# Risk-based Technology Qualification to

# address the marinization of SMRs

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**Abstract**

One of the proposed advantages of small modular reactors (SMRs) is that they could be built in controlled factory environments and transported to power plant sites for installation. This concept aligns with the nascent ideas of transportable nuclear power plants (TNPPs) and floating nuclear power plants (FNPPs) that could be constructed in shipyards specialized in building large, complex vessels. The proposition is that a maximum of components outside the SMR itself are built by the yard and its supply chain, using as much as possible the existing codes and standards that such industry is used to apply, from the marine and the offshore oil & gas sectors.

The author will present a risk-based technology qualification approach demonstrated with floating liquefied natural gas projects 10-15 years ago. This methodological approach helps with the process of identifying those components that will be designed, built, installed, operated, maintained and decommissioned considering a different environment, codes, and supply chains compared to traditional land-based nuclear facilities and then assessing the technology qualification activities that will be needed. The goal is to provide a methodology that can help realize the promised deployment potential of SMRs through non-traditional construction and siting approaches.

## INTRODUCTION

Nearly two decades ago solutions were being sought to exploiting open sea offshore gas fields that were thousands of miles away from the intended market for that gas. Knowing that the most economical transport of natural gas over long distances were pipelines cannot be deployed is liquefying it and transporting it by LNG Carriers, work started to engineer floating liquefaction facilities. They should be able to do what for decades had been done onshore. Receiving the feed gas from the field, remove the condensates, the mercury, the sulfur, the CO2, the water, separate the heavier compounds, liquefy it and store it, to finally offload it to a LNG Carrier that will send it thousands of miles away to an import terminal. And this had to be done safely and in a financially meaningful way.

There are now 7 floating liquefaction units or FLNG operating in the world with more than 20 new projects being considered. In order to get here the whole industry had to re-invent a land-based technology to be used in an open-sea one, subject to completely different environmental conditions, motions in the 6 degrees of freedom and operate for 20years or more without ever going back to shore for maintenance or repair.

A key component to how this was done was through risk-based new-technology qualification. The idea is to identify what is really innovative within a concept, identify what is the common ground from the merging applications, at that time the on-shore LNG terminals and the offshore oil floating units or FPSOs, and what are extrapolations of known applications. The paper is making use the guideline principles developed at the time Ref.[1].

The same approach can be applied to FOAK projects of TNPPs and FNPPs, this time merging the nuclear industry and the offshore oil&gas industry.

Many of the steps presented in the paper will appear as common sense and it will relate to concepts and activities familiar to both industries. The most valuable point of the contents of the following pages is the methodological structural process that, when followed, will support the reasons why certain activities are done and provide assurance to stakeholders that rational process was followed, corners were not cut and the new technology being developed was demonstrated in a diligent manner.

The objective of this process is to assess the technology in terms of maturity with regards to expected application, to identify component failure modes of the technology and to ensure the associated risks are controlled and mitigated to an acceptable level thanks to a number of qualification activities.

In the case of technologies which are not covered by existing recognized requirements (e.g. rules, standards, codes of practice), technology qualification can be used to demonstrate that are given technology provides an acceptable level of confidence. Technology qualification can also be used to confirm feasibility and absence of show-stoppers that may prevent the technology from being developed to maturity.

## TERMINOLOGY USED

For the purpose of the paper a certain number of terms will be used, some of which have different meaning or implications for the nuclear and the offshore oil and gas industries. Solely for the purposes of the paper, the definitions as presented in the annex, will be used without any intention of proposing them as the most appropriate terms outside the paper.

## RISK BASED NEW TECHNOLOGY QUALIFICATION APPLIED TO FNPPs and tnpps

### Scope and Technology Description

The starting point of the new technology qualification proposed is to define the battery limits of engagement, and for TNPPs and FNPPs is proposed to cover the systems and components that will be under the responsibility of the yard (manufactured, procured, built and integrated). Under this assumption the reactor itself and the first heat-exchanger loop will be assumed as owner-procured items and would be out of the scope.

The immediate second step is to properly describe the technology, what is the purpose for its development and of what will it be made of. It is important for a clear understanding by the interested parties that this description also includes the components not part of the scope.

