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# Study on Introduction of $CO_2$ Free Energy to Japan with Liquid Hydrogen

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## Abstract

In Japan, both $CO_2$(Carbon dioxide) emission reduction and energy security are the very important social issues after Fukushima Daiichi accident. On the other hand, FCV (Fuel Cell Vehicle) using hydrogen will be on the market in 2015. Introducing large mass hydrogen energy is being expected as expanding hydrogen applications, or solution to energy issues of Japan. And then, the Japanese government announced the road map for introducing hydrogen energy supply chain in this June,2014. Under these circumstances, imported $CO_2$ free hydrogen will be one of the solutions for energy security and $CO_2$ reduction, if the hydrogen price is affordable. To achieve this, Kawasaki Heavy Industries, Ltd. (KHI) performed a feasibility study on $CO_2$-free hydrogen energy supply chain from Australian brown coal linked with CCS (Carbon dioxide Capture and Storage) to Japan. In the study, hydrogen production systems utilizing brown coal gasification and $LH_2$ (liquid hydrogen) systems as storing and transporting hydrogen are examined. This paper shows the possibility of realizing the $CO_2$ free hydrogen supply chain, the cost breakdown of imported hydrogen cost, its cost competitiveness with conventional fossil, and $LH_2$ systems as key technologies of the hydrogen energy chain.

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***Keywords:*** **hydrogen energy, $CO_2$ free, brown coal, liquid hydrogen**

## 1 Introduction

In recent years, hydrogen energy is expected as the promising energy in Japan, because fossil-fuel sources have reached their limit, solutions to environmental problems as global warming will be needed, and nuclear power generation cannot be expected to expand any further. Commercials hydrogens applications such as household-use fuel cells (FC) and FCV will expand remarkably. The road map to the future has been proposed for the realization

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of the hydrogen economy through the coordination of business, academia, and government within the framework of the Energy Basic Plan announced by the Japanese government on this June, 2014.

The idea of hydrogen energy is believed to have originated when French science-fiction author Jules Verne predicted a hydrogen society in his book “Mysterious Island” in 1874 1). One hundred years later, the first World Hydrogen Energy Conference (WHEC) was held in 1974 2), giving a full-scale start to scientific studies. Hydrogen energy is being proposed both inside and outside Japan as a system to mutually complement the electricity. Recently it has finally been recognized as a practical system for solving energy problems.

This paper describes increasing hydrogen demand in future, the system of importing hydrogen to Japan from overseas coping with hydrogen demand towards the hydrogen economy, $CO_2$-free hydrogen system that our company proposed, and its $LH_2$ (liquid hydrogen) system which of hydrogen liquefiers and $LH_2$ carriers and etc..

## 2 Expanding demand for hydrogen and importing hydrogen from overseas

Hydrogen energy will be gradually incorporated into society as expanding hydrogen usage systems (e.g. shift from fuel cells to hydrogen engines and gas turbines), while being affected by the business structure (including hydrogen sources) and the geographic features of each region. Regarding the amount of hydrogen to be introduced, various research bodies in Japan have predicted future demand for hydrogen by using energy technology evaluation models under various limiting conditions.

For instance, the Institute of Applied Energy predicted the amount of hydrogen demand by presupposing hydrogen derived from overseas brown coal, natural gas, and wind power by setting as the limiting condition the reduction of $CO_2$ emissions with a target discharge reduction rate of 15% in 2020 and 80% in 2050, both as compared with 1990. Figure 1 3) shows the estimated demand for primary energy and hydrogen、assumed CIF (Cost, Insurance and Freight) is ¥35/Nm$^3$. Their forecast for hydrogen demand is about 29.9 MTOE (Mega Ton of Oil Equivalent) per year (hydrogen 98.2 x $10^9$ Nm$^3$, 8.83 x $10^6$ tons) in 2025. This amount of hydrogen, if converted to the amount of LNG by higher heating value conversion, is equivalent to 3.45 x $10^6$ tons/year

