

Novel Evaluation and Testing of Technology Qualification Process of Subsea Oil and Gas Products

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ABSTRACT

Use of robust products is of utmost importance in the subsea production systems to ensure the maximum utilization of the energy resources available under the seabed. To achieve highly reliable products, a comprehensive technology qualification program is proposed in this paper for the subsea electrical and electronics-based products. The recommended qualification program is specifically focused on a novel technology readiness level 4 (TRL4) process of the product used in an intended environment condition, which guarantees the product availability on the seabed without any operational failures. The analytical assessment on the products' design, operating conditions and compliance stress tests are proposed following the internationally recognized standards, e.g. The American Petroleum Institute (API), International Electrotechnical Commission (IEC), Institute of Electrical and Electronics Engineers (IEEE), International Organization for Standardization (ISO), European Standards (EN) and European Union (EU-directives). Modified environmental tests methods and novel product safety procedures are introduced for the first time to ensure that products meet the acceptance criteria set in the proposed TRL4 process. Finally, the proposed TRL4 process and its recommended test methods are exercised on the various functional units of the subsea electronic module. The experimental results show that the product is fit for use in the subsea environment after going through the proposed extensive qualification test program.

Nomenclature

AC	Alternating Current
API	The American Petroleum Institute
APSK	Asymmetric Phase-Shift Keying
CAN	Controller Area Network
CDN	Coupling / Decoupling Network
CE	Conformité Européenne
CEN	European Committee for Standardization
CISPR	Comité International Spécial des Perturbations Radioélectriques
DCV	Direction Controlled Valve
DNV	Det Norske Veritas
EEA	The European Economic Area
EN	European Standards

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EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EU	European Union
FAT	Factory Acceptance Test
FEA	Finite Element Analysis
FMECA	Failure Mode, Effects, and Criticality Analysis
kHz	kilo Hertz
kbps	kilo bits per second
MHz	Mega Hertz
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
mA	milli Ampere
Mbps	Mega bits per second
Mech.	Mechanical
min.	Minutes
OFDM	Orthogonal Frequency-Division Multiplexing
PC	Personal Computer
PCB	Printed Circuit Board
SEM	Subsea Electronics Module
TQP	Technology Qualification Program
TRL	Technology Readiness Level
USA	United States of America

1. Introduction

The energy sector, oil and gas, is utterly focused on the maximum consumption of the energy resources from the reservoirs with a prolonged operation of the install equipment at the lowest possible cost. The operators in the oil and gas industry are gradually working on two scenarios to develop a reliable and robust products to pump hydrocarbons without an interception. The first scenario is to monitor the existing assets using modern data analytic and improve the performance by using control techniques Aliev, Rzayev, Guluyev, Alizada, and Rzayeva (2018); Giro, Bernasconi, Giunta, and Cesari (2021). At the same time, the industry is exploring robust processes for the new products and systems development and the technology management to achieve quality excellence Mercado-Colmenero, Rubio-Paramio, Guerrero-Villar, and Martin-Donate (2018); Khalil, Jan, Tong, and Berawi (2017). It is aimed that the newly installed systems should be working on the seabed for a long period of time without any operational failures.

Robust product development is dependent on various factors, including the decisions of the design engineers to the choice of the components, their placement in the different areas on the Printed Circuit Board (PCB), and the intended environment where the product is being used. In the oil and gas industry, two conventional approaches:

quantitative reliability methods and experimental testing, are adopted to achieve highly reliable products with at least 25 years of lifetime of operation on the sea bed. Nevertheless, the target of both mentioned approaches is to achieve the technical and functional acceptance criteria that are set at the start of the product development cycle Mobin, Li, Cheraghi, and Wu (2019); Det NorskeVeritas (2017). Similar experimental based test approaches are adopted across various industrial applications on the prototype product to validate the design and also to check the durability of the products Li, Foss, Stelson, Van de ven, and Barth (2019); Vichard, Petrone, Harel, Ravey, Venet, and Hissel (2020). One of the key inputs to utilize these methods is the availability of Failure Mode, Effects, and Criticality Analysis (FMECA) European Committee for Electrotechnical Standardization (2018); Cai, Liu, Liu, Tian, Zhang, and Liu (2012) as per the framework defined within recommended practice API 17N American Petroleum Institute (2018a).

The FMECA structures the foundations for the detailed technical risk assessment, which leads to performing the analytical assessments or the experimental tests on the product under the umbrella of Technology Qualification Program (TQP) Det NorskeVeritas (2017); American Petroleum Institute (2018b). Subsea product qualification and risk management are derived and verified from various standards and recommended practices outlined by the American Petroleum Institute (API), and the International Organization for Standardization (ISO) American Petroleum Institute (2018a); ISO/TC 67 (2018). However, all electrical and electronics products developed under a 'subsea Qualification Strategy' should at least fulfil the industry prescribed test methods and requirements in American Petroleum Institute (2018); International Electrotechnical Commission (2010), as early as possible in the project life cycle. Also, the recommended practice of the Det Norske Veritas (DNV) Det NorskeVeritas (2017) provides the framework for the integrated software dependant systems used in the oil and gas industry.

In the technology qualification regime, environmental stress testing is an essential part of the experimental methods to obtain evidence for the intended use of the product in a specific environment. This process is known as a means of product reliability assurance, but it has been reported that conducting environmental stress testing (thermal and vibration stress testing) does not adequately detect all defects, especially in new product development Caruso (1996); Tustin (1986). Thermal stresses affect the performance of the electrical and electronic based products in terms of degrading the operational conduct in the different environments across the various industries Merienne, Lynn, McSweeney, and O'Shaughnessy (2019); Smet, Forest, Huselstein, Richardeau, Khatir, Lefebvre, and Berkani (2011). However, through varying the type of environmental stresses based on known failure modes and increasing their intensity, inherent defects can be accelerated to induce failure Bell, Cookson, Cope, Epperly, Fischer, Schlegel, and Skibinski (2001); Singleton, Strangas, and Aviyente (2017). This type of testing has evolved and is used in various applications from research and development of products to the quality control during the manufacturing Mo and Cai (2016); Parker and Harrison (1992); Chan (1995). In the current technology development era, the testing of products under the environmental stresses are not only limited to the electrical or electronics based systems but are applicable to electro-hydraulic systems as well such as subsea oil and gas, and automotive systems Zhang, Chen, Guo, Zhang, and Eben Li (2017).

