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Article

Risk Assessment for Natural Gas Hydrate Carriers: A Hazard Identification (HAZID) Study

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Abstract: Sea transport of natural gas in the form of hydrate pellets is a new technological approach. Introducing new technologies bears raises the possibility of introducing unknown risks or—in case of alternatives for already existing technical solutions—higher risk, either human-, environmental-, or property-related. The option of gas transport by natural gas hydrate pellets has been introduced within the Korean joint research project. One key task was the safety evaluation of the novel natural gas hydrate carrier (NGH carrier) developed in the project. The aim of this work was to support and assess the risk aspects of the development to ensure that the risk level for the newly developed concept is as low as for existing competing concepts, especially LNG carriers. The NGH carrier is based on the concept of the self-preservation effect and thereby preserves NGH in the form of pellets at atmospheric pressure and temperatures lower than −20 °C. In order to identify all the possible hazards in the system and then enhance the system safety, a Hazard Identification (HAZID) study was conducted. As a result of the HAZID, 80 identified hazards in total were explored and ranked in terms of risk index for the semi-quantitative risk evaluation. Among the hazards identified, three hazards were found to have unacceptable risk level and twenty eight to have acceptable but ALARP risk level. Regarding the hazards with unacceptable risk or ALARP risk, additional safety actions and recommendations for risk control were discussed and proposed in a SAFETY ACTION REGISTER, which would be considered and utilized by designers when developing the detailed system design in the future.

In conclusion, the overall safety level of the NGH carrier is considered acceptable. However, it was found that a few external hazards associated with extremely harsh weather could be critical threats to the system. Relevant safety actions against them, therefore, must be provided in the system design.

Keywords: natural gas hydrate (NGH); gas carrier; risk analysis; HAZID; system design; IMO

1. Introduction

Natural gas is one of the main energy resources as well as a chemical feedstock. The worldwide consumption of natural gas is rapidly increasing. However, gas markets are normally far away from gas reserves. There are many possible technologies of transporting gas, *i.e.*, pipeline, Liquefied Natural Gas (LNG), Compressed Natural Gas (CNG) and Natural Gas hydrate (NGH) transportation, from production fields to consumers elsewhere for use as a fuel or as a chemical feedstock in a petrochemical plant. Generally, natural gas is transported by pipelines or by ships as LNG. Because of costs of LNG production plants, it is well known that LNG transportation systems have been adopted only for very large gas fields [1,2].

NGH is a solid ice-like material which forms naturally in hydrocarbon transport systems at high pressure and low temperature, usually causing operational problems. However, exploitation of the gas transport potential of hydrates through the development of processes which aim to ship bulk volumes of hydrates from smaller or more remote fields has been considered. Gas hydrates are solids made up of natural gas and water. Each cubic meter of hydrate contains 160–180 cubic meters of gas. Several alternative methods for storing and transporting hydrates have been developed, for example, as a solid (crystals) or as a mixture of solid hydrates and oil (slurry). Natural gas hydrate technology represents a new non-pipeline technology that is suitable for the transport of small-to-medium annual volumes of natural gas over moderate distances. Namely, NGH pellets can be a medium for natural gas transportation for comparatively small gas fields for which LNG transportation systems are not economically applicable.

It is well known that natural gas hydrates contain large amounts (about 160~180 times their volume) of natural gas and they are easily to stored and safely transported at about −20 °C under atmospheric pressure due to so called "self-preservation effect". In 1996, Gudmundsson *et al.* [3] proposed the basic concept of the transportation of natural gas in the form of hydrate. This technique enables transport of the natural gas at mild temperature conditions under atmospheric pressure, because of the peculiar metastability of natural gas hydrates. Consequently, specifications of facilities including production plants are expected to be simpler and the total cost of gas transport is lower in comparison with LNG carriers.

In recent years, conceptual designs of NGH pellet carriers have been introduced in various academic societies [4]. On the other hand, ship design depends on safety requirements, which have not been determined for NGH pellet carriers [5]. For an actual NGH pellet carrier, safety requirement will be determined based on the tripartite agreement of competent authorities of port of loading, port of discharge and flag state of the ship. The International Maritime Organization (IMO), *i.e.*, the special organization under the United Nations, is a suitable organization for the development of internationally accepted safety measures, because this organization has been developing and maintaining a comprehensive regulatory framework for international shipping.

As with any novel concept the particular risks and technical challenges need to be initially identified and then addressed to determine how feasible such an approach is. Generally a recommended approach is therefore to conduct a HAZID or risk assessment before applying any new technology. Hazard identification should be by means of formal identification techniques, e.g., HAZID, Hazard and Operability (HAZOP), Failure Modes and Effects Analysis (FMEA) *etc.*, by competent personnel from a suitable variety of engineering disciplines, operational and design backgrounds. The identification should, as a minimum, focus on hazards that could directly, or indirectly, results in loss of life, major fire or explosion, cryogenic release, loss of structural integrity or control, the need for escape or evacuation and environmental impact. Because hazards are the source of events that can lead to undesirable consequences, analyses to understand risk exposures must begin with an understanding of the hazards present. Although hazard identification seldom provides information directly needed for decision making, it is a critical step. Overall, hazard identification focuses risk analysis on key hazards of interest and the types of mishaps that these hazards may create.

In order to increase the knowledge for the development of a NGH carrier and to identify the major issues or hazards that could have significant impact on the safety of the vessel, a HAZID study was carried out by a multi-disciplinary HAZID team, under the lead of the Classification Society (KR). HAZID workshops that are essential works of the study were conducted. The purpose of this study is to outline the works and methodology of the HAZID study conducted for the NGH carrier. The results of the study including findings, proposals and recommendations are also summarized and should be considered at the subsequent phase of system development.

2. Conceptual Design of an NGH Pellet Carrier

In recent years, there have been significant advances in and experience with risk assessment methodology. The NGH carrier developed by the project team represents a novel concept for the transport of natural gas hydrates compared with the existing technologies. The NGH transport carrier has not been built, so the appropriate international regulations for the vessel are not legislated, but Japan suggested to the International Maritime Organization (IMO) that the safety requirements for the NGH carrier should be developed while conducting a variety of researches on NGH in the late 2000s, and submitted a draft to guide NGH carrier development based on the IGC code in 2008.

However, the systems which are suggested by Japan are mostly about the way that the hydrate is unloaded in solid-state in the cargo hold. In the case of the hydrate pellets, they should be separated by force, because they could be matted under steady pressure. An onland storage tank for storing the hydrate which is unloaded from the NGH carrier also needs to be built. Furthermore a long conveyor belt which has some system for preventing the gas from leaking after its dissociation has to be installed, thus increasing the cost for the transport to land and the storage system. As a result of these considerations, the unloading system for solid-state forms like pellets has many merits, but the method has too many limitations for actualization, so we need to actively consider the compulsory transfer unloading system after the dissociation in the NGH carrier.

