Lessons learnt from completing formal safety assessments for FLNG facilities

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Introduction

Floating Liquefied Natural Gas (FLNG) projects and facilities present numerous challenges in adequately and comprehensively understanding, assessing and addressing the wide range of risks present. These include multiphase jet and spray fires, cryogenic releases, possibility of large deflagrations through to long escape paths, anoxia hazards, mooring and stability and carrier impacts.

Floating LNG facilities offer the opportunity of greatly expanding the field development possibilities, with the exclusion of long subsea pipelines and large onshore facilities. The facilities will be some of the largest vessels in the world and the largest offshore installations; however, they will still be greatly smaller than a comparative onshore plant. The reduction in size contributes to increase the risk level associated with many of the hazards presented by the production and liquefaction process, posing challenging (and new) issues to Risk Management.

As part of completing a number of Formal Safety Assessments (FSA) studies, including Fire Risk Assessment (FRA), Cryogenic Risk Assessment (CRA), Explosion Risk Assessment (ERA) and the Quantitive Risk Assessment (QRA) as well as inputting into the Health, Safety and Environment (HSE) design for these FLNG facilities, a number of lessons have been learnt. The main aspects of these lessons learnt relate to the two key differences of FLNG facilities compared to standard offshore jacket and FPSO facilities, these are the size of the facilities and the larger range of release types, including a greater number of 2-phase and vaporising cryogenic releases. The issues are discussed in the following sections for the QRA, FRA, CRA and ERA, which is where the key work was completed and the most lessons were learnt.

QRA

From the completion of Quantitative Risk Assessments for FLNG facilities, the following main lessons and areas of further study have been learnt:

- Adequately treating the applicability of existing leak frequency databases (particularly to cryogenic and 'new to offshore' equipment) and where further research and discussion is required;
- Methods to handle large scale events which can impact multiple areas/modules;
- The high level of uncertainty in the real manning and maintenance requirements for a new type of facility and the impact on the risks expected;
- The techniques to carry out more complex TR impairment calculations on large facilities with multiple TRs, including multiple escape routing calculations;
- How the conflict between the assessments for the facility design (estimating Design Accidental Loads, etc.) and accurately determining the risks to the individual impacts the studies; and
- How to adequately cover the other MAHs including ship collision, loss of containment from the hull, loss of mooring, helicopter impacts, etc. given the vessel size and layout.

For QRA, particularly facilities and those predominately working in the North Sea sector, the use of the HSE's hydrocarbon release database (HCRD) [HSE], is generally accepted as the best data source for leak frequencies for various equipment. The usage of this data has been extended to other areas, from onshore facilities through to areas with very different working environments and philosophies than the North Sea. The further extension of this to FLNG (most of which are currently envisioned to be located in areas other than the North Sea) and the various unusual (by offshore standards) equipment types that the process involves is seen as stretching the bounds of the applicability of the HCRD database. Nevertheless, as other sources of data are not available, it currently is the best fit available; however, further discussion of the applicability of the data to FLNG, and what measures (conservative or otherwise) should be included to make the usage of it acceptable. The primary questions are related to the applicability of the data to heat exchangers, piping, expanders, compressors and columns in near to or in cryogenic service. This can be shown in the scale between a more common Shell and Tube Heat Exchanger (S&T HE) and the Main Cryogenic Heat Exchanger (MCHE) used in the liquefaction process in Figure 1. The lessons learnt in the onshore LNG industry needs to be transferred, even where there are differences, to give a better idea of what is suitable and what is not as conservative as is believed. From our experience of completing these assessments, the impact of the changes in frequency for the main cryogenic equipment would have drastic effect on the FRA and ERA results for the main liquefaction and Heavy Hydrocarbon (HHC) fractionation areas/modules, and this is one area where both actual offshore experience and collective reasoning is required.