Despite the existence of these international recommended practices and procedures, it is clear that the qualification of underwater technology is still based on a narrow test process that simply involves passing conventional operational tests to save the cost and time of the qualification testing. This conservative cost driven approach has led to major quality issues and flaws in the products, which were not being correctly captured at product design verification phase, but only identified at system level test or at the system deployment stage, when the loss of the system reputation is much higher. Therefore, a comprehensive technology qualification approach is required that should be economically suitable to the oil and gas industry in order to achieve the highly reliable systems.

The pre-requisite of the product technology qualification program on the subsea electrical and electronics products is the successful completion of Technology Readiness Level 3 (TRL3) program on all the Printed Circuit Board (PCB), sub-assemblies, connectors, passive electronic devices, and mechanical parts being used in the product; the reader is referred to Det NorskeVeritas (2017); American Petroleum Institute (2018a) for the definition of the subsea product's TRL, which is in range from the TRL0 (unproven concept) to TRL7 (field proven product). TRL3 qualification ensures that each item in the product fulfills the functional and compliance requirements to achieve the adequate reliability of the final product, which is intended to use in the subsea. However, an assembly of the TRL3 qualified parts in a mechanical housing does not guarantee that the product is robust enough to use in the subsea environment. Thus a next-level qualification program, 'TRL4 qualification (pre-production system tested in the intended environment)' on a product is required to guarantee that the product should be fully functional with 100% of availability on the sea bed during production.

The key contributions of the presented work are therefore as follows:

1. The delivery of a reliable product is one of the burning topics of the oil and gas industry. In this context, this paper describes a comprehensive TRL 4 technology qualification program for the first time for underwater electrical and electronic products. The developed qualification program encapsulates the key steps, starting from the product compliance requirements to bring out a reliable product being used at high pressure and low temperature on the seabed without any failure. The novel TRL4 process presented in this paper ensures the products' safety and fit for use in the subsea environment in addition to the compliance with various international directives and standards. The schemed TRL4 process provides a comprehensive guide to conduct the qualification compared to conventional environmental stress testing, i.e., thermal and vibration testing only. It provides all guidance for conducting analytical evaluation, environmental stress testing and experimental verification of risks identified during FEMCA studies. This TRL4 qualification strategy is applied in the present work on various subsea products and is found to be an effective way to avoid product failures at the later stage of the integration testing.
2. Conventional environmental test methods in oil and gas industry have a few open questions, for example, they do not define whether to conduct the tests with or without the pressure compensated housing. This leads to confusion when carrying out the tests, and as a result to poor quality product. Thus, in this paper modified environmental test methods are derived and tailored to simulate the actual subsea harsh environment, and are associated with the TRL4 qualification process to increase the product reliability. For instance, it is proposed to conduct the thermal testing without the pressure compensated housing so that the electronic based components of the product sense the high and low temperature extremes. In addition, detailed thermal cycle parameters are proposed in Section 3.1 to ensure that the product must operate at both extreme temperatures and temperature fluctuations. Similarly, Section 3.2 addresses the open questions related to vibration testing, which provides the adequate knowledge and information to the test engineer to conduct the testing accurately and safely without damaging the product hardware.
3. Specific electromagnetic compatibility (EMC) and safety standards for subsea electrical and electronic products do not exist. Appropriate EMC and safety standards are proposed in this paper, which are chosen with care from the large number of generic EMC standards available for laboratory or industrial environments. The proposed standards (presented later in Table 1) meet the requirements of the EU directive [European Parliament, Council of the European Union \(2014\)](#) and the EMC requirements for the subsea product to prevent product malfunction. Overall, a process for implementing EMC testing of subsea products with some critical interpretations of EMC qualification practices and related topics is presented for the first time in this paper. An example is the selection of performance criteria 'A' or 'B' [International Electrotechnical Commission \(2016\)](#) for each of the EMC tests according to the design and functionality of the underwater product. The sequence of tests in the TRL4 process is proposed in this work to conduct the EMC and safety tests before the thermal and vibration stress tests due to the risks of product design changes due to the EMC and safety tests failures. The success of the proposed EMC and safety tests allows to check the robustness of the technology in terms of conformity of the product to internationally recognized standards.
4. The derived environmental test methods, and proposed EMC standards and product safety tests are further implemented on existing subsea products, with exemplary case studies of the Subsea Electronics Module (SEM). Detailed analytical and risk assessments are conducted in-house by using available tools to reduce the cost of the qualification process. For example, FMECA and finite element analysis (FEA) demonstrate the product's viability and mechanical strength. On the contrary, the proposed environmental and safety test methods are executed in the United Kingdom Accreditation Service (UKAS) approved test house on the product for the validation of the proposed TRL4 process. In this process for the presented case studies, all SEM interfaces, including Ethernet, Fault tolerance CAN, serial and analogue interfaces are tested at the maximum recommended cable lengths. Thus, SEM also complies to the recommended practice of the subsea instrumentation interface standardization (SIIS) committee [Oil and Gas Operators \(2016\)](#).

Following this introductory part, Section 2 presents the details of the technology qualification program of the product, specifically at the technology readiness level 4. The upgraded compliance tests for subsea products are introduced in section 3. The results of two case studies are reported in Section 4, followed by conclusions in Section 5.

