SAFETY REQUIREMENTS FOR LIQUEFIED HYDROGEN TANKERS

Kudou, J.[1], Ota, S.[2] and Senga, Y.[3]
[1] Research & development Group, Japan Ship Technology Research Association, 2-10-9 Akasaka, Minato-ku, Tokyo, 107-0052, Japan, kudou@jstra.jp
[2] Centre for International Cooperation, National Maritime Research Institute, 6-38-1, Shinkawa, Mitaka-shi, Tokyo, 181-0004, Japan, ohta@nmri.go.jp
[3] Natural Resources and Energy Department, Nippon Kaiji Kyokai, 4-7, Kioi-cho, Chiyoda-ku, Tokyo, 102-8567, Japan, senga@classnk.or.jp

ABSTRACT

R&D projects for establishing hydrogen supply chain have already been started in Japan in collaboration among the industry, government, and universities. One of the important subjects of the project is development of liquefied hydrogen tankers, i.e., ships carrying liquefied hydrogen in bulk. In general, basic safety requirements should be determined to design ships. However, the existing regulations do not specify the requirements for hydrogen tankers, while requirements for ships carrying many kinds of liquefied gases are specified in "International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk" (IGC Code) issued by the International Maritime Organization, i.e., a special organization under the United Nations. Therefore, the basic safety requirements for hydrogen tankers should be developed. We conducted bibliographic survey on the IGC Code, ISO/TR 15916:2004 "Basic considerations for the safety of hydrogen systems", and so on; in order to provide safety requirements taking into account the properties of liquid and gaseous hydrogen. In this paper, we provide safety requirements for liquefied hydrogen tankers as the basis for further consideration by relevant governments.

1 INTRODUCTION

1.1 Background

Hydrogen, which has a number of excellent features such as high gravimetric energy content and no greenhouse gas emission at the point of use, has recently attracted attention as a future clean energy amid increasing concerns toward exhaustion of fossil fuels and global warming. R&D projects for establishing hydrogen supply chain have already been started in Japan in collaboration among the industry, government, and universities. As the first step, it has been planned to carry liquefied hydrogen from Australia to Japan in near future. Figure 1, which is provided by Kawasaki Heavy Industries, Ltd., illustrates the Hydrogen Energy Supply Chain Concept. One of the important subjects of the project is development of liquefied hydrogen tankers, i.e., ships carrying liquefied hydrogen in bulk (liquefied hydrogen tankers). Figure 2, which is provided by Kawasaki Heavy Industries, Ltd., shows a concept of a liquefied hydrogen tanker which is planned to be constructed in near future for the purpose of experiments on liquefied hydrogen tankers.

Ships carrying liquefied gases in bulk (gas carriers), in general, should comply with "International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk" (IGC Code) [1] issued by the International Maritime Organization (IMO), i.e., a special organization under the United Nations. Hereafter, "the IGC Code" means the Code as amended by resolution of the Maritime Safety Committee of the IMO, MSC.370(93) adopted on 2014, so called "the revised IGC Code", which will enter into force on 1 January 2016.

