Risk Mitigation Effectiveness For LNG Terminal Station

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Abstract: Ensuring the safety of liquefied natural gas (LNG) receiving terminals, transportation routes, and storage facilities is paramount, especially with the increasing reliability of LNG for electricity generation nationwide. In order to mitigate potential incidents, it is critical to conduct thorough risk assessments that ensure the protection of these facilities throughout their entire lifecycle.
This paper aims to assess the effectiveness of mitigation measures implemented at LNG facilities, focusing on the approach of quantitative risk assessment (QRA). Intentional depressurization represents one such measure utilized to manage potential accidents involving LNG leakage from sendout pipes. Upon detecting a leak, intentional depressurization procedures are implemented to mitigate the situation.
This study investigates the effectiveness of intentionally decreasing pressure by simulating different situations and analyzing the results based on various targeted pressure values. The purpose of this investigation is to analyze the effectiveness of mitigation strategies in order to improve the safety and resilience of LNG facilities.

Keywords: Quantitative Risk Assessment, Liquefied Natural Gas, Mitigation Measure

1. INTRODUCTION

The National Atomic Research Institute (NARI) group has implemented the quantitative risk assessment (QRA) for liquefied natural gas (LNG) storage tank since 2019. LNG outward leakage from sendout pipe (pipe as below) is verified as the main contributor to risk. This can be explained by the design specification of the sendout pipe that considerable amount of LNG is pressurized in the pipe, whose whole length is fairly long relative to other piping in facilities. To depressurize the pipe as a mitigation measure to address its outward leakage, the LNG facilities used to isolate the pipe as well as deactivating the 2nd stage pump.

The base case of this study is that the occurrence of pipe rupture with no mitigation measures taken. The pressure of the LNG inside the pipe is 80 bar for the normal operating pressure of LNG facilities. This research based on a Pipe rupture sample to discuss the evolution of the accident scenario and the implementation of corresponding mitigation measures.

2. METHODS

The approach and the corresponding steps [1] recommended by UK HSE (Health and Safety Executive) to estimate the individual risk of certain postulated events are considered as follows: (1) Define categories of probability and frequency; (2) Define population groups; (3) Define event outcomes; (4) Estimate frequencies; (5) Estimate consequences; (6) Determine the impacts; (7) Estimate individual risk.

The flow chart in Figure 1 shows how to estimate the risk and mitigation effectiveness. QRA for the plant includes initiating events, frequency analysis, and consequence analysis. The initiating event is the failure of primary containment causing the leakage of chemicals, serious explosion and fire hazards [2~4].

Frequency analysis could list all possible events and assess each of the possible scenarios by event trees which consider all impacts and rescue actions as event tree nodes. Consequence analysis is implemented by SAFETI software of DNV GL and the results obtained include the leakage rate, vapor cloud dispersion footprint and the impact area of each event scenario. In general, LNG plants focus on accidents like ignition and fire, thus, the mitigative system is a general and essential design for LNG plants. In order to quantitate the LNG risk realistically, it is reasonable to include the fire mitigation system in QRA. INER has adopted the mitigation system such as pipe depressurization to reduce the risk in different pressure.