Figure 1 – Comparison in size and fittings of a MCHE (left) and S&T HE (right)

Most of the offshore QRA models developed within the industry (both by consultants and by operators) are based on the requirements outlined in the early 1990s to support safety case submissions. These models were generally developed for a generic platform facility, with processing modules, risers, accommodation and utility areas, generally separated from each other. The impact of one module to another, escalation of events, was reviewed as a separate outcome of the event tree, and from experience did not generally dictate any of the key risks, except where bordering the accommodation. The extension of these models to FPSOs in the 90's (particularly with the increase in the number of facilities in the late 90's) involved moving to a more 'spatial' approach to the events, with the possibility of one event impacting multiple modules/areas increasing as the number of barriers between modules was reduced. From experience, this was completed by putting areas into hypothetical areas/modules or through their combination into an effective 'super' area/module. This same process is further expanded on for FLNG facilities, but where the distances are greater again, as well as the size of the processing equipment, and the resulting events also growing. One of the key lessons learnt was how to accurately, and systematically, approach the events which cross area/module boundaries, with the implication of fatalities across these areas. The standard manner of approaching escalation as a barrier or 'pseudo' barrier approach had to be moved into a more spatial direction, with the implication of an event location and a receiving target requiring more detail. Within the changes this required, the extension of the key FSAs into a more spatial environment was required, and is discussed further in their own sections. Within the QRA modelling, this required better computation and inclusion of directionality, not only at a probability basis, but also as a change in the event basis, with bow/stern events resulting in much different interactions than port/stern events. Furthermore, the treatment of within and inter-module escalation required modifications to suit the larger nature of the facility. In general, this resulted in hybrid model, with numbers extracted from the spatial calculations and input into the module/area based QRA model. This gave acceptable results, but required a lot of handwork to integrate the results between the studies, and required considerable time to implement due to the number of design iterations. In future, a combined model is expected to be the most efficient and accurate method of integration, with the results in effect presented spatially, where the boundaries and modules are defined within that spatial context.

The manning requirements for FLNG vessels is currently estimated in much the same way as for other offshore facilities. Until a FLNG facility is operating, the accuracy of these manning estimates is unknown, particularly the time required in the liquefaction modules. Generally, from our experience, the meeting of risk criteria or reaching a tolerable As Low as Reasonably Practicable (ALARP) level has as much to do with the manning definition as it does to do with the actual location risks, with minimal manning required in the known high risk areas. Until an acceptable level of manning is established, the comparison of Location Specific Individual Risk (LSIR) values is seen as more valuable in determining the risk of a particular facility design, process or configuration.

One outcome from the completion of quantitative studies was the reduced importance of the Temporary Refuge (TR) impairment studies, due primarily to the much larger distances between TR and process, and the corresponding event size required. Additionally, due to the large sizes and the escape design, secondary TRs have been used on many designs. The predominate discussions around the TR was more in terms of the requirements for escape to them, and whether secondary TRs are necessary from a risk standpoint. Generally, the conservative viewpoint was that even if not required by the numbers, secondary TRs formed an inherently safer choice, particularly given the large distances of personnel travel required. This shows the requirement of a purely numeric approach to the risk discussion, with the consideration of other factors important in getting a 'good' design.

As for the discussion of the applicability of other databases for leak frequency, the impact and frequency of other MAHs, and where to draw this information from was a lesson learnt. Primarily this centred on the discussion of impacts to the hull and the internal Liquefied Natural Gas/Liquefied Petroleum Gas storage, both from ship collisions, and also topside events.

Although no significant loss of containment from a LNG carrier has occurred (CHECK), the consequences of such a loss is expected to be significant. Due to this, the accurate assessment of the possibility of loss of containment from the hull is needed. The level of impact that loss of containment requires, and the resulting consequences of it, requires further industry study and was only addressed in a cursory, yet conservative manner.

The occupational risks associated with working on a FLNG facility are generally taken to be similar to other offshore facilities (these were taken from [OGP, 2010]), with the discussion around the applicability of this not reaching a general consensus. It is assumed that the standard offshore procedures and practices being used. The main sources of fatalities from occupational work is swinging or dropped objects, falls from height and confined space entry, and these will equally apply for FLNG facilities. The major additional risk is due to the inclusion of cryogenic risks which is significantly different to other facilities, and the risks from offloading significantly different from oil offloading activities. Workers on LNG carriers are exposed to similar risks already, and the application of their occupational risk rates in combination with the general offshore process worker risks likely to give the best results. Unfortunately, detailed information for the risk onboard carriers is not widely distributed and therefore the accuracy of using general offshore occupational risk values is not known.

