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As Low As Reasonably Practicable (ALARP) Demonstration: A Case Study on Firewater Curtain Application for Liquified Petroleum Gas(LPG) Sphere

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ABSTRACT

As Low As Reasonably Practicable (ALARP) demonstration is a continuous process in ensuring risks are managed in all phases of a project lifecycle (i.e. Assess to Operate phase). However, there is often a misconception that risks reported within the ALARP region are misinterpreted as representing acceptable risk levels or risk levels that are ALARP. It is important that risks reported within the ALARP region of any risk tolerability framework should only be deemed acceptable or tolerable once it has been demonstrated that all reasonably practicable risk reduction measures have been implemented. INPEX has developed a systematic process for ALARP demonstration and this paper discusses the ALARP demonstration for the installation of firewater curtain for the Liquefied Petroleum Gas (LPG) sphere at the LNG regasification terminal. Hazard assessment conducted in the design phase were reviewed based on operating experience and parameters and consequence assessment were re-modelled using Potential Hazard Analysis Software Tool (PHAST). Consequence assessment revealed that for release size 25mm and above, the gas cloud dispersion and radiation distance could exceed the plant distance separation distance of 65m. This research also points out the limitation of consequence modelling using PHAST. Installation of firewater curtain does not provide additional risk reduction outweighing the expenditure required for firewater curtain installation. Existing risk reduction strategy and measures put in place are enough to control the residual risk arising from LPG sphere.

Keywords: ALARP demonstration, firewater curtain, LPG, PHAST

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INTRODUCTION

The ALARP principle recognizes that no industrial activity can be entirely free from risk. The concept of ALARP is now generally adopted as good practice by progressive companies, within a number of potentially high-risk industries, across much of the world. In this respect, INPEX applies the ALARP process as an integral part of its Health, Safety and Environment (HSE) Risk Management (Yonezawa, 2018) and the decision-making process.

The ALARP concept is based on achieving a balance between the costs, difficulty, trouble and time of risk reduction measures and the perceived actual benefits. ALARP requires the identification of potential risk reduction measures and a determination of whether it is 'reasonably practicable' to apply them. A systematic process of analysis is required to demonstrate ALARP. The need to perform some type of ALARP analysis is determined from the assessment of risk. The residual and potential risk is assessed, using quantitative or qualitative methods and criteria, to be in one of three broad regions as shown in Figure 1.

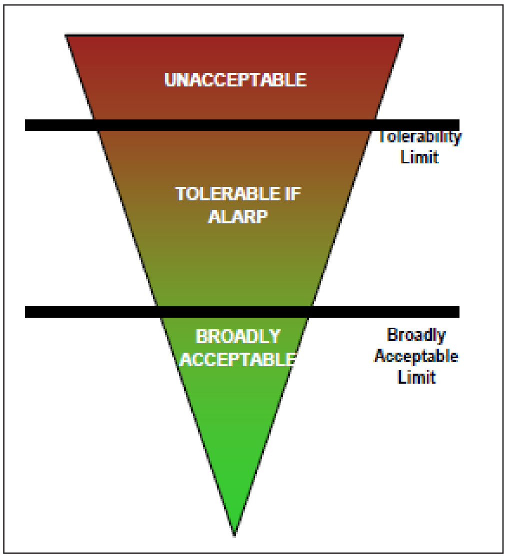

Figure 1. Risk tolerability framework (Yonezawa, 2012)

Risks assessed to be in the High (Unacceptable) band shall be given immediate attention (including, if necessary, suspension of activities or abandoning the associated design or development option) to minimize risk exposure such that the risk is reduced to the "Tolerable" band. Operation in the Intolerable region for a short duration may be considered only if there are no alternatives and approval is given by the INPEX Corporate HSE Committee (Yonezawa, 2018).

Risks assessed to be in the Medium (Tolerable) band shall be analyzed and reduced to levels that are demonstrably ALARP by the consideration of all possible risk reduction measures. Whereas, the Risks assessed to be in the Low (Broadly Acceptable) band do not require detailed working to demonstrate ALARP. The effort to analyze and reduce the risk further shall form part of a continuous improvement program. Where residual risks are determined to be Medium, an ALARP analysis will be required. The closer the risk is to the Intolerable zone the more detailed the ALARP analysis needs to be carried out.

The principles of ALARP apply to risks that are, first and foremost, assessed to fall within tolerable limits. This concept is illustrated in Figure 1. Generally, tolerability limits are typically defined in terms of Individual Risk Per Annum (IRPA). Individual Risk (IR) is calculated by identifying all sources of fatality risk to a given individual deriving from each source and summing these to give overall risk.

IRPA is a measure if the risk incurred by an individual working on an installation. Individual risk is a measure of the likelihood of fatality of an individual during one calendar year, accounting of the time that the individual spends on the installation. The risk to workforce and contractors shall be assessed based on IRPA to the most exposed worker group. Table 1 provides the INPEX workforce, IRPA criteria (Yonezawa, 2012).

Table 1
INPEX workforce, IRPA criteria

	INPEX workforce, IRPA	
Risk criteria	Tolerable limit	1E-03
	Broadly acceptable limit	1E-06

1E-03 refers to the tolerable limit in INPEX. IRPA number above this criterion is deemed to be unacceptable and requires a complete re-design or “no-go” operations. 1E-06 refers to a broadly acceptable limit, which indicates no additional risk reduction measures of ALARP demonstration is required if the IRPA number is lower than 1E-06. For the values in between the risk criteria`s INPEX requires a robust ALARP demonstration.