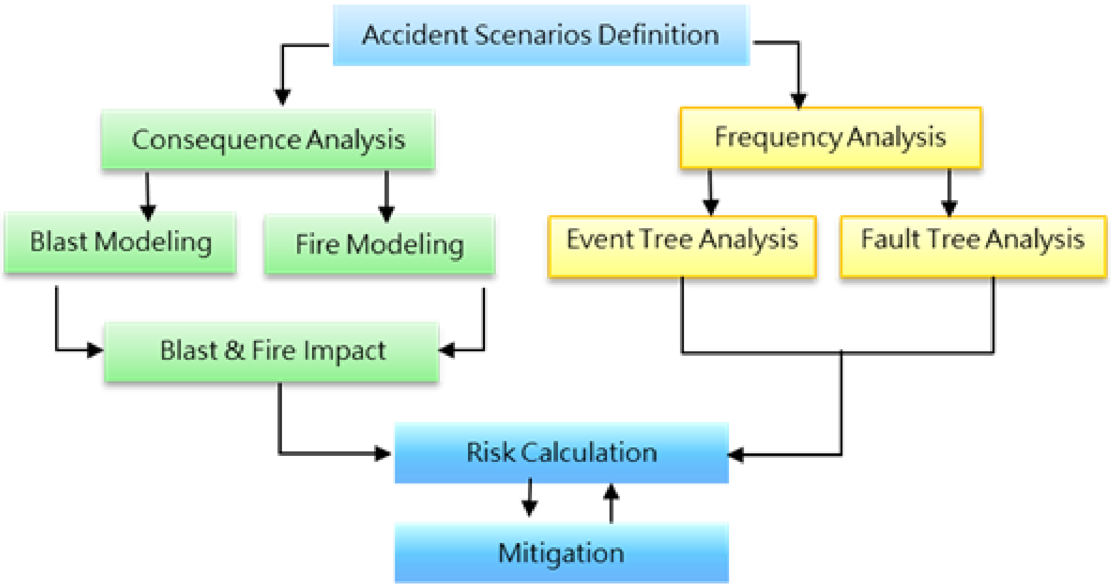

Figure 1. Process of Quantitative Risk Assessment

3. RISK ANALYSIS

Section 3.1 focuses on the estimation the risk of unmitigated case, while section 3.2 and 3.3 investigate the effectiveness of mitigation measures taken with varying pressure target. Four cases with mitigation measures were discussed in this study, whose target values are 60, 40, 20, and 4 bar individually.

3.1. Base Case (P=80 bar)

Parameter setting in case of 16” pipe rupture includes:

1. LNG material temperature of -158 °C, pressure of 80 bar and release inventory of1120 ton.
2. The lower wind speed (1.5 m/s) and atmospheric stability (Pasquill-Gifford Class F) are used when calculating the extent of each flammable vapor cloud consequence analysis.

This condition setting is more accurate representations of the actual conditions at the proposed site, with a worst-case wind speed.

The initiating event in this case is pipe rupture and the corresponding frequency is assumed to be 8.00E-06/yr. The event tree developed for the scenario is depicted in Figure 2.
The scenarios abovementioned and the frequency assumed are included in the event tree and categorized accordingly with the title NII and IG. The event tree includes headings of Not Immediate Ignition (NII) and Delayed Ignition (IG) that how accident scenarios could evolve such as flash fire (FF), vapor cloud explosion (VCE), and jet/pool fire (JPF). Upon its leakage, the immediate ignition probability of LNG is 0.3. For those who were ignited, the occurrences of jet fire (JF) or pool fire (PF) are expected following the ignition. The JF and PF are integrated and designated as JPF (SEQ#4) in Figure 2. On the other hand, for those unignited, upward dispersion is likely to be observed and liquefied gas evaporates afterwards, of which are referred as vapor cloud (cloud).

Different consequences are to be expected as cloud moves downwind provided with different conditions. The concentration of cloud and the relative size of space allowing it to flow through at the moment of coming after the sources of ignition are imperative for subsequent evolution of the scenarios. As indicated in Figure 2, supposing that cloud is ignited in narrow space and then VCE is to be observed as SEQ#3. In contrast, in case that cloud is ignited in open space, FF occurs, which is referred as SEQ#2. As stated earlier, concentration also matters that if the concentration of cloud is considerably diluted with air upon it hitting sources of ignition, such a scenario would be ended up with unignited leak since the concentration of cloud is below its flammable limit. Such a phenomenon is SEQ#1 in Figure 2.
Briefly, the initiating event is set as failure frequency of pipe rupture[5], and probability of NII and IG is refer from data of SAFETI[6].

