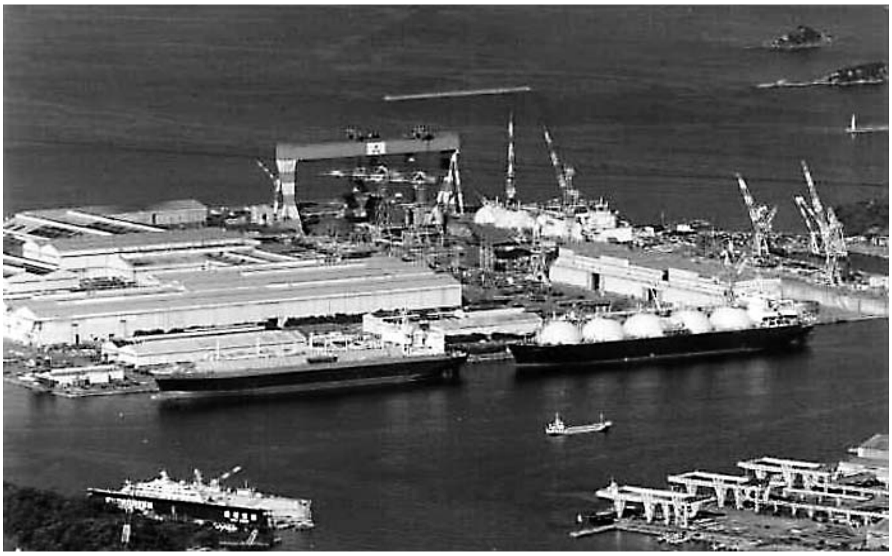

Fig. 1 Bird's-eye view of LNG carriers (spherical tank type and membrane tank type) now being built

for a high-performance ship's hull form suitable for shallower draft and wider beam has been implemented.

Development activities for membrane tank type LNG carriers were also continued in the seventies and later. Bearing in mind that structural reliability should be the important matter for improvement of the membrane tank type carrier, the soundness of the ship's structure was verified, and the key technique needed for the containment system was completed for practical application.

3. Today

At the present time, a 135 000-cubic meter class spherical tank type LNG carrier and a membrane tank type carrier are being built simultaneously. **Fig. 1** shows these LNG carriers under construction at MHI's Nagasaki Shipyard & Machinery Works Koyagi Plant.

For the installation of spherical tanks, improvements were made to the aluminum plate welding method, the structural transition joint manufacturing method, and the application method of tank insulation.

In addition, the reliquefaction plant for LNG carriers completed by MHI, a first in the world, is mounted on the LNG carrier and is working satisfactorily. **Fig. 2** shows an outline of the reliquefaction plant. For this, MHI jointly developed this high-efficiency reliquefaction system using nitrogen as the refrigerant.

For the construction of membrane tank type LNG carriers, an automatic welding apparatus was completed for the improvement of reliability in welding work and the process and quality control system "LOGIQ" was developed to increase the efficiency of controlling about seven hundred thousand component parts used in fabricating the insulation and membrane structures. The first 135 000-cubic meter class membrane tank type LNG carrier was delivered to the customer in August 2002, and

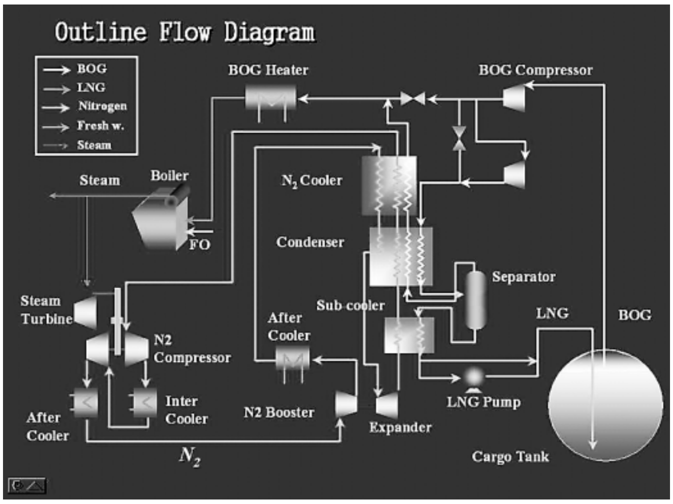

Fig. 2 Outline flow diagram of reliquefaction plant

its successors are now being built.

MHI is the world's first shipbuilder to have designed and constructed both spherical tank type and membrane tank type LNG carriers.

Table 1 shows the LNG carriers already constructed or being constructed now by MHI.