FRA

The completion of the Fire Risk Assessment as part of the FSA studies was an area where many iterations of both the design and the analysis methodology were carried out. From an initial starting point of conducting a firewall based exceedance curve approach, the final methodology resulted in the assessment of the risk in all spatial planes (3D risk integration), with further extension to cover the use of Computational Fluid Dynamics (CFD) consequences theorised. Along with this extension, many other areas were reviewed and lessons learnt from their appraisal. These include:

- The conflict between completing the assessment for interpretation by the QRA as well as the input into the structural and Passive Fire Protection (PFP) design;
- The optimal number of hole sizes, along with the impact of the choice of the representative size;
- The application of phenomenological modelling in a congested environment;
- When is a 2-phase release a jet, spray or liquid fire;
- The difficulty of CFD modelling (where undertaken); and
- The impact of fires onto escape routes and the assessment of multiple escape route impairment.

One of the primary lessons learnt for the FRA modelling (along with the other main Design Accidental Load (DAL) assessments for the ERA and CRA), was the conflict between outputs for integration into the QRA for determining the risk to individuals and the assessment for input into the barrier design as part of the DAL assessment. The conflict required the iteration of the methodologies for the FRA to output a satisfactory and robust for the DAL assessment, while still allowing risk integration into the overarching QRA model. For the FRA this primarily involved the extension of the modelling for the risk integration, with impacts from the riskiest modules dominating over larger areas, with the delineation of fire loads across decks and equipment which are dependent more on spatial results rather than results from within the area/module. However, as discussed previously, offshore QRA models tend to be area/module based, including the tool used for these projects, and therefore the reintegration of spatial results into the area/module delineation was the key aspect of the iteration of the methodologies and models. As such, the resulting methodology applied a best fit approach for each of the studies, with the DAL assessment being completed based on the output (spatial and distance based) and the risk to personnel being completed based on a different analysis technique (volumetric and distance based). However, there is some interaction between the two aspects, as the escalation and cross module impacts require elements of both. This was handled in a spatial manner; however further development into integrating the methodologies is expected to simplify the escalation assessment. This methodology is likely to require the moving to a spatial approach for the individual risk also, similar to onshore facilities, with elements of the existing approach adapted to suit.

As discussed above, the size of the FLNG facilities, and the multi-level nature of the modules requires a more spatial approach to the DAL estimation for PFP requirements. One of the main lessons learnt was the difficulty in using only exceedance curves for DAL estimation, with both combinative effect between modules and the size of the modules resulting in the need for an alternative approach for visualising and capturing the fire risk. Based on these requirements the fire risk was presented as a 3D contour map, solving both the spatial and combinative elements of the problems with the exceedance curve approach. An example of the output of this methodology is shown in Figure 2. Additionally this approach proved easier to both present and discuss with clients, extending its usefulness and aiding the design process. As with any approach there are limitations, particularly with graphical outputs, although they can be interpreted easily, they still require interaction with the design and full discussion to ensure they are both understood as intended.