It is important to note even though ALARP principle promotes safety improvements, it introduces scoping and execution uncertainties with potential impacts on both cost and production especially in the Operate stage of the project lifecycle. Often there are arguments on ways to demonstrate ALARP (i.e. qualitative vs quantitative) and putting too much focus on QRA (Quantitative Risk Assessment) and CBA (Cost Benefit Assessment) may lead to “*Reverse ALARP*”. Hence, the successful application of ALARP principles is closely linked to fundamental factors of perception, leadership, ownership and communication. A recent study has shown difference aspects to constructing a legally sound demonstration of ALARP. Keith (2019), concluded that an alternative way to produce a legally sound demonstration of ALARP comprised a Well-Reasoned Argument (WRA) and explained how it should be structured. However, the intention of this research was not to explain the use of WRA, nevertheless to provide details of INPEX approach in ALARP demonstration for a specific case study.

Figure 2 provides the examples of ALARP demonstration topics in each phase of the project lifecycle. It is important to note that, ALARP demonstration does not stop at SUP (Start-up point) but it also continues throughout Operate stage to ensure risks are managed adequately. The intent of this research is to discuss as to how ALARP demonstration for firewater curtain for LPG sphere, is achieved and demonstrated in INPEX.

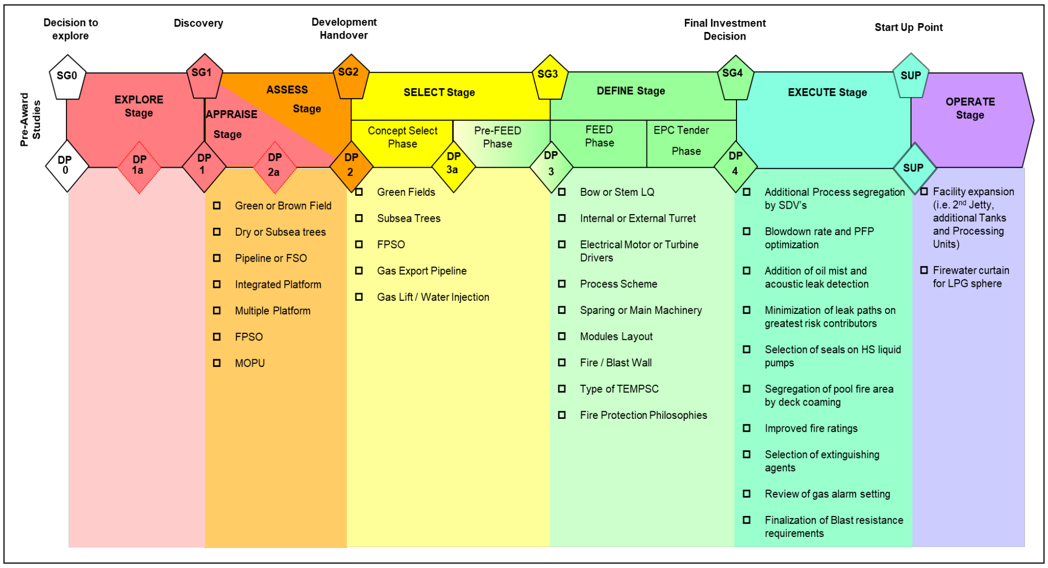

Figure 2. INPEX - ALARP demonstration examples for each phase of project lifecycle

RESEARCH BACKGROUND

The LNG regasification terminal in Japan is owned and operated by INPEX since the end of 2013. During EPC (Engineering, Procurement and Construction), as part of the FSA (Formal Safety Assessment), hazard assessment was conducted by the EPC contractor for LNG regasification terminal recommended the installation of the firewater curtain around the LPG spheres to reduce the escalation risk to the adjacent area, which is owned and operated by an independent power company.

Loss of Containment (LoC) of Hydrocarbon (HC) from LPG sphere is one of the MAE (Major Accident Event) identified for the LNG regasification terminal. A leak from the LPG sphere could cause a fire and explosion, and a threat to personnel and/or the loss of integrity of the facilities. The main safety issue is associated with the potential jet/pool fire and explosion by a LoC of HC which may cause fatal incidents and impact to the facilities. The risk ranking of LoC from LPG sphere is identified as "Tolerable if ALARP' and a specific Bow-Tie has been developed. The Bow-Tie contains associated Hardware, Human barriers and supporting HSE Management System (HSEMS). These barriers are further classified either as prevention or mitigation barriers and system put in place to ensure their effectiveness throughout LNG regasification terminal Operation phase.

In circa 2018, an independent power company commenced the preparation for construction of an independent power company on the land adjacent to the LNG regasification terminal. The closest hazardous installations are the LPG sphere tanks which are approximately 65 m from the site boundary.

An Operational Expenditure (OPEX) meeting was held by the LNG regasification terminal management and the committee approved the installation of the firewater curtain. In addition to the approval, an ALARP Demonstration for the installation of the firewater curtain was performed as part of HSEMS requirements. This paper provides details of the ALARP Demonstration studies that were carried out to fulfill the above requirements of the HSEMS.

