Use of Risk Assessment in the Approval In Principle of Subsea Cryogenic Pipelines

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ABSTRACT
Traditionally, ship and offshore classification rules are formulated based on proven engineering principles and operational experience. With increasing frequency, the marine and offshore industries develop novel applications or processes for which existing classification rules may not be directly applicable. For this reason, a new process for classification has been created to deal with a novel design, starting from the concept development stage. This new process draws upon engineering, testing and risk assessments in order to determine if the concept provides acceptable levels of safety in line with current offshore and marine industry practice. Central to this process are risk assessment techniques, which are used as a way to better understand and anticipate structural and operational issues related to the novel design. One intermediate step of this process is granting “Approval In Principle”, which expresses that the novel design has been analyzed and found to be technically feasible from both safety and functional perspectives.

This paper will describe this methodology, and will discuss its application to actual cases for granting the Approval In Principle to subsea cryogenic pipeline designs.

INTRODUCTION
Classification Societies are independent organizations that promote the security of life, property and the environment of ships and offshore structures. This is done by the establishment and administration of standards for the design, construction, and operational maintenance of marine vessels and structures. Classification rules and guides are largely of prescriptive nature, and have been historically established from principles of naval architecture, marine engineering and other scientific principles. They have proven satisfactory by service experience and systematic analysis, some of them for over a hundred years. However, new or novel concepts are continually emerging as the marine and offshore industries expand their traditional activities and challenge their existing boundaries in order to keep up with society’s needs. Such novel concepts do not have any prior in-service experience, neither any classification rules, statutory regulations nor industry standards directly applicable to them. Therefore novel concepts require a different and more flexible approach to classification, including the use of new tools and techniques in order to determine if the concept provides acceptable levels of safety in line with current offshore and marine industry practice.

The American Bureau of Shipping (ABS) has developed a guidance document, the Guidance Notes on the Review and Approval of Novel Concepts [Ref. 1], in order to offer a methodology for requesting the classification of a novel design and facilitate its approval. This methodology relies heavily on risk assessment techniques as a way to better understand and anticipate structural and operational issues related to the novel concept.

The following sections describe the application of the classification review methodology performed by ABS in conjunction with other stakeholders for the so called “Approval In Principle” of different designs of subsea cryogenic pipelines.
CRYOGENIC SUBSEA PIPELINES

Liquefied Natural Gas (LNG) is natural gas in its liquid form (-259°F at atmospheric pressure). The LNG market is expected to grow significantly in the coming years, so there will be considerable demand for more LNG plants and terminals. The challenge for these facilities is even greater in view of public opposition, mostly in the US, to the construction of these facilities onshore because of safety, security and environmental concerns. For these reasons, the oil and gas industry is looking offshore to locate LNG facilities. The development of designs for LNG offshore terminals, LNG single point moorings and LNG offshore offloading platforms is relatively recent. As a part of this development, the safe transport of large quantities of LNG from the LNG offshore terminals, SPM’s or offloading platforms to the storage tanks ashore for gas distribution has become a technical issue to resolve. It is for this reason that the design of cryogenic subsea pipelines became a crucial emerging technology.

A successful design of subsea cryogenic pipeline for LNG transportation needs to consider the following technical issues:

- Thermal contraction due to the low temperature of the LNG
- Thermodynamic performance (insulation to keep the LNG in its liquid state)
- Acceptable risk for LNG leakage

Different solutions are being considered to comply with the above technical requirements. A pipe-in-pipe (PIP) design, i.e. a pipeline system consisting of two coaxial pipes, is suitable for this application. The inner pipe transports the cryogenic fluid, the annular space encloses the necessary insulation and the outer pipe provides protection from the external environment (pressure, corrosion, impacts, etc.).

ABS has received the request from some design firms to consider the potential classification of a few subsea cryogenic pipeline designs. As there is no previous historical experience of subsea cryogenic pipelines, neither any directly applicable ABS rules, nor any other industry standards, these designs were evaluated for potential classification by ABS under the process delineated in the Guidance Notes on the Review and Approval of Novel Concepts. This process is described in the next section.