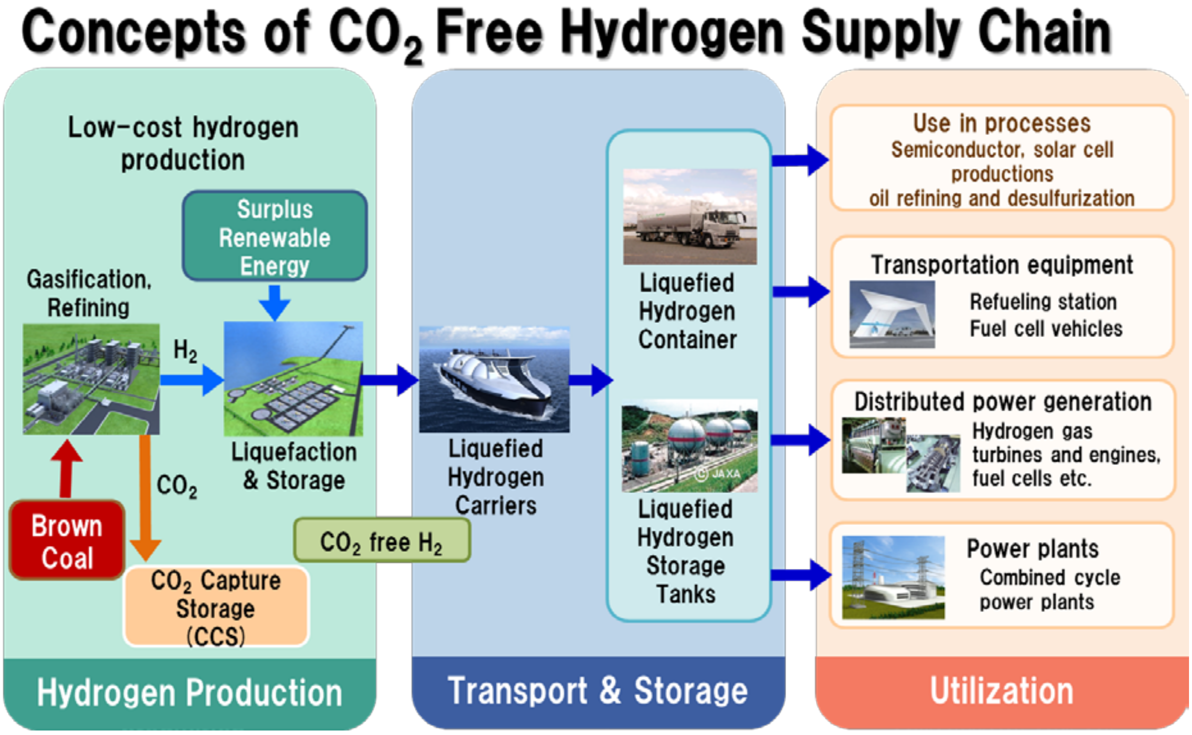

Figure 1. Hydrogen Energy Supply Chain Concept
(provided by Kawasaki Heavy Industries, Ltd.)

Figure 2. Liquefied hydrogen tanker (Pioneer Ship)
(provided by Kawasaki Heavy Industries, Ltd.)

The IGC Code requires that a ship carrying liquefied gases in bulk should comply with the minimum requirements for the cargo listed in chapter 19. However, the requirements for liquefied hydrogen are not specified in the IGC Code. Therefore, the basic safety requirements should be developed and agreed by the governments relevant to the carriage of this new cargo, i.e., liquefied hydrogen. The relevant governments are competent authorities of ports of loading and discharge and the flag Administration of the ship. As the first step of the project, the relevant governments will be Australia, which will be the competent authority of port of loading, and Japan, which will be the competent authority of port of discharge and the flag Administration of a liquefied hydrogen tanker. In other words, safety requirements agreed by these governments are indispensable for the development of carriage of new cargoes.

1.2 Purpose

The purpose of this study is to provide safety requirements for liquefied hydrogen tankers, which carry deep refrigerated liquid hydrogen near boiling point under atmospheric pressure, as the basis for further consideration by relevant governments. For this purpose, we conducted bibliographic survey in order to provide safety requirements taking into account the properties of liquid and gaseous hydrogen.

1.3 Procedure of this study

The requirements in the IGC Code can be categorized into two types. One is "general requirements" and the other one is "special requirements". The special requirements are specific requirements for respective cargoes. Majority of the general requirements in the IGC Code are applied to gas carriers regardless of their cargoes, i.e., liquefied gases. On the other hand, application of some general requirements in the IGC Code depend on cargoes, for the ground that more stringent requirements should be applied to more dangerous cargoes and that some of the general requirements should be applied to some types of cargoes owing to their reactivity.

In this study, first, the application of the general requirements to liquefied hydrogen is proposed based on the relation between cargoes and applicable requirements listed in the Code and the hazards involved in the carriage of liquefied hydrogen. Items of the general requirements are "Ship type", "Independent tank type C required", "Control of vapour space within cargo tank", "Vapour detection" and "Gauging".

Second, the special requirements for liquefied hydrogen are proposed, taking into account the properties of hydrogen identified through bibliographic survey on various references.

In the IGC Code, the set of applicable general requirements and the special requirements are called "minimum requirements". Therefore, the purpose of this study is to provide the draft "minimum requirements" for liquefied hydrogen.