Also with regard to the ship repair and conversion work for LNG carriers, including those built by other companies, MHI has a dominant share in receiving orders and is also tackling ship refurbishment work for life extension.

Table 2 shows the main specifications for the latest spherical tank type and membrane tank type LNG carriers now under construction. The latest LNG carriers have the following features:

(1) LNG carriers with a tank capacity of 135 000 cubic meters are now popular, but those with larger capacities are gradually increasing in number. Also, a 145 000-cubic meter class carrier, the largest in the world today, is now under construction as shown.

Table 1 LNG carriers completed/being constructed

Completed ships As of November 2002

Hull No.	Ship's name	Project name	Tank capacity (m^3)	Tank type	Delivery
1 870	Banshu Maru	Indonesia BadaK III	125 542	Spherical tank	1 983
1 889	Echigo Maru	Indonesia Arun	125 568	Spherical tank	1 983
1 890	Dewa Maru	Indonesia Arun	125 631	Spherical tank	1 984
1 996	Northwest Sanderling	North West Shelf	127 362	Spherical tank	1 989
2 000	Northwest Swift	North West Shelf	127 427	Spherical tank	1 989
2 011	Ekaputra	Indonesia, Taiwan	137 012	Spherical tank	1 990
2 042	Northwest Seaeagle	North West Shelf	127 452	Spherical tank	1 992
2 062	Dwiputra	Indonesia Badak F-train	127 386	Spherical tank	1 994
2 061	LNG Vesta	Indonesia Badak Badak F-train	127 386	Spherical tank	1 994
2 074	Northwest Stormpetrel	North West Shelf	127 443	Spherical tank	1 994
2 067	ISH	Abu Dhabi	137 304	Spherical tank	1 995
2 089	Al Khor	Qatar	137 354	Spherical tank	1 997
2 090	Al Wajbah	Qatar	137 309	Spherical tank	1 997
2 091	Doha	Qatar	137 252	Spherical tank	1 999
2 148	Golar Mazo	Indonesia, Taiwan	136 867	Spherical tank	2 000
2 117	Al Jasra	Qatar	137 227	Spherical tank	2 000
2 157	LNG Jamal	Oman	136 977	Spherical tank	2000
2 162	Lakshmi	Oman	137 248	Spherical tank	2 001
2 163	ABADI	Brunei	136 912	Spherical tank	2 002
2 165	Puteri Intan Satu	Malaysia Tiga	137 100	Membrane tank	2 002
2 172	Galea	Shell	136 600	Spherical tank	2 002
2 173	Gallina	Shell	136 600	Spherical tank	2 002

Being constructed (Ship's names are not decided.)

Hull No.	Ship's name	Project name	Tank capacity (m^3)	Tank type	Delivery (Scheduled)
2 169	–	Malaysia Tiga	137 100	Membrane tank	2 003
2 176	–	Tokyo Electric Power Company	136 600	Spherical tank	2 003
2 177	–	Malaysia Tiga	137 100	Membrane tank	2 004
2 183	–	Shell	136 600	Spherical tank	2 004
2 184	–	Snohvit	147 200	Spherical tank	2 005
2 185	–	Snohvit	147 200	Spherical tank	2 006
2 187	–	Tokyo Electric Power Company	136 600	Spherical tank	2 006

Table 2 Main dimensions of the latest LNG carriers

Project name	Malaysia Tiga	Tokyo Electric Power Company	Snohvit
Tank capacity (m^3)	135 000	135 000	145 000
Tank type	Membrane tank (GT 96)	Spherical tank	Spherical tank
No. of tanks	4	5	4
BOR (%/d)	0.15	0.15	0.15
Dimensions Overall length, Loa (m)	276.0	290.0	288.0
Breadth (m)	43.4	46.0	49.0
Depth (m)	25.5	25.5	26.8
Draught (m)	11.0	11.0	11.5
Dead weight (t)	66 700	67 900	74 400
Service speed (Kn)	19.5	19.2	19.5

(2) The BOR can be reduced to an extra low level of 0.10 per cent per day for spherical tank type LNG carriers as already applied to one of MHI-built carriers. However, a BOR of 0.15 per cent per day is popular now for economic reasons. As for the membrane tank type carrier, a BOR of 0.15 per cent per day has also been attained by increasing the thickness of the thermal insulator and simplifying the insulation structure.

(3) For ship's hull form designing, computational fluid dynamics (CFD) is utilized. Use of CFD for optimization of ship's hull form and propeller designs has made it possible to quickly complete designs for LNG carriers with high propulsion efficiency. This has also helped in the design of a high performance ship with an optimum main engine output and low fuel consumption rate.

