CHALLENGES IN USING RISK- AND PERFORMANCE-BASED DESIGN METHODS FOR FLNG SAFETY ENGINEERING

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ABSTRACT

Floating Liquefied Natural Gas (FLNG) facilities present new challenges in safety that result from the combination of complex processes, hazardous process fluids, harsh marine environments, and a reduced footprint compared to an equivalent onshore installation. The main process hazards onboard an FLNG are gas explosions within the topsides, jet fires or cryogenic spillage. These require safety barriers to prevent or mitigate escalation that go beyond those used on FPSO's and oil platforms. For instance, active fire protection is not recognised as efficient against jet fires and hence Passive Fire Protection (PFP) is required to prevent escalation. Prescriptive or deterministic methods can be used to determine the quantities of PFP to be applied, with the disadvantage that this can lead to excessive investment. To optimise weight and cost by minimizing quantities of PFP, Technip has been using risk and performance based methods on its recent FLNG projects. The design must also ensure that the topside equipment have sufficient mechanical strength to resist blast loads from explosions. Although risk and performance based methods are acknowledged by codes & standards such as ISO and regulations such as NORSOK, they are not yet accepted as standard engineering practice and a lot of effort was expended to educate and explain the approach to clients and certifying authorities. This presentation proposes a detailed discussion of these new risk and performance based methods, drawing on the experience gained on Technip's recent FLNG projects.

1. INTRODUCTION

Natural gas offers important energy-saving benefits when it is used instead of oil or coal. Its popularity as an energy source is expected to grow substantially in the future because natural gas can help achieve two important energy goals for the twenty-first century: providing energy supplies and services needed for social and economic development and reducing adverse impacts on global climate and the environment in general as opposed to oils or coal.

Floating Liquefied Natural Gas facilities (FLNGs) have the potential to revolutionize the way natural gas resources are developed. Moving the production and processing out to sea where the gas is found is a major innovation that brings huge new energy resources within reach. It also avoids the challenges of having neighbouring communities, the environmental impact and land use issues associated with constructing and operating a plant onshore, including laying pipelines to shore and building other infrastructure. FLNGs will be the largest floating offshore installations in the world but at the same time they will typically be one-sixth the size of an onshore plant of same capacity, thereby limiting the space available for layout of process equipment within the topsides as available space within the substructure is mainly dedicated to storage tanks and the specific marine equipment.

There are many major safety issues associated with the development of this new kind of facility. The potential risks due to processing of hazardous materials (flammable liquid and gas, cryogenic liquid, toxic and asphyxiating gas, etc.) are magnified due to the close proximity of a gas liquefaction facility to the living quarters. This context requires particularly detailed safety studies as inputs to the design. The main objective
of these safety studies is to demonstrate that the installation is designed so that the risks are reduced to levels “As Low As Reasonably Practicable” (ALARP) and that people will be able to escape safely in case of a major accidental event (lesson learned from Piper Alpha disaster).

Identified risks are mitigated in the early design stages of the FLNG project resulting in risk reduction measures. The associated safety studies are particularly challenging given the novelty of the FLNG as a concept and prescriptive methods that can be practical onshore are insufficient. This paper presents Technip experience in managing risks associated with FLNG facilities using risk and performance-based approaches for design development.

After an overview of the hazards specific to FLNG, the main strengths and weaknesses of prescriptive versus performance based approaches to ensure development of a safe FLNG design are presented. A performance based approach implies development of Safety Studies from which the Design Accidental Loads (DAL) from major accident events will be used as the basis for the definition of design requirements of safety protection measures such as Passive Fire Protection (PFP) / Cryogenic Spill Protection (CSP) and explosion rating for Safety Critical Elements (SCEs) such as structure, equipment or buildings.

2. INHERENT SAFETY DESIGN

2.1. FLNG Hazards

The FLNG facilities predominately handle hydrocarbon gas with associated condensate liquids, which will be processed, fractionated and stored as LNG (Liquefied Natural Gas), LPG (Liquefied Petroleum Gas) and condensate products. Depending on the liquefaction process technology, light hydrocarbons can be used as refrigerants within the process although nitrogen can be used instead.

Onboard FLNGs, the predominant hazards are fire, explosion and cryogenic spill resulting from the loss of containment within the process, the storage and/or the offloading facilities as shown in the figure 1 below.