The NGH carrier project has been initiated in Korea to develop new technologies for the exploration and mining of submarine gas hydrate resources as well as new concepts for the transport of natural gas from hydrate reservoirs. From 2009 to 2014 in total 30 partners from shipyards, the Classification Society and universities worked together in several subprojects of the joint project 'Development of a NGH carrier'. The main focus was on:

- Laboratory experiments and simulation models to investigate the production of natural gas hydrate from natural gas [6]; and,
- The development of new technologies for the production and transport of natural gas hydrate pellets.

The transport technology relies on the fact that natural gas hydrate shows a very slow dissociation rate at relatively mild conditions out of the stability field, known as the 'self-preservation effect', occurring at temperatures slightly below the freezing point of water. The self-preservation effect is a kinetic anomaly in which thermodynamically unstable hydrates, dissociate at rates up to several orders of magnitude slower than what could be expected. Experimental studies, focused mostly at ambient pressure [7–9] localize the anomaly in a fairly well defined temperature window, extending between 0 °C to −33 °C. The particularly well established dissociation rates of CH_4 hydrates decompressed to ambient pressure [7] show two strong minima (measured at 50% transformation) at ~ −23 °C and −6 °C separated by a region of clearly weaker phenomena.

Within the national project a Korean shipyard developed a concept for a natural gas hydrate pellet carrier with regard to the transport conditions, cargo capacity and requirements given by the assumed behavior of the cargo. The ship is about 250 m length and has a cargo capacity of 10,440 ton, as presented in Table 1.

Table 1. Principal particulars of the proposed NGH carrier.

LOA (Length Overall)	m	249.9
LBP (Length between perpendiculars)	m	239.0
Breadth	m	44.0
Depth	m	21.0
DWT (NGH)	ton	80,305.6
Tank volume (Natural gas)	ton	10,440

The tanks are distributed in six insulated and actively cooed compartments and connected to a specially designed cargo handling system for loading and unloading the hydrate pellets. Moreover, the major assumptions and physical properties of NGH pellets for ship design and risk assessment are summarized in Table 2. Figure 1 shows the appearance of ball-type NGH pellet which was used to estimate the stability and dissociation rate of the hydrate. The ball-type NGH pellets with typical diameters between 25 and 40 mm have smooth surface and transparent white color.

Table 2. Major assumptions and material properties for risk assessment in an NGH pellet carrier.

Specific Gravity of Hydrate		0.9	ton/m^3
Maximum loading rate (including porosity)		75	%
Weight ratio	Cargo NG	0.13	kg
	Cargo water	0.87	kg
Specific heat of hydrate		2.0934	kJ/kg·°C
Calories for dissociation of NGH		415.31	kJ/kg
Specific heat of water		4.187	kJ/kg·°C
Specific heat of NG		0.50	kcal/kg·°C

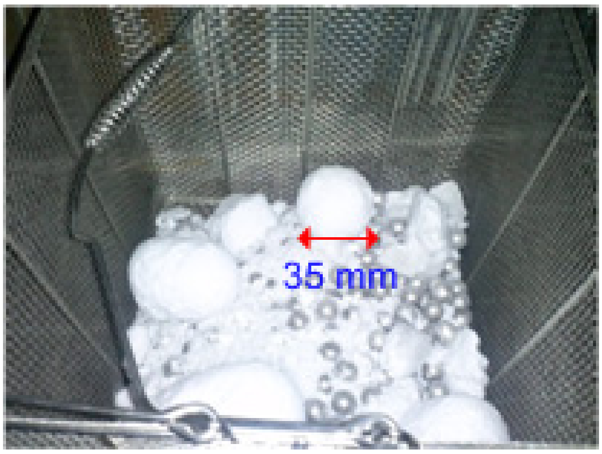


Figure 1. Appearance of ball-type NGH pellets (courtesy of Dongguk University, Korea).

The target system of the HAZID study is the NGH carrier which has been developed by Korean shipyard, Classification Society and universities. Figure 2 shows the detailed concepts of the NGH carrier.

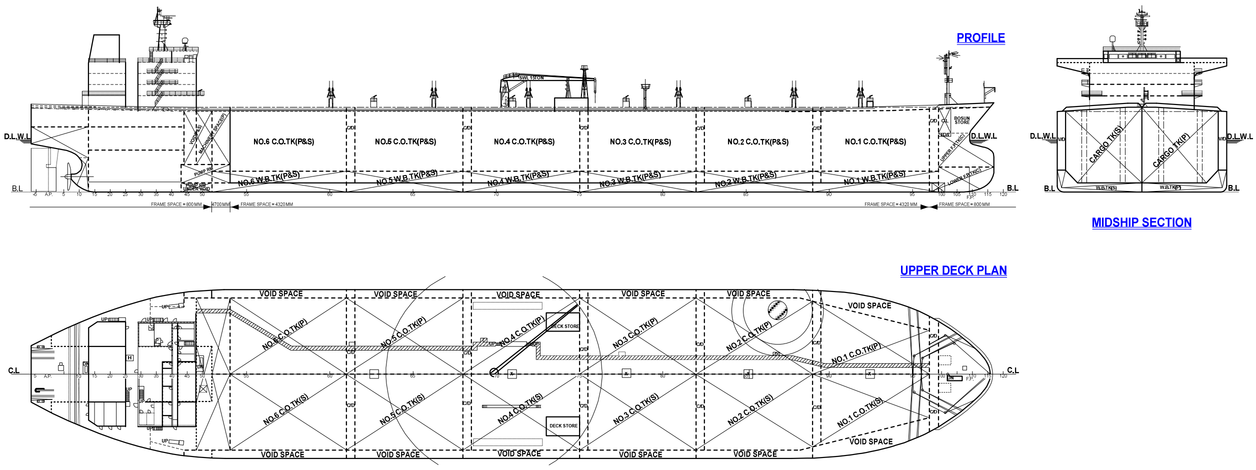


Figure 2. General arrangement of NGH carrier.

Figure 3 shows the dangerous spaces plan of the vessel. The dangerous spaces are the following areas or spaces where flammable or explosive gases or vapors from these substances and they are classified according to generation frequency and life period of the explosive gas atmosphere. 'Zone 0' is the area in which an explosive gas atmosphere is present continuously or is present for long periods. 'Zone 1' is the area in which an explosive gas atmosphere is sometimes likely to occur in normal operation. ‘Zone 2’ is the area in which an explosive gas atmosphere is not likely to occur in normal operation and, if it does occur, is likely to do so only infrequently and will exist for a short period only.

