Product assurance in the submarine supply chain

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Synopsis

Submarines are high value assets that require material integrity and equipment reliability, to operate in an extremely hostile environment. Physical and financial constraints, as with any design and build, require an assessment of the acceptable level of risk that allows a submarine to operate safely and remain affordable. These risks need to be robustly managed from identifying and quantifying the associated risk in the design stage, to assessing the risk associated with build quality and in-service degradation. Surface ships and submersibles, both commercial and naval, have a well-defined and prescribed product verification process in the form of Class Society Rules, adoption of which will provide assurance of the design safety, build quality and in-service capability, in an industry accepted approach. However, whilst attractive, these cannot be directly applied to a submarine.

The assurance process applied to a submarine must recognise and address: its unique operating environment, risks that are unique to a submarine operation and the physical constraints imposed. The number of submarine operating navies, capable submarine designers and builders in the world are limited. There are restrictions on the sharing of technology, design and build methods. Safe in service operation requires recourse to the original design intent, standards, and assumptions. Complex contracting arrangements may make it difficult to access such information particular as time passes. These presents a challenge to the development of a common traditional prescriptive rule based assurance process that would be internationally acceptable and available to all.

A goal based assurance approach benchmarked against industry practice can provide a solution to these problems. This paper demonstrates how an assurance processes can be successfully applied in full or in part to a submarine, system or equipment for the build and in-service programme using Lloyd's Register's (LR) new Submarine Assurance Framework.

Keywords: Submarine, Supply chain, Assurance, Certification, Safety

1 Introduction

Submarines are high value assets that require material integrity and equipment reliability, to enable them to operate in an extremely hostile environment. The consequence of failure can be immediate and catastrophic if flooding or propulsion malfunction cannot be resolved. Physical and financial constraints, as with any design and build, require an assessment of the acceptable level of risk that will allow a submarine to operate safely and remain affordable.

There is a significant responsibility on the Owner to provide a safe and capable platform. Risks need to be robustly managed. They are usually identified and quantified in the design stage, but they also need to be assessed and managed during the build and in-service stages, noting that service extensions often go well beyond the original design life. Risks due to manufacture and maintenance need to be managed, and assurance provided that suitable controls are in place.

Commercial shipping Owners and regulators have used Class Societies in an assurance role for many years, developing assurance processes, sharing knowledge, and gaining experience through incidents, accidents and failures. More recently, navies have been moving to a class based assurance system for warships. This has been

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Roger Coles Served as a sea going Engineering Officer with the RFA and PNTL then worked at James Fishers & Sons as a Superintendent Engineer. Graduated 1997 first class honours degree in Mechanical Engineering and joined Lloyds Register working on existing ship, offshore verification, nuclear reactor pressure system and ship new building. 2006 onwards full time on the Astute submarine project. becoming Senior Project Manager in 2012 for both Astute and Dreadnought project. Currently LR Submarine Programme Manager as principal surveyor responsible for structural mechanical and electrical aspects of product verification at the shipyard and suppliers works. Also, responsible for development of the submarine business
Matthew Palmer joined LR in 2012 after his previous role in the Royal Navy as an Engineering Office on Trafalgar Class submarines. Matthew works on developing Goal-based Standards, Rules and assurance products for naval submarines and unmanned marine system assurance products. Matthew is also the part of the Secretariat for the INSA Naval Ship and Submarine Code. Matthew has been leading the industry engagement, on the certification of unmanned marine systems under 24m.

for reasons of economy, to help set common safety standards, and to share best practice. For submarines, this has proved to be much more difficult, as design rules are difficult to share when the performance and safety margins are closely guarded secrets.

Ships and submarines do share some technologies. However, it is important to recognise that whilst this is the case, the operation, and operational environment, of naval ships and submarines are fundamentally different. This may be an obvious statement, but it is a major consideration when creating an assurance process for naval submarines.

Other significant differences include: the increased opportunity for immediate and catastrophic loss requiring enhanced assurance, the level of integration which make it difficult to separate safety and capability, a focus on stealth which may increase the integrity required for components which may not directly impact safety, and a pressure hull enclosure which makes replacement of equipment very difficult.