2 SELECTION OF APPLICABLE GENERAL REQUIREMENTS

2.1 Ship type

In the IGC Code, "ship type" should be assigned to each cargo. "Ship type" determines the application of the requirements for survival capability of ships which are related to stability under damaged conditions in case of casualties, as well as segregation of cargo containment systems from shell plating (outer shell of a ship). The IGC Code prescribes the following four ship types:

.1 A type 1G ship is a gas carrier intended to transport the products that require maximum preventive measures to preclude their escape;
.2 A type 2G ship is a gas carrier intended to transport the products that require significant preventive measures to preclude their escape;
.3 A type 2PG ship is a gas carrier of 150 m in length or less intended to transport the products that require significant preventive measures to preclude their escape, and where the products are carried in type C independent tanks under specific conditions; and
.4 A type 3G ship is a gas carrier intended to carry the products that require moderate preventive measures to preclude their escape.

It is known that the ship types are determined based on categories of cargoes but not based on the detailed properties of cargoes. As the results of bibliographic survey on the IGC Code and "United Nations Recommendations on the Transport of Dangerous Goods - Model Regulations" [2], the following issues are found:

.1 Type 1G is applied only to toxic gases, i.e., dangerous goods of class 2.3, but not applied to non-toxic gases, i.e., dangerous gases of class 2.1 and class 2.2;
.2 Type 2G and Type 2PG are applied mainly to non-toxic flammable gases, i.e., dangerous good of class 2.1;
.3 Type 3G is applied only to non-toxic and non-flammable gases, i.e., dangerous goods of class 2.2; and
.4 Type 2PG is not applicable to gases having temperature lower than -55°C.

Here, “class 2.1”, “class 2.2” and “class 2.3” are flammable gases, non-toxic and non-flammable gases, and toxic gases, respectively. The criteria for the classification are determined in the UN recommendations [2]. It should be noted that toxic and flammable gases are classified into class 2.3 with subsidiary risk class 2.1. Hydrogen is non-toxic flammable gas and dangerous good of class 2.1. As mentioned in table 1, type 1G is applied, in detail, to toxic gases heavier than air.

Table 1. Ship type for dangerous goods of class 2.3 (toxic gases)

Product Name	Ship Type	Specific gravity of vapour
Ammonia, anhydrous	2G/2PG	0.6
Chlorine	1G	2.4
Ethylene oxide	1G	1.5
Methyl bromide	1G	3.3
Sulphur dioxide	1G	2.3

Liquefied hydrogen is “refrigerated liquefied gas” and the temperature is about 20 K. Type 2PG is, therefore, not applicable to liquefied hydrogen. Thus, the requirements for type 2G ship should apply to liquefied hydrogen tankers.

The representative type 2G ships are Liquefied Natural Gas (LNG) carriers. With regard to survival capability and segregation of cargo containment systems from shell plating, it is appropriate to apply the requirements for LNG carriers to liquefied hydrogen tankers.

2.2 Independent tank type C

Tanks for liquefied gases can be categorized into several types, e.g., independent tanks, membrane tanks, integral tanks and semi-membrane tanks. Independent tanks are self-supporting type tanks not forming part of the ship's hull. There are three categories of independent tanks, i.e., type A, type B and type C. Type C independent tanks are pressure vessels and regarded as the most reliable tanks for preventing leakage of liquefied gases. According to the IGC Code, use of tanks other than type C independent tanks is prohibited for some cargoes.

As the results of bibliographic survey on the IGC Code, it is found that the requirement is applied only to dangerous goods of class 2.3 whose vapour is heavier than air and to carbon dioxide (UN 2187) of class 2.2. The reason of the application of the requirement to carbon dioxide can be understood that pressure in cargo tanks carrying carbon dioxide should be maintained to prevent solidification of the cargo. Therefore, there is no reason to apply the requirement to liquefied hydrogen.

2.3 Control of vapour space within cargo tank

For gases that may react with air, it is necessary to keep the atmosphere in the vapour space, i.e., a space above a liquefied cargo in a tank, without air by introducing an appropriate inert gas which is compatible chemically and operationally at all temperatures likely to occur within the spaces and the cargo. Apart from this, for gases which are non-flammable and may become corrosive or react dangerously with water, it is necessary to keep the vapour space dry. Namely, special environment controls such as drying and making inert the atmosphere in the vapour space are required for some liquid chemical products to prevent spontaneous reaction with air. It is not necessary to apply such requirements to liquefied hydrogen.

2.4 Vapour detection

The IGC Code requires installing gas detection equipment depending on the properties of cargoes to be carried. There are the following four types of gas detection:

F: Flammable vapour detection;
T: Toxic vapour detection;
F+T: Flammable and toxic vapour detection; and
A: Asphixiant.

