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Risk Assessment of Membrane Type LNG Storage Tanks in Korea-based on Fault Tree Analysis

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Abstract−For a liquefied natural gas (LNG) storage tank, the greatest concern is for the release of a large amount of LNG or its vapor due to the mechanical failures of main tank and its ancillary equipments or the malfunctions of various hardware components. Nowadays two types of LNG storage tank design, that is, 9%-Ni full containment and membrane concepts, are mostly applied to LNG industry. In Korea the membrane type has been nationally adopted from the beginning step of LNG project because of its higher flexibility in storage capacity comparing to the 9%-Ni type. All the while several huge membrane-type tanks have been built up and operating, the quantified results of risk associated with them has not been systematically delineated. Hence the method of fault tree analysis as a quantitative risk assessment has been here employed to identify and evaluate the risks related to the membrane-type LNG storage tank. Six top events leading greatly to the large release of natural gas are defined as internally induced major accidents and the failure frequencies of these events are calculated by using other sources of process equipment reliability data for the lack of membrane type-specific data.

Key words: Risk Assessment, Liquefied Natural Gas, Membrane-Type LNG Storage Tank, Fault Tree Analysis, Failure Frequencies

INTRODUCTION

To diversify energy sources and meet the strict standards of air pollution levels as well as to seek the handiness of energy handling in households, the amount of anthracite coal supply had been hastily cut off and liquefied natural gas (LNG) has been replaced for it in Korea. The LNG was first imported in 1987 and then the quantity supplied as a city gas has been rapidly increased throughout the nation. In a short period many huge LNG storage tanks have been built up and now under construction to store and reserve LNG for its expanding demand. There are generally four types of LNG tank containment, namely, single, double, full and membrane containments which are classified by British Standards Institute [1993]. The proper selection of LNG storage tank types is made according to location to be sited, safety, reliability, environmental considerations, and economic efficiency. In these days, taking the operational safety of tanks and associated equipments as well as the ease of maintenance into account, the types of full containment and membrane-type tank are mainly favored in LNG industry.

In the type of a full containment system the cylindrical tank wall has a double-wall structure. The rounded inner wall is made of 9%-Ni steel with the thickness of several centimeter in the top part to several tens of centimeter around the bottom wall to withstand the liquid hydrostatic pressure. The special steel alloy of 9% nickel is required to secure sufficient toughness to arrest a quick crack propagation even at the cryogenic temperature of about - 162 °C of the stored LNG. Even though the inner wall is able to contain the LNG without any other support, an outer wall of prestressed concrete is affixed to the inner steel wall for the sake of accomplishing the effects of external impact resistance, retaining thermal insulation, acting as a gastight barrier within the insulation and the roof space, and supporting as a foundation for the inner steel shell. The outer wall is connected rigidly to both bottom concrete slab and reinforcing concrete roof which has a spherical form. Usually the inner surface of the outer wall plays a role of vapor barrier and is insulated with the cold resistance relief material of poly urethane foam. As it can be seen, the outer concrete wall highly increases the tank safety and thus the tank is less susceptible to damage from external forces and fire. However, when it comes to augmenting the tank capacity with the tank height increasing in the axial direction, it will be very hard job to fabricate the inner steel wall because the wall thickness should be getting thicker to withstand the load of LNG. What will be more important in the safety problem is that even with the improvements of toughness established in the 9%-Ni steel, the probability of occurrence of crack could not be completely eliminated in highly stress concentrated parts. Hence to overcome these undesirable facts a new design concept of membrane was proposed to apply to aboveground LNG storage tank by S. N. Technigaz [Giribone et al., 1995]. At first the membrane was developed for LNG carriers, where the fatigue problem was almost a significant factor.

Apparently the membrane-type tank has also a concrete outer wall and hence looks identical to the full containment tank. However, the fundamental feature of the membrane type is different from the full containment tank in respect that the structural and tightness functions are separately considered. The inner shell is made of thin steel called membrane instead of 9%-Ni alloy in the full containment. The membrane made of 1.2 mm thick corrugated 304 stainless steel sheet to get rid of thermal impacts does not withstand the hydrostatic load of LNG. The hydrostatic load is transferred to the

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outer concrete wall through PVC insulation foam layer with plywood backing and anchoring the membrane. It means that all the flat parts of membrane have almost a zero stress. This will be a major advantage of the membrane-type tank in comparing with the 9%-Ni full containment tank. There is a small gap between the membrane and the plywood panel where nitrogen gas is filled up. The nitrogen space is engaged to keep the pressure to the normal tank-operation bounds and to monitor the natural gas concentration in the event of a leak. When the membrane shell is initially prepared before the start-up operation of the tank, the nitrogen gap is also used for the ammonia tightness test to check the welding status of the membrane sheets.