For surface ships, specification of Classification Society Rules invokes a set process for assurance of the design safety, build quality and in-service capability using an industry accepted, well-defined, prescribed approach, recognised by regulators. The question is, can a similar regulatory assurance processes be successfully applied to a submarine design, build and in-service programmes without significant modification?

We believe it can and a goal based approach to submarine assurance is the way forward. It allows greater freedom in standards selection, design innovation and recognition of each particular submarines' operational context. A customisable approach is possible within a goal based standard and it can enable the assurance process to be increased or decreased in response to the demands listed above.

2 A goal based approach

2.1 Drivers for goal based compliance

The first question we need to answer is, what do we mean by independent goal based assurance?

> *Goal based assurance is a method which establishes safety assurance activities through the selection of applicable tailored solutions (standards), with positive verification of their application to a product by a third party. A justification process is used to show that the selected solutions meet the assurance goals and are valid for the proposed operation of the asset. Objective evidence is sourced to record compliance and verify material state.*

There is a lot in that short statement and section three seeks to illustrate the principles using a worked example. In this section, we unpack that statement.

There are several ongoing changes in the submarine enterprise which make the flexibility of goal based assurance an attractive solution:

- The increasing challenges of submarine design: more complex systems, sensitive requirements, and interdependent functions.
- Reduction in national portfolios of standards for submarines, and confidence in the content which may be out of date.
- Reduction in technical capability within the submarine enterprise, for submarine design, build, maintenance and decommissioning coupled with a greater reliance on the submarine builder and commercial maintenance facilities.
- Increased demand for submarines, in particular, off the shelf designs.
- Increased commercial offerings of small but complex submarines to the global market.
- Increasing automation and sophistication of submarines and naval warfare.

2.2 Suitable candidates

There have been recent developments that offer a foundation for a goal based assurance framework and provide experience of application (James 2014, Hoppe 2008):

- Naval Ship Code (NSC) and the Naval Submarine Code (NSubC) by the International Naval Safety Association (NATO 2020, 2022). These provide a common structure and language for goal based standards in the Navy.

- Assurance processes for novel technology qualification (TQ) (API 2017) (LR 2022) (US DoD 2012). These standards introduce concepts of levels of rigour which require an assurance process appropriate to hazard and consequence. In the case of TQ, the maturity of the technology is also considered in the assessment of risk.
- LRs Code for Unmanned Marine Systems (LR 2017). An example of a goal based assurance regime which is being applied to define common assurance requirements for a variety of technologies, with varying complexity and risk.

Picking up first on the NSubC, which was developed by INSA as goal based submarine assurance standard. This was originally created in 2012 and developed by a specialist NATO team before being passed to INSA for maintenance. The NSubC follows the same structure as the (NSC), both use a tier structure as shown in figure 1.

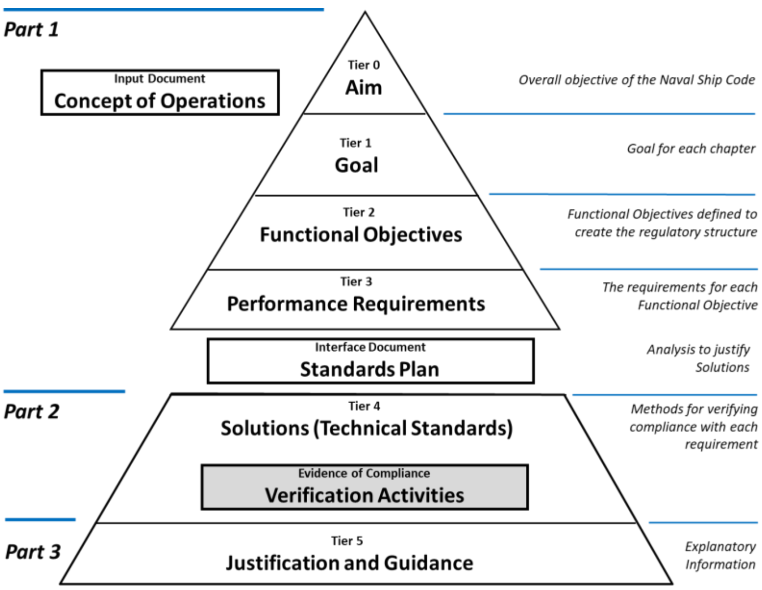

Figure 1. Naval Ship Code Parts and Tiers

Navies are seeing the benefits of using the NSubC as an overarching set of safety requirements in new build projects. So it is obvious that it makes sense to align any assurance framework with the NSubC structure. To make the code accessible to many navies, the NSubC is truncated at Tier 3 to avoid publishing sensitive information. This means that in its current form, the NSubC will not deliver assurance, the code requires a process to be created for it to be implemented.