"Asphixiant" is required for gases which may cause asphyxiation of persons in case of leakage. For liquefied hydrogen, flammable vapour detection should be required and the equipment should be suitable to detect hydrogen in case of leakage of the cargo or its vapour.

2.5 Gauging

On gas carriers, each cargo tank should be fitted with an appropriate liquid level gauging device, to ensure that a level reading is always obtainable whenever the cargo tank is operational. The types of liquid level gauging devices are the following four types and one of them should be selected for respective cargoes:

.1 "indirect devices", which determine the amount of cargo by means such as weighing or in-line flow metering;
.2 "closed devices which do not penetrate the cargo tank", such as devices using radio-isotopes or ultrasonic devices;
.3 "closed devices which penetrate the cargo tank", but which form part of a closed system and keep the cargo from being released, such as float type systems, electronic probes, magnetic probes and bubble tube indicators; and
.4 "restricted devices" which penetrate the tank and, when in use, permit a small quantity of cargo vapour or liquid to escape to the atmosphere, such as fixed tube and slip tube gauges.

In principle, liquid level gauging devices of "restricted devices" type are not permitted for flammable or toxic cargoes, such as methane. It is, therefore, appropriate to require one of the aforementioned types of ".1 to .3" for liquefied hydrogen, taking into account that these types of equipment are effective to prevent leakage of gases into air.

2.6 Summary of application of general requirements

The results of consideration explained in section 2 can be summarized as set out in Table 2, which is in the form of chapter 19 of the IGC Code.

Table 2: Draft summary of minimum requirements for liquefied hydrogen

a *Product name*	*b*	*c* *Ship type*	*d* *Independent tank type C required*	*e* *Control of vapour space within cargo tanks*	*f* *Vapour detection*	*g* *Gauging*	*h*	*i* *Special requirements*
Hydrogen		2G	-	-	F	C		

Column '*a*' is the name of product and columns '*b*' and '*h*' are kept blank, intentionally. Columns '*b*' and '*h*' had been used for the UN Numbers, which are assigned for respective dangerous goods in accordance with the International Maritime Dangerous Goods Code [3], and for the MFAG Table numbers, which are assigned for respective types of dangerous goods in accordance with the Medical

First Aid Guide for Use in Accidents Involving Dangerous Goods (MFAG) [4], and these columns are blank at present for the reason that the UN numbers and MFAG table numbers are not directly related to the carriage of liquefied gases in bulk. Column ‘*c*’ specifies the ship type applicable to the product (see paragraph 2.1). When column ‘*d*’ is filled with ‘-’ (hyphen), tanks other than independent tanks of type C may be used for the product (see paragraph 2.2). When column ‘*e*’ is filled with ‘-’ (hyphen), control of vapour space within cargo tanks, such as inerting and drying, is not required (see paragraph 2.3). When column ‘*f*’ is filled with ‘F’, gas detection equipment for flammable gases is required (see paragraph 2.4). When column ‘*g*’ is filled with ‘C’, devices other than “restricted devices” type can be used for liquid level gauging (see paragraph 2.5). Column ‘*i*’ specifies the special requirements for respective products and the special requirements for liquefied hydrogen are discussed in the next section.

3 CONSIDERATION ON SPECIAL REQUIREMENTS

3.1 Comparison of physical properties of hydrogen and methane

Shipbuilding and shipping industries have long experience of design, construction, and operation of LNG carriers, without any accident involving significant loss of lives. Furthermore, numerous researches have been carried out on safety of LNG carriers. It is, therefore, appropriate to compare the hazards of liquefied hydrogen and of LNG (methane) for consideration of safety measures for liquefied hydrogen tankers.

Table 3 shows the properties of hydrogen and methane. In this table, “ISO/TR 15916” means “ISO/TR 15916:2004 Basic consideration for the safety of hydrogen systems” [5]. “AIAA Safety Standard” means “Safety Standard for Hydrogen and Hydrogen Systems (Guide to Safety of Hydrogen and Hydrogen Systems)” published by American Institute of Aeronautics and Astronautics (AIAA) [6]. “UN Orange book” means “United Nations Recommendations on the Transport of Dangerous Goods - Model Regulations” [2].

This table indicates that liquefied/gas hydrogen has the following properties compared with LNG/methane: lower boiling temperature; lower liquid density; lower gas density; wider flammability range; higher ignitability (small ignition energy); and higher diffusivity.