Currently both types of LNG storage tanks are now operating in two LNG receiving terminals located in Pyeong Taeg and Incheon areas, Korea. Even secondly in the world the membrane-type tank was introduced and have been successfully employed for depositing such a large voulme of LNG as upto 100,000 m^3 per tank, the quantified results of risk associated with it has not been systematically examined and published while the risk and failure assessments in connection with the 9%-Ni containment had been performed for the peakshaving LNG plants in USA by American Gas Association [Welker et al., 1979] and Gas Research Institute [Johnson et al., 1980; Atallah et al., 1990]. Hence the present work has been focused on the potential hazards leading to release of large amount of LNG vapor from the membrane-type LNG containments located in Pyeong Taeg LNG receiving terminal. First we have identified all significant causes of tank failure to produce a release of LNG to the environment and the method of fault tree analysis as a quantitative risk assessment has been then employed to evaluate the overall failure frequencies which are synthesized from the component failure rate data obtained in similar LNG facilities and other industrial sources. Our assessment is restricted to the internally-induced events that could lead to catastrophic failure because the frequencies of these occurrence are highly dependent upon human error and equipment failure. Six internal prime events are here defined such as gross mechanical failure, overfilling of the storage tank, overpressurization of tank, implosion of tank due to underpressurization, rupture of LNG inlet line to tank, and rupture of LNG outlet line from tank. Unlike external events (e.g., earthquakes, sabotage and missile attack etc.), these internal events are under control of the operator and their frequency of occurrence may be reduced by taking appropriate measures.

FAULT TREE ANALYSIS

Fault trees originated in the aerospace industry and now have been extensively used by the chemical process industries. Fault tree analysis is a deductive method using Boolean logic symbols for identifying ways in which hazards could lead to accidents. There are AND and OR gates to name only the mostly used Boolean logic functions (refer to Fig. 1). The AND logic function is very important for describing events that interact in parallel, which means the output state is only active when input states are active simultaneously. If events are related in series, they must be connected to the top event by an OR gate. The other logic functions which are usually embedded in the fault trees can be found in the textbook written by Crowl et al. [1990]. The fault tree approach begins with a well defined

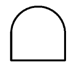
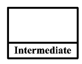
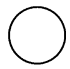
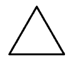
	OR Gate	The output event occurs if any of the input events occur
	AND Gate	The output event occurs only when all the input events exist simultaneously
	INTERMEDIATE Event	A fault event that results from the interactions of other fault events that are developed through logic gates such as those defined above
	BASIC Event	A component failure that requires no further development. A basic event is the lowest level of resolution in a fault tree
	EXTERNAL or HOUSE Event	A condition or an event that is assumed to exist as a boundary condition for the fault tree
	TRANSFER Symbols	The TRANSFER symbol indicates that the fault tree is developed further on another page. The symbols are labeled using numbers or a code to ensure that they can be differentiated. Transfer symbols are often used to avoid repeating identical logic in several places in a fault tree model

Fig. 1. The description of Boolean logic functions.

top event and works backwards towards the various scenarios that can cause the accident. In other words, the fault tree model is set up to generate a list of the failure combinations (failure modes) that trigger the concerned top event. In general, the top event could occur by a variety of different combinations of events which are called cut sets. However, with respect of probability of the top event we have to find a set with the highest which is named a minimal cut set. That is, a minimal cut set is a smallest combination of component failures which, if they all occur or exist simultaneously, will lead to the top event in a short cut. Such combinations are the “smallest” combinations in that all of the failures could contribute to the top event. Here we have found the minimal cut sets for each top event before building up fault trees.

Before setting up the falut trees, first of all, we have carried out the hazard identification for the possible internally-induced causes of failure of LNG tank leading to leak or release of large volume of LNG or its vapor. Six internal events listed below are identified as the prime causes that could do severely harm to tank safety:

· Gross mechanical failure of storage tank.
· Overfilling and spilling over the inner shell.
· Overpressurization that could lead to the activation of the relief valves.
· Underpressurization that could lead to the collapse of the inner shell.
· Rupture of the inlet LNG loading line to the tank.
· Rupture of the outlet LNG unloading line from the tank.