Studies on importing hydrogen from overseas sources have been conducted both inside and outside Japan since over 20 years ago 4). The most representative projects are the EQHHPP (Euro Quebec Project, 1986–1998) 5) carried out by Europe and Canada that uses renewable energy as the hydrogen source and $LH_2$ as the hydrogen transport medium, and WE-NET (World Energy Network, 1993–2003) 6) of Japan. EQHHPP transports by sea $LH_2$ that is produced and liquefied at a hydroelectric power plant in Quebec in Canada to Hamburg in Germany; the amount of hydrogen being transported is 1.5 x $10^4$ tons/year. WE-NET embraces more or less the same concept as EQHHPP, but the scale is a step higher than EQHHPP: power generation output is in the range of 1,000 to 4,000 MW and the amount of hydrogen transported is in the range of 1.43 to 5.56 x $10^5$ tons/year. For this project, efforts were focused on a study of the economic feasibility of the overall system, the conceptual design of component equipment, and the element technology development (element technologies concerning $LH_2$ carriers, hydrogen engines, and hydrogen turbines).

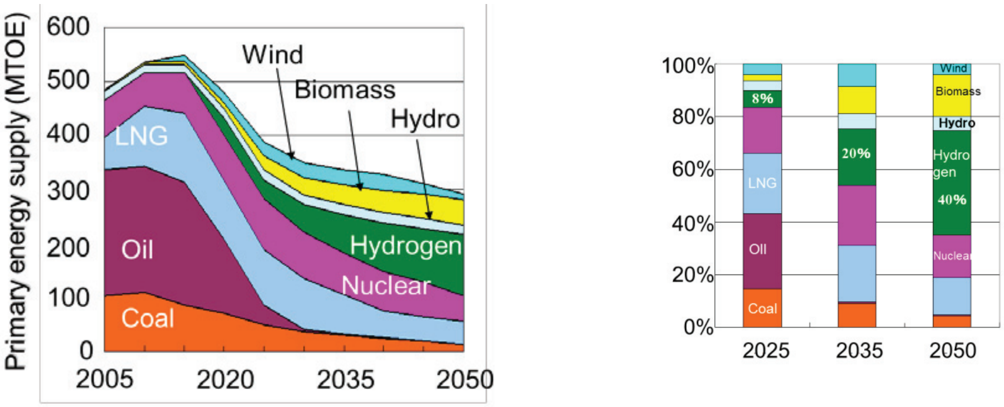

Figure 1 Estimated demand for primary energy and hydrogen in Japan

## 3 Kawasaki $CO_2$ free hydrogen supply chain concept and its economy aspects

### 3.1 Kawasaki $CO_2$ free hydrogen supply chain concept[7)]

Our company disclosed in 2010 the concept of a $CO_2$-free hydrogen supply chain that consists of producing hydrogen from brown coal in Australia and transporting it for consumption in Japan. A schematic system diagram of this concept is shown in Figure 2.

Hydrogen is produced by gasifying and gas-refining brown coal near the open cut mine in Victoria state, and transporting the $CO_2$, which is separated and collected in the hydrogen production process, for storage by the Carbon-Net Project being promoted by the State Government of Victoria. The hydrogen gas produced is carried by pipeline to a port facility located about 80 km away. The port facility consists of a hydrogen liquefaction plant with 770ton/day and a hydrogen loading base, where hydrogen is liquefied, stored, and then loaded onto a hydrogen carrier for transport to Japan. The annual hydrogen output is 225,500 tons and two hydrogen carriers (160,000 $m^3$ each, liquefied hydrogen load of 10,840 tons) make a cumulative total of 22 trips a year over the distance of nearly 9,000 km from Australia to Japan. Table 1 shows the scale of the hydrogen energy supply chain.