METHODS

A step by step approach was undertaken to complete the ALARP demonstration. The methodology was a combination of a physical site survey for verification purposes combined with a desktop review and consequences analysis. The process undertaken were as follows but not limited to:

- Site survey including pictures with necessary details (e.g. actual physical distance from the LPG sphere to the fence and to the boundary of the independent power company plant and the current condition of the flange on the drain line of the LPG sphere tank)
- Review the Engineering Company's report and re-evaluation. This included a review of the Engineering Company's assumptions to ensure the current Operating Status of the LNG regasification terminal and revalidated the results and recommendations. Existing QRA results as part of Operations Safety Case, were also re-assessed.
- Carried out consequence modeling using PHAST on initial modelling cases utilizing the same assumption and criteria as the Engineering Company to replicate the results. However, the modeling was performed using the latest version of PHAST (Version 8.11).
- Additional cases were then completed to meet HSEMS requirements and a comparison between initial work done by the Engineering Company and the current analysis was carried out.
- Based on all inputs undertaken from Step 1 to Step 4, an ALARP Demonstration as per Oil and Gas UK (previously known as UKOOA) and INPEX Guideline (Yonezawa, 2012) was completed.

SITE VISIT RESULTS

Figure 3 shows the site layout including the location of the LPG sphere as well as the open space adjacent to the LNG regasification terminal. This is where the independent power company's power plant, construction will take place. The detailed analysis was also carried out during the site visit to identify all potential leak paths, as part of line-walk verification, as initially identified in Piping and Instrumentation Diagrams (P&IDs).

As shown in Figure 4 and Figure 5, the known leak paths are identified as flanges from LPG sphere. These flanges are noted to be non-leak flanges. Figure 4 shows the configuration of a non-leak flange. The height from the ground is approximately 2m.

In addition to the above, it is also noted that flange located at the downstream of XV (Actuated Valve), is also provided with a deflector as shown in Figure 5. The deflector covers the flange thereby deflecting any potential releases. Noted that, if ignited, the probabilities

Figure 3. INPEX LNG regasification terminal site layout

Figure 4. INPEX LNG regasification terminal - Non-leak flange

that a jet fire directly impinging the LPG sphere will be reduced and chances of a BLEVE (Boiling Liquid Expanding Vapor Explosion) is expected to reduce.

As it can be seen in Figure 6, the height of the bund wall around LPG sphere tank is noted to be 1.65 m. The boundary between LNG regasification terminal and adjacent independent power company's power plant which is yet to be built at the time of writing this research, are separated by embankment. The height of the embankment is approximately 4.7 m, as can be observed from Figure 7. Based on site survey measurements the distance between LPG sphere tank and the adjacent power plant (i.e. independent power company) is noted to be 65m.

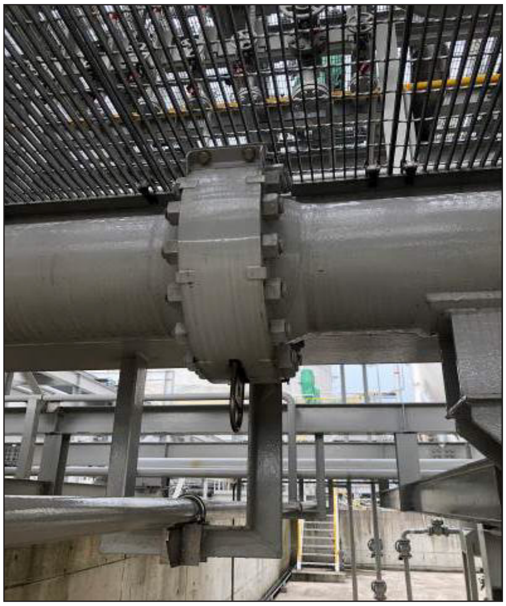

Figure 5. INPEX LNG regasification terminal Deflector on actuated valve

Figure 6. INPEX LNG regasification terminal - bund around LPG sphere

Figure 7. INPEX LNG regasification terminal - embankment between two plants

CONSEQUENCE ASSESSMENT

As described in the previous section, consequence assessment was performed using PHAST and previous studies conducted in the EPC phase were re-assessed based on current operating conditions of the LNG regasification terminal.

In this analysis, the previous FSA has been reviewed and concluded that some parameters and assumptions were not clearly indicated. The details are provided in Table 2. Note also that the previous assessment was conducted in 2010 utilized PHAST Version 6.54.

It is interesting to note that it is indeed Operators responsibility to ensure all FSA's performed during EPC phase are re-checked and re-validated like a 5 yearly HAZOP (Hazard and Operability) performed by a different Oil and Gas Operator.

It is very important for the Operator not to over-rely on consultants' output and it is the Operators responsibility to re-validate the results based on the latest current operating conditions. Therefore, it is important to note that in INPEX, a 5-yearly review of Safety Case(s) are performed to address the shortcomings of FSA(s) performed in the EPC phase.

Note that the consequence analysis was performed by PHAST 8.11 (latest version at the time of writing this research) and with up-to-date operating conditions representing the real operations. Table 2 and Table 3, provide the input parameter used by the EPC Contractor and INPEX respectively.