2. Product Technology Qualification Life Cycle

A technology qualification program (TQP) life cycle proposed and detailed in Arif, Rehman-Shaikh, and Evangelou (2021) provides a comprehensive and systematic process to conduct technology qualification, with a specific focus on the TRL3 qualification test program of subsea product's sub-assemblies/PCB. This TQP life cycle is adopted in the present work in the context of TRL4 qualification program of subsea electrical and electronics-based products, as shown in Fig. 1. Although the description of the building blocks for the TRL3 and TRL4 qualification life cycle are the same, the technicalities of the two qualification programs are very different from each other, especially, the qualification test program. The key differences are explained as follows:

1. The objective of the TRL4 qualification process is to conduct the analytical assessment and physical testing on the various PCBs, connectors and sub-assemblies, which are eclectically connected together and housed in a mechanical structure. The proposed TRL4 qualification process described in Figs. 2–3 is more rigorous in terms of physical testing from the TRL3 qualification process.
2. The proposed thermal testing is being conducted on the final finished product instead of at the component/PCB level. The intensity of the thermal stresses is higher in the TRL4 qualification program due to the product having more thermal mass than a component/PCB in TRL3 testing. The thermal tests are thoroughly described in Section 3.1.
3. The stress levels in the vibration test methods are different from the TRL3 qualification program. The vibration testing in TRL4 qualification testing is conducted on the finished product instead of at the component level. These test methods are highlighted in Section 3.2.
4. The proposed safety testing including the EMC, pressure and electrical safety testing are conducted on the final product level to ensure the product use in the laboratory and also at the system level. Although the designers consider the safety margins of the product's components during the design phase of the PCBs, connectors and housing, the safety related testing is not considered at the TRL3 level qualification. Once the product is finalised, the proposed safety tests are conducted during the TRL4 qualification to ensure the robustness and safety of the product from an electrical and mechanical prospective of the design.

The starting point of the TQP life cycle is always going through the requirements list, compliance criteria and functional requirements of the product in addition to the use of the product at a system level. Next steps are to conduct the system analysis, requirement capture and gap analysis to review the current status of the product's sub-assemblies/parts to ensure that the presented product for the qualification program must meet the TRL3 criteria.

Despite the completion of TRL3 qualification program at a sub-assembly level, it is proposed to run a separate qualification program at TRL4 level by using the proposed TQP life cycle, because the PCB/sub-assemblies, dry-mate connectors, wet-connectors and internal wiring assembled and enclosed in the housing as a product acquire different functional, environmental, mechanical and safety risks. To mitigate these risks with the product, a comprehensive qualification test program, named as a 'TRL4 qualification program' is essential, which predominantly addresses the compliance requirements (environmental, EMC) and analytical assessment of the product. The critical activities of the TRL4 level TQP life cycle are compliance testing, and analytical assessments that are based on the input from the findings of the gap analysis and FMECA studies (conducted during system analysis at the product level). Compliance (physical) testing is the most secure route to prove technology maturity. However, it is an expensive route of gathering evidence of product maturity. Thus, it is recommended in this paper to conduct the analytical assessment on the product's mechanical and electrical parts where possible, to keep the qualification cost low and also to ensure that product is fit-for-use in the harsh subsea environment. For instance, thermal analysis, finite element analysis, electrical power analysis, and communication bandwidth can be analyzed and accepted by all stakeholders before commencing the physical testing. Furthermore, it is recommended in the proposed TRL4 qualification program to conduct the analytical assessment at the early stages of product development to avoid the risk of product failures at the later stages of product testing.

The details of the TRL4 qualification process, and the methodology of conducting compliance testing (environmental and safety) are discussed next.

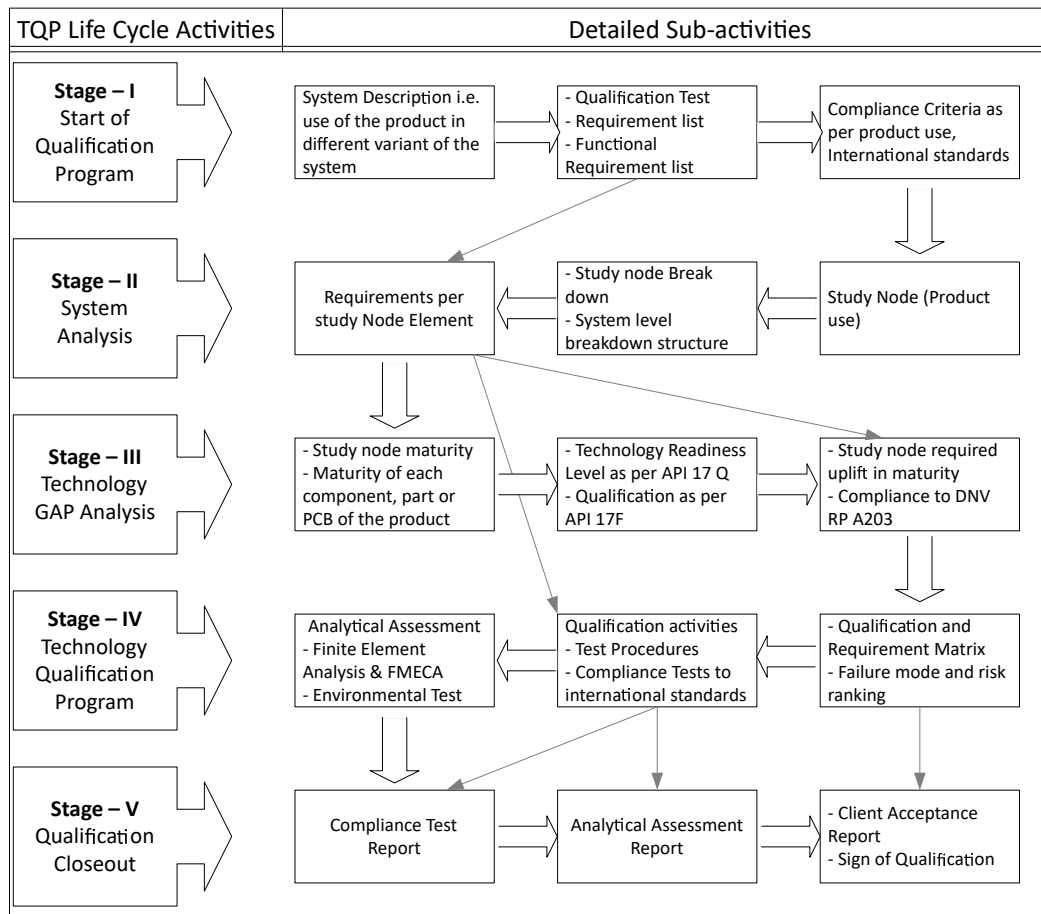


Figure 1: Proposed Technology Qualification Life Cycle for subsea Electrical and Electronics Products.