Brown coal is an under-utilized coal because its usage is limited to near the mining site because of its poor transportation efficiency due to high moisture content and the fact that it can cause spontaneous combustion when in a dry state. Nearly half of the coal deposits around the world are brown coal and Victoria State is known to have abundant reserves.

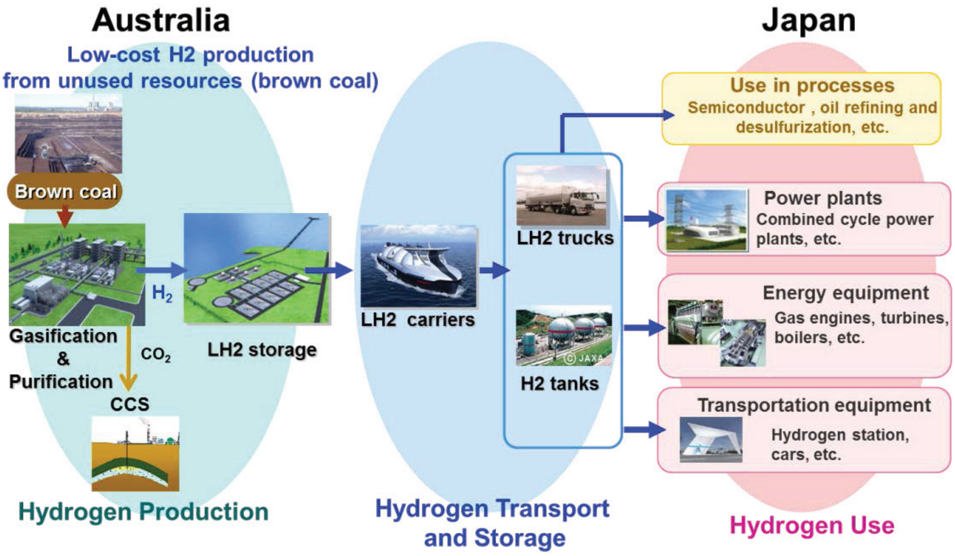

Figure 2 $CO_2$ free hydrogen supply chain concept

Table 1 Scale of the $CO_2$ free hydrogen supply chain

| Items | |
|---|---|
| Brown coal consumption | 4.74 M tons /year |
| Hydrogen production quantity | 0.764 MTOE /year |
| | 2.51G $Nm^3$ / year |
| | 225,500 tons /year |
| $CO_2$ stored amount | 4.39M tons /year |
| $LH_2$ carrier | 160,000 $m^3$ x two ships |

### 3.2 Study of its economy aspects[7),8)]

Figure 3 shows the overall facility costs of the hydrogen energy supply chain model and the ratio of each plant. Total cost is ¥743.6 billion (\$7.4 billion).The costs involved of hydrogen liquefier(33%) and hydrogen production(30%)is high. To calculate facility costs, the equipment capacity is decided in relation to the mass heat balance of each part and the cost of each component equipment is calculated, in addition to the civil engineering costs, electricity costs, machinery costs, and construction and installation costs. At the same time, a layout plan is worked out in order to compute the cost of site infrastructure including roads and management facilities.

As for the management expenses, electricity costs represent as large a portion as 43%. The largest amount of electrical power consumption is 47% by the hydrogen liquefaction plant. For the hydrogen production plant, the larger power consumption rates include 12% by the air separator, 17% by the gas refiner, and 12% by the $CO_2$ storage facility. This shows the importance of upgrading the performance of these facilities, including the hydrogen liquefying facility, in order to keep the management expenses low. Although hydrogen liquefaction is a technology already put to practical use in industrial-use hydrogen, larger-scale and higher-efficiency projects are expected to make positive progress in the future. The price of hydrogen was based on the facility expenses, management expenses, and annual hydrogen output. Its hydrogen price where the internal profit rate reaches 0%, in other words where the return on investment becomes 0, is ¥29.7/$\mathrm{Nm^3\ H_2}$(\$0.29 /$\mathrm{Nm^3H_2}$). Figure 4 shows its cost break (%).