A short technology description covering the following points shall act as the introduction to the qualification process:

* The intent of the technology developed.
* The environment and conditions under which the technology will be used.
* The expected life cycle of the technology.

The next items of the technology description will allow a deeper understanding of its purpose and how it is supposed to operate. This is done through a functional and a physical breakdowns.

#### Functional Breakdown

The functional breakdown aims at identifying all the functions performed by the system and the necessary inter-relations between them to properly perform a given task. Each of the components will satisfy one or several functions. An exhaustive functional breakdown will help deploying a thorough technology qualification plan. Functions are proposed to be categorized as:

* Principal Functions
* Auxiliary or Secondary Functions
* Constraint Functions.

For nuclear plants there are a series of functions that, from a generic point of view, would fall under the Constraint Functions but that for their relevance to the industry it might be necessary to have them have their own function category:

* Radiation Containment Barrier (1st to 3rd)
* Nuclear Safety Barriers (control of radioactivity, cooling of radioactive material, confinement of radioactive material)
* Security Barriers

A description and some proposed examples follow.

* Principal Functions (PF): The basic functions for which the system has been designed. Some examples of principal functions for a FNPP or a TNPP could be:
  + - * Energy Production
      * Electricity Production
      * Electricity/Energy Distribution
* Auxiliary or Secondary Functions (AF): Functions which are essential for the completion of principal functions. As examples of auxiliary functions, for FNPPs or TNPPs, the following could be considered:
  + - * Auxiliary systems fluids handling
      * Auxiliary Systems fuel handling
      * Ballast Water Storage
      * Electrical
      * Fresh Water Generation
      * Fresh Water Storage
      * Heat Transfer
      * HVAC
      * I&C
      * Lifting appliances
      * Power
      * Reactor components handling
      * Fuel Storage
      * Support Structure
      * …
* Constraint Functions (CF): Functions made necessary by the conditions to which the system is exposed due to the combination of different factors. For FNPPs and TNPPs examples of Constraint Functions could be:
  + - * Backup
      * Protection from the environment
      * Environment protection
      * Transport Structure
      * Emergency
      * Spare & Maintenance
      * Fire Fighting
      * Wasted fuel management and storage
      * Other offproducts Management
      * Satisfy the power demand conditions (Electrical Power System)
      * Fire-fighting (Emergency Systems)
      * Refuge, Evacuation and life-saving (Emergency Systems)
      * to shut down safely and in a timely manner in case of incident or hazard.
      * …

#### Physical Breakdown

This consists in identifying the physical systems, sub-systems and components down to a relevant level coherent to the functional description made before. The ideal situation is that each of them have their expected functions assigned, knowing that one component or system could be fulfilling more than one function. For example, longitudinal and transversal bulkheads can, at the same time, act as the primary support structure and also as 3rd radiation containment barrier.

#### Acceptance Criteria

Either through specific references to codes and standards, either through a general requirement expected as a successful function completion the acceptance criteria should be declared for each function. Finding difficulty in identifying the appropriate codes and standards or when wanting to use another industry’ codes will naturally point to components or systems that should be part of the new technology qualification process. In the case of FNPPs and TNPPs we would find in such latter case the use of marine and offshore steel or pipe class standards for structural and mechanical components that would have always been designed, fabricated, controlled and installed with nuclear land-based standards.

#### Life-cycle phases

The detailing of the expected life-cycle phases is a final component of the technology description as it will also allow identifying if a regulatory framework can be already identified for each of such phases. When missing it will already be pointing to a necessary action within the new technology qualification.

### Maturity Assessment

The maturity assessment proposed in this process is not the Technical Readiness Level (TRL) although it is related to it.

Technology Readiness Level provides a measure of the technology development state and Various scales are adopted depending on the domain, for examples see Ref.[1].

The maturity assessment proposed is of a more qualitative nature that allows addressing:

* Materials not quite used for the conditions and/or functions expected in the new technology
* Components that have been successfully used in the industry but not for one of the functions being considered in the new technology.
* Components that have been successfully used in the industry but never in a system, a configuration or interrelationship as proposed for the new technology.
* Components or systems that have been successfully used in a different industry, with different operational and/or environmental conditions.
* Components for which the codes or acceptance criteria being considered have not been applied before.