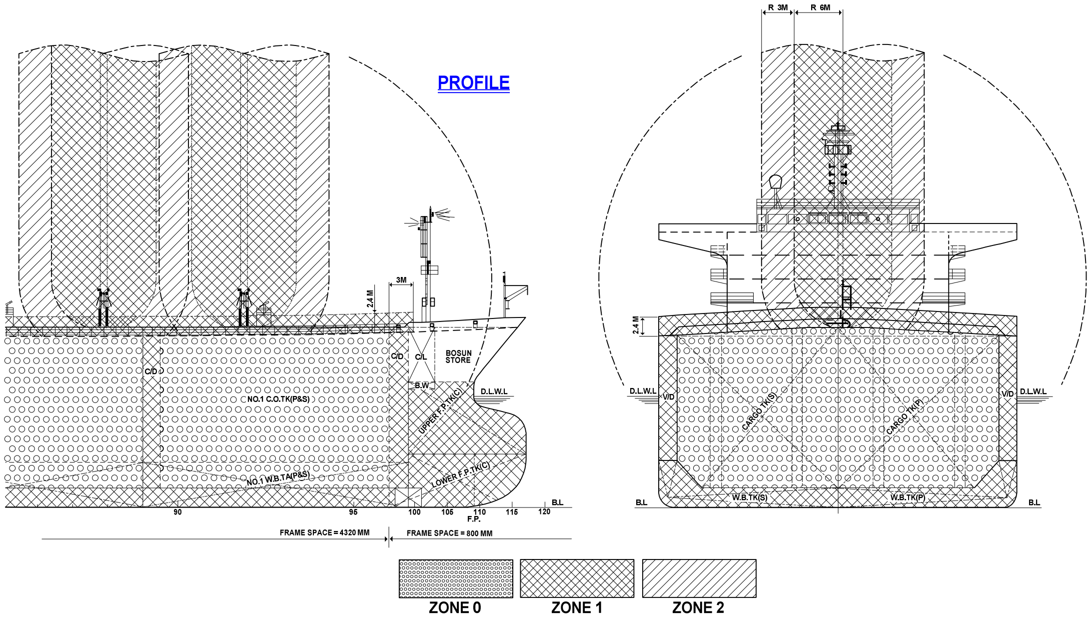


Figure 3. Dangerous zone plan in gas carrier according to IEC standard 60092-502.

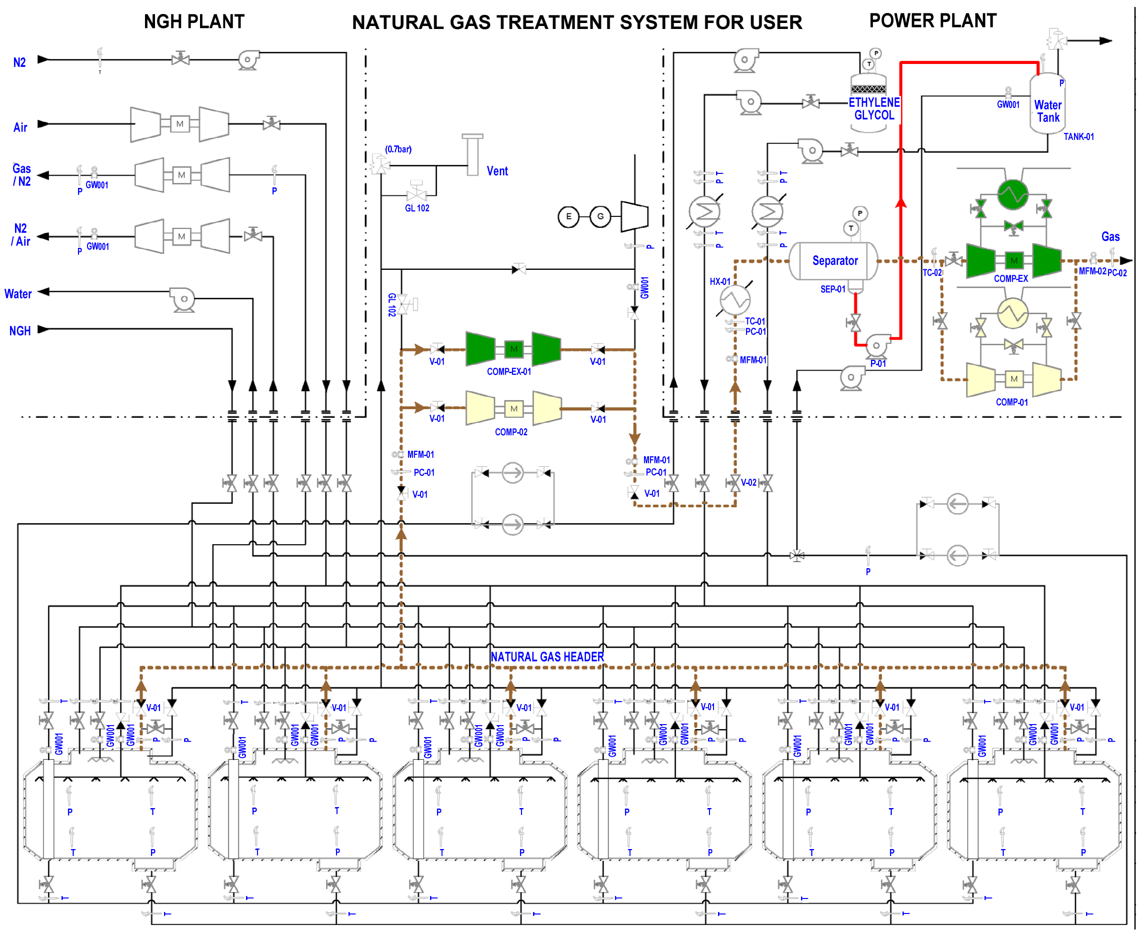


Figure 4. Conceptual flow diagram for NGH re-gasification system.

The concept of NGH carrier is based on a refrigerated bulk carrier [10,11] and has an enclosed cargo hold system to store NGH pellet in natural gas at −20 °C under atmospheric pressure. As for the unloading method, a re-gasification system in the ship was adopted. Figure 4 presents the process flow diagram for the NGH re-gasification system. The re-gasification system has four operation modes that include pre-docking operation, normal service, post-docking operation and emergency operation. The pre-docking operation is composed of an air supply to prevent nozzle freezing, water drainage to the NGH production plant, inerting using nitrogen and NGH loading. BOG (boil-off gas) treatment during transportation is the normal service. The water supply for the re-gasification system and the natural gas treatment system for users are classified as the post-docking operation. Table 3 shows six operation modes for the NGH carrier developed in this study.

Table 3. Operation and sub-operation modes in NGH carrier.