Regarding competitiveness of this cost. Figure 5 shows the cost comparison of the power generation cost of nuclear power, fossil fuel, oil, renewable energy, and brown-coal hydrogen in 2030.The cost of brown-coal hydrogen power generation is ¥16 /kWh, which is higher than that of fossil fuel power generation using coal or LNG, but is lower than that of renewable energy like wind power or solar power. So that, brown-coal hydrogen power generation promises a cost advantage as $CO_2$ free power generation.

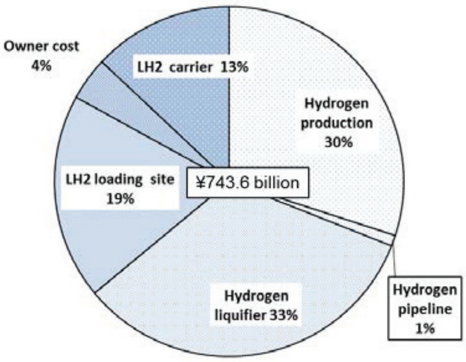

Figure 3 Cost break of overall facilities

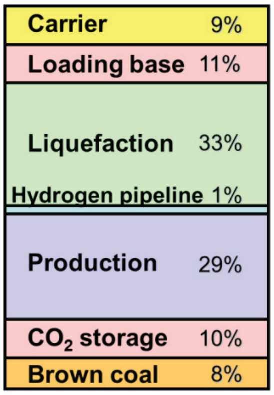

Figure 4 Cost break of hydrogen cost(¥29.7/$\mathrm{Nm^3}$)

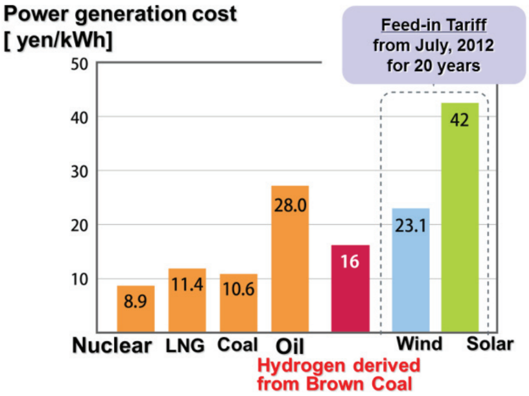

Figure 5 Comparison of various power generation cost

## 4 Transportation and storage of liquid hydrogen

### 4.1 Characteristics of $LH_2$ (liquid hydrogen)

The methods for transporting and storing hydrogen include using compressed gas, storage alloys, and chemical media, but only compressed gas and $LH_2$ have been commercialized. To use storage alloys or chemical media, it is necessary to charge energy in dehydrogenation process but the use of $LH_2$ requires only an energy charge in the production process.

The technological development of $LH_2$ started in the U.S.A. at the beginning of 1950s with the aim of developing rocket fuel for the space program. An $LH_2$ liquefier with a capacity of 30 tons/day was built in the latter half of 1950s, and the world's largest hydrogen liquefier with a capacity of 60 tons/day and an $LH_2$ storage tank with 3,200 $m^3$ capacity were completed in the 1960s9). $LH_2$ technology had almost been completed by that time.

Regarding the introduction and expansion of $LH_2$, the introduction process for LNG(predominately methan), which is a similar combustible cryogenic liquefied gas that has been used on a commercial level since the 1960s, may serve as a good reference. Table 2 shows a comparison of the physical properties of $LH_2$ and LNG. The density of $LH_2$ is lighter than that of LNG, but its capacity efficiency is as high as nearly 800 times the room temperature ambient pressure state and nearly 1.7 times the density of 70 MPa hydrogen gas (about 42 $kg/m^3$ at 0°C). The boiling point of $LH_2$ is about 90 degrees lower than that of LNG, and since the latent heat and the heating value per volume become small, advanced thermal insulation technology and liquefaction technology become necessary. The critical pressure (1.28 MPa) of $LH_2$ is lower than that of LNG (critical pressure: 4.6 MPa), and since the physical properties present large variations near the critical state, the special design of equipment would be required..