It is therefore proposed to use a two-entry matrix for such maturity ranking:

On one side would be 4 levels of technical maturity:

Proven

Limited References

Extrapolated from proven

Unproven

Note: If a TRL assessment exists for some of the components, this can be used as demonstration of the maturity level ranking selected

On the other side would be the intended application environment and conditions:

Similar

Different

The resulting matrix is then divided into 4 levels of maturity ranking: 0 to 4 as illustrated in Ref.[1].

The maturity ranking thus described will provide the expected depth of the new technology qualification for the component/system-function pair:

0 No new technology qualification activity is needed. Proven methods, tests, analysis can be used to provide evidence of the technology.

1 Light qualification activities are to be expected, based on desktop review and engineering studies.

2 Moderate qualification activities are to be expected, based on physical tests in addition to those for ranking 1.

3 High qualification activities are to be expected, extending the number and depth of tests and studies required for ranks 1 and 2.

A practical way of having this Technology Maturity ranking done is through a workshop where the following interested parties can be invited to participate:

Overall plant designer

Reactor designer

Main contractor

Independent party and facilitator

Depending on the level of design advancement it might be useful to have representatives of the regulatory body present at the workshop.

### Risk Assessment

In view of providing the basis for an optimal qualification plan that can be defended as properly following a due diligence process it is proposed to have a risk assessment for those components, systems and functions that have been found having a maturity ranking of 2 or above.

The objective is to be able to provide a criticality ranking based on a probability of failure and a severity of consequence due to failure of the items assessed.

Ideally such criticality ranking should be done for the different dimensions of safety, environment, and business. A sample of possible applicable risk assessments that could be employed are given in the Table 1 (extracted from Ref [2]).

A good starting point is a HAZID for Hazard Identification (with a guide given in Ref.[3]) to properly list the hazards that the facility will see, within the battery limits of the new technology qualification (see §1)

Table 1 Risk assessment studies options

|  |  |  |
| --- | --- | --- |
| Reference | Title | Application Context |
| EN ISO 17776 | Major accident hazard management during the design of new installations | Offshore Oil & Gas |
| EN 1474-3 | Installation and equipment for liquefied natural gas - Design and testing of marine transfer systems - Part 3: Offshore transfer systems | LNG Transfer systems |
| IEC 60812:2018 | Failure Modes and Effects analysis (FMEA and FMECA) | General |
| API RP 14J | Recommended Practice for Design and Hazards Analysis for Offshore Production Facilities | Offshore Oil & Gas |
| ISO 31000 | Risk management — Principles and guidelines | General |
| EN ISO 13702 | Control and mitigation of fires and explosions on offshore production installations | Offshore Oil & Gas |
| IEC 31010:2019 | Risk management — Risk assessment techniques | General |
| IEC 61882:2016 | Hazard and operability studies (HAZOP studies) - Application guide | General |
| IEC 61025 | Fault Tree Analysis | General |
| IMCA D039 | FME(C)A guide for diving systems | Diving Systems |
| IMO MSC/Circ.1023 - MEPC/Circ.392 MSC-MEPC.2/Circ.12/Rev.2 | Guidelines For Formal Safety Assessment (FSA) REVISED GUIDELINES FOR FORMAL SAFETY ASSESSMENT (FSA) | Rule Making Process |
| IEC 61508:2010 | Functional safety | electrical/electronic/programmable electronic systems |
| NORSOK Z-013:2010 | Risk and emergency preparedness assessment | Oil & Gas |
| ISO/IEC 27005:2018 | Information security risk management | Information Technology |

### Qualification Plan

A qualification plan is established to provide evidence that risks identified during the technology assessment are adequately addressed. This is done by defining the extent and detail of the qualification activities that are to be undertaken on each item above a maturity ranking of 1.