REVIEW AND APPROVAL OF NOVEL CONCEPTS

The ABS Guidance Notes on Review and Approval of Novel Concepts were developed to offer owners and designers a new methodology for requesting the classification of a novel design and to facilitate its approval. They are intended to cover proposed applications that have not been proven in the maritime or offshore industry and would therefore be considered novel for those environments. The methodology combines engineering analysis, field testing and risk assessments to compensate for the lack of prescriptive classification rules, in order to determine if the concept provides acceptable levels of safety in line with current offshore and marine industry practice.

Design companies, when exploring the possibilities of a new technology or concept, often seek input and expert opinion from classification societies, among others. They are looking for some confirmation that the design is feasible and will be capable of attaining classification. The ABS Guidance Notes offers the “Approval In Principle” (AIP) as a first milestone in the road for classification of novel concepts. The benefit of gaining AIP is that the client can obtain a document issued by a knowledgeable independent marine and offshore society as evidence of preliminary acceptability of the concept for classification to provide to regulatory bodies and project partners. It confirms that there are no significant impediments to further the development of the concept.
The Guidance Notes divide the class approval process into the following stages:

- Determine Approval Route
- Approval In Principle (concept development phase)
- Approval Road Map
- Final Class Approval (detailed design/construction/commissioning phase)
- Maintenance of Class (implementation/operational phase)

The process that the client and ABS would follow to achieve these milestones is outlined in Fig. 1. This process involves ABS and the client working together to accomplish the following:

**Determine Approval Route**

As a first step, the approval route to achieve AIP needs to be determined. This will involve the client and ABS meeting to discuss the concept, its purpose, its novel features and where it deviates from traditional approaches, the proposed operating envelope and the potential impact of the concept on other systems or components. Agreement will be reached as to the best methods to assess risk in the AIP phase as well as the appropriate level of engineering analysis.

**AIP and Approval Road Map**

As a minimum, the goal of achieving AIP should be the identification of all hazards and failure modes applicable to the novel concept application along with suitable support information demonstrating the control of these hazards and failure modes are feasible. Throughout this phase, as the concept is being evaluated, an Approval Road Map will be defined which will lay out conditions to achieving full approval. The road map will define clearly the approach needed from a risk assessment and engineering analysis standpoint to justify those novel aspects not covered by existing rules, codes and standards.

**Final Class Approval**

This phase covers typical class approval submittals comprised of typical drawings, specifications, calculation packages and support documentation, along with submissions of those items outlined in the Approval Road Map. Upon completion of this stage, the potential hazards and failure modes for the novel features will have been assessed versus agreed-upon acceptance criteria to a level of confidence necessary to grant full class approval to the design.

**Maintenance of Class**

As a final condition of class approval, ABS will determine the necessary additional conditions assigned to the maintenance of class via additional survey scope or frequency of attendance, condition monitoring, required maintenance and inspection techniques to maintain levels of monitoring assumed in the design phase which may have been necessary to achieve various design parameters, and finally as a means to verify assumptions and predictions made throughout the process.
** APPROVAL IN PRINCIPLE **

This section will discuss the AIP stage in more detail. AIP is a process by which ABS issues a statement-of-fact that a proposed novel concept or new technology complies with the intent of the most applicable ABS Rules and Guides as well as required appropriate industry codes and standards, subject to a list of conditions. These conditions, the Approval Road Map, will typically define a list of submittals necessary to be completed in later phases of the project in order to obtain full class approval.

In order to achieve AIP, all relevant failure modes and hazards related to the concept are required to be identified and addressed in an acceptable level of detail, to demonstrate to ABS that the concept is feasible for use in a marine or offshore application. This is accomplished through the preparation of appropriate engineering analyses and risk assessments at the Concept Phase so as to supply ABS with suitable information to make this determination. Participation by ABS personnel in the various risk assessments is also strongly encouraged to assist the approval process. The engineering and risk assessment analyses are to be compared with existing marine and offshore practice to demonstrate that the risk created by the novel concept is no more onerous than what currently exist.

The AIP process involves two types of analyses: the concept engineering evaluations and the concept level risk assessment.

** Concept Engineering Evaluations **

The objective of the concept engineering evaluation is to verify that the design is feasible with respect to intent and overall level of safety for all phases of operation (such as in-transit, installation, commissioning and operation for an offshore application) as far as practical within the information available at the concept design phase.