2.1. Novel Technology Readiness Level 4 Process

Figs. 2 and 3 highlight the proposed TRL4 qualification process which starts with the expectation that the product presented for the TRL4 qualification has met the TRL3 qualification criteria first. The TRL3 qualified parts of the final product include the various printed circuit boards, dry-mate connectors, wet-mate connectors and housing. Furthermore, all the parts in the product must have passed the Factory Acceptance Test (FAT) American Petroleum Institute (2018) to ensure the superior quality of the product presented for the TRL4 qualification program.

The proposed TRL4 process for the subsea electrical and electronic product comprises two primary performance criteria to assess the product technical maturity level. The first criterion is an analytical assessment, where various software and mathematical models are used to simulate the operational scenarios of the product to classify the power requirement, the strength of the product's mechanical housing and product reliability. The second performance criterion is based on the compliance testing of the product to analyze the products' functional behavior under the thermal and vibration conditions, its reliable operation in electromagnetic interference (EMI) and structural viability under-pressure subsea environment. Furthermore, it is proposed that special tests are designed based on the identified risk during the analytical assessment and results of the FMECA studies.

Traditionally, thermal and vibration tests are part of the product's qualification program, which are inadequate to provide alone the evidence that the product is fit for use in subsea environment. This paper introduces an extensive test program which includes the products' EMC, safety, and environmental (thermal and vibration) and pressure testing. Furthermore, the proposed program recommends the extended life testing of the subsea power supplies to check the operational availability of the product. For example, relays in the power supplies should be opened and closed

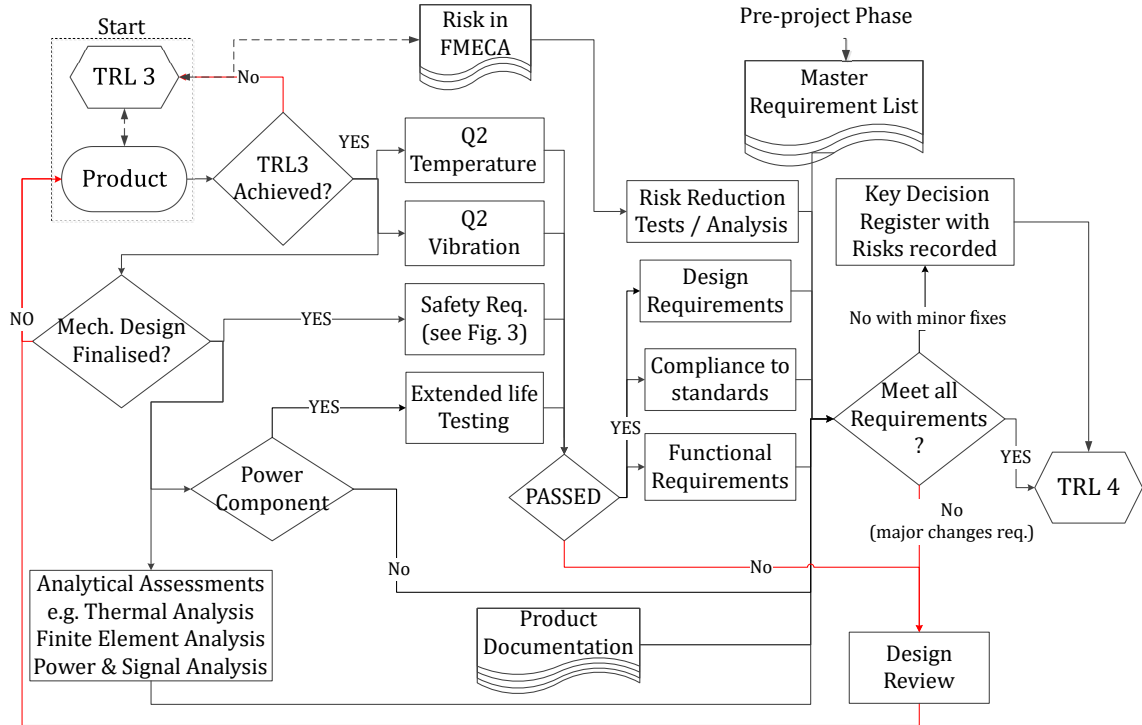


Figure 2: Proposed Technology Readiness Level 4 process for subsea Electrical and Electronics products, assuming all the sub-assemblies and/or PCBs of the product successfully completed the TRL3 qualification program.

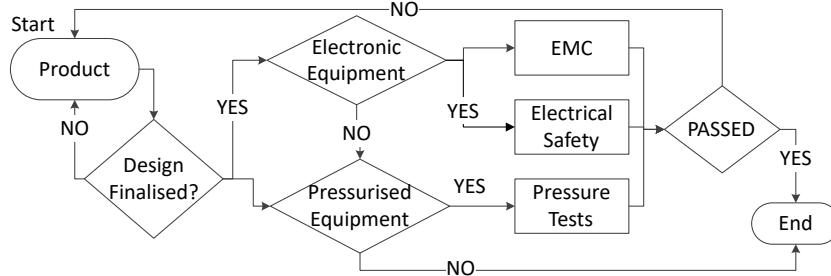


Figure 3: Proposed product safety procedure which can lead to filing an application for the CE marking.

continuously during thermal and vibration conditions for weeks/months to emulate the operational life of the relays' contacts.