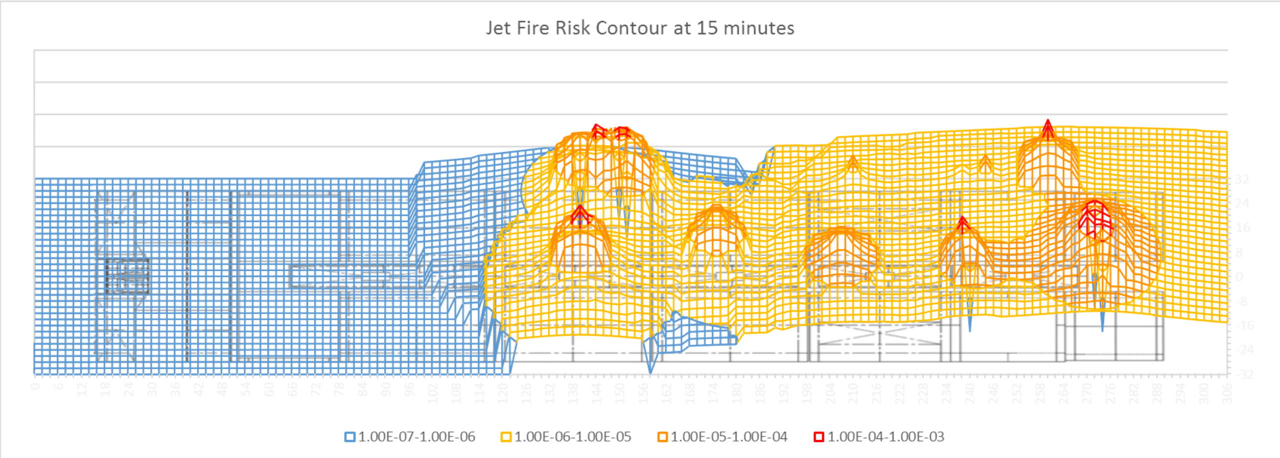

Figure 2 – Plot showing Jet Fire risk contours in X (bow to stern) and Y (port to starboard) in an elevation cut through for a FLNG facility

An important lesson learnt is about the representative hole sizes, after an initial analysis using a 3 hole size approach, part of the spatial approach to the FRA involved moving to a 5 hole size basis for all of the releases. This was completed as it was seen that the difference in the duration against jet fire distance between the hole sizes, particularly those around the 10-150mm range, had the potential to alter the results significantly. A key part of the issue was that the extent of PFP requirements normally countered with the duration of the protection required. If smaller hole sizes are used, the duration increased while the extents decreases, and vice versa with larger hole sizes. The use of 5 hole sizes reduced the latitude of change within each of the hole sizes, giving more accurate delineation to the duration/length conflict. However, the outcome of the effect of this change on the results showed that an alternate approach is warranted. The conservative approach is to use the lower end of the hole size band to determine the event duration and the upper end for the fire length, giving both aspects conservative results. Alternatively, an iterative approach that gives the longest fire length at a selected duration (5, 10, 15, etc. minutes) may be used, at the expense of complexity and computing requirements.

One of the main difficulties in completing the FRA was determining both the discharge (near-field) properties of a number of the events, particularly in the near cryogenic region, and deciding the cut offs between liquid, spray and gaseous releases. The flashing percentage for the majority of the releases results in a large percentage of spray releases which we classed as similar in consequence to gaseous jet releases. Further study is likely warranted into what the consequences of the spray releases, and what both ablative effects the fire has, and more generally the comparison of the impact relative to a jet fire. Additionally, consensus on the point when the spray releases become liquid was difficult, with the impact of the point chosen primarily affecting the design for Pool fire in the main liquefaction modules.

Due to the large nature of FLNG facilities, the escape design is quite different once personnel have escaped from the initial module. From the work completed, the risk of an event impacting all of the major primary escape routes (both process and cargo decks, on the port and starboard side) was low, with directionality, fire size and the actual impact of the congested modules requiring very large events to result in impairment. The primary assumptions centred on the ability for the events to impact both decks at once, or whether a certain duration of event is required until there is impact across both decks. This also formed part of the discussion of what impacts the smoke generated during the large release events would have across the decks, with the heat gradient generated potentially resulting in the drawing in off the smoke into the cargo deck. Based on this, the determination of the actual probability of having all escape routes impaired was difficult, which formed part of the difficulty in the discussions for the requirements for a secondary TR, as well as the fatality probabilities.

The use of phenomenological modelling (for example through the simulation in DNV PHAST) in completing the FRA was taken due to constraints in time and the availability of key input information required for CFD modelling. However, as part of the modelling completed for the ERA, the difficulty in using CFD to represent the variations in release type and location for the FRA would have required a greater number of cases and simulations than other facilities. As such, the differences or applicability of either type of modelling was not established. In general, it was expected that the conservative usage of phenomenological modelling was acceptable in determining fire lengths, however the actual heat and smoke impact calculated by CFD would have been useful, particularly for the impact to escape routes and the TR. It would be proposed that a combinative approach be used in future for Front End Engineering Design studies, with the factoring of the phenomenological results taken by a simplified set of CFD simulations.

The DAL assessment was further complicated by the size of the structures of the modules, with the failure of multiple elements possibly resulting in the failure of the module. The importance of the completion of both the structural design and the redundancy assessment was shown by the difficulty in determining the entire module failure rate without this information. Due to the lack of the information, the results were only used to determine the single point failure rate, which is insufficient for the final DALs. As such, giving final conclusions and recommendations for PFP was difficult, and further interpretation at a later stage was required.