No.	ID	Operation Mode	Sub-Operation Mode
1	EMER	Emergency operation mode	Emergency shutdown, Emergency depressurization, NGH jettisoning
2	STARTUP	Start-up operation mode	Inerting, Gassing-up, Cooling-down
3	SHTDN	Normal shutdown operation mode	NGH draining, Warming-up, Inerting, Aeration
4	LOAD	Loading operation mode	Drain system, Pipe drain system, Cooldown system, Loading system
5	NORMAL	Normal operation mode	Cargo hold and insulation, BOG handling system, Intact stability, Sloshing
6	UNLOAD	Unloading operation mode	Re-gasification system pretreatment

3. Risk Analysis

No specific rules for the construction of these ships exist at present. Like in other industries, in the maritime industry risk-based approaches are increasingly applied for the evaluation of novel ship design, such as the NGH carrier, that challenge the existing regulatory framework, *i.e.*, regulations of the International Maritime Organization (IMO) and classification rules. Based on the HAZID and an additional examination of risk analyses on LNG carriers [12] (FSA, 2007) and crude oil tankers [13] submitted in recent years to the IMO, Kaehler and Hamann [14] developed a risk model by considering the accident categories collision, grounding and accidental release of methane due to equipment failure in piping, valves and tanks. For these accident categories so-called high level event sequences were developed that form the basis of the event trees. Risk analysis is used to determine the risk level of the ship or ship system in order to ensure that the novel designs achieve at a minimum the same safety level of already established technology, as recommended in IMO [15]. The risk analysis process is shown in Figure 5.

3.1. Hazard Identification

Hazard identification (HAZID) is the process of identifying hazards which forms the essential first step of any risk assessment. There are two possible purposes in identifying hazards:

- To obtain a list of hazards for subsequent evaluation using other risk assessment techniques. This is sometimes known as "failure case selection".
- To perform a qualitative evaluation of the significance of the hazards and the measures for reducing the risks from them. This is sometimes known as "hazard assessment".

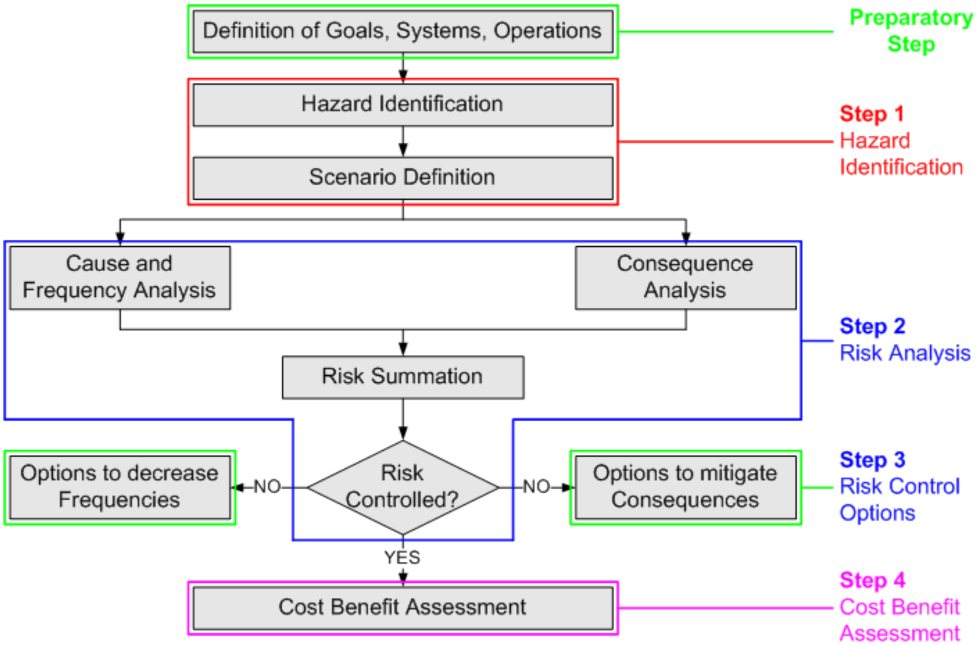


Figure 5. Steps of a risk analysis to determine the risk level in novel ship or ship system.

During the hazard identification stage, the criteria used for the screening of the hazards will be established and possible hazards and accidents will be reviewed. For this purpose, the facility will be divided into several sections. Furthermore, the identified hazards will be classified into critical and non-critical hazards. It is of great importance that the hazards considered non-critical are clearly documented in order to demonstrate that the events in question could be safely disregarded. The objectives of the HAZID procedure offered by research team are to identify main hazards, to review the effectiveness of selected safety measures and, where required, to expand the safety measures in order to achieve a tolerable residual risk.

The purpose of this HAZID study was:

- To identify the nature and scale of hazards that might present during the construction and operation phase of the NGH carrier
- To identify the possible causes associated with the identified hazards
- To identify the potential impact of hazards on humans, the environment and the vessel
- To evaluate the adequacy of existing safeguards (hardware systems and/or procedures) associated with the identified hazards, and
- To propose additional safety actions and recommendations for improving the safety of the NGH carrier.

3.2. Work Scope

For the natural gas hydrate carrier the HAZID was based on a brainstorming expert session. For the purpose of ranking the identified hazards, the probability of occurrence and the severity of the consequences were estimated using index tables. The ranking was performed on basis of the risk index (RI) which is the summation of FI and SI [16]. This approach is in full agreement with the proposals made in the Formal Safety Assessment (FSA) guidelines of IMO. In general, the FSA guidelines consider the environmental aspect only rudimentarily and contain no SI model for accidental occurrence.

For the KOREAN project team, three HAZID sessions focusing on general arrangement, loading and unloading operation system were performed, accompanying the development of the pellet carrier. The work scope of this HAZID is shown in Figure 6, and details of the system and its operation was described in previous section. The following show the scope of this study:

- Loading operation system
- General arrangement
- Unloading operation system

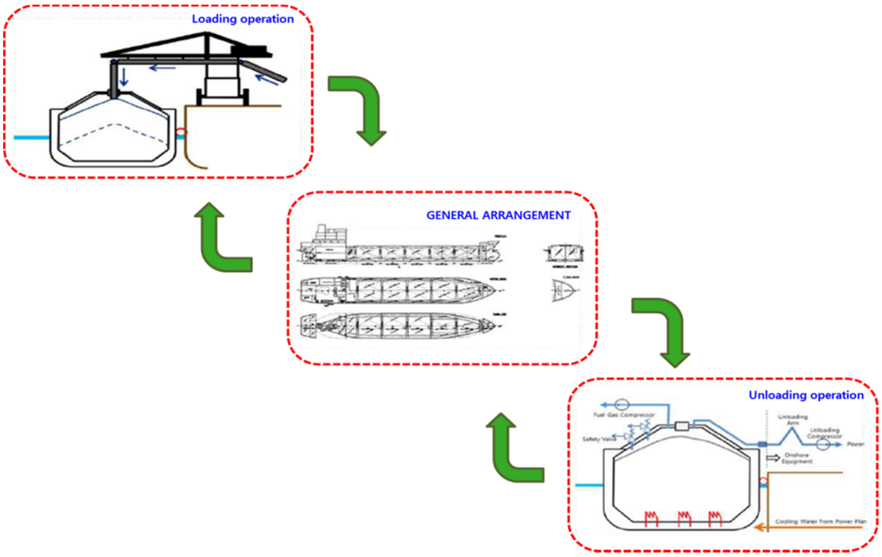


Figure 6. Technologies and system boundaries for HAZID of natural gas hydrate carrier.