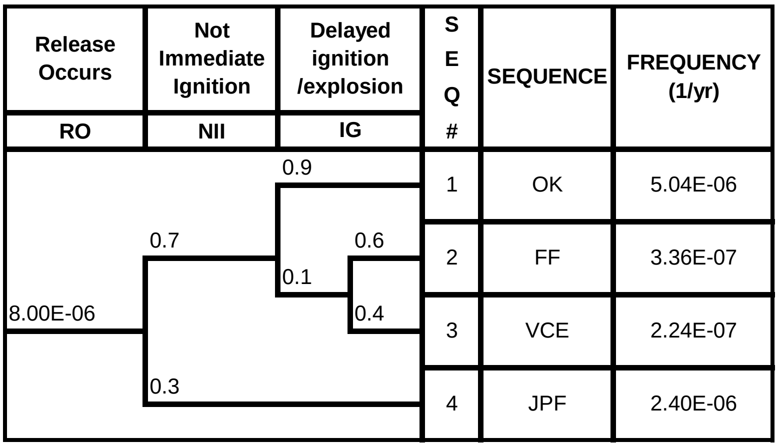

Figure 2. Event tree for pipe rupture

3.2. Consequence and Risk Analysis

Consequence Analysis

The primary focus of the consequence in this study is injury and fatalities. The criteria adopted for FF, PF JF and VCE are 40,000 ppm, 4 kW/ m^2 [7], 4 kW/ m^2 and 0.07 bar [8], respectively. The criteria basis is explained as follows.

The main constituent of LNG is methane, whose lower flammable limit (LFL) is 50,000 ppm or 5% vol. A conservative assumption is made that 40,000 ppm is set to be the LFL. Table 1 and Table 2 list the extent of damage versus heat flux level. “Glass breaks” is chosen as the criteria to result in fatalities from the perspectives of heat flux and overpressure.

Results for the base case (P=80 bar) are shown as follows. Maximum downwind distance of Cloud Footprint is 1,064 m and the same as Flash Fire (FF), while Concentration is 40,000 ppm (Figure 3). Maximum downwind distance of Pool Fire (PF) is 737 m, and Jet Fire (JF) is 742 m at thermal radiation equals to 4 kW/ m^2 in Figure 4. Maximum downwind distance of vapor cloud explosion (VCE) is 1,239 m under pressure of 0.07 bar (Figure 5).

Risk Analysis

Summarizing frequency and consequence of base case by SAFETI software, the maximum distance of the individual risk contour for 1.00E-06 per year and 1.00E-07 per year is about 1,000 m and 1,950 m shown as figure 6.