2.3 How do we deliver goal based assurance for submarines?

To be implemented effectively, the NSubC requires three key elements: firstly a set of solutions, typically project specifications, Rules, Codes or Standards, secondly a process to ensure that these are justified against the performance requirements, finally a verification or assurance process for the life of the submarine, to check that the submarine complies with the solution set.

LR have published a Submarine Assurance Framework (LR 2021) to implement the NSubC. It includes a standards justification process which is an addition to traditional classification assurance activities, but is critical for effective implementation of a goal based standard. The framework includes the familiar verification processes of: design appraisal, equipment certification and survey. This allows the existing classification societies processes and networks of surveyors to be used. A key benefits is that Marine suppliers are familiar with these verification processes and they can be simply invoked in a contract "*Equipment is to comply with the LR Submarine Assurance Framework*".

A goal based assurance process has to be applied over the full submarine lifecycle to provide a consistent approach to safety assurance activities during design, build, in-service, and disposal. In the current model used by navies, this assurance is often undertaken by different parties. Use of the classification society verification process allows a single party to provide assurance through the submarine lifecycle bringing benefits of consistency, traceability and collation of corporate knowledge.

One of the features of the process described is that is can be applied to an entire submarine, a system or individual component. Take a component as an example, a goal based assurance process should ask the following questions:

- What is the function of the component?
- What is environment that the component has to operate in?
- What system is part of?
- What elements does the component comprise of?
- What are the transverse issues that need to be considered, shock, noise etc?
- What are the normal, abnormal and emergency operating conditions?
- What risks does the component present?
- What are the consequences of failure?

This might seem rather basic, but without an assurance framework to force these questions, they might not get asked and key risks might be missed. The framework asks these questions through the standards justification and design verification process.

2.4 Submarine Assurance Framework

The framework provides a goal based assurance process. The document itself has two key parts to its structure.

- Volume 1 Parts 1 to 3 The Assurance Process with the key assurance elements just discussed.

  Standards Justification (SJ),

  Design Verification (DV) and

  Product verification (PV).

- Volume 1 Parts 4 onwards Technical Requirements. Currently whole boat requirements.

The framework can be applied in full to the submarine or in part to a product which may be a system, module, equipment or component within a system.

The assurance elements are not new, they are based on normal classification process but adapted for the risks associated with submarine operation. The standards justification process is taken from our experience of working with Naval Ship Rules and the goal-based NATO NSC. It includes the following documents.

A Submarine Assurance Plan is required to set out the scope of verification activities DV and PV. It is similar to a technical scope of work and will provide the means to issue a submarine assurance certificate.

A Standards Justification (SJ) Plan will define how the standards are to be justified as suitable for assessment of the product. The NSubC and technical requirements of the Submarine Assurance Framework along with the Concept of Operations will be used as the “measure” in the justification process. The justification process will ensure standards are correct, consistent, coherent and current. A good example is the EU Pressure equipment directive often used for pressure vessel certification. This relies on established codes such as ASME VIII or PD 5500. However, the criteria within these standards do not account for ship motions or shock, both of which are important for a submarine and a surface ship so they need to be augmented. The framework indicates what augments are required in the Technical Requirements part of framework (whole boat). Project policies, specifications and national standards will define what is to be achieved.

Once a suitable set of justified prescriptive technical requirements has been established from different sources, and augmented or tailored as necessary, the traditional processes of design verification (plan appraisal) and product verification (survey) can be applied.

Design Verification (DV) is the same as the class design appraisal activity, an independent check that the design complies with the chosen standards. The manner of verification needs to be defined and will depend on the criticality of the product being assessed. Design Verification may involve independent assessment, independent checks, audit or self-declaration. The definition of a standard is quite broad in the framework, it includes rules, codes, standards and project specifications, recognising that for a submarine, a product will be assessed against a compendium of technical requirements. The previous standards justification exercise will have ensured it is an appropriate coherent set of technical requirements.