CRA

The completion of the CRA modelling required a robust discussion of both the requirements for the design and the impact to personnel (particularly due to the high probability of a non-ignited release). The lack of standardised assumptions and methodologies for the assessment of cryogenic risk in the offshore environment also results in the requirement for further discussion and iteration. Out of this, a number of key elements and lessons learnt were formed, including:

- The impact of cryogenic releases on personnel and the probability of fatalities;
- When a 2-phase release results in a vapour, spray or liquid discharge;
- The requirements for the design against the cryogenic releases; and
- The optimum number of representative hole sizes, along with the impact of the choice of the representative size.

One of the main inputs into the overall risk assessment from the CRA is the direct impact on personnel. The criteria for how fire, explosion and toxic events impact on personnel is fairly well established. However, for the cryogenic impact, the impact on personnel, particularly for liquid spills, was an interpretative point of the methodology. Due to the high frequency of these events, a final methodology was established based on a temperature criteria, applied both for liquid and spray events. For vapour releases, the temperature criteria resulted was generally within the anoxic contours. Additionally, the integration of the results into the QRA model was initially crude as simple fatality factor on unignited releases, with further work to integrate cryogenic fatalities directly into the model (as a separate contribution) was made to give a better breakdown between the toxic, anoxic and cryogenic effects.

Particular effort was made to integrate the results of the CRA with the design requirements for the project, with much discussion centred on the level and detail of the outputs. For the liquid spills, the spill inventory, rate and the time varying flowrates of the cryogenic liquid were the prime outputs, with these being used in the drainage design for the modules with cryogenic materials. The time varying release details were in particular useful to determine the details of the overboard containment and release mechanisms for the facility. This was viewed closely due to the many details of the drainage design, and the requirements for the suitability of the release overboard during offloading operations. For the spray releases, a similar iterative approach as for the FRA was used, as the initial spray distance exceedance curves and module/area outputs were not seen as suitably cognisant of the spatial and combinative issues. The final methodology to be designed based on the lessons learnt used the same basis as the 3D risk integrated approach used in the FRA. The prime consequence output used was based on the liquid within the spray, as this was seen as the mechanism for the cryogenic cooling rather than the vapour temperature. For the vapour releases, thermal calculations were carried out to determine the rate and duration of cooling required to reach a temperature where embrittlement may occur. Based on this an approximate 20 minute duration of vapour contact was used as the cut off for embrittlement, which resulted in few events of concern.

The calculation of discharge properties for cryogenic liquid and close to cryogenic 2-phase and vapour releases has been studied in some detail in recent years, primarily for single component materials important to the LNG process but also for some multi component mixtures. This improvement in the understanding of the discharge from 2-phase sources has helped to give a good basis for the discharge results used in CRA. However, as for the FRA, the cut-offs between what is considered a liquid, spray and gaseous release was critical in the definition of the consequences, with each having very different effects, ranges and duration requirements, even more so than the FRA. Additionally, the calculation of multi-phase and multi-component releases still has much future development, with the problems associated with these releases requiring simplifications into single component and less detailed but more robust calculations.

Similar to the requirements for the FRA, the choice of the number of hole sizes and the representative size used within each range in the CRA had a significant impact on the final results of the CRA, with the extent and the frequency of the DAL loads determined in some measure by these choices. This was somewhat simplified by the less onerous impact on the duration requirements for spray releases, with any impact taken as requiring protection. As such, these could be treated conservatively by using representative sizes on the large end of the size range. For the liquid releases, a similar trend was seen, with some changes in the total volume flow with changing the representative size, but where the maximum flow dominated the consequences of interest. The requirements of the vapour releases however showed an opposite trend, with the duration being critical to reaching the consequences of interest, and where the smaller representative hole size would see worse consequences. The result of these requirements is to systematically weight up the different outputs required and choose representative releases sizes which give good results for the majority of the failure cases. Alternatively, a more detailed discharge analysis can be completed with the analysis completed for multiple sizes for each hole size range, giving results tailored to the requirements of each failure case and output required.