Table 2
EPC hazard assessment input parameters

Scenario	Flange Leak
PHAST	Ver. 6.54 (EPC) Ver. 8.11 (*INPEX*)
Criteria	
Dispersion	0.5 LFL* (1.0 mol %)
Explosion Pressure	9.8 kPa
Radiation	2.33 kW/m2
LPG Condition (Liquid)	
degC	40
MPaG	1.52
ton	1100
LPG Composition (mol %)	
Ethane	1.55
Propane	96.95
Butane	1.5
Information of Leak location	
Elevation (m)	2
Head (MPa)	0.055 (*Only in EPC input*)

Table 2 *(continue)*

Scenario	Flange Leak	
Distance to Boundary (m)	65	
Leak size (mm)	25	
Flange size	8B (*Note that in latest P&ID, 10B*)	
Leak Direction	Horizontal for dispersion / (*Selected most onerous direction. For Pool fire, vertical is more onerous*)	
Weather Conditions		
Wind velocity (m/s)	3.1	Wind velocity average at 10 m from June to August in 2006
Atmospheric stability	F*	-
Atmospheric Temperature (degC)	23.4	Average temperature from June to August in 2006
Humidity (%)	80	

**LFL – Lower Flammability Limit*
**F – Very stable - Pasquill Stability Class*

Table 3
INPEX input parameters

Scenario	Leak from the Flange at the bottom
PHAST	Ver. 8.11
LPG Condition (Liquid) ※Winter / Summer	
degC	7.0 / 27.5
MPaG	Bubble point
ton	913 / 975
LPG Composition (mol %)	
Ethane	1.55
Propane	96.95
Butane	1.5
Information of Leak location	
Elevation (m)	2
Distance to Boundary (m)	65
Leak size (mm)	5, 25, 50, 75, 100, 267.4
Flange size	(As-built P&ID, 10B = 267.4 mm)
Leak Direction	Horizontal Down on the ground
Weather Conditions	
Wind velocity (m/s)	2 / 5
Atmospheric stability	F / D*
Atmospheric Temperature (degC)	4.4 / 25.0 ※Winter / Summer

Table 3 *(continue)*

Scenario	Leak from the Flange at the bottom
Humidity (%)	87.8 / 85.4 ※Winter / Summer
Wind Direction	Prevailing Wind
Bund Information	
Bund height (m)	1.65
Bund area (m^2)	841
Bund failure modelling	Bund cannot fail (liquid overfill not possible)
Information on Terrain	
Surface roughness length (m)	0.5
Information on Tank ※Winter / Summer	
Tank head (m)	10.8 / 11.9

*D – Neutral - Pasquill Stability Class

CONSEQUENCE RESULTS

The consequence results are provided in Table 4. This includes both comparison of the consequence assessment performed during EPC phase as well as assessments carried out during ALARP demonstration study.

It can be observed that dispersion results are similar for the down on the ground release direction for both cases (i.e. EPC vs INPEX). On the other hand, the jet fire results are also reported to be similar for the horizontal release for both cases (i.e. EPC vs INPEX).

As for a pool fire, INPEX case gives more severe results. This can be explained by the fact that the flame Surface Emissive Power of LPG pool fire has been increased in PHAST between Version 6.54 (used by EPC Contractor) and the latest Version 8.11 used by INPEX.

Amongst other issues observed in EPC consequence assessments are as follows:

- Operating conditions considered are not realistic. (i.e. temperature and pressure do not reflect actual operating condition.)
- No bund has been considered.
- Only one leak size and one weather condition calculated.
- Uncertainties about PHAST parameters not communicated in the study (i.e. surface roughness)
- Uncertainties about actual release elevation considered (i.e. 1m or 2m)

The needs for updating the existing risk profile in operations Safety Case were assessed and the results from consequence analysis concluded that the QRA results was accepted "as is" as no major changes in risk profile were noted.

The Location Specific Individual Risk (LSIR) results are shown in Figure 8. As it can be seen, the LSIR at adjacent power plant is between 1E-04 and 1E-05 per year, which is within the in acceptable risk tolerability of INPEX.

Table 4
Consequence assessment results for 25mm hole size

Cases	Release direction	Flow rate (kg/s)	Dist. (m) to 50% LFL	Jet fire		Pool fire		Comment
				Flame length (m)	Radiation dist. (m) to 2.33 kW/m^2	Pool Diameter (m)	Radiation dist. (m) to 2.33 kW/m^2	-
EPC results	Most onerous between Horizontal and Down impinging on the ground	11.0	116.0	-	78.0	-	127.0	
INPEX	Horizontal	11.6	82.1	34.2	78.5	N/A	N/A	-
	Down on the ground	11.6	122.0	34.2	61.4	41.0	223.0	Results for late pool fire are reported (early pool fire gives less onerous results)
	Horizontal at 1m release elevation	11.6	114.0	34.2	78.3	N/A	N/A	-
	Down on the ground at elevation 1m	11.6	122.0	34.2	61.5	41.0	223.0	Results for late pool fire are reported (early pool fire gives less onerous results)

Figure 8. INPEX LNG regasification terminal - LSIR contours

ALARP DEMONSTRATION

Based on the above site survey, revalidated of existing hazard assessment study and consequence analysis, an ALARP demonstration was undertaken. The ALARP decision context was determined based on UKOOA (now known as Oil and Gas UK) and UK HSE (UKOOA,1999; UKHSE, 2014) as shown in Figure 9. The decision context type was determined to be "A" because the hazard is LPG, a well-known hazard, with no unusual characteristics.

However, due to some uncertainty which exists about the extent of potential damage from accidental releases that require risk analysis, therefore, a "lower A" decision context type was selected which involved consideration of the following means of calibration:

- Codes & standards
- Good practice
- Engineering judgment
- Risk based analysis (Consequence Analysis)

Based on the decision context type concluded for this study (i.e. lower A), 3 options were considered for ALARP demonstration. Table 5, Table 6 and Table 7 provide the advantages and disadvantages of these options. Table 8 provides the discussion summary, means of calibration and option selection.

Option 1 is the base case, which is the installation of firewater curtain with manual activation. Manual activation requires operators' action to activate the firewater system in the event of confirmed fire or gas detection. Manual activation was considered as it had the minimum impact to production as the LNG regasification terminal was currently under operation.