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**Figure 1: Overview of FLNG specific hazardous outcomes**

*Flash fire, explosion, pool fire or jet fire:*
A hydrocarbon release within the topsides of a FLNG may result in a pool fire, jet fire, flash fire or vapor cloud explosion depending on many parameters such as the phase of the released product, the release location, the ignition (immediate or delayed).

The flames and subsequent heat radiation from fire events may lead to injuries or fatalities as well as damage to unprotected structures, equipment, etc. Similarly, the overpressure generated in the event of an explosion may also impact personnel, structures, equipment, etc.
Cryogenic Spillage:
The cryogenic temperature of LNG or refrigerant products can expose personnel to cold burn injuries. The visibility for personnel during escape and emergency response can also be impaired due to fog formation (atmospheric humidity condensation in the event of an accidental release of cryogenics).

The embrittlement and possible failure of unprotected carbon steel may occur below a critical temperature. This phenomenon is almost instantaneous in the event of contact of carbon steel with cryogenic liquids. This may have an impact on the supporting and integrity functions of process decks, structures and hull of the FLNG.

Rapid Phase Transition (RPT):
A Rapid Phase Transition is the result of the mixing of a cryogenic liquid with seawater. The rapid increase of the vaporization rate may result in a physical explosion with the potential of damage.

Toxicity:
Depending on the composition of the feed gas, some streams could contain toxic substances. The effects on the personnel depend on the concentration, nature of the substances and exposure duration.

Asphyxiation:
Some refrigerant components such as nitrogen are asphyxiants. In addition due to the high expansion rate of a vaporizing liquid (e.g. expansion rate of LNG =1:600) and/or bad conditions of ventilation, produced vapor can significantly reduce the oxygen content of the atmosphere down to hazardous levels to personnel.

2.2. Inherent Safety Principles

In order to manage the hazards previously identified and their associated effects, the design needs to be developed according to Inherent Safety principles described in [1] and [2] as follows:

Hazard prevention, to reduce the frequency of loss of containment and ignition:

- Reduce the leakage probability by:
  - Minimizing numbers of known common leakage sources (e.g. flanges, pumps, valves).
  - Minimizing line lengths.
  - Designing to proven standards using high quality materials and components.
  - Using high integrity components (e.g. dual-seal pumps).
  - Not permitting any heavy lift over unprotected live hydrocarbon process equipment or lines.

- Reduce the ignition probability following a leak by:
  - Providing effective ventilation and drainage systems to remove or disperse released fluids.
  - Venting contained inventories at safe location.
  - Implementing electrical equipment, instrumentation etc. suitable for classified areas.
  - Automatically isolating potential ignition sources (e.g. electrical equipment) on confirmed gas detection.
  - Segregating strong ignition sources from potential hydrocarbon releases sources.

Control and mitigation to reduce the severity of the consequences of loss of containment:

- Reduce the released quantity by:
  - Minimizing hydrocarbon inventories and pressures.
  - Implementing effective early gas detection systems.
  - Initiating emergency shutdown and depressurization.
• Reduce the consequences of ignited releases by:
  ✓ Grouping process equipment and sections by type of hazards.
  ✓ Segregating and separating critical equipment by providing the necessary separation distance or by installing fire/blast protection arrangements.
  ✓ Applying active or passive fire protection to critical structures and equipment.
  ✓ Designing critical structures and equipment against blast.

• Reduce the consequences of cryogenic releases (not ignited) by:
  ✓ Grouping cryogenic equipment and providing effective drainage systems to dispose of released fluids.
  ✓ Segregating and separating critical equipment by providing the necessary separation distances.
  ✓ Applying passive cryogenic protection to critical structures and equipment.

Once identified, these hazards shall be managed using various approaches for the safe design of the facility.

3. SAFETY DESIGN APPROACHES

3.1. Comparison of Prescriptive versus Performance Based Approaches

Different approaches are possible for the safety design of a new facility, as shown in figure 2 below.
primarily on the means to reach them. The approach can be very efficient and well controlled for conventional design cases. From the knowledge of these design rules, one can design a technical solution without the explicit definition of the objectives/goals to be achieved. However the design may depend on the good understanding of the local regulations and codes and standards framework. The prescriptive approach has been applied with success for a long time on onshore and offshore facilities including LNG carriers through SOLAS [3] or other well-known rules.