In relation to compliance testing, the API 17F American Petroleum Institute (2018) provides the source definition for environmental testing, named as Q2. It includes tests best summarized as a bump, shake and bake, addressing thermal and vibration impact. These tests are modified in this paper according to experience acquired by extensive experimental testing and by reviewing other industrial environmental stress test methods. The details of the modified tests are highlighted in Section 3. In addition to environmental stress tests, it is recommended in this paper to conduct product safety and EMC testing to satisfy the product compliance to the various international standards, especially in compliance with the EU directives European Parliament, Council of the European Union (2014), European Parliament, Council of the European Union (2014). EMC testing is proposed as a critical part of the TRL4 qualification process, which assures that the product is unaffected by the emissions of neighboring equipment. Until now, there are no harmonised or specific standards for the EMC testing of products which are operational in a subsea environment. This paper proposes a comprehensive list of EMC standards (see Table 1 in Section 3.3), based on extensive work

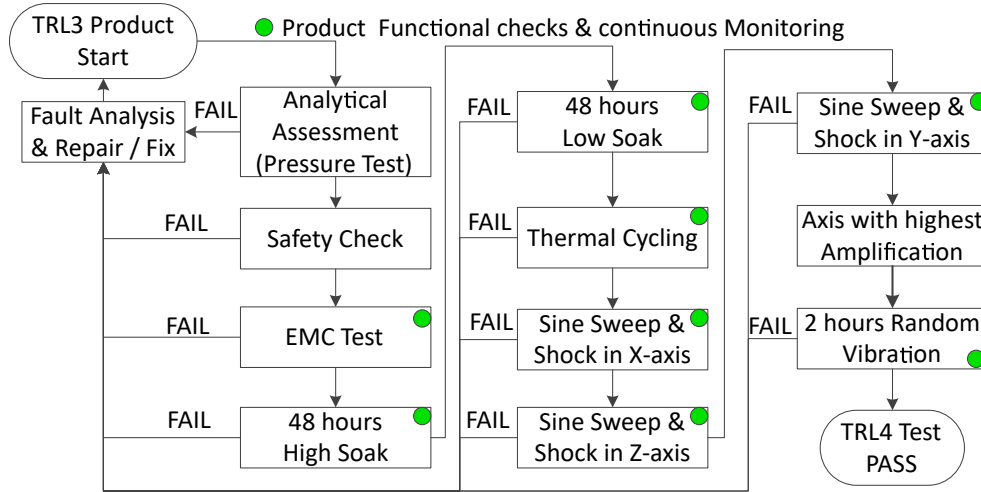


Figure 4: EMC, Safety, Q2 Thermal and Vibration Tests Flow Diagram for the product TRL4 qualification program.

experience with subsea electrical and electronic based products. For any given product, the appropriate standards from the proposed list should be chosen according to product usage.

A detailed compliance review is recommended as a part of the TRL4 process in Fig. 2 on completion of the analytical assessment and compliance testing. A product compliance, and functional and design requirements should be verified and documented for the record of product qualification. In case of any shortcomings in the product during the compliance testing, the risk must be analyzed with the product line management and then documented in the key risk register.

3. Proposed TRL4 Compliance Tests Methods

This section highlights the proposed TRL4 test methods for the compliance testing of the subsea electrical and electronic product. Fig. 4 portrays the test flow diagram that ensures the cost effective testing while this testing process guarantees to capture the design flaws at the earlier stage of the product qualification. The main product failure in subsea industry is found to be due to the EMI phenomena, which ultimately leads to design changes. Thus, it is proposed to conduct the EMC and safety checks before the start of the environmental stress test. The proposed TRL4 test methods are explained next.

3.1. Thermal Stress

The subsea electrical and electronics products are presented for the 48 hours high soak steady temperature test followed by the low temperature test for the same time duration. It is proposed to conduct the high soak test at 70° C without the product's pressure compensated housing. However, in some cases it is unsafe to operate a few products e.g. power supplies, without the external housing due to the hazardous voltage. In this particular scenario, it is proposed to maintain 70° C inside the pressure compensated housing by adjusting the thermal chamber temperature so that the electronics should experience the 70° C temperature. A similar setup should be arranged for conducting the low temperature test at -18° C either without the product's pressure compensated housing or by maintaining the -18° C inside the housing. The product should be electrical power 'ON' under full load condition during both high and low soak temperature tests. A power cycle of the product is recommended once the product temperature reaches the steady state value, to verify the product functionality at the temperature extremes.

Following the steady soak temperature tests, the thermal cycle test is highly recommended, which is the most effective method to find the flaws, especially in the electronics circuits, due to the induction of alternate expansion and contraction as the temperature varies between high and low set temperatures limits Department of Defense, USA (2019); U.S. Department of Defense (2015). The temperature range is based on at least 30 minutes high and low soak at steady temperatures with the ramp rate of a minimum $|dT/dt| \geq 5^\circ\text{C}/\text{min}$, where T is the thermal chamber temperature. Due to the rapid change of the temperature during the thermal cycle, there may be moisture on the

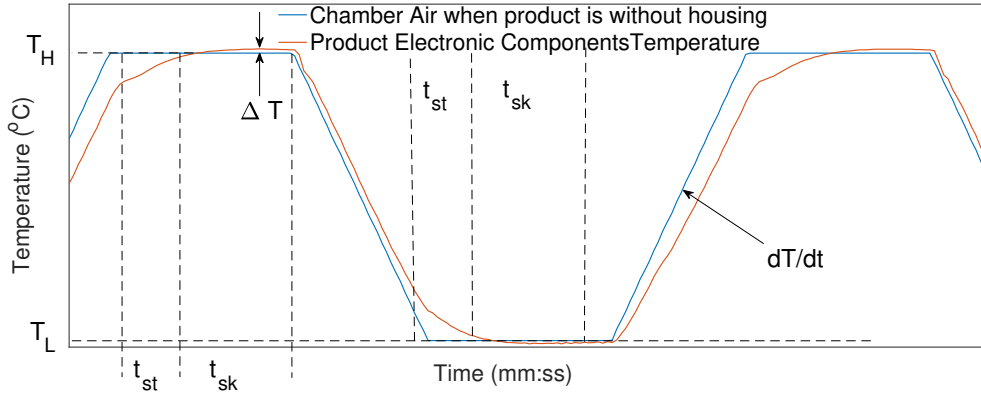


Figure 5: Proposed Thermal Cycle Profile with the suggested soak (t_{sk}) and stable (t_{st}) time when the unit under test is powered ON.

mechanical parts of the product which can damage the electronics. Thus, dry-nitrogen is purged into the thermal chamber to keep the air dry. Alternatively, air dryers are available that bring the dew point down to -30°C , and a gentle flow of this dry air is sufficient to flush moisture out.