Option 2 is to install firewater curtain with automatic activation by fire and gas detection system. This option would require shutdown of LNG regasification terminal as modification to DCS (Distribution Control System) at CCR (Central Control Room). Noted that, this option was noted to be highest in terms of OPEX compared to Option 1 and Option 3. Option 3 is not to install firewater curtain and maintain/improve the current existing risk reduction measures and improve HSEMS requirements (e.g. people and system).

Table 5
Option 1 - Details

Advantage	Disadvantage
Lower cost than automatic activation Some benefit expected on LPG dilution and fire radiation Note 1 Note 1: PHAST cannot provide any reduction of benefit concerning gas dilution and fire radiation reduction. Expert judgement and assumptions with regards of reduction should be made to determine the benefits.	Manual activation requiring more time HSE risk during construction (SIMOPS, hot work)

Table 6
Option 2 – Details

Advantage	Disadvantage
Do not require human intervention to activate (fast activation – 2 min) Some benefit expected on gas dilution and fire radiation Note 1 Note 1: PHAST analysis cannot provide any reduction of benefit concerning gas dilution and fire radiation reduction. Expert judgement and assumptions with regards of reduction should be made to determine the benefits.	High OPEX and impact on production due to shutdown requirements. HSE risk during construction (SIMOPS, hot work)

Table 7
Option 3 – Details

Advantage	Disadvantage
No additional cost	Continuous risk management

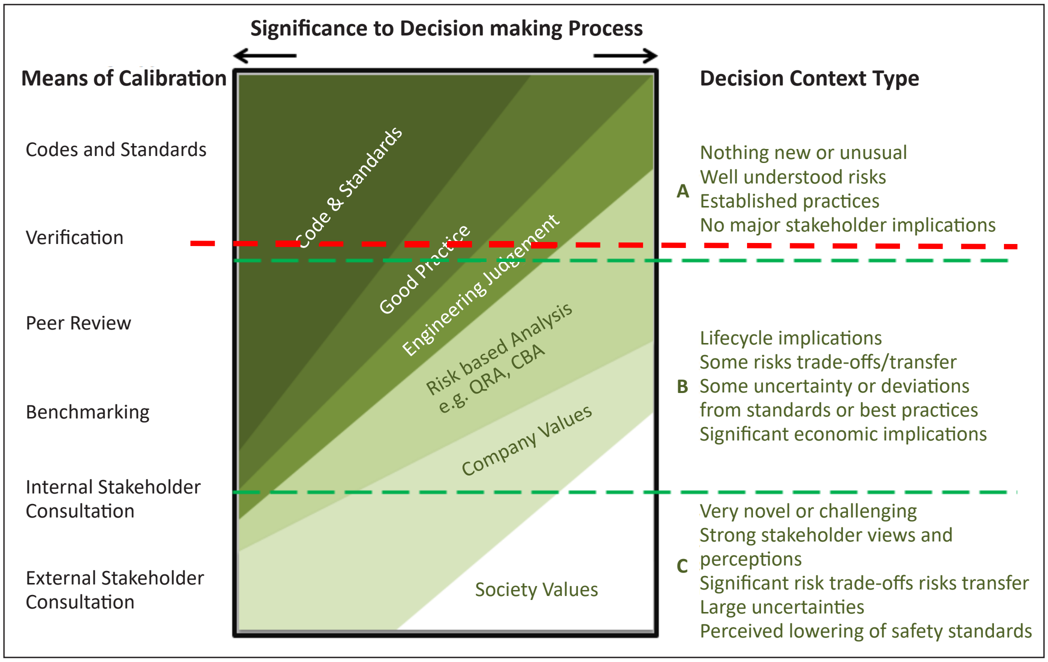

Figure 9. INPEX Corporate HSE - ALARP decision context

Table 8
Discussion summary for means of calibration and option selection

Means of Calibration	Explanation	Preferred Option
Codes & Standards	**<u>National Regulations</u>** Various national regulations were reviewed and no mandatory requirement (except as explained below) for firewater curtain by Japanese National Regulations were observed. Amongst national regulations which were studied in detail are as follows: • Gas Business Act (ガス事業法), e-GOV Japan. (1931) • Fire Service Act (消防法), e-GOV Japan. (2019a) • Regulation on the regulation of dangerous goods -危険物の規制に関する規則", e-GOV Japan. (2019b) • Act on the Prevention of Disaster in Petroleum Industrial Complexes and Other Petroleum Facilities (石油コンビナート等災害防止法), e-GOV Japan. (2017) • Disaster Assessment Guidelines for Petroleum Industrial Complexes and Other Petroleum Facilities (石油コンビナートの防災アセスメント指針), e-GOV Japan. (2001) Noted that, National Regulation #3 above, mentions that if separation distance is less than 50m the firewater curtain is required. As for this case study, this requirement will not be applicable as the separation distance is more than 65m.	3