(4) For economical ship operation, boil-off gas (BOG) is efficiently utilized by a combination of low BOR and forcing vaporizer.

(5) The design and specifications of LNG carriers have been elaborated by paying special attention to their details aimed at ease of maintenance to be carried out for many years, including that on structure and layout, selection of component materials and types of paints, etc. Especially for the structural designing, MHI has completed the sloshing load analysis and has also developed advanced methods for analysis of structural strength and fatigue strength. A unique discrete analysis method (DISAM) for analyzing fatigue strength against sea waves has been completed and practically applied. The completion of these analysis methods has enhanced the reliability of design for fatigue strength structures, and now allows application of a forty-year fatigue design for newly built ships.

(6) For simple and safe operation of a ship, various automatic systems such as the integrated automation system (IAS), the shipboard management system (SMS), and the integrated bridge system (IBS) are installed on LNG carriers. Also for purposes of environment protection, advanced systems such as an automatic ballast water replacement system, alternative refrigerant for substituting chlorofluorocarbons, and so on, are used on LNG carriers. MHI received the environmental protection notation (EP notation) from Lloyd's Register of Shipping for its newly built LNG carrier, which was the first application to an LNG carrier in the world.

4. Tomorrow

The most important matter in designing LNG carriers is to simultaneously satisfy safe, reliable and economic conditions. Lately, reduction of LNG chain cost is being discussed more often than subjects such as safety and reliability of LNG carriers, which are considered to have been confirmed by years of ship operations.