Fig. 5 illustrates the thermal cycle profile for product testing without the pressure compensated housing, thus the electrical and electronics parts of the product are directly exposed to the thermal chamber temperature. The product should be put at high and low design temperatures (T_H and T_L) for at least 30 min. However, due to the thermal inertia and imperfect heat transfer during the Q2 thermal cycling, there could be a lag between the product temperature and that of the chamber air. Thus, it is proposed that the soak time $t_{sk} \geq 30$ min for each of the high and low temperature extremes, while additional time t_{st} is allowed for the product to reach in the range of $\Delta_T = \pm 3\%$ of the temperature extremes.

However, two approaches can be adopted for the thermal cycle test. Option-1: conduct the thermal cycle test with the final finished product, i.e., with all the electronic PCBs, wiring and other electrical/optical-fibre components inside the pressure compensated nitrogen-filled housing. In this case, the difference between the chamber air and inside the housing temperatures increases with increasing product's thermal inertia of the housing which stops the airflow to the inside electronics. For example, in the region of high temperature soak in the thermal cycle, initially, the temperature inside the housing is always less than the temperature observed by the PCBs. But at some point, the temperature inside the housing starts increasing and goes above the chamber temperature. Similarly, the product would take more time to reach the low temperature soak since the housing would take time to cool down. Option-2: conduct the thermal cycle test of the product with the final product without the pressure compensated housing, where the PCBs, internal wiring and connectors are exposed to the same temperature of the thermal chamber, and chamber air is circulated/forced to all parts of the product.

Option-1 is a difficult, time-consuming and expensive approach to adopt because the test engineer runs a few trials to find the optimal temperature of the thermal chamber so that the temperature inside the housing should not increase above the design test temperature, i.e., 70°C for the subsea product. Furthermore, the stabilise time t_{st} is much higher as compared to option-2, where a test is conducted without the housing. Thus, overall time t_{Total} would be much higher than the usual 30 minutes soak time. Having in view the mentioned issues of pressure-compensated-housing, it is proposed to conduct thermal testing without the product housing, which results in a much faster test completion with a lower cost. Also, it is appropriate to run the chamber for a couple of thermal cycles to find the optimal thermal profile for the cycling testing which may vary from product to product. The proposed test method without the pressure compensated housing should be adopted during high and low soak temperature tests.

3.2. Vibration Stress

Vibration Stress consists of three main tests: sine sweep, shock and random vibration. The test parameters and their respective acceptance criteria are specified in API 17F American Petroleum Institute (2018). Although, API 17F American Petroleum Institute (2018) defines the test parameters of the vibration testing, there are a few open questions which are addressed first time in this paper based on the authors' experience of conducting the qualification

testing along with assessing various military standards U.S. Department of Defense (2015); Department of Defense, USA (2019); Department of the Army, Navy and Airforce, USA (1993).

1) A test fixture is always required for conducting the vibration testing of any product. Mostly the test fixtures are designed to hold the product securely. However, the improper design of the test fixtures can damage the product under testing. It is proposed to conduct the verification testing of the test fixture using the sine sweep test parameters prior to starting vibration testing. The measurement accelerometers should be placed at various locations of the fixture to measure and ensure that there should not be any amplification ($g_n = 0$) during the test. This step ensures that the test fixture is designed properly and fit for use with the product.

2) Currently, the vibration testing of the product is performed either with and without the pressure compensated housing. Nevertheless, it is impossible to measure the vibration levels on the PCBs or other internal parts of the product in case the vibration testing is conducted with the product's housing. On the other hand, the vibration stresses on the internal parts provide useful information about the design and the robustness of the product, when the vibration test is conducted without the external housing. It is suggested in this paper to perform the vibration testing both with and without the external pressure compensated housing to envisage the vibration level on the structure as well as on the internal electrical/electronic parts of the product. However, vibration testing should be performed only with the housing if the product has high voltage components, where the safety of the product and the operator is vital.

3) Placement of the control and measurement accelerometers are the utmost important task in vibration testing. It is recommended to identify suitable locations of the control accelerometers during the test fixture verification testing, which are mostly on the front face of the test fixture and perpendicular to the armature of the vibration machine. Besides, it is also advised to place at least two control accelerometers on the front face of the test fixture, due to the large size and mass of vibration fixtures needed to accommodate the large size of subsea products. For example, one control accelerometer should be at the lower end of test fixture plate and another one should be at upper end of test fixture plate to capture the whole frequency spectrum of the vibration. The vibration controller should take the average from the readings of the two control accelerometers and send an appropriate control signal to the vibration machine. Similarly, the measurement accelerometers should be placed at the critical parts of the product to ensure that the product is resilient enough while operating on the seabed in a trembling condition.

Acceptance Criteria: The product should pass all functional tests during and after each of the thermal and vibration stress tests.

3.3. Recommended EMI Compatibility Tests

Oil and gas industry does not have any specific EMC standards for their products. Hence, the industry relies on the available standards from other industries under the guidance of EEA/EU EMC Directive '2014/30/EU' [European Parliament, Council of the European Union \(2014\)](#). Nevertheless, it is a difficult task for the test engineers to establish suitable EMC standards for subsea products. Incorrect choice of the standards may damage the product electronic components, and may also lead to inadequate testing of the product due to lack of understanding of the EMC standards.

As the EMC compliance is always an important consideration due to economic and reputation damage that can result because of technology non-conformance to EMC Directives and failure due to EMI phenomena, it is strongly recommended to at least carry out the EMC testing on subsea products under the generic standards EN 61000-6-2 and EN 61000-6-4. In addition, a test engineer should carefully choose the mentioned standards from Table 1 according to the type and use of the product in the subsea environment. As a result of testing according to the proposed standards, the subsea products could have the track record of operating reliably and safely in the subsea and topside environments without interfering with the nearby equipment/products. Furthermore, the performance criteria of the product must be discussed and agreed in consultation with the designer/manufacturer of the product before commencing the EMC tests.