In order to introduce large mass $LH_2$ in the future it is important to incorporate high-efficient large-scale hydrogen liquefaction and large-scale storage tanks with high performance thermal insulation, considering economic advantages and safety design, while paying due attention to the physical properties of $LH_2$.

Table 2 Comparison of $LH_2$ and LNG

| | **$LH_2$ ($H_2$)** | **LNG ($CH_4$)** |
|---|---|---|
| **Boiling point K** | **20.3** | **442.5** |
| **Saturated liquid density $kg/m^3$** | **70.8** | **442.5** |
| **Saturated gas density $kg/m^3$** | **1.34** | **1.82** |
| **Critical temperature K** | **32.9** | **190** |
| **Critical Pressure MPa** | **1.28** | **4.60** |
| **Latent heat kJ/L (kJ/kg)** | **31.4 (444)** | **226(510)** |
| **Surface tension mN/m** | **1.98** | **13.4** |
| **Prandtl Number** | **1.0** | **1.7** |
| **Lower heating value MJ/L(MJ/kg)** | **8.5(120)** | **22.1(50)** |
| **Flammability limit (%)** | **4.0 to 75.0** | **5.3 to 17.0** |

### 4.2 Liquefaction of hydrogen gas

The minimum liquefaction work (exergy) is thermodynamically determined from the quantity state at the starting point and the ending point. The minimum liquefaction work is the total of work for pre-cooling the room-temperature gas (300K) to the saturated gas (20K), work for condensing the saturated gas, and work for converting orthohydrogen to para hydrogen. The formula of this work is expressed by the following equation1):

$$W_{th} = \int_{T_O}^{T_e} \frac{T_O - T}{T} c_p dT + \frac{T_O - T_e}{T_e} \cdot Q_l + \int_{c_1}^{c_2} \frac{T_O - T_e}{T_e} Q_{OP} dc$$

Where,

$W_{th}$: Minimum liquefaction work, $T_o$: Ambient temperature, $C_p$: Specific heat at constant pressure
$T_e$: Saturation temperature, $Q_l$: Latent heat, C: Para-concentration, $Q_{op}$: Ortho-para conversion heat

Hydrogen is divided into orthohydrogen with a higher energy order and parahydrogen with a lower energy order depending on the direction of the nuclear spin, and the room-temperature hydrogen gas consists of 25% para-hydrogen and 75% orthohydrogen, while the $LH_2$ consists of parahydrogen at 99.8%, and its composition ratio is dependent on the temperature. The ortho-para conversion energy is for converting from ortho to parahydrogen.

The minimum liquefaction work for liquefying hydrogen gas in a room-temperature ambient-pressure status is about 3.90 kWh/kg (0.35 kWh/$Nm^3$), which is greater than that of LNG (0.3 kWh/kg).The ratios of the pre-cooling work, condensation work, and ortho-para conversion work within the liquefaction work of hydrogen gas are 40%, 44%, and 16%, respectively. The ratio of pre-cooling work is larger than that for LNG. The actual liquefaction work becomes greater than the minimum liquefaction work due to the energy losses, including the mechanical loss and the friction loss of the component equipment, and the external input heat. The liquefaction work is about 1 kWh/$Nm^3$ and the liquefaction efficiency (minimum liquefaction work/actual liquefaction work) is thought to be in the range of 35% to 30%. To build a hydrogen society, it will become important to lower the $LH_2$ production cost through the reduction of the charge (compression) power by enhancing liquefaction efficiency.