Product Verification (PV) involves the survey and inspection of components. Classification requires traceability for important products right back to the point of initial manufacture, the cast or pour of the metal into a mould. It requires verification that manufacturing facilities can produce consistent, quality components through a system of works approval. We have seen large castings rejected multiple times for failing integrity requirements when manufacturing outside the range of a class works approval.

The process requires equipment be appropriately tested and qualified for use in the marine environment in which it will be used, though a system of Type Approval. We have seen installed equipment replaced when the detailed conditions of approval were compared to the intended operating environment, system demands or emergency requirements such as fire.

The manufacture, assembly, and testing of equipment in the works, is to be monitored and independently witnessed at key points during the manufacturing process, manufacturing process are monitored and audited. The surveys and inspections are to be defined in advance in a product Inspection and Test Plan (ITP). The process is significantly more robust than simple attendance at a factory acceptance test (FAT) or a first article inspection. The process includes regular patrol of production processes and facilities to ensure they are delivering the required quality. The Product Verification Plan required by the framework includes all of these elements and confirmation that the verification processes applied, are appropriate for the criticality of the product. Completed equipment and components will be certified as complaint, with suitable records and evidence in place. The classification process adopted, ensures this is in place before the equipment leaves the factory. We have seen many cases of equipment evidence being chased up well after installation in the submarine with the potential to significantly delay production.

Product Verification does not conclude at equipment completion, the proposed framework will apply the same assurance process and verification activities to the build and assembly of the submarine. The product verification activities are this time, described in a Construction Test and Inspection Plan. On completion of verification activities and assembly of all the appropriate evidence, a submarine assurance certificate can be issued to support acceptance. Interim certificates may be issued to confirm completion of a build stage or unit.

Product Verification can continue through into service with continued material state survey, condition assessment and measurement, plus verification of any modification or upgrade. To support this, criteria need to be established for measurement and assessment of allowable degradation and material state deficiencies. The framework requires these to be included in an In-Service Verification Plan which is to be defined during the design and build phase and not several years after delivery as the submarine approaches its first refit.

As discussed, the framework can be applied in part or in full. If applied in part, it is essential that Vol 1, Pt 4, the whole boat chapter is used along with the system, equipment, component or material performance requirements. The whole boat chapter reinforces the concept that a submarine is a complex interrelated set of systems which have dependencies and interactions with each other. These must be respected.

The elements of the framework are not novel, but its application to a submarine is. The framework can enforce a degree of discipline and rigor in a project using accountability to a third party to help ensure quality products are installed. The framework offers a tool to addresses manufacturing and in service risk.

2.5 Technical Requirements (whole boat)

The whole boat requirements define the key attributes that make a submarine, a submarine. All engineered components in the world have requirements that they must meet. e.g. The temperature range of operation for a battery, the water depth for a watch. These are physical attributes and assurance is required to make sure that the equipment will work in the defined environment. Items are typically subject to prototype or production testing to verify satisfactory performance. Whilst prototyping is expensive for a whole submarine, key equipment can be subject to an assurance process to demonstrate suitability. The framework identifies the attributes which need to be assured for equipment in a submarine environment and proposes a Type Approval process. Some of these are different from commercial submersibles or surface ships. For example, submarines can create an unexpected environment: sudden changes in internal atmospheric pressure from operating with a snort mast, shock from an underwater explosion or limits on signatures which can give away a position.

As well as physical criteria to be achieved, there are certain processes to be applied to ensure equipment is safe for use on a submarine such that it does not pose a threat to the submarine or the crew. An example of this is control of hazardous atmospheres. Processes are required to identify hazards from flammable or toxic fluids and gasses, then manage the risks to the: crew, submarine, and equipment, for both short and long exposure. A submarine has an enclosed atmosphere with limited opportunity to purge or exhaust gasses so there are some unique challenges.