As an illustrative example of the application of fault tree analysis to a membrane-type LNG tank, we estimated the frequencies of occurrence of the above mentioned internal events for the membrane-type LNG tank which has been under operation in Pyeong Taeg LNG Receiving Terminal since 1987. The tank has a shape of a cylindrical, flat-bottom, round-roof, and above-ground containment with a capacity of approximately 100,000 m^3. The inside of the tank is installed of 18-8(Cr-Ni) Austenite membrane for the compensation of thermal contraction when it contacts LNG. The side and bottom walls of the tank are composed of 90 cm pre-

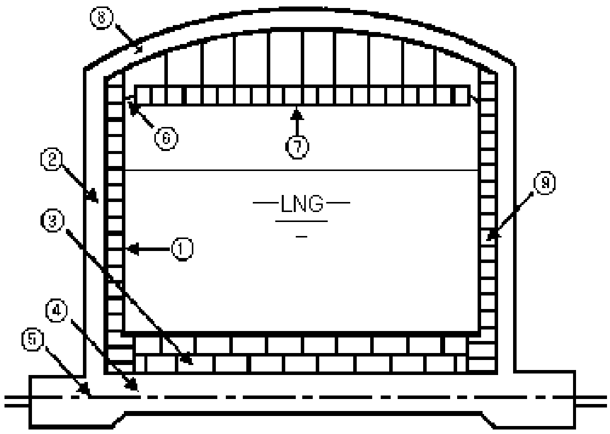


Fig. 2. The schematic configuration of membrane-type LNG storage tank.

1. Primary container (membrane)
2. Secondary container (concrete)
3. Bottom insulation
4. Foundation
5. Foundation heating system
6. Flexible insulation seal
7. Suspended roof (insulated)
8. Concrete roof
9. Insulation on inside of pre-stressed concrete outer tank

stressed concrete, PVC insulation foam and plywood from the outside. Nitrogen with a slightly higher pressure than the atmosphere is filled within the annular space between the membrane and plywood panel. On the upper part of the tank a disk-shaped deck with glasswool covered is suspended from the ceiling of the roof. The schematic configuration of membrane-type LNG storage tank is depicted in Fig. 2.

In order to set up the fault tree scheme as a quantitative risk analysis, here we will briefly explain the method of how to get the failure rate data. When selecting the right failure data for this kind of quantitative risk analysis, the practical situation is to secure valid historical data from the identical component of equipments in the same application. However, in most case, these data are unavailable and thus we have no choice but to rely upon appropriate generic data as surrogates for or supplements to the plant-specific data. However we don't have to worry about the unreliability probably arising from the generic data because the risk analysis methodology itself has the inherent uncertainties to some extents. The major advantage of the employment of generic failure rate data is to identify the hierarchy of the risk contributors to an undesirable event.

As far as the membrane-type LNG tank is concerned, we cannot find any plant-specific failure rate data because of its short history and small scale of facility units in comparison with the other chemical plants. Thus, for the sources of the failure data as a preliminary generic database we mostly depend upon the databases such as the Guidelines for Process Equipment Reliability Data published by the Center for Chemical Process Safety (CCPS) of the American Institute of Chemical Engineers (AIChE) [1989], the Utility Requirements Document prepared by the Electric Power Research Institute (EPRI) [1995], the Standard 500 published by the Institute of Electrical and Electronics Engineers (IEEE) [1984], and the Offshore Reliability Data [1997]. After the appropriate generic data has been collected, the source data are then screened and traced to identify the applicable boundaries to which the component-specific failure is assigned and to check the existence of any crossing-references among the sources. During these procedures of selecting generic data and making a single data point if there are similar ones, unacceptable circumstances, which may create very large tolerance of uncertainty, could also be avoided by using the operation and maintenance manuals of LNG tank, the physical and chemical properties of LNG, and failure modes experienced in the other LNG facilities.

CALCULATION METHODS FOR FAILURE RATE

Before proceeding to show our main results, we have defined in our own way the acronyms standing for the equipments, gauges, switches, and any other components of the membrane-type LNG Tank as listed in Table 1. These are introduced only for our convenience sake to describe events. In Table 2, we have shown an exemplary sample sheet to list up the databases of failure probabilities of components, which were later used as input data for the calculation of the aimed gross mechanical failure frequency of LNG tank. Here, the first two letters are for the system name, that is, TK means LNG storage tank, then the following characters attached by numbers stands for tag numbers of component exposed to failure, and the final single letter is characterizing the failure mode of the event such as defined in Table 3.