4. CASE STUDIES – Subsea Electronics Module

The proposed technology readiness level 4 test methods are applied on three Subsea Electronics Modules (SEM); the results are presented as a case study in this section. SEM is designed to house various PCB's, with each PCB providing a variety of power, signal and communications interfaces to and from external equipment and sensors. Typical communication interfaces in SEMS are: RS485, CAN, Ethernet, analogue inputs, and modem communication (orthogonal frequency-division multiplexing (OFDM) and asymmetric phase-shift keying (APSK))

Table 1

Proposed EMC standards used during the TRL4 qualification of subsea products. These standards are available to download from CEN website <https://www.cen.eu/work/products/ENs/Pages/default.aspx>

no.	EMC Standards Title	Doc. No.
1.	Emission standard for industrial environments.	EN 61000-6-4
2.	Immunity standard for industrial environments.	EN 61000-6-2
3.	Limits for harmonic current emissions (equipment input current $\leq 16A$ per phase).	EN 61000-3-2
4.	Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current $\leq 16A$ per phase and not subject to conditional connection.	EN 61000-3-3
5.	Specification for radio disturbance and immunity measuring apparatus and methods.	CISPR 16-1-2
6.	Specification for radio disturbance and immunity measuring apparatus and methods	CISPR 16-2-1
7.	Information technology equipment - Radio disturbance characteristics - Limits and methods of measurement.	CISPR 22: EN 55022
8.	Electrical fast transient/burst immunity test.	EN 61000-4-4
9.	Surge immunity test.	EN 61000-4-5
10.	Immunity to conducted disturbances, induced by radio frequency fields.	EN 61000-4-6
11.	Voltage dips, short interruptions and voltage variations immunity tests.	EN 61000-4-11
12.	Harmonics and inter-harmonics including mains signaling at AC power port, low frequency immunity.	EN 61000-4-13
13.	Immunity to conducted common mode disturbances in the frequency range 0 to 150 kHz immunity test.	EN 61000-4-16

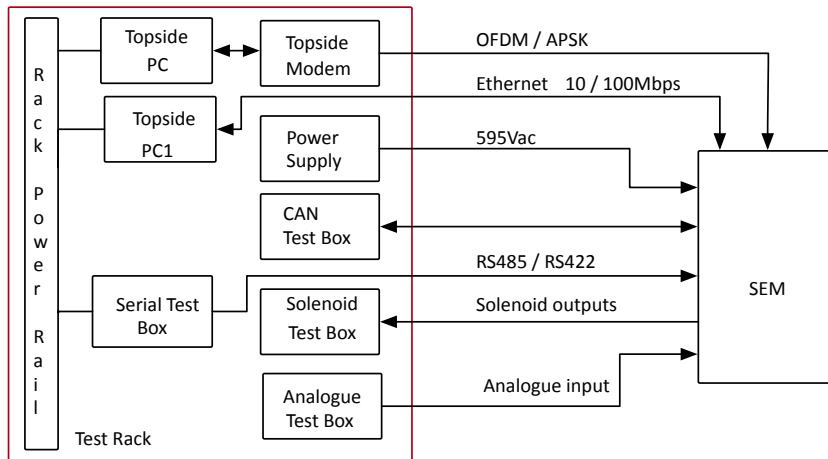


Figure 6: SEM functional test setup during environmental stresses & EMC testing, with the Auxiliary test equipment.

interface. Furthermore, a solenoid PCB is geared towards control of Direction Controlled Valves (DCV). The hydraulic fluid going through the DCVs controls the opening and closing of production valves located on the Xmas Tree (an assembly of valves, spools, and fittings used to regulate the flow of hydrocarbons, chemicals and water etc. to a well).

Functional test setup of the SEM consists of a 'deliverable SEM', an alternating current (AC) power source and a rack assembly with an array of test-boxes designed to simulate the load for communications interfaces, as shown in Fig. 6. All SEM interfaces are connected to test-boxes with the maximum length of the cable, for example, 1) Ethernet channels are connected with 100 meters CAT5 cable, 2) fault tolerance CAN channels are plugged in with 144 meters cable, 3) serial RS485 & RS422 channels are tested with 1200 meters long cable, to reduce the risk of failures over a long distance which was identified during FMECA analysis. This test setup is kept during thermal, vibration and EMC testing. The details of the environmental and EMC test results are presented in following subsections.

4.1. Environmental Stress Tests Results

4.1.1. Part 1 – Thermal Stress

Thermal stress tests are completed on the fully operational SEM in an environmental chamber without the external housing, as described in Section 3.1. The SEM is powered ON for all thermal stresses and full loads are applied on all power and communication interfaces. The SEM is presented for 50 thermal cycles during the thermal cycle stress according to the thermal profile shown in Fig. 5.

The SEM is under continuous monitoring throughout the thermal stress testing and data are logged for each of the communication interfaces. Functional tests are successfully carried out before and after high temperature, low temperature and thermal cycle stress tests. Table 4 shows the brief results of SEM interfaces without any communication or functional tests losses. At the completion of thermal stress on all three SEMs, it can be concluded that the SEMs withstand the thermal stresses and PASS the TRL4 thermal tests.

4.1.2. Part 2 – Vibration Stress

Vibration stress tests are conducted on three SEMs without the pressure compensated housing. Control and measurement accelerometers are bonded to the test jig and on the SEM. A sine sweep is performed one-by-one on all three axes under the resonance sweep test parameters of ± 2 mm displacement between 5–25 Hz and $5g_n$ constant acceleration between 25–150 Hz. Fig. 7(a) portrays the resonance sweep response of SEM's components in Y-axis, where amplification is less than the acceptable limit of $g_n < 50 \text{ m/s}^2$. Following the sine sweep, four shocks (half-sine shock pulses) are applied in each of six directions along three mutually perpendicular axes with $g_n = 10$ for 11 ms. The SEM continues to function as expected and no errors are observed during the continuous monitoring.

Analysis of the data produced by the vibration tests in sine sweep shows that there are minimal amplification factors in all axes i.e., $g_n < 50 \text{ m/s}^2$. Fig. 7(a) shows the two traces of the measurement accelerometers which are placed on the power supply and the Ethernet switch of the SEM respectively. However, it is noticed that the measurement accelerometers recorded a higher amplification in Y-axis as compared to Z-axis and X-axis. Thus, the subsequent 2-hours random vibration test is conducted in the Y-axis direction. Fig. 7(b) shows the graphical representation of the random vibration test. Table 4 shows that all interfaces of the SEM are functional throughout the test and no errors are recorded during the vibration stress test. After the analysis of logged data, it is concluded that all three SEMs PASS the vibration testing of TRL4 qualification process.