FLNGs being a new technology, are not covered by existing regulations, codes and standards and good engineering practices as they do not account for the specific safety concerns of this new concept such as cryogenic risk within the process modules of an offshore facility.

The evolution of design practices allows the use of a performance-based approach. This alternate to the prescriptive approach is now proposed in the design rules such as the ISO 19000 series for offshore facilities [4].

The performance-based approach relies on the explicit definition of the safety objectives and functional requirements (e.g. performance standards). The design shall be developed to fulfil these objectives in a more flexible manner compared to the prescriptive approach. The design process focuses primarily on the objectives. This allows the development of innovative solutions and optimization of the design.

The performance-based approach requires the definition of realistic hazard scenarios (e.g. fire, explosion or cryogenic releases events), which could even be deterministic (e.g. worst case approach) or probabilistic (risk-based). These accidental scenarios are the basis of the Design Accidental Load specification as defined in [5] or [6].

The design process requires more resources (skills, computational tools, etc.) in the engineering phases since the owner and, as a consequence the contractor, shall demonstrate the compliance of the design solution with the safety objectives. This could be a challenge because any design solution is specific to the facility and requires the acceptance by the local Authority and frequently the insurer, classification society, etc. All parties shall ensure that they understand, agree and are aware of the limitation of the proposed design solution to avoid further rework. However developing such alternative solutions provides opportunities for reduction of Material Take Off (MTO) and associated cost with also possible reduction of the construction schedule for the implementation of the technical solutions (e.g. reduction of the Passive Fire Protection quantities).

The strengths and weaknesses of both approaches are summarized in the table below:
### Table 1: Strengths and weaknesses of approaches

<table>
<thead>
<tr>
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<th><strong>Prescriptive Approach</strong> (Focus on Means)</th>
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</thead>
</table>
| **Strengths**    | • Very efficient for conventional cases  
• Well-known and well controlled  
• Straightforward application  
• Compliance is “easy” to demonstrate for the designer, to endorse (owner) and to accept (authority, classification society) |
| **Weaknesses**   | • Implicit objectives  
• Special cases not covered  
• Long process for acceptance of any deviation to the codes & regulations |

<table>
<thead>
<tr>
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<th><strong>Performance-based Approach</strong> (Focus on Objectives)</th>
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</table>
| **Strengths**    | • More flexible to cope with project specificities  
• Explicit definition of objectives and associated performance criteria  
• Optimisation of mitigation measures (cost reduction, reduced MTO, less time on construction site for implementation) |
| **Weaknesses**   | • Acceptance criteria may be more difficult to define (by owner or authorities) or acceptance may be more difficult to grant.  
• More resources (skills) needed for each step of the detailed design process  
• Time consuming during engineering phase (demonstration that the system satisfies the performance criteria)  
• Safety Management System required during the entire lifecycle of the facility to account for potential design modifications which can change scenarios |

The risk-based Approach (e.g. NORSOK Z-013) was developed in the North Sea for offshore installations after the Piper Alpha disaster. It combines together a frequency analysis and a consequence analysis in order to evaluate the risk from the potential accidental events. This approach allows managing the risk through the design of the facility and providing opportunities for design optimization. Indeed if only the worst case is considered, the facility would not be designable. However the risk-based approach requires more resources because dedicated studies need to be performed (frequency analysis, consequence analysis, etc.). Regardless, it should be kept in mind that the optimisation of the design through the use of the Risk and Performance-based approach shall be a tool to enhance the general safety of the facility and not a solution for lowering the risk reduction measures through the demonstration that some of them do not provide sufficient benefits regarding the cost involved.

### 3.2 Risk-Based Design

The risk based design approach is illustrated on the figure 3 below.
According to the references [6] and [7], the safety objectives in case of an accidental event are to reduce:

- Injury/fatality to personnel,
- Damage to the environment,
- Damage to the assets and loss of production.

In order to achieve these objectives, Safety philosophies are developed. They require that the following main safety functions must be maintained as a minimum:

- Escape, evacuation and rescue,
- Prevention of escalation of accident situation outside of the immediate vicinity of the accident.