ERA

One of the more comprehensive and time consuming FSAs for al facilities is generally the ERA if competed based on a CFD probabilistic methodology. Due to the size and variations in the gas processing streams for FLNG, as well as the lack of industry experience, this was a complicated part of the works undertaken. Additionally the majority of the assumptions made are difficult to check, verify and review until more FLNG developments are further progressed and built. The main difficulties in the works carried out included the following:

- Determining the level of congestion in the as-built modules, particularly the liquefaction modules;

- The effect of gas dispersion and explosions on adjacent and other modules;
- What the best design guidelines are for explosion design in terms of module siting, safety gaps and Temporary Refuge/Living Quarters location;
- The ventilation levels in modules furthest from the bow and the cargo deck;
- The effect on the gas dispersion of the openings in the process deck and around the edge of the process deck on the cargo deck; and
- Integration of the DAL assessment with the requirements of the overall QRA.

One of the key inputs into the CFD explosion simulations is the level of congestion present within the modules. Generally, for other facility types this is completed by using existing knowledge of the as built or the final 3D models, and has been built based on experience over many projects and facilities. This experience is not available for FLNG, and as such, alternative measures have to be taken to build up the expectations for the congestion. These include estimates based on other facility types for common equipment, estimates of piping weights, overall deck requirements, etc. The main difficulty with all these approaches is there is no consensus or experience to check the results against, and therefore the correct approach would be to carry out sensitivity studies on the impact of the analysis, however for a large CFD analysis this is both costly and time consuming. Additionally, the impacts of increasing or decreasing the congestion levels are well known from other studies, with the main difficulty being in the ability to design the facility to the more conservative assumptions. A middle point of using the current models as a basis with the growth factors normally seen between design and construction used for the DAL outputs and a more conservative assumption for the individual risk quantification was seen as an acceptable compromise.

One of the harder aspects of completing the study and key to the methodology used is the correct representation of all the leak sources and the correct inclusion of across module releases and explosion consequences. This issue is generally seen for all FPSO type facilities, however the scale and number of modules for FLNG makes the issue more dramatic. The principle part of this is the correct selection and separation of the different leak types. The main method used was to separate by temperature and molecular weight, and then release location. This approach was seen as the one that covered the majority of the release consequences, particularly the differences in the dispersion behaviour. The differences in buoyancy between the release types was shown in the resulting CFD dispersion simulations as the main differential between the releases. Apart from the buoyancy, most of the releases showed similar behaviour, with the interaction of the ventilation and the geometry being driven more by the average air velocity than other factors, showing a more wind driven mechanism than discharge based. For the explosion consequences, the explosion pressures went across all of the adjacent modules, with the reduction being approximately 30% for the DAL sized explosions. To ensure that the cumulative explosion frequency was captured, a fairly large area of the facility had to be assessed in the simulations; however, the results showed that the reduction factor was fairly standard between the modules and more dependent on cloud size. The final summation of these effects required more work than standard jacket facilities, and the cumulative effect should be taken into account when determining the methodology for the study.

The input of the explosion analysis on the design in terms of reducing the blast pressures and the required structural design was made difficult due to the overall lack of experience with the facilities. This therefore required the extrapolation of the currently held knowledge onto issues for the plant layout. However, due to the size of the modules, and the possibility for large releases and hence explosive clouds showed some previously held assumptions to not fully translate to the FLNG facilities. One of the prime examples of this was the discussions around the requirements, location and size of the safety gaps between modules. Based on previous experience, gaps between areas/modules generally resulted in the reducing of the explosions crossing between areas, reducing the final explosion pressure. However, due to the large size of the modules (20 000 m3) the impact of the safety gaps is minimised, and progressively larger gaps are required to reduce the explosion effects. Ideally, a flame speed (or other measure) to gap size requirement linkage needs to be established to give optimal recommendations for the facility layout. The main recommendation given was in combination with the siting of the modulus, in terms of separating the high risk modules from the low risk modules, to reduce the impact and cumulative effects on the low risk modules. A large proportion of this work is completed based on the process requirements or in early studies, and as such, this recommendation can only be based on previous experience, rather than specific simulations for a facility. Another key siting issue is for the location of the Living Quarters relative to the weather veining of the vessel, with the experience showing that the large size of the utilities and equipment rooms required not resulting in much direct impact from explosions onto the TR, particularly for N_2 refrigerant designs. As such, other factors including smoke impact and design requirements were seen as contributing more to the design selection. Further experience is required, as well as industry discussion to determine more effective recommendations and guidelines for the blast design on FLNG facilities.