In EU, feasibility studies and element tests have been conducted with the aim of improving liquefaction efficiency and increasing the production scale. As a practical example, the IDEALHY Project (2011–2013) that was carried out as a part of the 7th Framework Programme (FP7) was aimed at a larger-scale model (liquefaction amount: up to 200 tons/day) and liquefaction efficiency (about 0.5 kWh/$Nm^3$) twice the existing level. As an example, figure 6 shows the process flow of the advanced $H_2$ liqueifier[9)] considered in the IDEALHY Project. For the means to achieve higher efficiency, refrigerant is optimized by using nitrogen for the 90K or higher refrigeration of the recycle system, while a mixed refrigerant (hydrogen-neon-helium) is used for the 90K or lower refrigeration of the recycle system. Recovering the compression work by increasing the number of expansion turbines used in the recycle system and improving the liquefaction efficiency by using a wet turbine instead of a JT valve in the feed system were also studied.

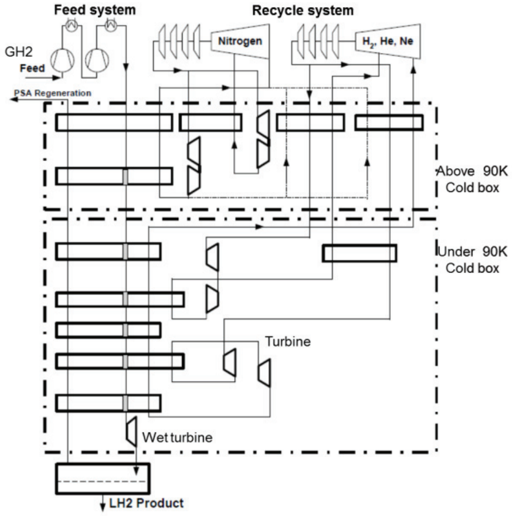

Figure 6 Flow diagram of advanced hydrogen liquefying process [10)]

## 4.3 Stationary storage of liquid hydrogen

The thermal insulation technology designed to reduce the evaporation of $LH_2$, which has a low boiling point and low latent heat, is very important. LNG tanks have a solid atmospheric pressure thermal insulation structure, but for the $LH_2$ tank, in many cases, high-vacuum thermal insulation (degree of vacuum: $10^{-2}$ Pa or less) is used for small and medium-sized tanks (e.g. capacity: 40 $m^3$), while low-vacuum thermal insulation (degree of vacuum: 1 Pa or less) is used for large tanks, with the aim of significantly reducing the heat leak.

The heat flux is about 1 $W/m^2$, but even at the same heat influx, if the tank increases in size, the ratio of surface area in relation to volume becomes smaller and the liquid evaporation rate (%/day) becomes smaller. Figure 7 and Figure 8 11) shows an external view of the largest $LH_2$ tanks (capacity: 540 $m^3$) in Japan, which were built by our company for the JAXA (Japan Aerospace Exploration Agency) Tanegashima Space Center, and its structural configuration respectively. These $LH_2$ tanks are a double-shell spherical tank using perlite vacuum thermal insulation, and the evaporation rate is 0.18 %/day or less. Regarding the capacity the $LH_2$ tanks to be used for storage on land for the pilot $CO_2$-free hydrogen supply chain and the verification supply chain, tanks with a capacity of about 3,000 $m^3$ and about 50,000 $m^3$, respectively, are being considered, which we believe is a logical extension of our company's existing $LH_2$ tank technology.

Figure 7 Overview of $LH_2$ storage tank

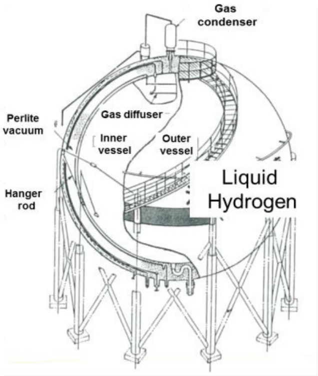

Figure 8 Structural configuration of $LH_2$ storage tank

## 4.4 Ocean transportation of $LH_2$ (liquid hydrogen)

There is as yet no performance record for a dedicated ocean-going $LH_2$ carrier, although the barge (capacity: about 1,000 $m^3$) retained by NASA in the U.S.A. for carrying $LH_2$ from Louisiana to Florida9) may serve as an example of a domestic carrier.