Table 3. Comparison of Physical Properties of Hydrogen and Methane

	Hydrogen	Methane	References
Boiling temperature (K)*	20.3	111.6	ISO/TR 15916 Annex A Table A.3
Liquid density (kg/m^3)*	70.8	422.5	ISO/TR 15916 Annex A Table A.3
Gas density (kg/m^3)** (Air: 1.198)	0.084	0.716	AIAA Safety Standard
Heat of vaporization (J/g)*	454.6	510.4	ISO/TR 15916 Annex A Table A.3
Lower flammability limit (% vol. fraction)***	4.0	5.3	ISO/TR 15916 Annex B Table B.2
Upper flammability limit (% vol. fraction)***	75.0	17.0	ISO/TR 15916 Annex B Table B.2
Lower detonation limit (%vol. fraction)***	18.3	6.3	ISO/TR 15916 Annex B Table B.2
Upper detonation limit (% vol. fraction)***	59.0	13.5	ISO/TR 15916 Annex B Table B.2
Minimum ignition energy (MJ)***	0.017	0.274	ISO/TR 15916 Annex B Table B.2
Auto-ignition temp.(°C)***	585	537	ISO/TR 15916 Annex B Table B.2
Toxicity	Non	Non	UN Orange book
Diffusion coefficient in air (cm^2/s)	0.61	0.16	ISO/TR 15916 Annex A Table A.2
Temperature at critical point (K)	33.19****	190.55	*****
Pressure at critical point (kPaA)	1315****	4595	*****

Remarks:
* At their normal boiling points for comparison purpose.
** At normal temperature and pressure.
*** Ignition and combustion properties for air mixtures at 25°C and 101.3 kPaA.
**** Normal Hydrogen
***** Hydrogen: ISO/TR 15916 Annex A Table A.1
Methane: The Japan Society of Mechanical Engineers, Data Book, Thermophysical Properties of Fluids (1983)

3.2 Hazards to be considered

The hazards related to liquefied hydrogen should be clarified, in order to develop special requirements. The hazards can be enumerated as follows:

Low temperature hazard: the temperature of liquefied hydrogen will be around 20 K. According to ISO/TR 15916, many materials experience a reduction in size, a drastic decrease in their ductility, and a decrease in their specific heat when they are cooled to liquefied hydrogen temperatures. ISO/TR 15916 also refers to that condensing air, oxygen enrichment and solidified impurities should be taken into consideration;

Hydrogen embrittlement: a significant loss of structural strength of materials may occur when exposed to hydrogen;

High permeability: hydrogen gas is easily leaking from valves, flange connections, and seals in piping systems;

Low density and high diffusivity: hydrogen gas will rise and diffuse rapidly in surrounding atmosphere in case of leakage, because hydrogen is lighter and more diffusive than gaseous methane in air;

High ignitability: ISO/TR 15916 refers to that the ignition energy of hydrogen is small and hydrogen may be ignited by a static electricity or a spark owing to contacting metal materials;

Fire hazard: hydrogen fire is practically invisible and its radiating heat is so small, owing to low emissivity, that a person may not notice it. Namely, in case of hydrogen fire, a person does not feel the heat of hydrogen until the person directly contacts with hydrogen flame. When a person directly contacts with hydrogen flame, the person is heavy burned because the temperatures of hydrogen flame is high. The flame also emits ultraviolet radiation as other fire hazard;

High pressure hazard: as compressed hydrogen has considerable potential/stored energy under very high pressures, a blast wave generated by the release of this energy should be considered as a high pressure hazard. The increase of volume for the phase change of liquefied hydrogen to hydrogen gas may cause overpressure of containment structures such as a storage vessel or piping to the point of bursting;

Health hazard: health hazards such as frostbite due to contacting directly with cold gas or liquefied hydrogen, hypothermia by prolonged exposure, or asphyxiation as a result of oxygen depletion should be considered; and

Wider range of flammability limits: hydrogen has wider range of flammability limits than those of methane (LNG).

Furthermore, vacuum insulation will be used for containment system for liquefied hydrogen, owing to low temperature. In such case, due consideration should be given to rapid pressure rise of the cargo containment system owing to ingress of heat in case of failure of the vacuum insulation.