While performing the quantified failure frquencies of the events, we need two types of failure probability values for a component hardware: probability that a system or component doesn't respond as required on demand (unavailability), and probability that a system or component fails during mission time given that it successfully started (unreliability). Hence component unavailability is calculated from the demand failure probability. A demand failure is a failure of a component to change its state of respond as required upon demand. Typical examples of the demand failures are the fail-

Table 1. Symbols for major equipments, guages, switches and valves

Symbol	Full name
LI	Level Indicator
LOIA	Loss of Instrument Air
LOSP	Loss of Off Site Power
LSL	Low Level Switch
LSLL	Level Switch Low Low
PIC	Pressure Indicator Controller
PCV	Pressure Control Valve
PAL	Low Pressure Alarm
PALL	Pressure Alarm Low Low
PAH	High Pressure Alarm
PAHH	Pressure Alarm High High
PSH	High Pressure Switch
PSHHH	Pressure Switch Extra High
PSV	Pressure Safety Valve
RPM	Butterfly Valve Motorized
RSM	Globe Valve Motorized
TSV	Temperature Safety Valve

Table 2. Some results of failure rates (λ) used for the calculation of failure probabilities

Name	Descriptions	Mode	λ	Duration	Unit	Remarks
TKPSV0123C	PSV-1xx.01/02/03 fail to open at 230 g_f	0	2.12×10^{-4}	-	-	CCPS 4.3.3.2
TKLI131012F	LI-131.01 & 131.02 fail to indicate level	1	1.00×10^{-6}	8760	h	EPRI
TKLSH131013A	LSH-131.01 & 131.03 fail to actuate	0	1.00×10^{-3}	-	-	EPRI
TKLSHH13102A	LSHH-131.02 fails to actuate	0	1.00×10^{-3}	-	-	EPRI
TKPAH131061A	PAH-131.06 & 131.01 fail to actuate	0	2.50×10^{-4}	-	-	EPRI
TKPAL131014A	PAL-131.01 & PALL-131.04 fail to actuate	0	2.50×10^{-4}	-	-	EPRI
TKPSHHH13105A	PSHHH-131.05 fails to open RPM-131.13	0	2.50×10^{-4}	-	-	EPRI
TKPSV131045C	PSV-131.04/05 fail to open at −2.5 g_f	0	2.12×10^{-4}	-	-	CCPS 4.3.3.2
TKRPM13113C	RPM-131.13 fails to open at 215 g_f	0	2.20×10^{-3}	-	-	CCPS 4.3.3.2
TKRPM13101C	RPM-131.01 fails to close	1	3.59×10^{-6}	8760	h	CCPS 3.5.3.3
TKRSM13112C	RSM-131.12 fails to open on demand	0	2.20×10^{-3}	-	-	CCPS 3.5.3.3
TKRSM13112H	Operator fails to open RSM-131.12	0	1.00×10^{-2}	-	-	Engineering Judgement

Table 3. Characteristic symbols for failure mode

Failure symbol	Description
A	Fails to actuate (to provide output)
B	Break or rupture
C	Fails closed or fails to open
F	Fails to function
H	Human error
I	Spurious signal
O	Fails open or fails to close
R	Fails to run
S	Fails to start
T	Tube rupture

ure of a pump to start on demand, and a failure of a motor operated valve to open on demand. If the failure data is given as the probability per request, the failure data is given as the probability per demand. The value itself is the component unavailability and will be calculated using the following equation:

$$U=\lambda_d\times N,$$

where U is the probability of a component failure to response when it is required on demand, λ_d is the probability of a component to fail per demand, and N represents the number of demands.

The component unreliability is calculated using the running failure rate. The running failure is the failure of a component to continue to operate during its mission time given that it has successfully started to operate. A typical example of the running failure is a pump failure to run through its mission time. The failure data for this type of failure mode is given as the failure probability per unit time. The component unreliability is calculated with the running failure rate and mission time using the following equation:

$$P=\lambda_m\times T.$$

Here P is the probability of a component failure during mission time, λ_m is the probability of a component to fail per hour, and T stands for the mission time period in hours.

Most of the unavailability or unreliability of a component has been calculated using the methods described above. However, it is requested to be more cautious when we deal with the unavailability or unreliability of "redundant" configurations. No matter how well redundant system is applied, there are always limits of achievable levels for the availability or reliability. These limits can be represented as the common cause failure (CCF) of the redundant when components or discrete items arranged for the same purpose or function are susceptible to a simultaneous failure. These CCF factors have to be considered from the design step of any process. Here, the β-factor model has been employed to estimate the rate of CCF applicable to two or more systems operating in parallel systems. The model has been highly recommended for treating CCF in many references (EPRI URD [1995]; NUREG/CR-4780 [1998]) because the characteristics of the model are simple and intuitive. The unavailability or unreliability of system due to CCF is calculated using the following equation:

$$C=\beta\times P(\text{or } U),$$

where C is the probability of CCF in the redundant system, and β is CCF factor which is defined as the ratio of the dependent failures to the total failures.