2.6 Critical components

One of the key processes in the whole boat requirements that which determines the risk a system, equipment or component poses to the submarine and its crew. It is necessary to assess each item and determine its criticality. Many navies have their own process for categorising equipment e.g. UK DEF-STAN 02-207, US SUBSAFE. The framework provides a categorisation methodology compatible with these standards and the opportunity to develop a navies own risk matrix and targets for risk to the following: an individual, a group or loss of the submarine. All systems equipment and components are to have a criticality assigned.

The criticality will depend on the immediate risk to the crew or submarine, e.g. fire or flooding. Plus loss of function which could lead to an immediate incident or reduction in safety margin e.g. propulsion. Critically could also be dependent on the impact on production and ease of replacement e.g. equipment larger than the pressure hull access openings.

For a worked example, see figure 2. A submarine hull valve which could lead to unrecoverable flooding will be of the highest category (black). If protected, the inboard part of the system may be considered a lesser category (red). Systems which use the cooling water but are separated by a heat exchange may be of a lower category still (yellow) as then do not immediately lead to a significant incident. However, if the loss of the inboard system compromises a key safety function, its category may be escalated to a higher level (red or black). An item may also require a higher category if there are risks associated with the technology or manufacturing method, for example a flexible section in an externally connected sea water cooling circuit could be the highest category (black) because we do not have any operating experience in a submarine environment.

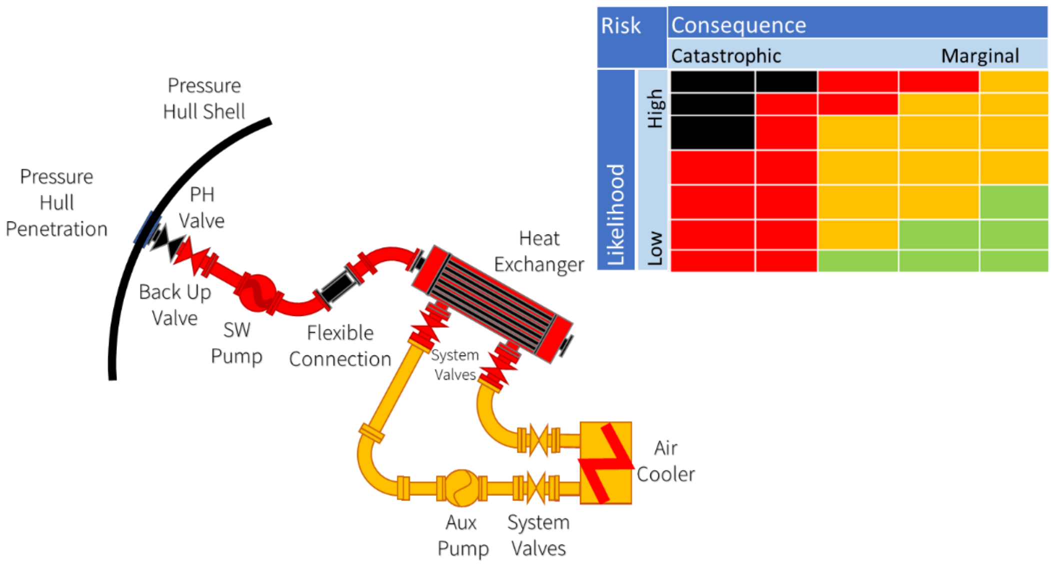

Figure 2. System and equipment risk and categories

3 Implementation

For a ship or offshore structure which is classed. The Classification Society Rules are specified in the headline contract between the owner and the builder. The simple phrase “to be built in accordance with *classification society* rules and regulations for the classification of *product*” invokes a complete process of assurance and verification activities which are prescribed by the rules and understood by the marine industry and its supply chain. The scope of assurance is well defined by the Rules. Statutory aspects such as lifesaving have an equally well establish process of assurance through IMO conventions, codes and circulars.

For naval ships, where parts of the supply chain are unfamiliar with class rules or, for offshore projects, where there are a mix of class and national standards, it is not quite so automatic. Supply chain certification is actively managed through equipment specifications and class society work instructions to ensure the correct scope and level of assurance is provided.

The framework requires active management of the assurance activities and adopts these processes. The way in which this is managed is described in the Submarine Assurance Plan. An example of a hull valve is provided to show how this works.

3.1 Hull Valve

A valve will consist of a number of components including, valve body, fasteners, valves, seats, seals, spindle, bonnet, and actuators. There are a variety of standards and design requirements to consider plus the valve has the potential to indirectly impact submarine systems.