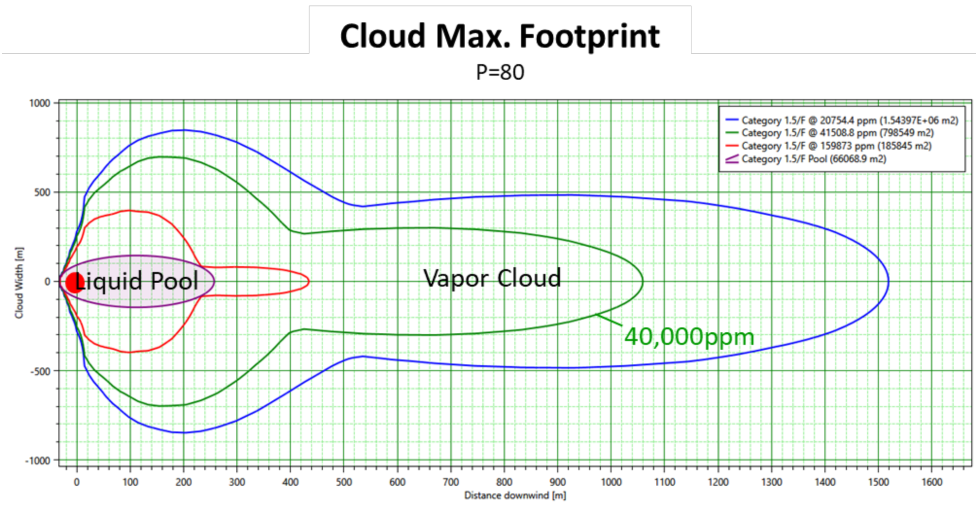

Figure 3. LNG cloud maximum footprint and liquid pool

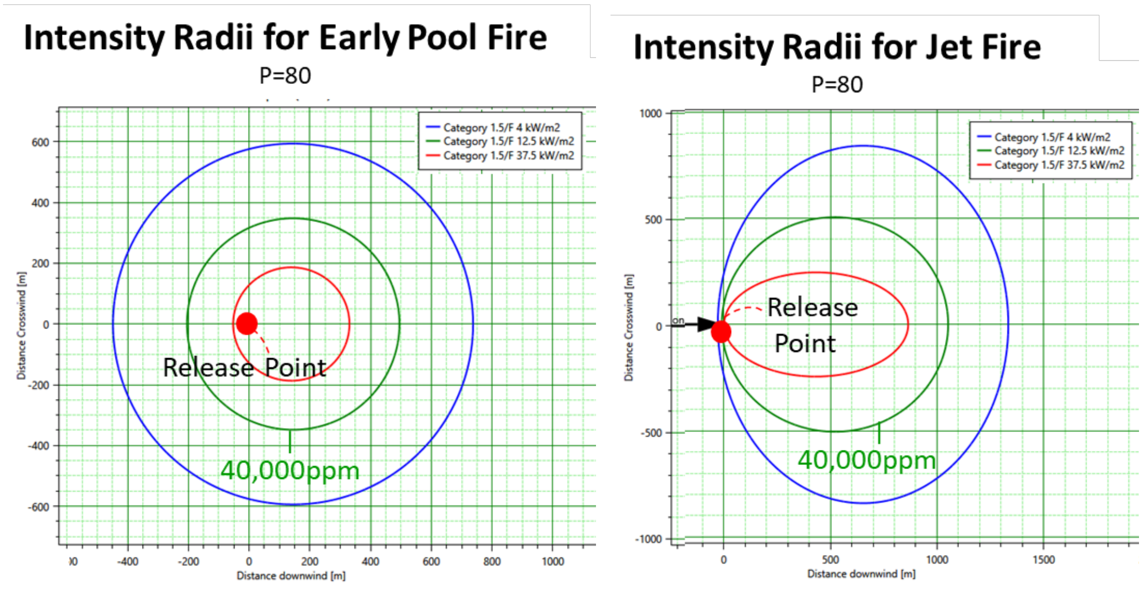

Figure 4. LNG maximum distance of pool fire (PF) and jet fire (JF)

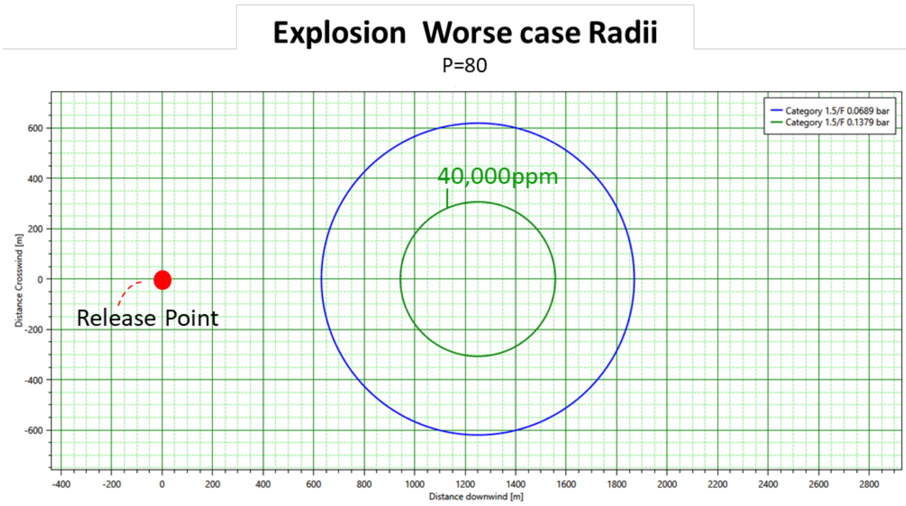

Figure 5. LNG maximum distance of vapor cloud explosion (VCE)