Table 8 *(continue)*

Means of Calibration	Explanation	Preferred Option
	Company Standards Notwithstanding the above, INPEX internal Technical Specifications, INPEX/DEP/SAF/0180 (Hirayama, 2017), states that firewater curtain shall not be used for dilution purposes. **International Standards** On top of National Regulations and Company Standards, International Standards and recommended good practices such as NFPA, Oil and Gas UK, IOGP. were also reviewed. It was observed that no particular requirement addressed in these standards with regards to utilization of firewater curtain for LPG dilution. However, it is interesting to note that the application of firewater curtain is referenced as means to aid escape, evacuation and rescue from fire radiation. Based on the above analysis, it is concluded that the preferred option based on "*Codes and Standards*" is Option 3.	
Good Practice	A review of various industrial LPG related installations in Japan were conducted. The results are as follows: • 23 installations comprising LPG sphere tanks identified (e.g. LNG terminal and refineries) • Amongst these 23 installations, none seemed to have perimeter firewater curtain installed. However, it is important to note that this review was not meant to be an exhaustive review or site survey but the review was made by readily available public information. As such firewater curtain around LPG sphere may still exist but does not appear to be a common practice, in Japan. Based on the above analysis conducted on 23 installations in Japan, it is concluded that the preferred option based on "*Good Practice*", are Options 1, 2 or 3.	1, 2 or 3
Engineering Judgment	The FSA performed by EPC Contractor indicated that firewater curtain can reduce the downwind gas concentration of 50%-90% based on experiments conducted with LNG 30 years ago (Matsuda et al., 1988). However, LPG is heavy gas (LNG light gas), therefore this cannot be used as a direct application. Several other literature survey was carried out and the following was concluded: • Various papers for LNG application. The dilution effects provided by firewater curtain in case of LNG release are well documented • Research conducted by Matsuda et al. (1988), indicated some dilution effect for LPG. However, it should be noted that the research was based on small scale experiment (e.g. LPG leak flow rate of 0.06 kg/s of gas) and not a comparison to scenarios (i.e. large release size with higher release rate) considered in INPEX's consequence assessment. It is not evident if the same dilution effects can be obtained for larger releases. • Research conducted by Qi et al. (2016), indicates that dilution of gas cloud can be expected for heavy gas (i.e. CO_2). However, there are large uncertainties. Physical mechanism by which water curtains can dilute gas is noted as follows: ▫ Absorption by water - Not applicable to LPG as non-polar HC (e.g. not soluble in water)	1, 2 or 3

Table 8 *(continue)*

Means of Calibration	Explanation	Preferred Option
	- Air turbulence created at the proximity of the water spray enhancing mixing of the gas with air (e.g. applicable to LNG/ LPG) - "Barrier effect" created by the water curtain pushing the gas upward: not applicable for LPG as heavy gas (i.e. however applicable to LNG as light gas) Research conducted by Qi et al. (2016), also indicated the efficiency provided by firewater curtain to dilute gas is dependent on the followings: • Wind speed (e.g. less dilution for higher wind speed) • The ratio of HC leak rate to Water flow rate (e.g. dilution is more effective for small HC leak and high firewater application rate) • Other parameters (spray nozzle type, the distance between leak source and Water Curtain) In conclusion, even though some dilution effect can be expected, this cannot reasonably be quantified and it is expected to be significantly less efficient for LPG compared to LNG, hence it is concluded that the preferred options based on "Engineering Judgement" are Options 1, 2 or 3.	
Risk Based Analysis (Consequence Analysis)	As explained in previous sections, a detailed consequence analysis was carried out using the up-to-date operating parameters and the latest version of PHAST by INPEX. Amongst assumptions which were used for consequence modelling of LPG leak are as follows: • Use of realistic operating and weather conditions (winter and summer) • Range of leak sizes from small leak to full bore rupture • Modelling of Gas Cloud Dispersion, Jet Fire and Pool Fire • Use of latest PHAST Version 8.11 • Use of assumptions and parameters in line with INPEX Standards and Guidelines Noted also some of the existing barriers could not be taken credit in PHAST modelling. This is due to PHAST limitation as PHAST currently cannot predict the effect of bund wall for various consequences. Noted that the bund wall is 1.65 m high and embankment is 4.7 m high. These values are not taken into account, in PHAST modelling. Potential leak paths are identified as flanges located at the bottom of the LPG sphere (i.e. 2 inch, 3 inch and 10 inch). It is also important to note that biggest flange (i.e. 10 inch) within the bund of LPG bunded area are fully welded limiting leak source. Table 8a, 8b and 8c, provides the consequence results for gas cloud dispersion, jet fire radiation and pool fire radiation, respectively.	

Table 8a
Gas cloud dispersion results

Op. Cond.	Leak diam (mm)	Release direction	Flowrate (kg/s)	Gas dispersion			
				Distance (m) to LFL (2F)	**Distance (m) to LFL (5D)**	**Distance (m) to 1/2 LFL (2F)**	**Distance (m) to 1/2 LFL (5D)**
Winter	5	Horizontal	0.3	5.7	4.9	9.0	7.1
		Down on the ground	0.3	10.2	9.5	14.9	14.2