3.3. HAZID Team

For the purpose of the improvement of a conceptual design of an NGH pellet carrier and development of the IMO guidelines, a HAZID team with a total of 10 members was assembled for conducting this study. A safety engineer (facilitator) from the Classification Society facilitated the HAZID workshop and provided knowledge on the HAZID methodology. All the items discussed and determined during the workshop were also recorded relevantly in the HAZID worksheet by an engineer (recorder). Several experts related to the development of the NGH carrier, from Korean shipyards, universities and the Classification Society, joined the team and attended the HAZID workshop. All of them were qualified experts with considerable experiences and expertise in the design and development of various ships. The HAZID workshops were conducted as a facilitated, team-based brainstorming using hazard guidewords as prompts for identification. The guidewords, which were complied by the facilitator before the workshop in a HAZID CHECKLIST, as shown in Appendix 1, were provided to HAZID team members at the beginning of the workshop.

As for the construction and operation phase of the NGH carrier, all kinds of potential hazards, causes, consequences and risk indices were explored by the HAZID team during the workshop. Then, various safeguards, which were already existing or being planned to be applied for reducing the risk associated with the specific hazard, were reviewed and also, if necessary, further applicable safety measures were examined. Discussed items in the workshop were relevantly recorded in the HAZID WORKSHEET (for lack of space, the table will not be dealt with here) All the findings and decisions from the workshop are the result of consensus of the team members and based on the experience and expertise of the qualified experts. In this work, specific semi-quantitative risk evaluation criteria, such as risk matrices, was used for the evaluation and prioritization of the risks associated with identified hazards during the workshop.

3.4. Risk Evaluation Criteria

Risk analysis is used to determine the risk level of the ship or ship system in order to ensure that the novel designs achieve at minimum the same safety level of already established technology. Consequently, it is considered reasonable that the risks criteria established for safety of conventional ships are applicable to this system. Various international activities for the enhancement of safety of ships have been carried out since the late 1990s [17]. One of the IMO dicuments was taken into consideration as the most appropriate one in this stud, thus risk evaluation criteria for discussion and decision of the HAZID team during the workshop were defined considering "The Guidelines for Formal Safety Assessment for use in the IMO rule-making process (MSC/Circ.1023-MEPC/Cir.392)" proposed by IMO (2007) [18].

3.4.1. Frequency Index (FI), Severity Index (SI) and Risk Index (RI)

In order to facilitate examination and decisions about the frequency (or probability) and severity of hazards identified by the HAZID team, frequency/severity categorization and related indices were defined as presented in Tables 4 and 5. According to the recommendations in the IMO guideline, the indices are on a logarithmic scale. Regarding each hazard, the most appropriate frequency/severity indexes were discussed during the workshop and finally determined through full agreement among the members of HAZID team. Furthermore, a risk index is determined by just multiplying the frequency index and severity index:

$$Risk\ Index = Frequency\ Index * Severity\ Index \quad (1)$$

Table 4. Definitions for the frequency index table for ships.

FI	Frequency	Description
5	Frequent	Likely to occur once per three months on one ship
4	Probable	Likely to occur once per six months on one ship
3	Occasional	Likely to occur once per one year on one ship
2	Remote	Likely to occur once per ten years on one ship
1	Improbable	Likely to occur once per thirty years on one ship

Table 5. Definitions for the severity index table for ships.

SI	Severity	Description			
		People	Assets	Environment	Reputation
1	Moderate	Slight injury	$ 91,000	Slight effect	Slight impact
2	Serious	Minor injury	$ 910,000	Minor effect	Minor impact
3	Major	Major injury	$ 9,100,000	Localized effect	Considerable impact
4	Catastrophic	Single fatality	$ 23,000,000	Major effect	National impact
5	Disastrous	Multiple fatalities	$ 46,000,000	Massive effect	International impact

To all the hazards identified, relevant risk indices were given, and then it was thus possible to prioritize the hazards. In other words, by comparing the risk index of each hazard, the HAZID team could understand which hazard has higher risk level and so should be paid close attention.

3.4.2. Risk Matrix and Evaluation Criteria

The risk matrix in this study, which is the combination of the frequency and severity indices defined above is presented in Table 6. Here the as low as reasonably practicable (ALARP) principle, which is commonly accepted for maritime safety issues and is the recommendation of the IMO guidelines, was considered for the risk evaluation criteria of this study.

The intolerable region presented in the red-colored area has risk indices of more than 10. No hazard in the region is acceptable, and proper safety actions for risk reduction, such as design changes, safety systems, inspection/maintenance procedure, *etc.*, must be investigated and provided to the system designers. The negligible region which is the blue-colored area has risk indices of less than 3. Any hazard in this region is broadly acceptable, and further safety actions for risk reduction are not necessary. The ALART region, which is the yellow-colored area, lies between the intolerable and the negligible. In this region, all the hazards have acceptable risk levels in principle, but additional safety actions should be applied for further safety enhancement of the system on the basis of their cost-effectiveness (ALARP principle). To summarize:

- *Intolerable region*: Risk index ≥ 10
- *ALARP region*: $3 <$ Risk index < 10
- *Negligible region*: Risk index ≤ 3

Table 6. Risk matrix to risk assessment in NGH ship operations.

FI	Frequency	Severity				
		1	2	3	4	5
		Moderate	Serious	Major	Catastrophic	Disastrous
5	Frequent	5	10	15	20	25
4	Probable	4	8	12	16	20
3	Occasional	3	6	9	12	15
2	Remote	2	4	6	8	10
1	Improbable	1	2	3	4	5

4. Results and Discussion

In the HAZID study regarding the NGH carrier, a large number of potential hazards were identified, and their possible consequences and various safeguards already provided in the system design were discussed thoroughly by the members of HAZID team. Additional safety actions required for risk reduction were investigated as well.

4.1. Overview

As stated above, the design and operation of the NGH carrier should be evaluated by risk analysis early in the design process. Hazard identification should be carried out based on the design. At a minimum, due consideration should be given to the risks owing to fire and explosion related to cargo holds, cargo handling systems, other systems related to cargo and special features of the NGHP carrier.

As a result of the HAZID and post-HAZID processing, 80 hazards (or hazardous scenarios) in total were identified and among them, 31 hazards (approximately 39%) were deemed worthy to be considered as presented in Table 7 and Figure 7. The remainder, *i.e.*, 49 hazards (approximately 61%), were meaningless or not available because it was estimated that they would cause no harmful effects or not be unique to the NGH carrier and have identical consequences in conventional vessels such as LNG carriers, and thus need no further consideration.

Most of the available hazards were related to the following three categories;

- Section 2-(1) Loading operation
- Section 2-(2) Normal service
- Section 2-(3) Unloading operation

Table 7. Number of hazards by hazard category.