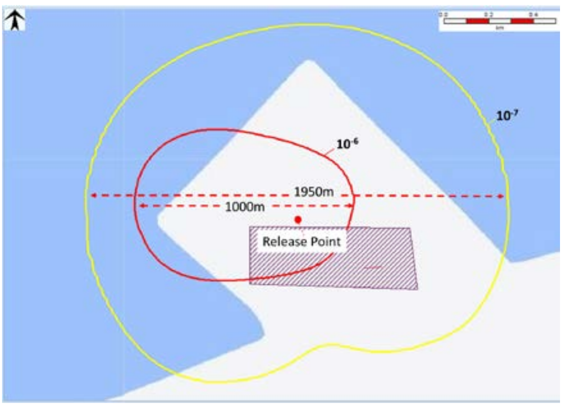

Figure 6. The individual risk contour for base case

3.3. Mitigation Case

This research adopted the mitigation system such as the emergency shutdown (ESD) system stopping 2nd stage pump to reduce the risk. The consequence and impact for four different depressurization cases are also discussed. On the other hand, the frequency in this research is fixed. There are one base case and four mitigation cases. They are P=80, 60, 40, 20, and 4 bar, respectively. Table 3 shows the input parameters according to different pressure, the peak flowrate and velocity would be updated.

In each mitigative case, the frequency of the occurrence of rupture, as well as the designated frequency for each sequence remain unchanged. The only parameter modified for each case is the targeted pressure value while conducting depressurization. Since the pipe is isolated from its ends upon the occurrence of the rupture, it is granted that all the LNG inside the pipe eventually leaks outward. Furthermore, as shown in Table 3, both the maximum mass flow rate and the velocity of the outward flow increase as the pressure of LNG inside the pipe increases.

Table 1. Fire modeling input parameters

	Base Case(1)	Case(2)	Case(3)	Case(4)	Case(5)
Pressure (Bar)	80	60	40	20	4
Peak flowrate [kg/s]	6,090	5,336	4,438	2,996	1,379
Velocity [m/s]	110	96	80	55	27
End time of release [s]	184	211	253	375	815

3.4. Results

Table 2 summarizes the impact distance downwind for SEQ#2~SEQ#4 with different depressurization target values. For the liquid pool, the maximum impact distance is observed while the pressure target is set to be 80 bar. Therefore, its impact distance downwind is also the largest one comparing to other cases.

Similarly, among all the cases, the JF flame length reaches a maximum when the target value of depressurization is set to be 80 bar, and its impact distance downwind is the largest.
Regarding vapor cloud, its impact distance in the case with pressure target of 20 bar is the largest one, and so are flash fire and vapor cloud explosion. However, the diameter of the VCE in the case with pressure target of 40 bar is the largest one. It is inferred that the size of the PF is strongly associated with the pressure inside the pipe. This conclusion also applies to jet fire.

For the dispersion of vapor cloud, both the two factors, the pressure inside the pipe and the duration of release, affect the analysis. The area covered is greater with a longer release duration. However, in the case that the differential pressure between the pressures inside the pipe and the atmosphere is small, the concentration of natural gas released in the vicinity of the rupture is relatively low and would be further diluted with air afterwards. Consequently, the impact distance downwind of vapor cloud could be interpreted as the products of the concentration of natural gas in the vicinity of the rupture and the release duration. Noted that the impact area of FF and VCE are positively correlated with the impact distance downwind of vapor cloud.

Once leakage is detected, to depressurize the pipe is the typical mitigation measure adopted by LNG facilities, considering the amount of LNG released would substantially decrease as pipe is depressurized. In addition, the smaller the pressure target, the less the natural gas is released. Intuitively speaking, that less nature gas is released leads to lower risk. However, the simulation findings in this study do not support this statement entirely. To depressurize the pipe indeed suppresses the PF and VF in the way that the impact area becomes smaller. In addition, the mitigation effectiveness is observed to be more significant as the pressure target value is smaller. However, this conclusion cannot be applied to the cases for FF and VCE. The reasons for this finding are explained as follows.

With regard to the cloud, its impact area is the largest one among all the cases. The case with pressure target of 20 bar not only has sufficient differential pressure to release adequate natural gas in the vicinity of rupture but also allows proper release duration, yielding a certain level of impact distance downwind of clouds. The FF and VCE are directly associated with the area covered by flammable vapor cloud, therefore, the consequence distance of FF and VCE is the largest one compared with other cases. Based on the findings above, it cannot be roughly concluded that the lower the depressurization target value the safer it is expected.