This implies identification of Safety Critical Elements (SCEs), whose definition, according to [7], is:

“Any structure, plant, equipment, system (including computer software) or component part whose failure could cause or contribute substantially to a major accident is safety-critical, as is any which is intended to prevent or limit the effect of a major accident.”
The SCEs may be ranked according to their criticality rating using the definition given in the table hereunder:

**Table 2: Criticality rating definition based on UKOOA Fire and Explosion Guidance**

<table>
<thead>
<tr>
<th>Criticality rating</th>
<th>Description</th>
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<tbody>
<tr>
<td>1</td>
<td>Items whose failure would lead to direct impairment of the living quarter (LQ), emergency escape and rescue (EER) systems including the associated supporting structure and the main deck.</td>
</tr>
<tr>
<td>2</td>
<td>Items whose failure could lead to major cryogenic and/or pressurized and/or flammable release and any other relevant items failure (e.g. collapse) affecting more than one module or compartment</td>
</tr>
<tr>
<td>3</td>
<td>Items whose failure would only lead to escalation within the same module or compartment.</td>
</tr>
</tbody>
</table>

This classification influences the Risk Acceptance Criteria (RAC) to be considered for the design of the SCEs. Indeed, SCEs considered as criticality 1 will have a stronger design than SCEs considered as criticality 2 or 3.

The Risk-based design relies upon outputs from the following safety studies:

- the Explosion Risk Analysis,
- the Fire Risk Analysis and
- the Cryogenic Risk Analysis.

In these studies, all identified failure cases (i.e. including all leak sizes, isolation and non-isolation, blowdown and non-blowdown cases) are combined into a risk integration model together with their frequency and associated consequences. The risk tool integrates the effects from all scenarios in order to give a complete risk picture of the facility for each kind of hazardous outcome.

The risk-based design approach combines the results of the safety studies with the project Risk Acceptance Criteria (RAC) in order to define the magnitude of the Design Accidental Loads (DAL). This RAC is the frequency of exceedance up to a certain consequence magnitude of a Major Accidental Event (MAE) as shown in the figure below for explosion events. The SCEs are then designed to withstand the given DAL.

![Figure 4: Example of overpressure DAL at a given RAC](image-url)
For other accidental events, such exceedance curves may be developed for individual SCEs. However, risk contours may be sometimes preferred for practical purpose. An example of an application case is described in the next section.

3.3. Application Cases for Design of Passive Fire Protection

Jet fire events are the main contributors to the FLNG risk profile. Since active fire protection is ineffective against jet fire impingement, Passive Fire Protection (PFP) becomes consequently the first means of fire protection. Systematic application of passive fire protection can significantly impact FLNG weight, cost, construction schedule and, in operation, maintenance/inspection which is why a risk based-approach is preferred to optimize PFP quantities.

The objective is to define the area/zone where passive fire protection is required and the duration of the integrity to be maintained for different SCEs, taking into account not only the consequences but also the frequency of occurrence of MAEs.

The different steps considered for Passive Fire Protection risk-based approach were:

1. **Identification of SCEs requiring protection based on a criticality rating** taking into account the potential for escalation induced by its failure.

2. **Specification of the survival time or minimum duration of item functionality** under accidental conditions:
   - Survival time is the minimum time of exposure considered for the rupture of process equipment/piping or the collapse of a steel support/structure for different accidental events.
   - Minimum duration of item functionality is the minimum time required of the item to ensure its function until the system can be placed in “safe” position (e.g. duration of the depressurization or total evacuation).

3. **Identification of hazard extents**
   Identification of the protection extent and duration based on the Fire Risk Analysis which provides hazard frequency contours for the flame impingement and thermal radiation exposure at different units of times. The plot hereafter shows typical fire hazard frequency contours.

![Fire hazard frequency contours](image)

**Figure 5: Fire hazard frequency contours**

Each contour delimits an area into which the frequency of a given outcome (flame impingement, radiation level) exceeds a frequency level. These contours are developed for different time steps since the impact of fire events are typically depending on the exposure duration).