	Hazard Category									Sum
	Section 1-(1)	Section 1-(2)	Section 1-(3)	Section 1-(4)	Section 1-(5)	Section 2-(1)	Section 2-(2)	Section 2-(3)	Section 3-(1)	
N.A. Hazards	16	8	4	4	5	3	2	1	6	49
Available Hazards	1	2	1	0	0	11	10	7	0	31

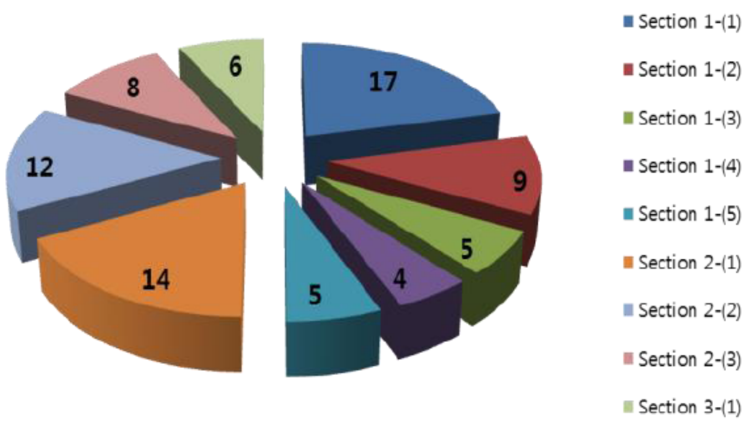


Figure 7. Hazard distribution based on the three categories.

Hazards on the six categories below were mostly considered unavailable or meaningless for the NGH carrier.

- Section 1-(1) Impact of natural and environmental hazard on the NGH carrier
- Section 1-(2) Impact of the NGH carrier on the natural environment
- Section 1-(3) Impact of the NGH carrier on the human environment
- Section 1-(4) Effects on the NGH carrier of man-made hazards/constraints
- Section 1-(5) Effects from infrastructures supporting the NGH carrier
- Section 3-(1) Health hazards.

For the sake of prioritization and semi-quantitative risk evaluation, all the hazards identified in this study, excluding the unavailable hazards, were ranked in terms of risk index according to the above stated 'Risk evaluation criteria'. The number of hazards classified by the risk index is shown in Table 8. In the table, the largest risk index was '12' and it was given to one hazard.

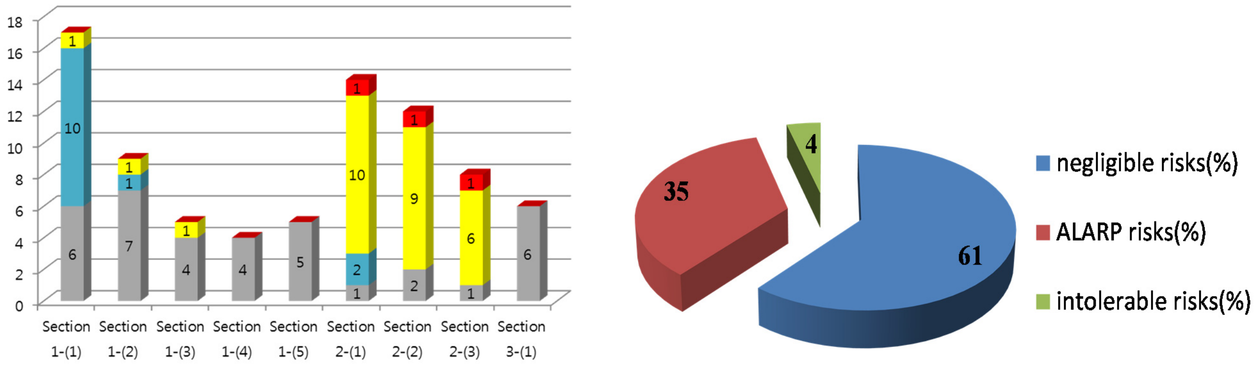
Table 8. Number of hazards by risk index.

		Negligible Region		ALARP Region			Intolerable Region	
Risk Index	N.A.	2	3	4	5	6	10	12
Number of Hazards	36	2	12	18	1	8	2	1

Table 9 show the number of hazards classified according to both the hazard category and the risk region. Considering only the available hazards, 61% has negligible risks and 35% has ALARP risks as shown in Figure 8. The portion of hazards with the intolerable risks, in other words unacceptable risks, is 4% and therefore not very large.

Table 9. Number of hazards by hazards category and risk region.

No.	Hazard Category	N.A. Hazards	Hazards with the Negligible Risk	Hazards with the ALARP Risk	Hazards with the Intolerable Risk	Sum
1	Section 1-(1)	6	10	1	0	17
2	Section 1-(2)	7	1	1	0	9
3	Section 1-(3)	4	0	1	0	5
4	Section 1-(4)	4	0	0	0	4
5	Section 1-(5)	5	0	0	0	5
6	Section 2-(1)	1	2	10	1	14
7	Section 2-(2)	2	0	9	1	12
8	Section 2-(3)	1	0	6	1	8
9	Section 3-(1)	6	0	0	0	6
	Sum	**36**	**13**	**28**	**3**	**80**



(**a**) (**b**)

Figure 8. Hazard distribution (**a**) and proportions of negligible, ALARP and intolerable risks (**b**).

4.2. Hazard Review

4.2.1. Hazards with Intolerable Risk

Hazards in the intolerable risk are just 3 in Table 9. Their risk levels are too high to be acceptable for the NGH carrier. It means that additional safety actions must be invented and applied to the current design of the system to ensure the risks due to these hazards can be reduced to a satisfactory level, such as below the upper limit of the ALARP region, regardless of the cost-effectiveness.

It is found that all the hazards having the intolerable risk are mainly related to three hazard categories: 'Section 2-(1) Loading operation', 'Section 2-(2) Normal service' and 'Section 2-(3) Unloading operation' as presented in Table 9. Therefore, it is understood that, for more enhanced safety of the NGH carrier, internal factors associated with the operating as well as external environmental conditions are to be investigated with prudence. The relevant hazards are listed in HAZARD REGISTER as presented in Appendix 2 and the required safety actions, which must be implemented by designers and developers in the future and then approved by the HAZID facilitator or safety supervisor in general, are listed in SAFETY ACTION REGISTER as presented in Appendix 3 (for lack of space, just the sheet for one case is presented here).

4.2.2. Hazards with ALARP Risk

Hazards in the ALARP risk region are 28 in total. They are acceptable in principle from the viewpoint of the system safety. However, in order to improve the current safety in the system against the hazards, practical and reasonable safety actions may be considered and applied on the basis of the results of cost-benefit assessment.

It is found that all the hazards having the ALARP risk are mainly related to three hazard categories, 'Section 2-(1) Loading operation', 'Section 2-(2) Normal service' and 'Section 2-(3) Unloading operation'. These results were caused by the same reasons mentioned above, *i.e.*, the intolerable risk. The relevant hazards are also listed in HAZARD REGISTER as presented in Appendix 2 and the recommended safety actions, which should be considered by designers and developers in the future but do not need to be approved by the HAZID facilitator or safety supervisor, are listed in SAFETY ACTION REGISTER.