Table 8 *(continue)*

Means of Calibration	Explanation								Preferred Option
	Winter	25	Horizontal	7.4	30.3	24.9	**91.3**	59.3	3
			Down on the ground	7.4	54.6	33.0	**76.5**	45.8	
		50	Horizontal	29.6	**100.5**	**83.4**	**215.1**	**148.1**	
			Down on the ground	29.6	**104.0**	58.2	**138.5**	**87.8**	
		75	Horizontal	66.6	**165.3**	**147.5**	**340.5**	**230.0**	
			Down on the ground	66.6	**159.4**	**84.7**	**207.2**	**123.4**	
		100	Horizontal	118.4	**228.6**	**207.9**	**465.7**	**309.7**	
			Down on the ground	118.4	**214.9**	**109.1**	**274.8**	**156.7**	
		267.4	Horizontal	846.6	**607.9**	**583.6**	**1262.2**	**821.2**	
			Down on the ground	846.6	**617.4**	**266.2**	**780.7**	**369.1**	
	Summer	5	Horizontal	0.4	6.1	5.3	9.9	7.8	
			Down on the ground	0.4	14.2	13.2	20.3	18.7	
		25	Horizontal	9.7	36.9	28.3	**89.7**	**67.3**	
			Down on the ground	9.7	**80.7**	44.2	**109.1**	**68.3**	
		50	Horizontal	38.7	**95.6**	**86.3**	**217.8**	**181.0**	
			Down on the ground	38.7	**155.1**	**81.4**	**200.7**	**118.5**	
		75	Horizontal	87.0	**158.2**	**163.9**	**339.4**	**285.4**	
			Down on the ground	87.0	**233.9**	**116.6**	**297.8**	**165.5**	
		100	Horizontal	154.8	**218.1**	**238.1**	**454.8**	**387.8**	
			Down on the ground	154.8	**313.2**	**151.3**	**395.7**	**211.9**	
		267.4	Horizontal	1106.5	**575.4**	**695.1**	**1109.8**	**1046.9**	
			Down on the ground	1106.5	**875.7**	**389.4**	**1122.3**	**528.6**	

*LFL – Lower Flammability Limit
*1/2 LFL – 50% of Lower Flammability Limit
*F – Very stable - Pasquill Stability Class
*D – Very stable - Pasquill Stability Class

Distances highlighted in bold black fonts are those scenarios which exceed the plant separation distance of 65m.

Pertinent points from the above results are as follows;

- Winter Case:
  - In the most unfavourable condition (leak direction and 2F weather condition) leak with a flow rate in excess of 15 kg/s (typically 36 mm leak) has the potential to result in LFL reaching the site boundary.
  - Large flammable cloud (LFL > 100 m, with potential to reach the main facility) can be experienced for leak in excess of 30 kg/s (50 mm leak).
- Summer case shows a very large difference between horizontal and vertical downward release. Generally, results are more severe compared to winter because of increased pressure in the sphere and higher ambient temperature causing increased LPG flashing and LPG pool vaporization in case of the leak.

Table 8 *(continue)*

Means of Calibration	Explanation	Preferred Option
	• Time for the flammable gas cloud to reach the site boundary. Typically: □ 5 ~ 15 sec for horizontal release □ 20 ~ 60 sec for vertical downward release • Even assuming 50% dilution provided by Water Curtain (optimistic), large leaks will still have the potential to reach the adjacent facility. Table 8b and 8c provide the results for radiation distances results for jet fire and pool fire respectively.	

Table 8b
Jet fire radiation distance results

Op. Cond.	Leak diam (mm)	Release direction	Flowrate (kg/s)	Jet fire				
				Flame length (m)	Dist. (m) to 5.0 kW/m²	Dist. (m) to 6.3 kW/m²	Dist. (m) to 12.5 kW/m²	Dist. (m) to 37.5 kW/m²
Winter	5	Horizontal	0.3	8.6	13.9	13.1	11.2	8.5
		Down on the ground	0.3	7.6				
	25	Horizontal	7.4	34.5	61.2	58.0	50.1	40.6
		Down on the ground	7.4	30.8				
	50	Horizontal	29.6	62.5	**114.6**	**108.4**	**93.3**	**75.5**
		Down on the ground	29.6	55.9				
	75	Horizontal	66.6	**88.3**	**165.1**	**156.1**	**134.1**	**108.4**
		Down on the ground	66.6	**79.0**				
	100	Horizontal	118.4	**112.8**	**214.0**	**202.2**	**173.4**	**140.0**
		Down on the ground	118.4	**100.9**				
	267.4	Horizontal	846.6	**259.3**	**517.2**	**488.0**	**416.6**	**335.0**
		Down on the ground	846.6	**232.1**				
Summer	5	Horizontal	0.4	9.0	14.5	13.8	11.9	8.9
		Down on the ground	0.4	9.0				
	25	Horizontal	9.7	36.7	63.9	60.7	52.7	43.1
		Down on the ground	9.7	36.7				
	50	Horizontal	38.7	**66.7**	**119.3**	**113.2**	**98.0**	**80.2**
		Down on the ground	38.7	**66.7**				
	75	Horizontal	87.0	**94.5**	**171.7**	**162.8**	**140.8**	**115.0**
		Down on the ground	87.0	**94.5**				
	100	Horizontal	154.8	**120.8**	**222.2**	**210.5**	**181.9**	**148.5**
		Down on the ground	154.8	**120.8**				
	267.4	Horizontal	1106.5	**279.1**	**530.0**	**501.9**	**432.7**	**352.8**
		Down on the ground	1106.5	**279.1**				