Most novel applications have aspects that are novel and aspects that are conventional. The concept engineering evaluation shall consider not only the verification of the novel aspects, but also verify the effect of the novel aspect on the conventional aspects. This is done to ensure that the application of existing codes and standards to the non-novel features is still valid.
**Concept Level Risk Assessments**

Risk assessments at the conceptual stages of a novel concept are part of the requirement to obtain AIP. The specific requirements for risk assessments are based on the degree of novelty of the application. At a minimum, a qualitative risk assessment on the new concept will be required.

In general for the concept development phase, a design basis, preliminary engineering and possibly testing results are available for use in the risk assessments. A qualitative risk assessment technique is generally the most suited method at this concept design phase.

There are various qualitative risk techniques that can be applied, such as HAZID (Hazard Identification), What-if and HAZOP (Hazard and Operability Analysis). However, the most appropriate technique depends on the available concept design information and type of system being proposed.

Conducting a qualitative risk assessment involves a team brainstorming session that provides a unique forum for designers, operational and safety personnel, as well as ABS representatives, to discuss the concept in a structured manner. Prior to conducting a qualitative risk evaluation, the organization proposing the novel concept has to submit information on what method will be used, what subject matter experts will participate and what scope the assessment will have. Additionally, a risk ranking methodology or risk matrix must be submitted and approved by ABS.

**NOVEL FEATURES IN CRYOGENIC SUBSEA PIPELINE DESIGNS**

Nowadays the use of insulated pipe-in-pipe pipelines is no news in the oil and gas industry. Advances in technology, especially temperature management, have generated significant interest in the development of marginal or more technically difficult hydrocarbon fields, such as High Temperature/High Pressure (HT/HP) reservoirs. During the late 90’s, the subsea transport of HT/HP products, such as gas condensates, was technically possible by means of the development of the PIP technology. The finite element method for stress and thermal analysis provided a better in-depth understanding of the behavior of HP/HT flow lines.

Recent years have seen a number of pipeline projects in which PIP configuration was implemented. Penguin fields (Ref. 2), Jade fields (Ref. 3) and Erskine fields (Ref. 4), Dunbar (Ref. 5) and Etap (Ref. 5 & 6) fields, all in the UK sector of North Sea, benefited from PIP pipeline configuration to transport HT/HP products. Penguin pipeline was laid on the seabed (66 km) whereas Erskine and Jade pipelines were buried. The original Erskine PIP pipeline fractured at a field joint and the field was out of operation for a year and a replacement PIP pipeline was designed, procured and installed (Ref. 4). As a consequence of the experiences gained in the development of the HP/HT fields mainly in the North Sea, new design criteria for insulated PIP pipelines were established, fabrication and installation methods were improved and the criticality of the quality control in installation was better understood (Ref. 7).

Cryogenic land-based pipelines are also common in the chemical and energy industries for products such as liquid nitrogen and LNG. A typical example is the cryogenic pipelines from the LNG loading/unloading jetties to the LNG storage tanks. The pipeline materials most used for cryogenic service are stainless steels and nickel alloys with a 9 % or higher nickel content. The pipelines are insulated to limit the boil-off during transport to an acceptable level for safety and operation.

Using the existing subsea PIP technology and the land-based cryogenic pipelines applications, new concepts of subsea cryogenic PIP pipeline have been developed by well known offshore companies.

The basic design consists of an inner pipe of cryogenic material covered by a layer of high performance insulation and an outer pipe, commonly of carbon steel or stainless steel. For more
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Protection against external mechanical damage, an additional external barrier pipe or a concrete coating may be provided. The cryogenic materials being considered in these designs are similar to those used in cryogenic land-based pipelines, mainly nickel alloys with a 9% or higher nickel content. A prevalent selection is an alloy with 36% nickel content, which is widely used in the LNG membrane tanks of many LNG ships operating today.

The intended use of a 36% Nickel alloy as the cryogenic material for the LNG carrier pipe is based on the excellent mechanical characteristics of the material at very low temperatures and, most important for the pipeline application, its very low coefficient of thermal expansion. This unique feature eliminates the need for thermal expansion/contraction bellows and loops in the pipeline while ensuring low levels of thermal stresses throughout the pipeline.

Another basic feature of these designs is the use of insulation of very high thermal performance, with very low thermal conductivity. This insulation is aimed to prevent excessive boil-off of LNG along the length of the pipeline as well as to maintain the external carbon steel pipes at temperatures above freezing.

Particular attention is paid in the design of the bulkheads connecting the nickel alloy inner pipe and the carbon steel outer pipe, where used, for both stress and thermal transmission, in order to prevent carbon steel to reach temperatures below 0°C.