3.3 Bibliographic survey

For consideration of the special requirements for liquefied hydrogen tankers, bibliographic survey was carried out based on “ISO/TR 15916:2004 Basic consideration for the safety of hydrogen systems” [5], “Safety Standard for Hydrogen and Hydrogen Systems (Guide to Safety of Hydrogen and Hydrogen Systems)” published by AIAA [6], etc.

3.4 Possible special requirements

3.4.1 Against low temperature hazard

According to ISO/TR 15916, selection of materials is essential to prevent accident owing to low temperature. Selection of materials for cargo containment system is, therefore, important likewise. On the other hand, according to the IGC Code, materials whose design temperatures are lower than -165°C should be specially agreed with the Administration. Thus, no special requirements are necessary for the selection of materials for cargo containment systems. Namely, selection of materials is a matter of design, rather than a matter of international requirements.

The IGC Code requires testing of materials used for thermal insulation for various properties. The minimum test temperature is -196°C and the requirements in the IGC Code do not refer to the normal boiling point of hydrogen, i.e., -253°C. In case of carriage of liquefied hydrogen, a special requirement should be provided to consider the design temperature, in view of testing of materials used for thermal insulation. The following text can be the special requirement in this regard:

> “Where minimum design temperature is under -196°C, property testing for insulation materials should be carried out at an appropriate temperature suitable for the environment.”

Normal boiling point of nitrogen is -196°C and air condensation and accumulation of liquid oxygen may take place at this temperature. For this reason, the following special requirement for nitrogen has already been included in the IGC Code: “Material of construction and ancillary equipment such as insulation shall be resistant to the effect of high oxygen concentrations caused by condensation and enrichment at the low temperatures attained in parts of the cargo system. Due consideration shall be given to ventilation in such areas where condensation might occur to avoid the stratification of oxygen- enriched atmosphere.” Similar requirements are applicable to hydrogen. Furthermore, it is deemed better to specify safety measures rather than just require “due consideration”. The following text can, therefore, be the special requirements in this regard:

> “Materials of construction and ancillary equipment such as insulation should be resistant to the effects of high oxygen concentrations caused by condensation and enrichment at the low temperatures attained in parts of the cargo system. (Refer to the requirement for nitrogen.) For low temperature parts such as cargo pipes containing cold hydrogen, appropriate measures should be taken to prevent the surfaces exposed to ambient air from lowering temperature to the congealing point of oxygen (-183°C). For places where preventive measures against low temperature are not sufficiently effective, such as cargo manifolds, other appropriate measures such as ventilation which avoids the formulation of highly enriched oxygen and the installation of trays recovering liquid air may be permitted in lieu of the preventive measures.”

As mentioned in paragraph 3.2, ISO/TR 15916 refers to solidified impurities. Impurities in liquefied hydrogen, e.g., carbon dioxide, may solidify and cause clogging inside pipes and valves for liquefied hydrogen. The removal of impure substances, which may be condensed in pipes, should be considered. Installation of filters can be an appropriate measure. The following text can be the special requirement in this regard:

> “Appropriate equipment such as filters should be provided in cargo piping systems to remove impure substances condensed at low temperature.”

3.4.2 Against hydrogen embrittlement

ISO/TR 15916 refers to the necessity of appropriate material selection against hydrogen embrittlement. Aging of materials by hydrogen embrittlement is also noted in the standard. AIAA Safety Standard [6] introduces some appropriate materials against hydrogen embrittlement, and refers to that aluminum is the most unaffected material to hydrogen embrittlement. The selection of appropriate materials should therefore be required to prevent failures owing to hydrogen embrittlement. The following text can be the special requirement in this regard:

> “At places where contact with hydrogen is anticipated, suitable materials should be used to prevent any deterioration owing to hydrogen embrittlement, as necessary.”

3.4.3 Against high permeability

To prevent undetected accumulation of hydrogen in a confined space, effective measures should be employed depending on possibility of leakage of hydrogen taking the high permeability into account. The effective measures can be double tube structure composing no oxygen atmosphere or fixed hydrogen leak detectors in highly hazardous places with regard to hydrogen leakage. The following text can be the special requirement in this regard:

> “Double structure composing no flammable atmosphere, or fixed hydrogen detectors being capable of detecting hydrogen leak, should be provided for places where leakage of hydrogen may occur, such as cargo valves, flanges, and seals.”

Tightness tests for cargo tanks and cargo pipes/valves are required by the IGC Code. Hydrogen or helium should be used as the media for tightness test, instead of air, taking into account the high permeability of hydrogen. The following text can be the special requirement in this regard:

> “Helium or hydrogen should be used as the tightness test media for cargo tank and cargo piping.”