RESULTS

The Interpreted Reliability Analysis Code Package named as KIRAP by Korean Atomic Energy Research Institute (KAERI) has been employed to generate the fault trees and minimal cut sets to perform our quantification processes [Han, 1999]. The fault tree based on the above-mentioned major internal events for the large release from the membrane-type LNG tank is shown in Fig. 3. From now on in details we will show the sub-fault trees connecting to the top events in the following subsections.

1. Gross Mechanical Failure

A gross mechanical loss of LNG tank is mainly attributed to the careless operators and the malfunctions of the process equipments when they are demanded to operate or while they are running. Due to the lack of plant-specific failure data, the failure probabilities presented here are evaluated mostly based upon generic data sources of the mechanical components associated with the tank operation. In addition, we have examined trouble memos sheet by sheet for acquiring plant-specific data as possible as we can. For examples, the

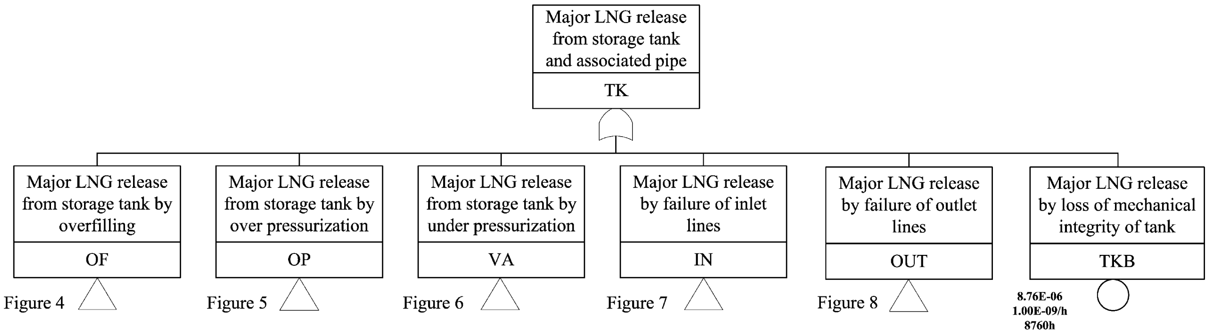


Fig. 3. The categories of major accident scenario for LNG tank.

trouble memos issued for the instrument air and boil-off-gas (BOG) compressors have been reviewed because the failures of these compressors are the main contributors to causing high pressure and vacuum phenomena within the tank.

Because of the huge bulk of database for the mechanical loss of the membrane-type LNG tank, we have only calculated the frequencies of occurrence in the gross mechanical failure which may lead to the release of a large amount of LNG or its vapor. The evaluated result shows this event frequency of 8.8×10^{-6}/year which means this event may occur once in more than 110,000 years.

2. Overfilling

Overfilling is the first scenario leading to a major release of LNG from tank. LNG storage tank is subject to high level when the tank is being filled and level indicator fails to indicate true level to operator or operator fails to correctly observe level indicator. At this time, if two redundant high level alarms fail to actuate or the operator fails to take correct action after recognizing the high level alarms, the level in the tank continuously increases until high level switch actuates to close inlet valve on unloading line. However, failure of interlock such as the high level switch fails to actuate or the inlet valve fails to close results in overfilling of LNG tank. Fig. 4 shows a fault tree for overfilling scenario. The evaluated result shows this event frequency of 1.2×10^{-5}/year.

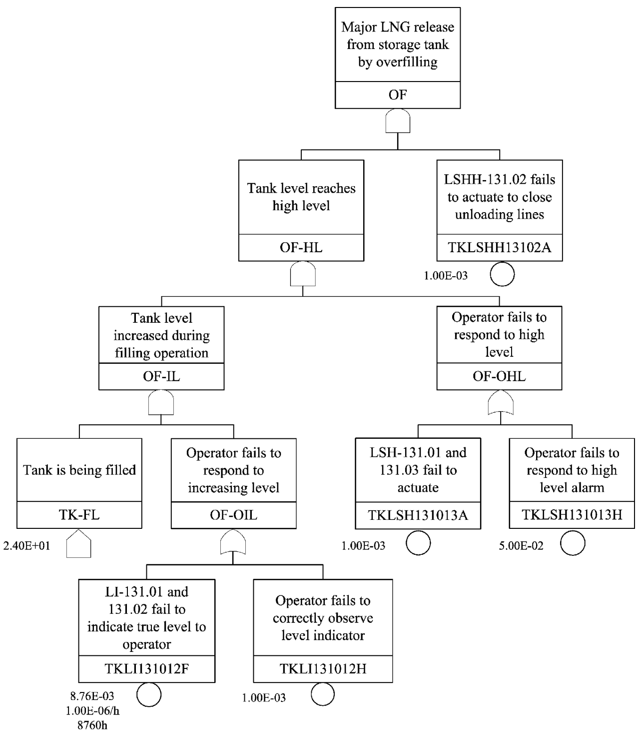


Fig. 4. Fault tree for overfilling from LNG tank.