During the involvement of ABS in the Approval In Principle of these designs, a number of novel features were identified. Among these novel features the following are the most notable ones which constituted the focus of ABS’ Approval In Principle analysis:

- The use of large diameter nickel alloy pipes
- The use of nickel alloys in larger thickness than previously used
- The welding mechanical characteristics of nickel alloy material and of this material with stainless steel and carbon steel.
- The use of high performance insulation in subsea pipelines

QUALITATIVE RISK ASSESSMENT

Upon an accidental release of LNG from a subsea LNG pipeline, the potential consequences can be developed only after considering the specific conditions at the given time and given location where the pipeline is installed. Factors such as water depths, water temperature, currents, ship traffic, nearby installations, population, etc. will all influence the potential consequences. But given that under worst circumstances, consequences can be serious, the main objective of the subsea pipeline design is to reduce the probability of a LNG leakage to an acceptable level.

For the Approval In Principle phase, the objective of the risk assessment is to identify all the potential mechanisms and scenarios that can initiate a leakage of LNG, in order to assure that all such scenarios were properly considered during the conceptual design phase, and there are no scenarios that lack appropriate prevention or mitigation measures.

This objective was accomplished by a qualitative risk assessment. This section describes the process followed in the assessment.

Reviewing Documentation

A series of meetings between ABS and the different design firms were conducted previous to the risk assessment. The objective of these meetings was to review the preliminary design documentation so that the key members of the ABS team become familiar with the important aspects of the novel concept. During this step, the novel features were discussed, i.e. elements of the design that go beyond that which has previously been built or beyond that envisaged in the existing ABS rules and
other published requirements for this type of technology. The type of documents reviewed and used previous to and during the qualitative risk assessment included the following:

- Design specification and configuration
- Design details of bulkheads and spacing
- Joint design characteristics, including supporting calculations
- Details of safety devices and control, monitoring and alarm systems, as applicable
- Emergency shutdown details and consequences
- Pipe-laying process
- Fill Up/empty procedure
- Proposals for surveys and inspections during construction, installation, operation and maintenance
- Any engineering analyses performed (mechanical, thermal, FEM, etc.)
- Qualification test plan and test procedures (if available)

Performing the Assessment

ABS hosted the risk assessment meetings. ABS personnel took the role of facilitator and recorder. Other ABS personnel also participated in the brainstorming sessions as technical subject matter experts. Representatives from different organizations were invited as technical experts, covering all aspects of the proposed design to be reviewed, including process design, pipeline design, fabrication, codes & standards, cryogenic service, materials and welding. The number of participants at each meeting ranged from 12 to 16, which is within the recommended range for brainstorming sessions (enough people to cover all technical areas, avoiding the problems of managing a large group).

Typically the sessions lasted for two days for each design reviewed. The group sessions were divided into three distinctive parts. The first part consisted of a presentation of the design and available documentation, including an overview of the risk assessment methodology to be used and establishment of the scope of the analysis. The problems of interest that the analysis was to address were also discussed and agreed. The remaining two parts consisted of the identification and evaluation of hazards with two different techniques to look at the pipeline design from a more global or “system” perspective and from a more detailed or “component” perspective. The analysis included all modes of operation, including normal, fill-up/empty procedures, maintenance/inspection activities, installation and decommissioning.

The global or “system” level analysis was performed following a HAZID technique. This technique is a brainstorming group session without much structure, to facilitate the free flowing of ideas, to identify potential hazards associated with each part of the system that have the potential to result in a significant consequence.

The detailed or component level analysis was performed following a similar procedure to the FMEA (Failure Modes and Effect Analysis) for each typical sector of the transport system (pipeline, bulkheads, etc.). This process requires the subdivision of the system for analysis into distinctive and manageable elements. For each element, the potential failure modes are identified, i.e. ways that each element of the system can fail to achieve its intended function which can lead to accidents of interest for the analysis (leak of LNG)

Both types of analysis included an evaluation of the following for each failure of interest:

- The range of possible effects or consequences
- Ways in which the failure can occur (causes)
- Ways in which the failure mode can be detected and isolated
- Safeguards that are in place or could be implemented, to protect against accidents resulting from the failure mode
A qualitative risk evaluation, by characterizing, for each identified failure, its likelihood, its severity, and the resulting level of risk using an appropriate risk matrix. The ABS SafeShip Risk Management Module software was used to document the analysis. This software was developed by ABS to facilitate the performance and recording of qualitative risk assessments. A typical risk matrix used for the estimation of likelihood and consequence is shown in Fig. 2. It is a 5x5 matrix, i.e. it is divided in five categories for likelihood (frequency of occurrence) and five categories for consequence. Three categories of risk (low, medium and high) are defined based on the different likelihood/consequence combinations.