In addition to the enlargement of LNG receiving ter-

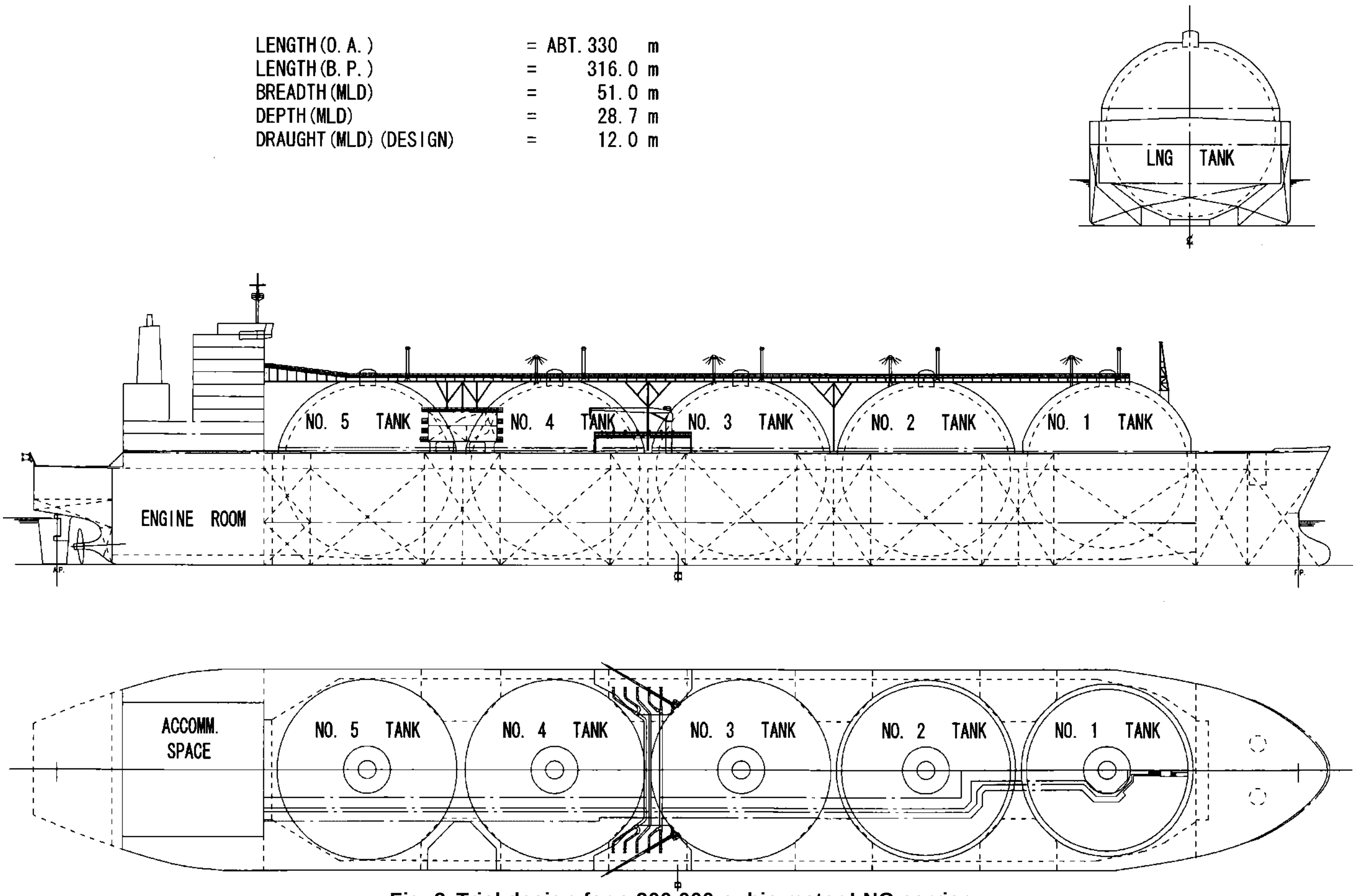

Fig. 3 Trial design for a 200 000-cubic meter LNG carrier

minals, LNG carriers and LNG land storage tanks, there are proposals for the development of the next-generation propulsion plant and a new concept gas carrier.

4.1 Large LNG carriers

The purpose of increasing the size of LNG carriers is to help lower the unit transportation cost. As the quantity of LNG to be transported for a project does not vary much, employment of large LNGs can reduce the number of shipping operations and greatly save transporting costs.

For example, in the case of an LNG transport project for transporting five million tons per year from the Middle East to Japan, this requires seven 135 000-cubic meter carriers, six 160 000-cubic meter carriers or five 200 000-cubic meter carriers.

This means that the transportation cost for the operation of a 135 000-cubic meter LNG carrier can be reduced by six per cent when a 160 000-cubic meter carrier is used instead, or by fourteen per cent with the use of a 200 000-cubic meter carrier.

A trial design for a 200 000-cubic meter LNG carrier is shown in **Fig. 3**.

For the operation of large LNG carriers, it is important to take into account the capacity of existing LNG terminals, especially those of receiving terminals. The transportation cost can be reduced by operating large LNG carriers as mentioned above, but this matter must be discussed as a part of the overall LNG chain operating cost including the costs of the construction of new terminals or modification of existing receiving terminals. As a 145 000-cubic meter carrier is generally considered to be the largest one usable in the current situation, MHI is now building two 145 000-cubic meter LNG carriers for its customers.

4.2 Next-generation propulsion plant

A part of the LNG loaded on an LNG carrier produces boil-off gas (BOG) due to the difference in temperature between the LNG itself and the environment, as well as the kinetic energies produced by the movement of the ship. This BOG is used to drive steam turbines. As BOG belongs to the LNG cargo, use of various types of plants is being examined for more efficient use of BOG.

Typical methods being examined for application to next-generation plants are "dual fuel diesel engine," "combined gas and steam turbines (gas turbine engine + steam turbine engine)" and "diesel engine with reliquefaction plant."

In the case of the dual fuel diesel engine, multi-fuel firing of BOG and heavy oil is possible and combustion efficiency is similar to that of conventional diesel engine. However, this necessitates increasing the BOG pressure for combustion as fuel and supplying a pilot fuel. Another disadvantage of this method is that BOG cannot be fired alone, and the operation is not flexible. In addition, diesel engine firing at high temperature increases NOx emissions.

In the case of the combined gas and steam turbines (gas turbine engine + steam turbine engine), BOG is fired in the gas turbine and the exhaust gas is used to generate steam for driving the steam turbine. Similar to the effect obtained from the operation of a cogeneration system for power plants on land, fuel consumption efficiency is improved when compared to ordinary steam turbines. However, this method requires the supply of high-quality petroleum fuel, though the exhaust gas is relatively clean as in the case of steam turbines, and BOG cannot be used for multi-fuel firing. They are not advantageous for this method.

In the case of diesel engine with reliquefaction plant, because BOG is reliquefied and returned directly to the LNG tanks, the ship's propelling system can be separated from the BOG processing system. This allows the use of ordinary cargo ship engines, which helps to significantly reduce fuel consumption. The additional expenses of this method include the cost of reliquefaction plant and extra fuel oil to generate the electric power for its operation. However, the consumption of extra fuel can be reduced by efficient utilization of the exhaust gas from the diesel engines.

The economical valuation of the above-mentioned methods depends largely on the difference in price between BOG and fuel oil. When the price of BOG is lower than that of fuel oil, use of "steam turbine engine" will be the most economical method. However, use of "dual fuel diesel engine" may become advantageous if the price of fuel oil rises. When viewed from an environmental protection standpoint, "a combination of gas turbine and steam turbine" may become more attractive. When the value of BOG is estimated to be higher than others, use of diesel engine with reliquefaction plant may become advantageous.