A qualification plan should include the following information:

* identify qualification activities to validate
* give acceptance criteria
* describe tests to be performed
* describe the planning
* identify the responsibilities
* specify the surveillance and inspection requirements

The acceptance criteria should be, as far as possible, expressed in quantitative way (target values as: maximum pressure, temperature, speed,...) either based on project operational and accidental limits or based on recognized codes and standards that will be referred to.

Some of the qualification activities can be declared as being part of the project specific classification/certification requirements while others will need to be successfully executed before moving into the construction phase.

Throughout the different steps different technology qualification activities will start to become apparent, even before reaching the risk assessment stage. For example, components that are usually fabricated in land NPPs according to the nuclear industry recognized standards, may now want to be fabricated, welded, tested and installed according to those the shipyard and its supply chain are acquainted with (structural steels, piping classes, pressure vessels). For these components then the qualification activity will be a gap analysis between the marine & offshore codes and standards and the usually applied nuclear industry standard (when falling under a nuclear safety class requiring demonstrating compliance to a certain code). The result of the gap analysis might lead to accepting the marine & offshore codes proposed (thus ending the qualification scope) or to a change of the shipyard scope and owner-procured items list.

For items for which a criticality rating has been carried out, the extension of the qualification activities and the recommended participation of an independent party confirming the appropriate execution of such activities, will increase with the criticality.

Qualification activities may generally be grouped into the following different categories:

engineering analysis (Analytical analysis, Numerical analysis)

testing (Materials testing including destructive tests, repeated testing, long term testing, accelerated tests, working tests, pressure tests, performance tests, fail-safe tests)

manufacturing

surveys and inspections

quality system (quality assurance and quality control)

### Execution

The execution of the qualification plan consists in carrying out the qualification activities and document the performance for the concerned activities compared to the acceptance criteria.

The execution of the qualification plan should be recorded with the proposed following documents, as relevant:

Reports relative to the qualification activities such as: tests reports, engineering reports, fabrication reports, inspection reports and- Quality Assurance/Quality Control (QA/QC) reports.

Performance reports to demonstrate compliance against the acceptance criteria, including margins against target specifications, sensibility analysis and the assumptions and limitations.

## CONCLUSION

The paper presented a proposed methodological guideline to support a due diligence process demonstration when joining nuclear and marine & offshore civil actors in order to deliver FOAK FNPPs and TNPPs with the intention of deploying plants economically without compromising safety and to the required project performance expectations.

It has been drafted based on the guidelines developed to support the natural gas liquefaction floating facilities deployment and adapted based on the discussions and exchanges the author has had with different actors of both the nuclear and the marine and offshore industries.

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References

1. Guidance Note NI525, Bureau Veritas Marine & Offshore “Risk-based qualification of new technology - Methodological guidelines”
2. Guidance Note NI635, Bureau Veritas Marine & Offshore “ Index on applicable risk analysis for marine and offshore”
3. ISO 17776: Offshore production installations

acronyms

Table 2 Acronyms used

|  |  |
| --- | --- |
| ACRONYM | Description |
| FLNG | Floating Liquefaction Natural Gas |
| FMECA | Failure Modes, Effects and Criticality Analysis (FMEA and FMECA) |
| FNPP | Floating Nuclear Power Plant |
| FOAK | First of a kind |
| FPSO | Floating Production Storage and Offloading |
| HAZID | Hazards Identification |
| LNG | Liquefied Natural Gas |
| NPP | Nuclear Power Plant |
| SMR | Small Modular Reactor |
| TNPP | Transportable Nuclear Power Plant |

annex: TERMS USED IN THE PAPER

**Certification**: independent assessment by a third-party confirming compliance to a pre-defined set of standards and criteria of a predetermined equipment, system, or installation. It can include design review, quality controls, witnessing of physical tests and surveillance of the fabrication and construction process. Certification activities end once the equipment, system or installation is commissioned and declared by the owner/operator ready for operation.

**Classification**: The objective of the Classification is to verify the structural strength and integrity of essential parts of the unit’s hull and its appendages, the reliability and function of the propulsion and steering systems, power generation and those other features and auxiliary systems which have been built into the unit in order to maintain essential services on board. Compliance is done against the Classification Society own Rules, that are publicly available for most of the IACS (International Association of Classification Societies) members. Harmonized rules[[1]](#footnote-2) exist for some sea-going vessels but this is not the case for the rules covering offshore floating units. Nevertheless, the industry and the leading International Classification Societies recognize overall equivalence between them.