3. Overpressurization

The second scenario is tank rupture by overpressure. Pressure rise in LNG tank can be occurred due to blockage of discharge line by valve failure, or sudden drop in barometric pressure, or rollover. At this time, if high pressure alarm fails to actuate or the operator fails to take correct action after recognizing the high pressure alarm, the pressure in the tank continuously increases. When this deviation occurs, the tank can be damaged if pressure control system on flare line and high high pressure switch fails to actuate, and pressure relief valves fails to open. Additionally failure of BOG (boil off gas) control, loss of instrument air, and loss of offsite power are considered as another causes for overpressure scenario. In such cases, LNG tank can be damaged if the incident is not restored within 10 hours and pressure relief system fails to actuate. Fig. 5 shows a fault tree for overpressure scenario. The evaluated result shows this event frequency of 6.5×10^{-7}/year.

4. Underpressurization

The third scenario is LNG tank damage by vacuum. LNG tank is subject to low pressure when pressure control system on flare line fails actuating due to controller malfunction or control valve failure, or barometric pressure increases abruptly. At this time, if gas make-up system fails to actuate or the operator fails to take correct action after recognizing the low pressure alarm, the pressure in the tank continuously decreases before vacuum breaker opens. However, failure of vacuum breaker to open on demand results in tank damage. Fig. 6 shows a fault tree for vacuum scenario. The evaluated result shows this event frequency of 2.9×10^{-10}/year.

5. Rupture of LNG Loading/Unloading Lines

Here, we consider the failures of two kinds of major LNG transmitting pipes mounted atop the LNG storage tank as the final scenarios to be assessed. One is for lodaing LNG to the tank and the other is for the discharge of LNG from the tank. The lines are not always under operation, hence there will be some zones where LNG is locked and isolated from the main stock in the tank. Once the lines are isolated, LNG will evaporate due to heat input from surroundings and result in high pressure in this section. This situation has been considered for a major concern of the presiding risk be-

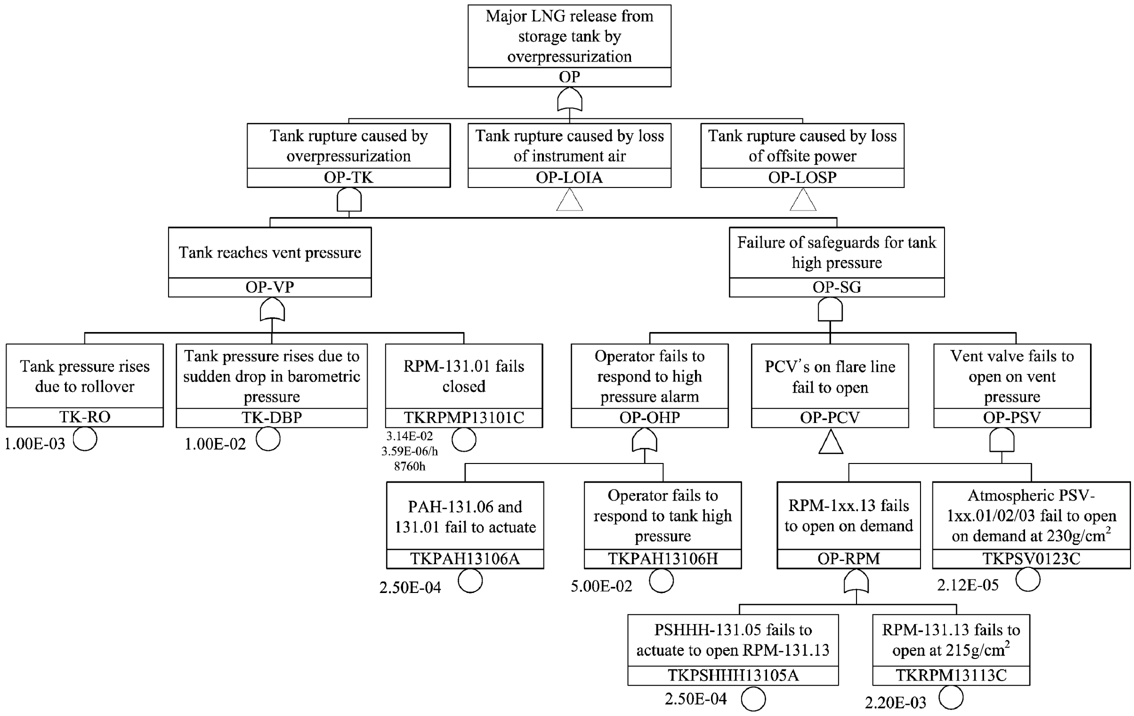


Fig. 5. Fault tree (portion) for overpressure in LNG tank.