MHI is continuously developing each of these plant type systems for commercial application, and produces steam turbines and diesel engines as its standard products. Furthermore, MHI produces from time to time gas turbines for installation on warships and cruise ships.

MHI is the only shipbuilder in the world that has already completed a reliquefaction plant for LNG carriers, and it is in a position to supply the optimum "diesel engine with reliquefaction plant," which is regarded as the most promising next-generation propulsion plant. A schematic diagram of the reliquefaction plant is shown in **Fig. 4**.

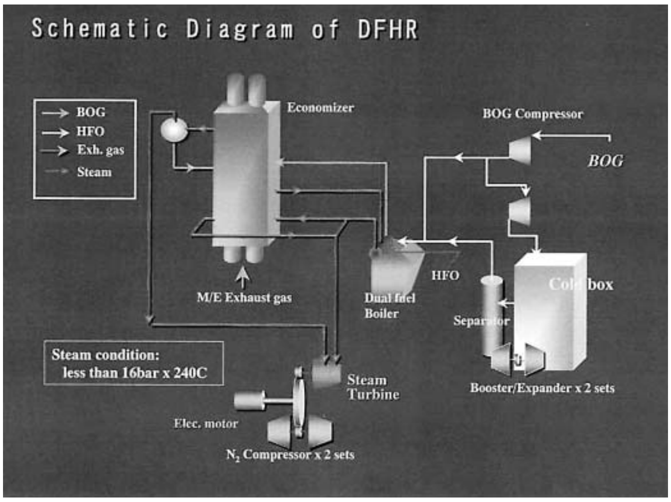

Fig. 4 Schematic diagram of a next-generation propulsion plant with reliquefaction plant

4.3 New type natural gas carriers

There is a possibility that new methods of transporting some natural gases will be used in the future. Such natural gases as compressed natural gas (CNG), methane hydrate, and dimethyl ether (DME) are considered to be cargo that can be transported in different ways. The purpose of using different transportation methods is to reduce the chain cost for the processes of gas production, storage, transportation and regasification.

Table 3 shows the physical characteristics of these natural gases as cargo.

CNG is a high-pressure, low specific gravity cargo, but is fairly good for reducing the regasification cost. It is believed that a considerable amount of chain cost can be saved when it is transported over short distances between places where the infrastructure for gas treatment is already available.

Methane hydrate is transported in the form of frozen methane, and is considered to be an easy-to-handle cargo when compared to LNG, though its net calorific value per unit weight is low.

DME is expected to become an alternative fuel to LPG in the future. It has a higher specific gravity and boiling

Table 3 Physical characteristics of natural gases

(Unit)	LNG	CNG	Methane hydrate	DME	LPG
State	Liquid	Gas	Solid	Liquid	Liquid
Temperature (°C)	−162	10	−15	−25	−42
Specific gravity (t/m^3)	0.43	0.23	0.85 to 0.95	0.74	0.58
Pressure (kg/cm^2)	Near atmospheric pressure	210	Near atmospheric pressure	Near atmospheric pressure	Near atmospheric pressure
Low calorific value (kcal/kg)	12 000	12 000	1 000 to 2 000	6 900	11 100

point than LPG, and is reported to be treatable with facilities similar to those used for LPG.

MHI has already started fundamental research on the transportation methods for the above-mentioned natural gases. As soon as the studies on the suitability of the structure and materials of the tanks as well as their safety are completed, MHI will develop economical carriers for each of these cargoes.

5. Conclusion

The sea transportation of LNG has been increasing constantly since commercial LNG transportation started in 1964, and about 130 LNG carriers are currently being operated as of the end of 2002.

MHI has acquired the technology for the construction of liquefied natural gas carriers since it completed the world's first fully refrigerated type LPG carrier in 1962. MHI also introduced the technology for the construction of spherical tank type and membrane tank type LNG carriers in the seventies, and developed various techniques to ensure safety, reliability and economy for their application to actual ships. Today, MHI is the world's largest supplier of LPG and LNG carriers, and is confident that it is supplying advanced liquefied natural gas carriers to meet the satisfaction of each customer.

Recently, various proposals for the reduction of LNG chain cost have been discussed. MHI will bring forward the construction of large-sized carriers, next-generation propulsion plants and modification of existing tanks, and will develop economical carriers to meet the needs of our customers.

Technical development has been carried out so far with the assistance and cooperation of many other organizations in the related industries. MHI wishes to express its thanks to those organizations for their cooperation, and requests for their further assistance in the future, which will enable MHI to build safe, reliable and economical next-generation LNG carriers.

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