The provision of instruction manuals is recommended to let the persons concerned know and confirm the operating procedures for the prevention of leakage during transport, early detection in case of leakage, and appropriate measures after such events. For this, the IGC Code requires that the information should be on board and available to all concerned, giving the necessary data for the safe carriage of cargo. In details, the IGC Code requires such information on action to be taken in the event of spills or leak, counter-measures against accidental personal contact, procedures for cargo transfer, and emergency procedures to be on board. With regard to the manuals on procedures for liquefied hydrogen transfer, the requirements in the IGC Code are applicable and no special requirement is necessary.

3.4.4 Against low density and high diffusivity

Although low density and high diffusivity of hydrogen may reduce the possibility of formation of flammable atmosphere in open spaces, adequate ventilation is necessary for enclosed spaces in cargo areas where formation of hydrogen-oxygen/air mixture is anticipated. The IGC Code requires fixed ventilation systems or portable mechanical ventilation for such enclosed spaces. These requirements are applicable to liquefied hydrogen tankers and no special requirement is necessary in this regard.

3.4.5 Against high ignitability

The IGC Code requires electrical bonds of the piping and the cargo tanks, exclusion of all sources of ignition, electrical installations to minimize the risk of fire and explosion from flammable products and so on, in order to prevent ignition of flammable cargoes. The IGC Code further requires compliance with the relevant standards issued by the International Electrotechnical Commission (IEC) and the IEC standards specify the details of such safety measures depending on the respective properties of flammable gases including hydrogen. According to IEC 60079-12 [7], electrical equipment used in hydrogen/air mixture should be, at least, the type of “II-C” and “T-1” as the group based on the maximum experimental safe gap for flameproof enclosures and the temperature class based on maximum surface temperature, respectively. Thus, it can be said that the requirements in the IGC Code and the IEC standards are sufficient with regard to the high ignitability of hydrogen. Thus, no special requirement is necessary in this regard.

3.4.6 Against fire hazard

To avoid the influences of flame and UV radiation induced by hydrogen fire on safety of personnel, it is effective to use fire-fighter’s outfits and protective equipment. The IGC Code requires fire-fighter’s outfits and safety equipment for ships carrying flammable products. Thus, no special requirement is necessary in this regard, although this issue should be considered as the matter of cargo information, which is already required by the IGC Code.

3.4.7 Against high pressure hazard

High pressure hazard is common for hydrogen and the other flammable gases listed in the IGC Code. To prevent overpressure, the IGC Code requires various measures such as pressure control and pressure design. Specifically, provision of pressure control of cargo tanks requires fitting of pressure relief valves for the cargo tanks. Furthermore, the IGC Code requires temperature control by the use of mechanical refrigeration and/or design to withstand possible increase of temperature and pressure. In addition, the IGC Code specifies the filling limit of cargo tanks taking into account cargo volume increase by its thermal expansion. These requirements are applicable for hydrogen and no special requirement is necessary in this regard.

3.4.8 Against health hazard

With regard to the influences of cold hydrogen on persons’ bodies, suitable protective equipment is effective. In this aspect, the IGC Code requires suitable protective equipment, taking into account the character of the products. Thus no special requirement is necessary in this regard.

3.4.9 Against wider range of flammability limits

Dry chemical powder fire-extinguishing or carbon dioxide fire-extinguishing systems are deemed to be effective in case of hydrogen fire, and such fire-extinguishing systems have already been required by the IGC Code. Thus, special installation requirements for other types of fire-extinguishing systems are not necessary, except the increase of amount of carbon dioxide.

The IGC Code requires that enclosed cargo machinery spaces and enclosed cargo motor room within the cargo area of any ship shall be provided with a fixed fire-extinguishing system complying with the provisions of the FSS Code [8] and taking into account the necessary concentrations/application rate required for extinguishing gas fires. Chapter 5 of the FSS Code [9], i.e., “fixed gas fire-extinguishing systems”, requires that the quantity of carbon dioxide for cargo spaces, unless otherwise provided, shall be sufficient to give a minimum volume of free gas equal to 30% of the gross volume of the largest cargo space to be protected in the ship. Namely, with regard to the amount of carbon dioxide for fire-extinguishing systems, 30% of the gross volume of the protected space is required, unless otherwise specified. On the other hand, NFPA 12 [10] requires that the design quantity of carbon dioxide for hydrogen fire should be 75% of the gross volume of the protected space or more. The following text can be the special requirement in this regard:

> “The amount of carbon dioxide carried for a carbon dioxide fire-extinguishing system should be sufficient to provide a quantity of free gas equal to 75% or more of the gross volume of the cargo compressor and pump rooms in all cases.”