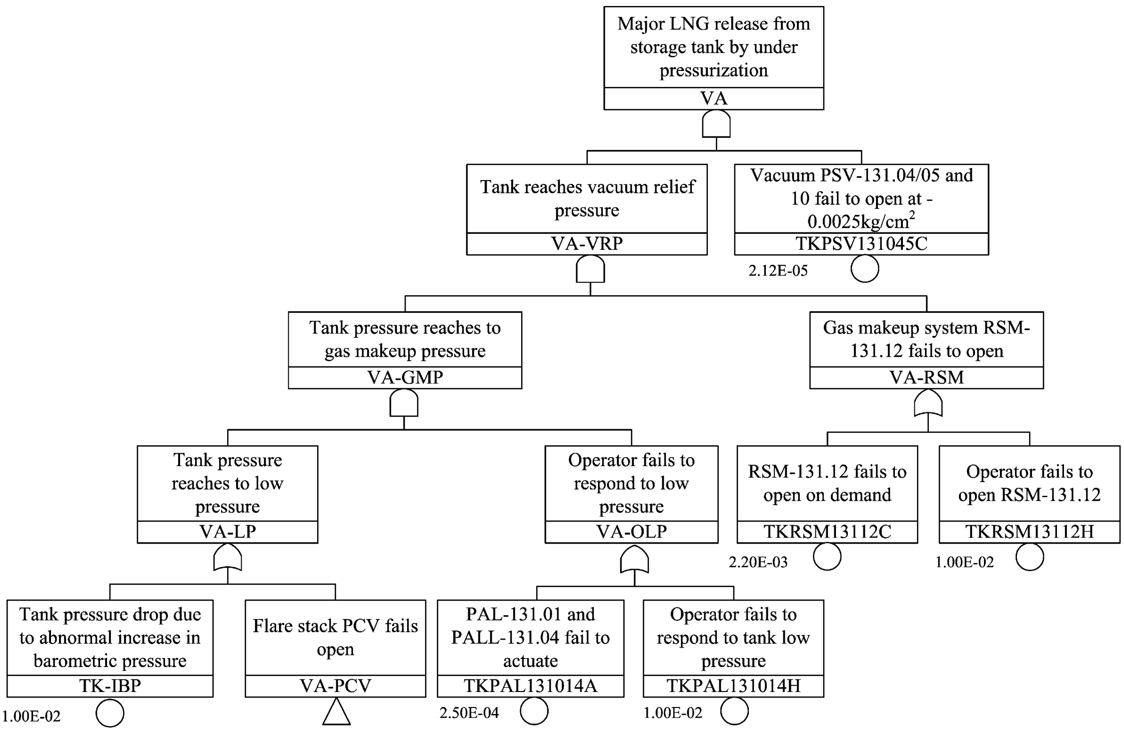


Fig. 6. Fault tree (portion) for vacuum in LNG tank.

cause it has a potential to make damages to the piping lines if the safety degassing valves at the sections fail to open at their setting points. That is, the piping systems could be damaged by the malfunction of pressure relief when a degassing function required for any isolated section on the line fails to actuate. The degassing valves are usually employed for this purpose and they are being driven on the pneumatic controller. Thus, the failure causes of degassing system could be attributed to the loss of instrument air or the blackout of offsite power. The evaluated result shows these events frequency of 2.6×10^{-6}/year for inlet line and 2.8×10^{-5}/year for outlet line as