Figure 7 to Figure 9 compare the size and the footprint of vapor cloud between the case of pressure of 80 bar and the case depressurized to 4 bar. The findings are summarized as follows.

1. For JF, PF, FF and VCE, the impact area becomes smaller after depressurization, such that the pressure of the natural gas notably decreases from 80 bar to 4 bar.
2. After depressurization, the pressure of the nature gas in pipe is decreased to 4 bar, the height of the VC dispersion and the range it can reach are reduced. Although the distance it could reach is shorter, the dispersion range is larger. The backward dispersion is also observed against the wind direction.
3. The impact range of jet fire becomes smaller obviously when the depressurization target value is set to be 4 bar.
4. The impact range of VCE is smaller and the distance it could reach is longer in the case of 4 bar after depressurization, compared with the case of 80 bar.

Table 2. Maximum consequence distance of mitigation cases

	Base Case(1)	Case(2)	Case(3)	Case(4)	Case(5)
	P=80	P=60	P=40	P=20	P=4
Liquid pool (m)*	205	204	198	175	126
Distance downwind of PF under condition of 4 kw	737	719	686	603	451
Flame length of JF [m]	742	710	667	497	293
Distance downwind of JF under condition of 4 kw	1,334	1,276	1,197	880	498
Cloud Max Footprint (m) under condition of 40,000 ppm	1,064	1,076	1,112	1,266	1,005
Flash Fire (m) under condition of 40,000 ppm	1,064	1,076	1,112	1,266	1,005
Maximum distance of VCE [m]	1,869	1,834	1,932	2,478	2,177
Diameter of VCE under condition of 0.07 bar	1,239	1,248	1,345	1,216	514

*. The value underlined is the maximum one for each parameter. For example, 205 (m), for the liquid pool parameter.

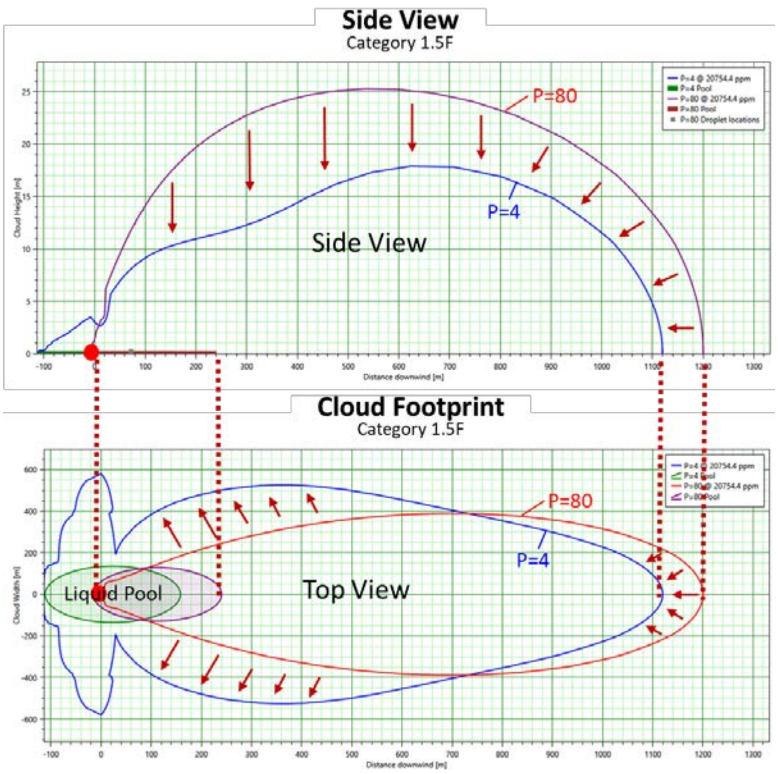

Figure 7. LNG cloud footprint and liquid pool (top view and side view)
for base case (P=80 bar) and case 5 (P=4 bar)