Figure 3. Valve Components

3.2 The Plan

A Submarine Assurance Plan needs to be developed to define the scope of assurance activity. It will require input from the submarine designer in addition to the valve manufacturer. This is more than just an equipment specification. The plan will need to reference the designer's submarine safety management and safety assurance system which should determine how the equipment is to be assured and the project processes to be followed. These processes are to include: quality assurance, systems engineering, system decomposition, design, construction, through life support, hazard identification, assessment of criticality and primary design standards.

If contracting with a valve manufacturer, these procedures, or the output from them will need to be flowed down from the submarine designer. For a low level component such as a valve, the submarine designer's engineering design and speciation processes should have been followed to derive a series of requirements for the component. Engineering requirements should be captured in the valve equipment specification and the framework effectively requires the content to be justified. The requirements will include:

- Performance requirements based on the system design and operating environment. e.g. Operating pressure, flow rates, shock.
- Safety requirements based on an assessment of criticality e.g. response time, fire integrity.
- Duty cycle and maintenance, requirements based on maintenance philosophy e.g. number of operations between overhauls.
- Quality requirements based on criticality, e.g. inspection requirements, measurements, verification tests.

The verification process for each of the requirements will need to be defined in the Submarine Assurance Plan. For a valve, the plan will have to describe all three assurance processes in the framework: Standards Justification (SJ), Design Verification (DV) and Product Verification (PV). Verification activities will be required for each of these stages.

3.3 Suitable standards

A standards plan is required which will define the material specifications, materials standards, rules, and defence standards to be applied. There are likely to be a number of standards covering the materials, design requirements, testing and NDE. The framework offers an opportunity to utilise commercial standards and augment them with submarine requirements through project specifications. Care is needed as traditional naval standards include a lot of corporate knowledge which should not be discarded, but it is recognised, they may constrain solutions. Standards for a hull valve may include those listed in table 4:

Table 4. Potential standards for a hull valve.

Function	Standard	Title
Valve design	ISO 17292	Metal ball valves for the oil, petrochemical and associated industries
	EN 1983	Industrial Valves: Steel Ball Valves
	EN 13445	Pressure vessels not subject to flame.
	EN 12516	Industrial valves: Mechanical resistance of the enclosure. enclosures
	EN 12570	Industrial Valves: Operating Element Sizing Method
	ISO 5211	Industrial valves: Coupling of the actuators of the partial rotation valves
Naval Requirements	DEF STAN 02-375	Valve Design and Manufacture
Actuator Design	EN 15714	Industrial valves. Actuators.
Materials	LR Rules	Rules for the Manufacture, Testing and Certification of Materials
Watertight Integrity	DEF STAN 02-136	Design, testing and acceptance requirements for watertight integrity
Shock	STANAG 4549	Testing of equipment on shock testing machines
	STANAG 4142	Shock Resistance Analysis of Equipment for Surface Ships
	MIL DTL 901 E	Shock tests, (high-impact) shipboard machinery, equipment, and systems,
Fire Integrity	ISO 10497	Fire type-testing requirements
	ISO 19921	Ships and marine technology
Vibration	LR Rules	Type approval test specification
Cleanliness	Specification	Equipment Specification

The operating context for the following three items needs to be defined so that we can ensure that we fully understand all of the requirements and demands which influence the valve. All of the subsequent steps of the framework need this information to ensure that the assurance provided is appropriate.

- The submarine. The Concept of Operations for the submarine is needed to understand how the valve will be impacted by how the submarine is operated e.g. subject to shock or cold weather.
- The system in which the valve is fitted. A System Operating Concept is needed to describe what demands the system places on the valve e.g. pressure, flow, media, reversionary modes.
- The valve itself. A Valve Operating Concept is needed to describe how the valves is to be used e.g. number of cycles, means of operation, back up valve.