4. **Optimization of the protection extent** considering duration of exposure, structural/supporting redundancy, inherent strength of the SCEs, physical segregation (wall, adequate drainage,...)
4. CHALLENGES AND LIMITS OF THE RISK AND PERFORMANCE-BASED APPROACHES

As highlighted in the previous sections, the application of a Performance and Risk-based approaches as the basis for the safety engineering activities requires much more resources (human and computational) in comparison to the prescriptive approach. The safety studies (e.g. Fire Risk Analysis, Cryogenic Risk Analysis and Explosion Risk Analysis) are detailed studies that require involvement of skilled and experienced safety engineers as they are very sensitive to the modelling assumptions, the rule-sets, the input data considered and the tools used for the risk assessment.

Typically, the Fire and Cryogenic Risk Assessment comprises of thousands of unitary scenarios modelings since several probabilistic leak sizes, leak directions, weather conditions, etc. are considered. In addition, the Explosion Risk Analysis for a FLNG facility is a 3D computational Fluids dynamics (CFD) study since it is the only manner to implement the local geometrical effects which have a strong impact on the gas explosion severity. Hence, performing such safety studies in a timescale compatible with the duration of a typical engineering project phase is often a challenge, especially for the CFD studies. Indeed, they rely on the 3D model of the FLNG which needs to be as representative as possible of the actual facility in order to derive accurate results. On the other hand, the results of the safety studies are important inputs for many engineering disciplines. For example, structural engineers require the explosion DALs as soon as possible to be able to use the results for structural calculations.

The design work process is somewhat iterative and requires efficient communication between engineering disciplines to avoid rework. The cost of the safety studies should be balanced against the potential optimization and associated cost and weight saving of the PFP/CSP requirement.

The safety studies supporting the risk-based approach provide very detailed results (e.g. one overpressure DAL per SCE) but the results are subject to some uncertainties/limitations. Therefore, the results shall be checked carefully by the safety engineers and special attention shall be paid to their utilization for safety design purpose. As an example, the specification of the passive protection requirement shall generally not only rely on the results of safety studies. Indeed, as mentioned above although the fire hazard frequency contours provides useful information for definition of passive protection requirement, these studies results are very sensitive to the release location chosen (typically one release location is chosen and assumed to be representative of one isolatable section). Therefore, expertise, experience and engineering judgement are required to specify final protection requirements and safety design considering location, redundancy, functionality, criticality of the SCEs.

The application of a Performance and Risk-based approaches also results in significant modifications of the internal work process (more interfaces between the engineering disciplines are generated and several multi-disciplinary workshops are required to agree on the safety studies inputs and assumptions) but it also modifies the way to work with the Client. Indeed, Client’s involvement and commitment in developing the most sensitive assumptions but also in providing the risk acceptance criteria is necessary. More generally, the application of Risk and Performance-based approaches has to be carried out in the spirit of cooperation and awareness of the importance of the potential issues.

Since the application of the Performance-based approach is a recent evolution in safety engineering, its use on real engineering projects requires the development of innovative tools and methodologies as well as the use of more sophisticated software tools in the entire engineering chain and not only for the safety studies. This may be a long and complicated process but in return this opens the door to new innovative design solutions and opportunities for optimization ensuring the level of safety of the FLNG is ALARP.

Finally, although the Performance and Risk-based approaches are referenced in some codes and standards (NORSOK, ISO), their application for real installations still requires to be carefully explained to all the stakeholders such as the Owner and also the Certification/Validation bodies as well as the permitting Authorities.
5. CONCLUSION

After a brief presentation of the hazards and inherent safety principles to be considered when performing the safety engineering studies related to a FLNG facility, the reasons associated with the necessity to use performance based approach for FLNG facilities rather than a prescriptive approach have been described as well as main advantages and drawbacks of each design approach. After presenting examples on how the Performance and Risk-based approaches can be used for safety design purpose, the challenges in using such approaches on real FLNG projects have been highlighted.

In the course of its FLNG projects Technip has developed robust risk-based study methods that meet all the challenges by merging the know-how from past experience in both large onshore LNG projects and offshore projects such as FPSOs. Innovative, acceptable safety protection systems and protection means have been provided in designs that are now under construction, ensuring that FLNG is both safe and also economically viable.

REFERENCES

[1] ISO 13702 - Petroleum and natural gas industries Control and mitigation of fires and explosions on offshore production installations - Requirements and guidelines (February 2000)