We have conducted the concept design of a large-scale $LH_2$ carrier (capacity:160,000 $m^3$) for CO2-free hydrogen supply chain and a small-scale $LH_2$ carrier (capacity: 2,500 $m^3$) for the pilot supply chain. Figure 9 and Figure 10 show their image drawings respectively. For the large-scale $LH_2$ carrier, four units of vacuum panel type MOS-type spherical tank (capacity: 40,000 $m^3$) are fitted, and the evaporation gas is used as propulsion fuel. These two types of tank feature an evaporation rate of 0.2 %/day or less, and their thermal insulating performance is nearly 1/10 that of the heat input of an LNG carrier. The design of the $LH_2$ carrier is based on the IGC Code (International Code for the Construction and Equipment of Ships Carrying Liquefied Gas in Bulk) set forth by the IMO (International Maritime Organization) that is applied to LNG carriers. For the small-scale $LH_2$ carrier, two units of accumulator cylinder-type vacuum thermal-insulating tank (capacity: about 1,250 $m^3$) that accumulates the evaporation gas inside the tank are fitted. A diesel engine is proposed for the main engine.

| **Items** | |
|---|---|
| **Class pf ship** | **Large ship (Spherical tank)** |
| **Type of Ship** | **Monohull ship** |
| **Tank capacity** | **160,000 $m^3$ (40,000$m^3$ x 4 unit)** |
| **Tank method** | **Spherical tank ,Type-B** |
| **Thermal insulation** | **Vacuum panel** |
| **BOG(Boil off gas rate)** | **0.2%/day** |
| **Propulsion system** | **Hydrogen gas engine** |

Figure 9 Large $LH_2$ Carrier

| **Items** | |
|---|---|
| **Class of ship** | **Small accumulated ship** |
| **Type of ship** | **Monohull** |
| **Tank capacity** | **2500m$^3$ (1250m$^3$ x 2 unit)** |
| **Tank method** | **Cylindrical tank ,Type-C** |
| **Thermal insulation** | **High vacuum multilayer** |
| **BOG** | **0.2%/day** |
| **Propulsion system** | **Diesel engine** |

Figure 10 Small $LH_2$ carrier

Our company obtained the world's first Approval in Principle (AP) for the Cargo Container System (CCS) of a small $LH_2$ carrier from the Nippon Kaiji Kyokai (NK, Japanese classification society) in February 2014. Regarding the acquisition of this approval, our company made proposals of requirements by taking into account the physical properties of $LH_2$ in addition to the IGC Code and risk evaluations conducted by means of HAZID (Hazard Identification) Analysis. Figure 11 shows the external appearance of the cargo containment system. The cargo containment system is a horizontal cylindrical-type double-shell tank consisting of an inner chamber and an outer chamber, and vacuum heat-insulation is used for the heat insulation layer and GFRP (Glass-Fiber-Reinforced Plastic) is used for the inner chamber support structure aiming at enhancing the heat insulation performance. As the method of unloading $LH_2$ from the tank, it is possible to use the pressure-feed method by using a loading pump or the pressurized method. Moreover, a dome is provided at the top of the facility in order to allow inspecting the inside of the tank.

The safety standards for $LH_2$ carriers are not stipulated in the IGC Code, but the transportation of those cargos that are not specifically described in the code is allowed as a provisional measure until the relevant agreement is reached as long as there exist certain standards jointly approved by the shipping country (Australia), the receiving country (Japan), and the ship registration country. For this reason, the governments of Australia and Japan are scheduled to conduct a conference in order to discuss possible safety standards.