A review of the standards and their justification is required. The assessment will be based on:

- Suitability for use in the context of operation. e.g. submarine motions, fatigue, differential pressure. All derived from the Concept of Operations.
- A current and coherent set of standards and requirements that are in date with no overlaps or gaps.
- Suitability for the component criticality. e.g. Black category (loss of submarine)
- Standards are to include relevant whole boat transverse requirements e.g. Shock.
- Standards which satisfy whole boat requirements e.g. material smoke and toxicity (actuator sensors)
- Standards which meet the framework goals. In the absence of goals in the framework, either of the following could be used for their derivation:
    - o A standard specifically written for the application (e.g. DEF-STAN 02-375 Valve Design and Manufacture) or
    - o Goals could be derived on a project by project basis. For example using: ANEP 102 NSubC Ch IV Reg 6 and Ch III Reg 2, ANEP 77 NSC Pt1 Ch IV Reg 6 which are not quite detailed enough so in this example, they would need to be supplemented with performance requirements derived from NSR Vol2 Pt 7 Ch1.
- Suitability of any tailoring or modification of the standards by the project specifications.

3.4 Design Verification

A Design Verification Plan is required to describe how the verification will be undertaken. It will include all the activities undertaken to verify that the valve is suitable for its intended use and purpose. This could include design assessments for the following aspects:

- Submarine transverse requirements matrix
- Pressure stress and deflection assessment for the maximum pressure and pressure differentials using finite element analysis.
- Fatigue and crack growth for the operating pressure cycles and dive cycles using analytical methods.
- Engineering assessment of mechanical components under maximum torque and cyclic loads e.g. shaft, gears.
- Bolt torque calculations.
- Valve seat wear calculations.
- Wracking (bending) analysis using finite element analysis.
- Modelling of emergency shut-off manoeuvre using computational fluid dynamics.
- Shock analysis for fastenings, valve body and actuator using finite element and analytical methods .
- Fire resistance engineering justification .
- Corrosion engineering assessment.
- Test plan and test procedures.

A design verification of the hull valve will be undertaken by reviewing the submitted analysis reports. For critical items which could lead directly to the loss of the submarine (black category) independent analysis may be undertaken. This could be a check using a simpler analysis method or a full repeat of an analysis using alternative software. Such validation may not be needed if comprehensive testing is carried out. Finite element and CFD analysis are to be undertaken by competent persons using recognised software and methods, detailed analysis reports, containing suitable information will be required for assessment.

For a new valve design, the design verification will include qualification and prototype testing. All tests are to be performed at a recognised test facility, approved in accordance with national standards and are to use agreed procedures. For critical items (black category) both testing and analysis may be required. Certain tests will require independent 3rd party attendance to confirm adherence to the test protocols and verification of result. Tests may include:

- Pressure testing for operating profile and over pressures.
- Pressure cycles for fatigue.
- Emergency shut-off test/trial.
- Valve Manoeuvring tests for wear and fatigue.
- Shock qualification.
- Fire test to suitable standards.
- Accelerated corrosion tests.
- Wracking (bending) test.

The reviews of analysis reports and test reports are to be undertaken by suitable subject matter experts in the following disciplines: piping systems, CFD analysis, FE Analysis, transverse requirements, materials. Design appraisal documents can be issued for the review of each report and test report. A Design Verification report will be issued on conclusion of all assurance activities. It will confirm adherence to the Submarine Assurance Plan and provide a record of the approved design documentation. A copy of the design verification evidence will be retained to support future assurance stages.

3.5 Product Verification

A Product Verification Plan is required to describe how the verification will be undertaken. The level of verification will be determined by the component criticality. To develop the plan, the following are required: a breakdown of the components, the intended procurement and manufacturing methods. It can then be confirmed that verification activities and certification are appropriate for each component. The breakdown is to be undertaken to the lowest supplier level so that the source of all components and materials is known. The verification method at lower levels depends on component criticality. Selected component suppliers will be required to provide an ITP with the proposed verification activities. An ITP will be required for each manufacturer in the valve supply chain.