4.2.3. Hazards with Negligible Risk

Hazards in the negligible risk region are 36 in total. They rarely affect the safety of the NGH carrier even though existing. Hence, the current safety in the system against the hazards can be considered sufficient, and then no further safety action for risk control is needed.

As has been the practice in other industries for decades, risk analysis had gained more and more importance in shipping industries in the last decade. From the perspective of the regulators such as IMO or Classification Societies, the benefits of risk analysis are the pro-active and transparent nature of the analysis. In recognition of the fact that a new concept, such as a NGH carrier, represents elements of novel technology, the generic prescriptive requirements used in IMO or Classification Rules are also supplemented by recommendations to use risk assessment to identify and mitigate against hazards associated with any new technology and novel applications of existing technology.

5. Conclusions

This study has assessed the risk analysis results of a proposed NGH carrier. For the sake of ensuring the enhanced safety of the system, a HAZID study was conducted by a HAZID team that consisted of several experts in various areas such as hull structure design, process design, machinery/equipment design and material research, and then many kinds of possible hazards and related safety actions were examined and proposed. The worksheets, in which all the findings and decisions during the HAZID workshop were recorded relevantly, are contained in the form of a HAZID Worksheet. Eighty hazards in total were produced by the HAZID study. Almost half of them (exactly 49 hazards) were not harmful or similar to the hazards of the conventional vessels such as LNG carriers or crude oil tankers and thus they do not need to be dealt with further. The other half, 31 hazards, were unique to the NGH carrier. Significant hazards which have intolerable risks or ALARP risks are listed in the HAZARD REGISTER presented in Appendix 2.

As a result of analyzing the identified hazards, the following perspectives on the safety of the NGH carrier were deduced:

- The majority of hazards to the NGH carrier fall in the acceptable risk region.
- Critical hazards having an unacceptable risk level are just a few.
- Hazards due to both the external factors associated with the environmental conditions and the internal factors associated with the process operation are the main concerns for the NGH carrier.
- Regarding the external hazards associated with extremely harsh weather, relevant safety actions for risk reduction must be provided in the system design.
- Regarding the internal hazards associated with the process operations, it is recommended that additional safety actions for risk reduction should be investigated on the basis of the ALARP principle.
- Harmful effects of the NGH carrier on the natural environment and residential areas (third parties) are expected not to exist or to be of similar level as those of conventional vessels, including LNG carriers.
- Security hazards, such as internal and external attacks, strikes and pirates, the NGH carrier are similar to those of existing LNG carriers and current practices being used are considered appropriate.
- Health hazards to the crew onboard are insignificant.

Finally, it is recommended to carry out another risk analysis in the future, following this HAZID study. Then the knowledge needa to be enhanced and large scale experimenta are essential to verify and revise the results of the presented analysis. Generally the NGH carrier provides a reduced risk in comparison to a LNG carrier, so a typical, but not necessarily exhaustive, list of hazards for an NGH carrier would be:

- Loss of cargo tank
- Gas release into enclosed spaces
- Fire and explosion
- Collisions and impacts
- Structural and/or foundation failures
- Dropped objects
- Stability failure
- Loss of mooring or other position keeping means.

Furthermore, a hazard and operability (HAZOP) study, which usually concentrates on the system and process operation, may be implemented. More useful and detailed information on the system design for improving its safety could be obtained through further risk analysis such as a HAZOP study.

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Author Contributions

Hokeun Kang was responsible for the overall coordination of the research team and contributed main researcher who initiates and organizes research reported in the paper. He was involved in each phase of research activities what includes: communication with other researcher, presentation of collected data and suggestions for the research. Kipyoung Kim and Youtaek Kim made some suggestions and performed HAZID work. All co-authors contributed to the writing of the final research article.

Appendix 1

HAZID Checklist (Guidewords)

Section 1—External Hazards

Hazard Category	Guideword	Possible Cause
(1) Impact of natural and environmental hazards on the NGH Transport Vessel	1. Climatic extremes	101. High ambient temperature 102. Low ambient temperature 103. Snow/ice 104. Swell/waves 105. Typhoon/hurricane 106. Flooding 107. Wind 108. Dust 109. Fog
	2. Lightning	110. Electrical strike
	3. Seismic events	111. Tsunami
	4. Miscellaneous	※ Might be explored/decided during HAZID workshop
(2) Impact of the NGH Transport Vessel on the natural environment	1. Continuous/frequent discharge to air	201. Vents 202. Fugitive emissions
	2. Continuous/frequent discharge to water	203. Target/legislative requirements 204. Drainage facilities
	3. Emergency/upset discharge	205. Vents 206. Drainage
	4. Waste disposal options	207. Pollution 208. Ignition source
	5. Miscellaneous	※ Might be explored/decided during HAZID workshop
(3) Impact of the NGH Transport Vessel on the human environment	1. Proximity to transport corridors	301. Shipping lanes 302. Fishing grounds
	2. Proximity to centers of population	303. Villages/towns
	3. Adjacent land use	304. Construction yard
	4. Miscellaneous	※ Might be explored/decided during HAZID workshop
(4) Effects on the NGH Transport Vessel of man-made hazards/constraints	1. Security hazards	401. Internal and external security threats
	2. Social/political unrest	402. Strikes 403. Pirate
	3. Miscellaneous	※ Might be explored/decided during HAZID workshop
(5) Effects from infrastructures supporting the NGH Transport Vessel	1. Normal communication links with the system	501. Road links 502. Air links 503. Water links 504. Personnel transport to/from site
	2. Supply support to the system	505. Chemicals/consumables/spares means of supply 506. Fuel supply to site
	3. Mutual aid/emergency services	507. Tugs 508. Firefighting boats in harbor
	4. Miscellaneous	※ Might be explored/decided during HAZID workshop

Section 2—Facility Hazards

Hazard Category	Guideword	Possible Cause
(1) Loading operation	1. Drain system	601. Oil spill on the deck 602. The damage of the valve 603. Freezing the residual water 604. Pyrophoric substance
	2. Pipe drain system	605. The pressure in the pipe 606. The failure of the drain
	3. Cooldown system	607. Freezing in the pipe 608. The damage of the pipe and the nozzle 609. The blockage of the vent line
	4. Loading system	610. The damage of the internals 611. The blockage of the NGH loading pipe 612. The generation of the BOG 613. The bias of the loading
	5. Miscellaneous	※ Might be explored/decided during HAZID workshop
(2) Normal service	1. Cargo hold and insulation	701. The damage of the cargo hold 702. The leak of the loading 703. The explosion in the void 704. The generation of the dissociation gas 705. The flooding in the void
	2. BOG handling system	706. Freezing the vent line 707. The damage of the safety relief valve 708. The damage of the safety relief valve of the buffer tank 709. The excess of the BOG removal capacity
	3. Intact stability	710. The loss of the stability
	4. Sloshing	711. Sloshing
	5. Miscellaneous	※ Might be explored/decided during HAZID workshop
(3) Unloading operation	1. Regasification system	801. The damage of the circulating pump 802. The blockage of the water injection nozzle 803. The damage of the pipe 804. The excess of the gas production 805. The sudden stops while unloading
	2. Pretreatment	806. The blockage of the nozzle 807. The damage of the drain valve
	3. Miscellaneous	※ Might be explored/decided during HAZID workshop