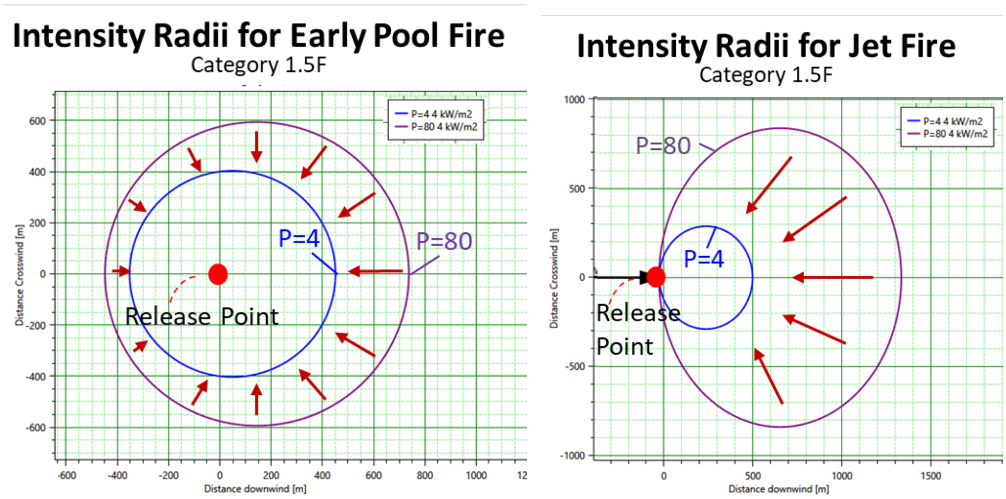

Figure 8. LNG Maximum distance of PF & JF for base case (P=80) and case 5 (P=4)

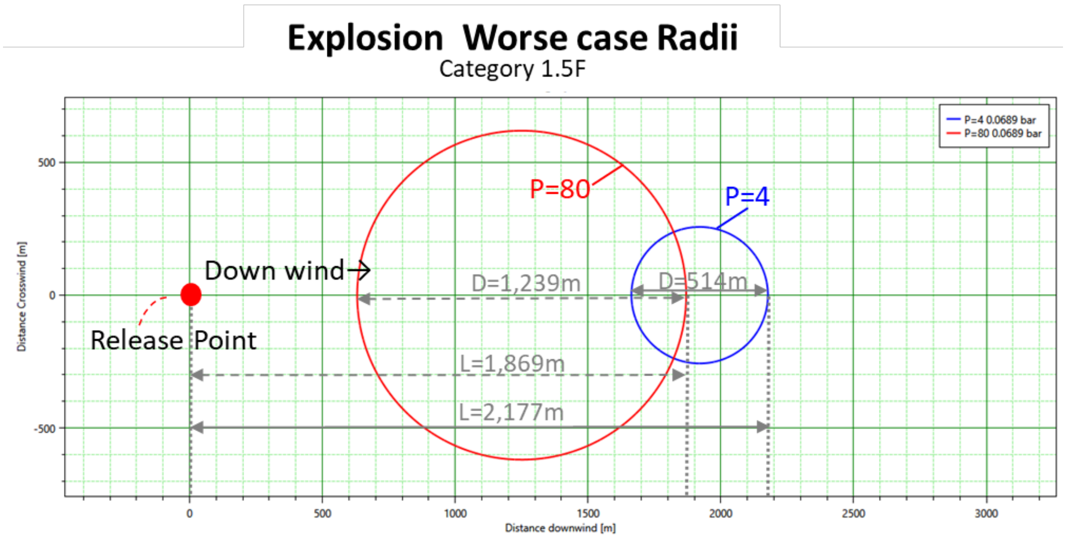

Figure 9. LNG maximum distance of vapor cloud explosion (VCE)
for base case (P=80 bar) and case 5 (P=4 bar)

Overall, the mitigative depressurization is favorable, as confirmed in Table 3, that both individual risk and total risk of the mitigative cases are smaller than the base case. Furthermore, as rupture is detected and the target value is set to be 4 bar after depressurization, the overall risk is observed to be the smallest among all cases.