The Product Verification Plan and associated quality plan/policy, plus the ITPs are to be reviewed. The review will be based on the following:

- Manufacturer's quality process is appropriate for the product and its criticality.
- Quality requirements are adequately captured in the ITP. Sufficient hold, witness and review points provided at appropriate stages, e.g. pressure tests, with appropriate independent survey. Audit is proposed for appropriate processes. e.g. materials traceability.
- Inspection points and levels of assurance are appropriate for the component criticality. They are of sufficient depth and intervention to verify key manufacturing stages with suitable records being generated. e.g. heat treatment furnace records.
- Relevant requirements for any special or novel manufacturing processes which require particular controls are included. e.g. heat treatment or surface treatments.
- Verification requirements for the component adequately address the physical transverse requirements e.g. prototype testing for shock
- Verification requirements meet the requirements and expectation of the design standards. e.g. proof tests for system or deep diving pressure.
- Assurance requirements are broadly equivalent to marine industry component of a similar criticality e.g. Ships or offshore platforms.
- Verification requirements are suitable for the proposed manufacturing process and historical performance of supplier.

With the verification process determined, the necessary verification activities can be performed and regular visit reports and certificates issued to confirm the process is being followed. The verification activities can be contracted by the shipyard, component supplier or by a manufacture in the supply chain. We have developed software tools to support tracking of progress through equipment ITP activity and to host inspection reports. This is to ensure appropriate records are made and the process to completion is visible. Reporting will capture data and evidence to support the final certification of the product.

The above is focussed on the supply chain because we are dealing with a hull valve and delivery of a valve certificate. However, there are assurance activities associated with the satisfactory installation of the valve at the shipyard. Where contracted by the ship builder and verification activities are required in the yard, the shipyard Construction Test and Inspection plan will be reviewed in a similar manner to the above. We would expect to report on satisfactory completion of the shipyard assurance activities in a similar manner to those at the manufacturer.

Similarly, an In-Service Verification Plan can be developed to support the assurance of the valve through life. This will involve verification of: inspection, condition monitoring records, maintenance, overhaul, operational testing and any component revalidation activities e.g. proof testing, with suitable criteria defined, ideally with the designer's input. Replacement or repair items will follow the above new build verification process.

3.6 Certification

Through all the above processes it is important to record and communicate non-compliances with the standards, product verification plans and requirements. Proposals for repair, replacement or concessions will be reviewed and agreed by subject matter experts. Whilst programme and cost constraints will be noted, recommendations should be on an solely independent technical basis.

On completion, a submarine assurance certificate can be issued, it will have a clearly defined scope and confirm that all verification activities have been satisfactorily completed in accordance with the Product Verification Plan. The certificate will refer to output from the Standards Justification and Design Verification stages. Caveats and operational restrictions as a result of non-compliances will be clearly defined e.g. reduced inspection period or reduced operating pressures. The certificate will reference key subsidiary certificates and records, e.g. material certificates, test certificates and supplier documentation that provides the evidence for assurance. A copy of documents and manufacturing records should be retained in a suitable data store to support any evidence review of later technical enquiries.

4 Conclusion

Submarines are high value assets that require material integrity and equipment reliability to operate in an extremely hostile environment. However, we do not have an infinite resource to undertake our assurance, so we must undertake an assessment of the acceptable level of risk we can carry, and reconcile that with our budget to ensure the submarine can operate safely and still be affordable. These risks need to be understood and robustly managed. This involves identifying and quantifying the associated risk in the design stage, assessing the risk associated with build quality and in-service degradation to ensure the end of life risk is understood.

In this paper we have described the LR Submarine Assurance Framework which deconstructs the classification assurance process used for surface ships and submersibles to provide an end to end process for understanding and managing risk on a submarine. It allows the classification assurance process with its inherent benefits to be adapted and modified for the unique risks faced by a submarine. The process will provide assurance of the design safety, build quality and in-service capability using a goal based assurance approach which as been benchmarked against industry practice.

The intent is to provide the submarine enterprise with a common framework which gives a consistent rigorous method of assessment, records of design intent and records of construction from an independent third party engaged through the lifecycle of the submarine. This paper demonstrates how an assurance processes can be successfully applied in full or in part to a submarine, system or equipment for the build and in-service programme.

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Glossary of Terms

ANEP	Allied Naval Engineering Publications
CTIP	Construction Test and Inspection Plan
DSTAN	Defence Standard
DV	Design Verification
INSA	International Naval Safety Association
ITP	Inspection and Test Plan
NSC	Naval Ship Code
NSR	Naval Ship Rules
NSubC	Naval Submarine Code
PV	Product Verification
SAF	Submarine Assurance Framework
SJ	Standards Justification