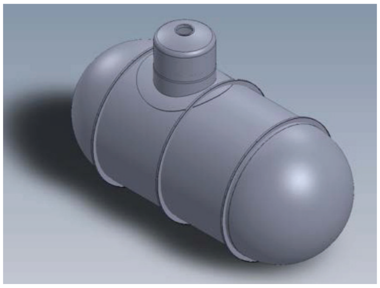

Figure 11 External appearance of the cargo containment system

## 6 Summary

This paper described the technical and economic feasibility of a $CO_2$ free hydrogen energy supply chain model from Australia to Japan with $LH_2$ and its transportation and storage of $LH_2$. Its conclusions are as follows.

-Hydrogen energy will be expected in the future as for solution of global warning and energy security in Japan, thus large mass hydrogen will be needed.

-The CIF cost of hydrogen when the CO2 free hydrogen energy supply chain realized in 2025 will be ¥29.7/Nm$^3$ .

-If hydrogen is used as a carbon-free fuel for commercial-scale power generation, it will be more expensive than carbon or LNG power generation in 2030, but it will be cheaper than renewable energy power generation. Hydrogen power generation will remain more competitive if introducing the carbon tax
-The large-scale $LH_2$ technology that is the essence of the hydrogen energy supply chain will use the LNG system technology as a base. Especially, high-efficient large-scale hydrogen liquefaction and large-scale $LH_2$ carrier will be needed, considering their economic advantages and safety design.
-Regarding the first step for building a $LH_2$ carrier, we obtained the world's first Approval in Principle (AP) for the Cargo Container System (CCS) of a small $LH_2$ carrier from the Nippon Kaiji Kyokai (NK) in February 2014.

We are confident that the $CO_2$ free hydrogen energy supply chain proposed by our company will make a positive contribution to the realization of a hydrogen society as the large-scale introduction of hydrogen is expected to arrive in the near future.

## References

1) Walter Peschka, Liquid Hydrogen Fuel of the Future; Springer-Verlag Wien New York;1992
2) International Association for Hydrogen Energy, Brochure
3) Ishimoto, Y. Evaluating the hydrogen demand in each sector, *32 th HESS Conference* 2012 , in Japanese
4) Michasel Ball, Martine Wietshel, The Hydrogen Economy Opportunities and Challenge; Cambridge Univ. press; 2012
5) For example, Giacomazzii, G.,Greitz J. Euro-Quebec Hydro-Hydrogen Project(EQHHPP): A challenge to Cryogenic Technology; *Cryogenic 33* ,1993,767-771
6) For example, Iwata,A.,Kamiy, S. Kawagoe,E. Technical Development for Large Storage of liquid hydrogen in WE-NET; *11th World Energy Conf. Stuttgart ,German 1995*
7) Inoue,K.,Yoshino,Y.,Kamiya, S., Harada.,E.; Feasibility study of CO2-Free by hydrogen supply chain utilizing Australian brown coal link with CO2, *CRYOGENICS 2012 ,IIR International Conference,2012*
8) Yamashita,S. Yoshino.,Y.,Yoshimura,K.,Shindo.,K. Harada.,E; Feasibility Study on the Hydrogen Energy Supply Chain for Low Carbon Society; *Journal of Japan Society of and Resources, Vol 35.No2 2* ,2014 in Japanese
9) Verfonder.K. Safety Consideration on liquid hydrogen; Brand/Volume10, Forschungszentrum Julich GmbH ,2008
10) Quack H.et al, Search for the best processes to liquefy hydrogen in very large plants; *12th cryogenic -IIR Conference-Dresde*n,2012
11) Takashi,K. et al. Design and Construction of Liquefied Hydrogen Storage and Supply System for H-II Launch Vehicle, *Kawasaki Technical Report vol 102*,1989.in Japanese
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