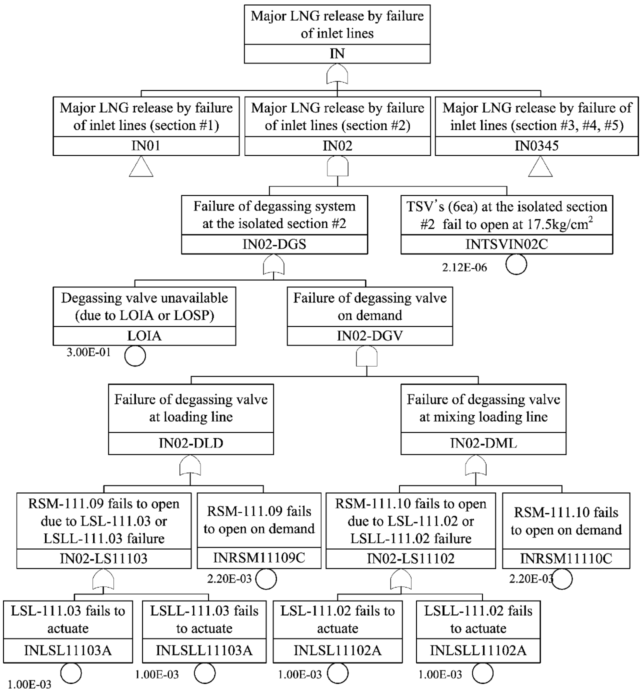


Fig. 7. Fault tree (portion) for failure of inlet lines.

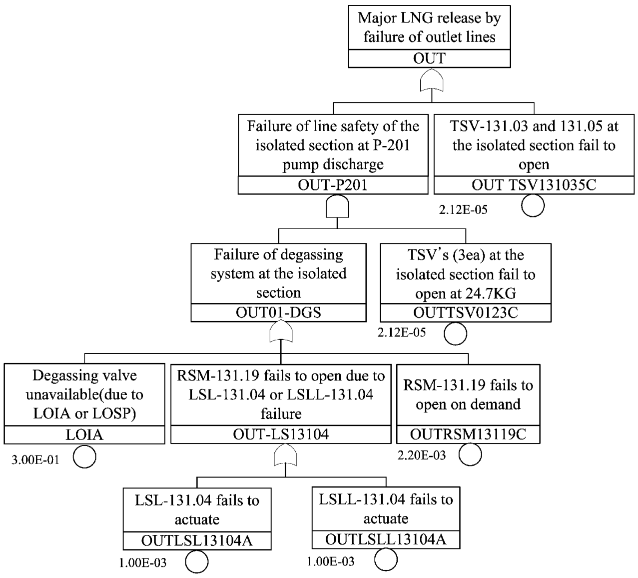


Fig. 8. Fault tree (portion) for failure of outlet lines.

shown in Fig. 7 and Fig. 8, respectively.

CONCLUSIONS

Based on the risk assessment of 100,000 m^3 membrane-type LNG storage tanks located in Korea, we have obtained the gross failure frequencies for six top events which might lead to a great deal of LNG release by virtue of the fault tree analysis. The calculated and specified frequency of each failure occurrence shown on the trees has been derived by including the potential probabilities of the failures to respond as required on demand, to run during mission time, unavailability due to the jobs of test and maintenance, common cause failures, and human error. From the current analysis, the membrane-type storage tank has an acceptable level of failure frequency with the magnitude of 8.8×10^{-6} in its gross mechanical failure. However, it has to be noted that the assessment has been conducted by using other data bases obtained from similar prosesses and facilities for the lack of the plant-specific data for membrane-type LNG storage tanks.

The result of this study will play an important role of a guideline toward a regulatory framework including any necessary standards and analytical tools acceptable in implementation. In the near future, to estabilish more concrete LNG storage safety, the following creative works should be executed,

(a) Structuring a probabilistic framework of the risk oriented accident analysis and its Monte Carlo simulations [Theofanous, 1996],
(b) Accident sequence development depending on the uncertainties and sensitivities,
(c) Consequence analysis to connect accident evolutions to resulting damages (to life and property).

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NOMENCLATURE

BOG : boil off gas
C : probability of CCF
CCF : common cause failure
DBP : decreased barometric pressure
DGV : degassing valve
DLD : degassing valve on loading line
DML : degassing valve on mixing loading line
FL : filling
GMP : gas makeup pressure
HL : high level
IBP : increased barometric pressure
IL : increased level
IN : inlet pipe line
IN01(02) : #1(#2) isolated section of inlet line
IN0345 : #3, #4, #5 isolated section of inlet line
LNG : liquefied natural gas
LP : low pressure
N : number of demands
OF : overfilling
OHP : operator failure to high pressure
OIL : operator failure to increased level
OLP : operator failure to low pressure
OP : overpressure
OUT : outlet pipe line
P : failure probability during mission time
RO : rollover
SG : safe guard

T : mission time [h]
TK : tank
U : failure probability to response
VA : vacuum
VP : vent pressure
VRP : vacuum relief pressure

Greek Letters

β : CCF factor
λ_d : failure probability per demand
λ_m : failure probability per hour [h^{-1}]

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