Risk can be expressed to be the product of frequency and consequence. As illustrated in Figure 2, the frequency of JPF (SEQ#4) is the highest one, which is four times of the summation of FF (SEQ#2) and VCE (SEQ#3). This also explains why the overall risk changes in an obvious manner as the consequences of JPF change. In addition, while the depressurization target value is smaller, therefore, the corresponding risk induced by JPF and the overall risk become smaller.

Table 3. Individual risk

	Base Case(1)	Case(2)	Case(3)	Case(4)	Case(5)
	P=80	P=60	P=40	P=20	P=4
Distance for Individual risk of 10^{-6}/yr (m)	1,000	1,000	950	800	500
Distance for risk of 10^{-7}/yr (m)	1,950	1,900	1,900	1,700	1,200

4. CONCLUSION

To conclude, decreasing the target values would reduce the risk of PF and JF such that the impact distance becomes smaller. In addition, the impact distance under the condition of target pressure of 4 bar is the significantly smallest as illustrated in Figure 10.

However, this result cannot be applied to the cases for FF and VCE. As the target value decreases, the pressure inside the pipe becomes smaller accordingly and the time duration for vapor cloud release becomes longer. As the depressurization target values are smaller, the decrement for the impact distance of FF and VCE are not observed until the target pressure value is down to 4 bar, as shown in Figure 10. Although the distance dispersed for VCE is the longest while the target pressure is set to be 4 bar, its diameter is the smallest one. Therefore, the consequence of VCE is small comparing to other cases while the target pressure is set to be 4 bar. In addition, the pressure is significantly reduced from 80 bar to 4 bar, the impact distance could be limited to the shortest and best result.
This study on LNG terminal station safety is conducted from the PRA viewpoint, by introducing of consequence analysis (blast and fire modeling) and frequency analysis (event tree and fault tree technical element). Its quantification results in this work are expected to serve as a basis for the critical infrastructure (CI) resilience management.

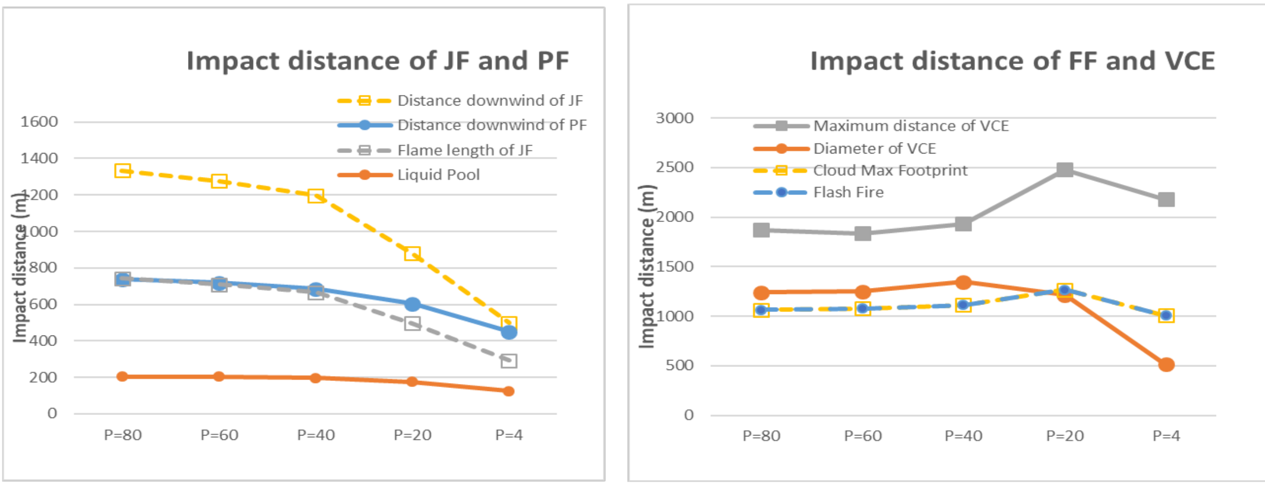

Figure 10. Impact distance of JF, PF, FF and, VCE

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