In conjunction with the siting requirements, the issues around the ventilation within the modules, particularly those towards the stern and the cargo area, has a large impact on the dispersed explosive clouds and the final blast results. Additionally, the applicability of ATEX, API 505 [1997] IP15 [2003], ISO 13702 [1999] and other standards to the requirement for ventilation to prevent flammable atmospheres, does not match the scale of the facilities. The main variable looked at for the ventilation design was the velocities within the modules (generally referenced against the external wind) as the main sign of the effectiveness of the ventilation. This measure showed better results than the more commonly used air change per hour metric, as the size of the modules, and their open frontage gives highly varying results within the modules. In terms of correctly siting the modules, the refrigerant modules containing the main compressors and expanders generally formed the most blockage, and the positioning of these was critical to air flow. However, due to the large size, there was in general difficulty in getting the best ventilation throughout the facility. Ideally, the most effective measure would be to have the facility hull design such that there is a misalignment between the wind and ship heading, particularly for low wind speeds, which would give much better ventilation and also explosion DAL results, with the clouds not crossing through multiple modules as easily.

The design of the offloading station and the distance from the end of the process equipment to the edge of the deck proved difficult to ensure that there was no gas going between the two main decks. This particularly important due to the confinement on the cargo deck level, which causes much higher explosion pressures. These explosion pressures additionally act on the cargo tanks, with the possibility of escalation to a much larger event. The best design to address these issues would be to have a process deck that extends over out over the cargo deck and no or only small openings in the process deck down to the cargo deck. Alternatively, there is the option of closing in the cargo deck (into sub sections) with an alternative explosion protection system involving halon/inert gas, water/powder or other active systems to prevent explosions, in combination with a strict ignition prevention system.

The dominant output of the ERA was the requirements of the DAL assessment, with the effect on personnel taken as a more secondary concern. In general, this approach is acceptable as the QRA model assumes that after an explosion, there will be a subsequent jet fire, which is generally similar in size to the area covered by the explosion fatalities. Due to this, any inequities in the explosion results are covered by the jet fire calculations. The main issue with this approach for the FLNG facilities (it would also apply to other large facilities) is the less directional impact of the explosions compared to the jet fires. It is instead expected that while the jet fire and explosion may cover similar areas in terms of fatalities, the location of these areas is quite different, with the explosion centred on the release or ignition location, and the jet fire more direct across to one module. This was seen later on in the studies, and covered by taking a more conservative basis with the explosion fatality results where they were seen as insufficient for some areas/modules, but it is important to understand the differences required in the methodology due to the facility size and layout.

Summary and Conclusions

Based on the studies completed, there is a number of key differences in the process and layout for FLNG facilities that require alternative or an augmented approach for the completion of FSA assessments. The key issues are the size and the variation in the release discharge consequences. These issues impact the studies in a multitude of ways as discussed, and they should be thought through as the study methodologies are defined and carried out. In addition to these, there are a number of other issues that cut across all of the studies. These include:

- The requirements for the facility design and the risk assessments required for regulatory and other approval;
- Ensuring timely delivery of the studies and input into the design;
- What is an tolerable and expected level of risk for a FLNG facility;
- The appropriateness of databases used as part of the FSA studies;
- The moving to a set methodology for the studies and integrating the lessons across them; and
- What will be required in the future for assessments of FLNG facilities?

A number of these items are linked together with the main discussion surrounding the requirements, the methodology and the integration of the studies being key to performing the work. Getting this correct helps to perform the studies at the right time and in the right schedule. This is key to ensuring that safety and risk is taken into consideration in the design, particularly important for a facility type that is large in scale, novel and inherently different to other offshore facilities. Due to the number of other offshore facilities that have been designed previously, good design practices from the point of view of safety have been reinforced and lessons learnt, and other disciplines are aware of the potential requirements. For FLNG, this reinforcement has not taken place, and the outcomes expected may be counterintuitive and as novel as the FLNG facility type, and therefore the timely input into the design is critical. Based on the lessons learnt in the carrying out studies for the design of FLNG facilities, as discussed in this paper, they can be completed in knowledge of the problems, challenges and difficulties which can be encountered, ensuring that they are carried out accurately and can give timely input into the facility design.

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