3.4.10 Safety measures for vacuum insulation

Vacuum insulation system will be used for liquefied hydrogen containment systems. Insulation capability of vacuum system may be adversely affected by damage to the system, depending on design of the system. If rapid deterioration of whole insulation system took place, rapid increase of temperature in the cargo tank would occur and/or rate of vaporisation of liquefied hydrogen might exceed the capacity of pressure relief valves. To prevent such dangerous deterioration of insulation, appropriate safety measures should be taken. The following text can be the special requirement in this regard:

> “When deterioration of insulation capability by single damage is possible, appropriate safety measures should be adopted taking into account of the deterioration.”

3.4.11 Against ortho-para transition

With regard to two isomeric forms of hydrogen, which are ortho and para, the ratio of ortho isomeric form in a cargo, i.e., liquefied hydrogen for shipment, will be lowered to the negligible level at the time of liquefaction through transition process using catalysts. Therefore, no special requirements are necessary in this regard. If the ratio of ortho isomeric form of a cargo at shipment should be non-negligible, special consideration for ortho para transition could be necessary.

3.5 Summary of special requirements

As mentioned in paragraph 3.4, we propose eight special requirements for liquefied hydrogen tankers. Table 2 with these special requirements provides the draft minimum requirements for liquefied hydrogen in bulk.

4 CONCLUSION

In this study, we provide safety requirements for liquefied hydrogen tankers as the basis for further consideration by relevant governments. Some of the tentative results of this study, i.e., draft requirements for such ships, have already been considered by Australian and Japanese governments. The authors will continue to support the work of Japanese government on the development of safety requirements for liquefied hydrogen tankers.

5 ACKNOWLEDGEMENTS

The authors deeply appreciate the members of Kawasaki Heavy Industries, Ltd. and the Maritime Bureau of Ministry of Land, Infrastructure, Transport and Tourism for their contribution and provision of the important information on hydrogen safety. The authors further appreciate the members of the committee on liquefied hydrogen tankers established by Japan Ship Technology Research Association.

6 REFERENCES

1. International Maritime Organization (IMO), “International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk” as adopted by the Maritime Safety Committee of the IMO by resolution of MSC.5(48) and amended by resolutions up to MSC.370(93) adopted on 2014
2. United Nations, UN Recommendations on the Transport of Dangerous Goods - Model Regulations, Eighteenth revised edition, 2013
3. International Maritime Organization (IMO), “International Maritime Dangerous Goods (IMDG) Code” adopted by the Maritime Safety Committee of the IMO by resolution MSC.122(75) and amended by resolutions up to MSC.372(93) adopted on 2014
4. International Maritime Organization (IMO), the revised text of the Medical First Aid Guide for Use in Accidents Involving Dangerous Goods (MFAG) approved by the Maritime Safety Committee of the IMO as MSC/Circ.857, 1998
5. International Organization for Standardization (ISO), ISO/TR 15916:2004, Basic consideration for the safety of hydrogen systems, 2004
6. American Institute of Aeronautics and Astronautics (AIAA), “Safety Standard for Hydrogen and Hydrogen Systems (Guide to Safety of Hydrogen and Hydrogen Systems)”, 2005
7. International Electrotechnical Commission, IEC 60079-12:1978 Electrical apparatus for explosive gas atmospheres - Classification of mixtures of gases or vapours with air (First edition), 1978
8. International Maritime Organization (IMO), “International Code for Fire Safety Systems” (FSS Code) adopted by the Maritime Safety Committee of the IMO by resolution MSC.98(73) and amended by resolutions up to MSC.367(93) adopted on 2014
9. International Maritime Organization (IMO), Chapter 5 of the FSS Code “Fixed gas fire-extinguishing systems” adopted by the Maritime Safety Committee of the IMO by resolution MSC.98(73) and amended by resolutions MSC.206(81) and MSC.339(91) adopted on 2006 and 2012, respectively
10. National Fire Protection Association, NFPA 12: Standard on Carbon Dioxide Extinguishing Systems 2005 Edition