Section 3—Health Hazards

Hazard Category	Guideword	Possible Cause
(1) Health hazards	1. Disease hazards	901. Endemic disease 902. Malarial mosquitoes
	2. Carcinogenic	903. Chemicals in use
	3. Toxic	904. Toxic chemicals in use 905. Chemicals giving toxic combustion products at high temperature
	4. Miscellaneous	※ Might be explored/decided during HAZID workshop

Appendix 2

Hazard Register

No.	Hazard ID	Hazard Category	Cause	Consequence	Op. Mode	RI	Remark
1	804	Section 2-(3)	The excess of the gas production	* The damage of the cargo hold.	UNLOAD	12.0	Intolerable risk
2	605	Section 2-(1)	The pressure in the pipe	* The explosion.	LOAD	10.0	Intolerable risk
3	706	Section 2-(2)	Freezing the vent line	* The damage of the cargo hold by the pressure rise.	NORMAL	10.0	Intolerable risk
4	602	Section 2-(1)	The damage of the valve	* The rupture of the pipe because of the pressure rise. * The leak of the gas.	LOAD	6.0	ALARP risk
5	603	Section 2-(1)	Freezing the residual water	* The rupture of the pipe at cooldown and normal operation. * The interruption of operation in regasification system. * The interruption of operation in cooldown system and pretreatment system.	LOAD	6.0	ALARP risk
6	604	Section 2-(1)	Pyrophoric substance	* The explosion by the pyrophoric substance. * The damage of the cargo hold by the failure of the pressure control in the pipe.	LOAD	6.0	ALARP risk
7	610	Section 2-(1)	The damage of the internals	* The damage of the insulation for the cargo hold. * The damage of the insulation. * The damage of the regasification.	LOAD	6.0	ALARP risk
8	702	Section 2-(2)	The leak of the loading	* The explosion in the void.	NORMAL	6.0	ALARP risk
9	801	Section 2-(3)	The damage of the circulating pump	* To shut regasification system down.	UNLOAD	6.0	ALARP risk
10	802	Section 2-(3)	The blockage of the water injection nozzle	* The regasification system is out of control.	UNLOAD	6.0	ALARP risk
11	803	Section 2-(3)	The damage of the pipe	* The delay of the regasification system. * The fire explosion.	UNLOAD	6.0	ALARP risk
12	601	Section 2-(1)	Oil spill on the deck	* The drain system is out of control. * The negligent accident.	LOAD	5.0	ALARP risk
13	103	Section 1-(1)	Snow/ice	* Blockage of BOG vent line due to icing. * Bad operation of external valves due to icing.	All	4.0	ALARP risk

Hazard Register. *Cont.*

No.	Hazard ID	Hazard Category	Cause	Consequence	Op. Mode	RI	Remark
14	206	Section 1-(2)	Drainage	* Explosion risk due to NGH jettisoning into the sea. * Marine pollution due to NGH jettisoning into the sea.	EMER	4.0	ALARP risk
15	301	Section 1-(3)	Shipping lanes	* Fracture on hull structure due to collision. * Fracture on piping, equipments and supporting structure due to collision.	All	4.0	ALARP risk
16	607	Section 2-(1)	Freezing in the pipe	* The leak of the gas. * The explosion. * The rupture of the pipe.	LOAD	4.0	ALARP risk
17	609	Section 2-(1)	The blockage of the vent line	* The damage of the cargo hold.	LOAD	4.0	ALARP risk
18	611	Section 2-(1)	The blockage of the NGH loading pipe	* The blockage of the NGH loading pipe.	LOAD	4.0	ALARP risk
19	612	Section 2-(1)	The excess of the generation of the BOG	* Environmental pollution. * The damage of the cargo hold by the pressure. * The damage of the cargo.	LOAD	4.0	ALARP risk
20	613	Section 2-(1)	The bias of the loading	* Heeling.	LOAD	4.0	ALARP risk
21	703	Section 2-(2)	The explosion in the void	* The damage of the insulation on the side. * The excess of the generation of the BOG.	NORMAL	4.0	ALARP risk
22	704	Section 2-(2)	The generation of the dissociation gas	* The damage of the cargo. * The damage of the cargo hold by the pressure rise.	NORMAL	4.0	ALARP risk
23	707	Section 2-(2)	The damage of the safety relief valve	* The damage of the cargo hold by the pressure rise.	NORMAL	4.0	ALARP risk
24	708	Section 2-(2)	The damage of the safety relief valve of the buffer tank	* The damage of the buffer tank.	NORMAL	4.0	ALARP risk
25	709	Section 2-(2)	The excess of the BOG removal capacity	* Environmental pollution.	NORMAL	4.0	ALARP risk
26	710	Section 2-(2)	The loss of the stability	* Stopping navigation.	NORMAL	4.0	ALARP risk
27	711	Section 2-(2)	Sloshing	* The damage of the cargo hold.	NORMAL	4.0	ALARP risk
28	805	Section 2-(3)	The sudden stops while unloading	* The leak of the gas while the regasification operation.	UNLOAD	4.0	ALARP risk
29	806	Section 2-(3)	The blockage of the nozzle	* To stop the operation.	UNLOAD	4.0	ALARP risk
30	807	Section 2-(3)	The damage of the drain valve	* The delay of the operation.	UNLOAD	4.0	ALARP risk

Appendix 3

Safety Action Register

SAFETY ACTION REGISTER				**No. (1) of (8)**
PROJECT	Development of NGH carrier			
TASK	HAZID Study on the NGH Transport Vessel			
DOCUMENT	HAZID Report			
TARGET SYSTEM	The NGH Transport Vessel			
Hazard ID	**Op. Mode**	**Risk Index**	**Risk Level**	**Remark**
804	UNLOAD	12.0	Intolerable	Section 2-(3)

[√] Course of Action (Compulsory) :

[ ] Recommendation (Advisory) :

1. System analysis should be performed, the parameters should be carefully defined.
2. The measures to block the hydrothermal supply should be prepared.
3. The dual-line should be managed.

Written by: HAZID facilitator **Signed:** **Date:** (dd/mm/yyyy)

Response:

Written by: **Signed:** **Date:** (dd/mm/yyyy)

Close out:

Written by: **Signed:** **Date:** (dd/mm/yyyy)

Conflicts of Interest

The authors declare no conflict of interest.

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