Table 8 *(continue)*

Means of Calibration	Explanation	Preferred Option

Table 8c
Pool fire radiation distance results

Op. Cond.	Leak diam (mm)	Release direction	Flowrate (kg/s)	Pool Fire: Pool Diameter (m)	Pool Fire: Dist. (m) to 5.0 kW/m2	Pool Fire: Dist. (m) to 6.3 kW/m2	Pool Fire: Dist. (m) to 12.5 kW/m2	Pool Fire: Dist. (m) to 37.5 kW/m2
Winter	5	Horizontal	0.3					
		Down on the ground	0.3	8.8	45.0	40.9	30.6	14.8
	25	Horizontal	7.4					
		Down on the ground	7.4	32.7	**136.1**	**124.4**	**94.8**	58.8
	50	Horizontal	29.6					
		Down on the ground	29.6	32.7	**136.1**	**124.4**	**94.8**	58.8
	75	Horizontal	66.6					
		Down on the ground	66.6	32.7	**136.1**	**124.4**	**94.8**	58.8
	100	Horizontal	118.4					
		Down on the ground	118.4	32.7	**136.1**	**124.4**	**94.8**	58.8
	267.4	Horizontal	846.6					
		Down on the ground	846.6	32.7	**136.1**	**124.4**	**94.8**	58.8
Summer	5	Horizontal	0.4					
		Down on the ground	0.4	8.8	44.4	40.4	30.0	13.9
	25	Horizontal	9.7					
		Down on the ground	9.7	32.7	**133.2**	**121.9**	**93.6**	54.1
	50	Horizontal	38.7					
		Down on the ground	38.7	32.7	**133.2**	**121.9**	**93.6**	54.1
	75	Horizontal	87.0					
		Down on the ground	87.0	32.7	**133.2**	**121.9**	**93.6**	54.1
	100	Horizontal	154.8					
		Down on the ground	154.8	32.7	**133.2**	**121.9**	**93.6**	54.1
	267.4	Horizontal	1106.5					
		Down on the ground	1106.5	32.7	**133.2**	**121.9**	**93.6**	54.1

Distances highlighted in bold black fonts are those scenarios which exceed the plant separation distance of 65m.

As for benefit from the firewater curtain that can be expected to reduce radiation effects are as follows:

- Effective against radiation from pool fire, however the flame height for a full surface bund fire is expected to be more than typical firewater curtain height, therefore firewater curtain will not be fully effective.
- No significant benefit for reduction of effects from large jet fire (i.e. with a flame length extending beyond bund limit)
- No benefit for reduction of overpressure/radiation effects from potential BLEVE

Table 8 *(continue)*

Means of Calibration	Explanation	Preferred Option
	Therefore, it can be concluded that, though some dilution effect can be expected, this cannot reasonably be quantified, and it is expected to be significantly less efficient for larger release cases as can be seen in Table 8a and 8b respectively. As such, it is concluded that the preferred option based on "*Consequence Assessment*" is Option 3.	

It is important to note, Risk (R) is the outcome of Consequences (C) and Probability (P) (R = C x P). In this sense, the installation of a firewater Curtain may be effective in reducing the "*consequences*" (e.g. gas dispersion, radiation) and will need to be quantified or justified technically. As explained in this study, no large effectiveness in terms of "*fire radiation*" and dilution for "*gas dispersion*" can be found or justified to-date.

Hence, even if a QRA was performed, the results would be likely be the same unless various assumptions are taken into consideration. The assumptions are as follows but not limited to:

- Effectiveness of firewater curtain in dilution for LPG gas clouds especially for large release size
- Effectiveness of embankment between two plants
- Response time of firewater curtain activation
- Ignition probabilities
- Frequency of releases
- Success rate of firewater activations

This is also in agreement with the analysis by Keith (2019), which concludes that QRA, PRA (Predictive Risk Assessment) and RAMs (Risk Assessment Matrix) have been comprehensively debunked because they contain multiple errors and constitute a prediction, which has been shown to be little more than guesswork. Hence for these above very reasons, this study only focussed on the consequence analysis as part of the ALARP Demonstration.

JUSTIFICATION FOR OPTIONS CONSIDERED

In view of the various aspects which were considered and explained in the previous section, the installation of a firewater curtain at the perimeter of the LPG sphere was determined not to be necessary. The main arguments to support this recommendation are as follows:

- INPEX Technical Standards do not recommend the use of a firewater curtain for the dilution of LPG releases
- Based on the literature survey that was conducted, there are large uncertainties associated with the dilution effect. In any case, the benefit expected is low for large releases and has the potential to reach the adjacent site even if the firewater curtain was installed.

- Firewater curtain activation time would be more than the time for the gas cloud to reach the adjacent site.
- Benefits on fire radiation are also expected to be limited especially for large releases.

Hence the risk reduction which is provided by the installation of a firewater curtain cannot be justified.

CONCLUSION

Based on the ALARP demonstration performed in this case study the following can be concluded:

- It is important that each Operator take ownership of all FSAs conducted in the EPC phase and re-validate them as part of the Operations Safety Case re-validation exercise.
- All FSA's to be updated based on the latest operating conditions to ensure the realistic HSE Risks determination
- ALARP demonstration decision context to be correctly based on the each scenarios/ options should be considered
- QRA and CBA (Cost Benefit Analysis) are not the only ways to demonstrate ALARP.

It is important to note that the current HSE risk (MAE risk), which has already been identified for the, does not change. Hence the residual risk of the selected option (i.e. no firewater curtain) is as per existing risk ranking (i.e. no change in risk status). Furthermore, it is important to note that all HSE Risks (MAE and Top 10 HSE Risks) are currently being managed by using a centralized HSE Risk Management Software, which is continuously reviewed.

Additional recommendations have been made to further mitigate the risk with other means. Other risk reduction measures, on top of existing current measures which have been proposed, are listed as follows but not limited to:

- A Preventive Maintenance regime (e.g. increased maintenance/inspection on LPG critical systems)
- Emergency Preparedness – Communication line to be established and tested (upon completion of adjacent independent power company's power plant)
- Traffic Light System linked to the GPA (General Plant Alarm) to provide a means of an early warning to the adjacent independent power company's power plant.

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