Classification usually starts at pre-design stage and in most cases continues up to decommission, although in some locations with the Safety Case regulations operators can drop Class surveillance once the unit has its licence to operate and is under the state safety and environment regulator surveillance.

Classification activities will cover:

Plan & document approval based on Class and agreed Rules & Standards

For some Classification Societies: Independent Analyses

Appraisal of the design of materials and equipment used in the construction

Survey during material and equipment factory acceptance tests

Audits of manufacturers QA/QC[[2]](#footnote-3) procedures

Certification of welders and welding equipment

Certification of inspection technicians and inspection equipment

Survey during construction at shipyards and attendance at tests and trials

In-Service Surveys based on Class and agreed Rules & Standards

Note: In the IAEA glossary, Classification may have a different meaning, e.g., Safety Classification is the assignment to a limited number of safety classes of systems and components and other items of equipment on the basis of their functions and their safety significance.

**Construction**: physical activity leading to the erection of entire plant blocks made up of a fabricated elements plus the subsequent connections (for example through welding) between blocks in order to build the plant.

Note: In the IAEA glossary, construction is understood to be the process of manufacturing and assembling the components of a facility, the carrying out of civil works, the installation of components and equipment, and the performance of associated tests. Construction is one of the six major stages of the lifetime of a nuclear power plant and often requires a license from the nuclear regulator.

**Fabrication**: physical activity leading to the completion of items such as pipes, HVAC (Heating, Ventilation, Air Conditioning), forged items, done directly at the construction yard with its own means and usually plant-specific (one-of-a-kind). It also relates to the cutting of metal pieces and plates that will be used in the construction.

**Installation**: usually following transport it is the physical activity in which the plant is placed in its final operating site prior to commissioning and brought online.

Note: In the IAEA glossary, Installation is an activity of Construction.

**Integration**: physical activity of installing manufactured equipment to the construction blocks and making the necessary connections with the different systems (mechanical, electrical, instrumentation & control, etc.) to have them operate as per design considerations.

**Manufacturing**: physical activity leading to the completion of a part, piece or whole equipment based on the deliverables provided by the Detail Design activity. Usually takes place at dedicated sites of specialised manufacturers.

**Plant**: the entirety of the nuclear power generation installation made of a steel hull within which is installed the nuclear self-contained reactor and all its associated safety, auxiliary and heat transfer systems as well as the necessary electrical and mechanical equipment for the electrical power generation, transformation and connection for distribution to the onshore power grid.

Note: In the Marine & Offshore industry, *Plant* may be called *Power Barge*.

**Surveillance**: within the context of the paper, it refers to an independent party’s (different to the owner/designer/operator) activity covering the design review (including numerical analysis review and drawings compliance checks), factory acceptance tests (FAT) witnessing, safety compliance tests witnessing, welders qualification review, welding quality checks, material quality checks, integration checks, commissioning tests witnessing and quality control procedures review. The level and degree of surveillance will vary between project phases.

**Technology Qualification**: A series of activities performed by the conceptual designer, manufacturers, independent 3rd parties and regulators in order to confirm that a technology, a piece of equipment, a fabrication process or all of the above is deemed conforming to the safety requirements, that it can be fabricated reliably within a defined set of specifications and can fulfill its design requirements. The activities can include independent document and calculations review, laboratory tests, destruction tests, aging tests and at-scale operational tests.

Note: In the IAEA glossary, Qualification is understood to refer to a process of determining whether a system or component is suitable for operational use. For example, equipment qualification is defined as the generation and maintenance of evidence to ensure that equipment will operate on demand, under specified service conditions, to meet the performance requirements. The proof of equipment can perform its function is sometimes terms substantiation.

1. https://iacs.org.uk/resolutions/common-structural-rules [↑](#footnote-ref-2)
2. Quality Assurance / Quality Control [↑](#footnote-ref-3)