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<thead>
<tr>
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<th>INCIDENTAL (A)</th>
<th>MINOR (B)</th>
<th>SERIOUS (C)</th>
<th>MAJOR (D)</th>
<th>CATASTROPHIC (E)</th>
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<td>Low Risk</td>
<td>Low Risk</td>
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Figure 2: Typical risk matrix used for qualitative risk assessments

Results of the Assessment

The results of each qualitative risk assessment were recorded in a so called hazard register. The hazard register is a summary of all the hazards identified, listed in a table format. The table contains the following fields:

- Event/Deviation/Failure Mode
- Possible Causes
- Potential Consequences/Effects
- Likelihood and Consequence category
- Risk category
- Safeguards/Indications
- Actions/Recommendations

Due to confidentiality agreements with each design company, it is not possible to provide technical details of the designs and the specific recommendations annotated. The following is a list with a selected number of issues identified.
Inner Pipe:
A leak in the inner pipe will result in LNG flow into the annular region, and LNG contact with the outer pipe. The insulation properties will be lost. Vaporized LNG in annulus could increase pressure and collapse inner pipe. If the outer pipe cannot withstand cryogenic temperatures, it could fail resulting in an LNG leak to the seawater. Rapid Phase Transition (RPT) may occur if large LNG release at once.

Potential Causes:
- Peak pressure during transient conditions (water hammer)
- Thermal cycling of pipeline causing premature pipe failure
- Excessive erosion due to contaminants inside pipe (e.g. water, carbon dioxide)
- Cavitation at bulkhead transitions
- Material transition failures (galvanic action, different thermal stresses, welds)
- Thermal transient during startup (piping cooldown rate)
- Weld failures (critical issue, no experience with welding 36% nickel alloys of the necessary thicker pipes)
- Hydrotect of pipeline with water may leave water behind (pipe corrosion, ice formation)

Insulation:
Loss of insulation will result in freezing of the pipeline, an increase of boil off rate (need to relieve inner pipe internal pressure). Potential for brittle fracture of outer pipe if made of carbon steel.

Potential Causes:
- Buckling of outer pipeline due to impact during installation, later aggravated with seawater pressure, and crashing onto insulating material.
- Contamination of insulation
- Improper installation
- Insulation damage due to welding work on casing during set-up
- Damage during pipeline installation (stretching of pipes during towing could affect insulation)
- Aging of insulation (no history)

Outer Pipe:
Water will come into contact with the inner pipe, losing all insulation capability and freezing of pipe. LNG will start to evaporate. Pressure build-up needs to be relieved. Depending on water depth and design parameters, the inner pipe may collapse due to high external pressure. LNG leak to the sea may result.

Potential Causes:
- Mechanical damage during installation
- Corrosion
- Buckling due to improper support for pipeline span
- Weld defects
- Impact from external sources (vessels, dropped anchor)
- Overstresses due to other natural events (hurricanes, earthquakes, landslides, etc.)

Table 1: Results of the Assessment
During the brainstorming sessions, as hazardous issues were identified, the potential ways of preventing or mitigating them were discussed for each design, both existing measures and recommended measures. From these discussions, a number of requirements for each design were identified, and were noted as action items for the design company, either as pre-requisites before granting Approval In Principle, or as a condition for full classification indicated in the approval road map.

CONCLUSIONS
The qualitative risk analyses performed under the process for Approval In Principle of novel concepts was very effective in identifying risk issues and discussing how they could be prevented and/or mitigated. It should be stressed that the use of risk assessment was done as a complement to other valuable analysis methods, rather than as a replacement for them. Engineering evaluations, as well as experience gained in other similar designs were all necessary to use in order to arrive at a novel design with acceptable risk.

The analysis of proposed subsea cryogenic pipeline designs concluded that they are technically feasible from both safety and functional perspectives. ABS has therefore granted Approval In Principle to proposed designs.

REFERENCES