4.2. Subsea Electronics Module Safety Test Results

Electromagnetic Compatibility (EMC) is accessed on the SEM according to the standards referred in Table 1. The EN 61000-6-4 (emission), EN 000-6-2 (immunity), and EN 61000-4-6 (immunity radio frequency) are deemed the most appropriate standards to apply in the present case study, under the following performance criteria.

Performance Criterion A: The SEM shall continue to operate as intended throughout testing with no change in operating mode or data corruption as indicated by the monitoring of support equipment.

Performance Criterion B: During testing the SEM is allowed to change state temporally but must self recover back to its normal operating mode upon completion of the test.

4.2.1. Part 1 – SEM Conducted Emission Test Results

The SEM successfully completed the emission test according to the test parameters described in Table 2. The test setup complies with all the dimension requirements set in CISPR 16-4-2 International Electrotechnical Commission (2011). The successful compliance to the emission test criterion means that the signals such as CAN, Ethernet and serial are protected from noise when SEM communication signals and power ports are used in the vicinity to each other and also from unwanted noise.

Fig. 8 shows the results of the conducted emission on the SEM's input Live line using the voltage probe. When the SEM is powered at $595 V_{AC}$ with all interfaces running at full load, there are emissions which exceed the average limits with a margin of 3 dB at 25 MHz. However, this is further reduced by adding a ferrite with two turns on the SEM's input Live line which reduces the margin to about 6 dB below the average limit at 25 MHz. Similar tests are successfully conducted on all of the power and communication interfaces of the SEM and no significant issues are encountered.

4.2.2. Part 2 – SEM Immunity Test Results

Immunity testing measures the ability of a SEM to withstand different types of electromagnetic phenomena coming from the connected instruments and other products with SEM. The Immunity test is conducted on all SEM's signal

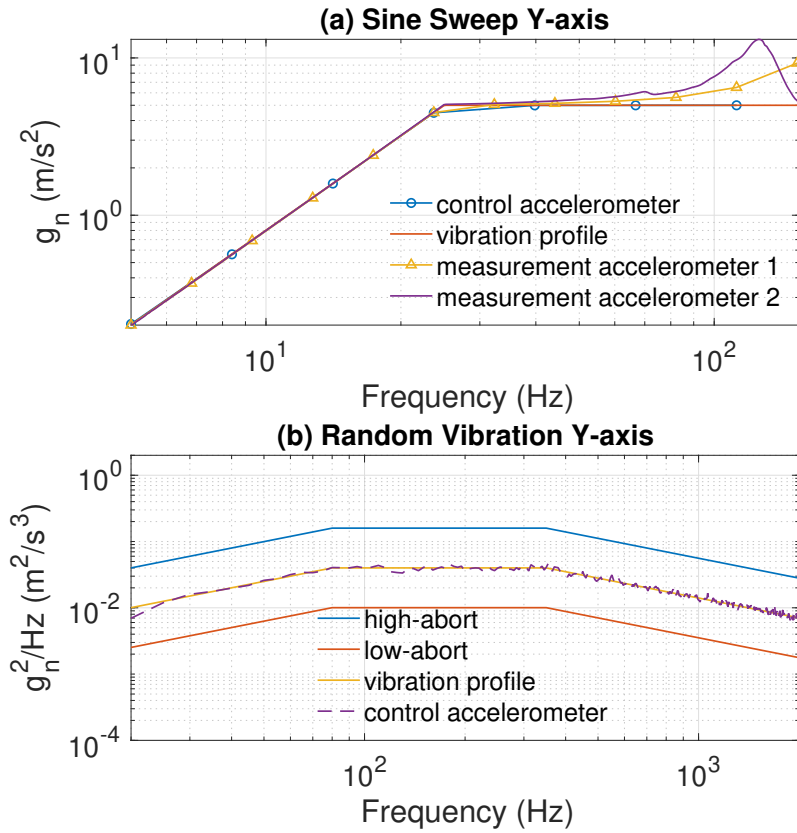


Figure 7: Q2 Vibration tests of the Subsea Electronics Module TRL4 Qualification without pressure compensated external housing (vibration profile: the input to the vibration machine to follow the program (profile) as stated in [American Petroleum Institute \(2018\)](#); high/low abort: the vibration machine stops if the response of the control accelerometer is above/below this line; control accelerometer: this is placed either on the vibration table or test fixture, and the vibration controller changes the vibration levels based on the feedback signal generated by the control accelerometer; measurement accelerometers: these are mostly placed on the sensitive components of the product to check the vibration level, and if $g_n > 50 \text{ m/s}^2$ the sine sweep test is considered as FAIL).

Table 2

Conducted Emission Test Parameters.

Frequency Range	10 kHz to 30 MHz
Frequency Step Size	200 Hz (10 kHz to 150 kHz band) 4.5 kHz (150 kHz to 30 MHz band)
Measurement Bandwidth	200 Hz and 9 kHz
Detectors	Peak, Quasi-peak and Average
Quasi-peak Detector Dwell	Minimum 2 sec per frequency point
SEM Operation Voltage	595V _{AC} , 50 Hz

and data buses simultaneously via clamp. Two coupling methods are used depending upon the type of cable under test: Clamp and Coupling / Decoupling Network (CDN). The test setup used complies with all the dimension requirements set out in the Immunity standard EN 61000-4-6:2013. The Radio Frequency (RF) conducted common mode immunity tests are carried out using the bulk current injection clamp according to the test parameters mentioned in Table 3. The successful completion of the RF immunity test shows that SEM is fully functional in the presence of the electromagnetic disturbances which are coming from intended RF transmitter in the frequency range 9 kHz to 80 MHz.

The fast transient immunity tests are successfully carried out using the capacitive clamp at the voltage level of $\pm 1 \text{ kV}$ and $\pm 2 \text{ kV}$ as per standard EN 61000-4-4. There are no failures recorded during fast transient testing on the

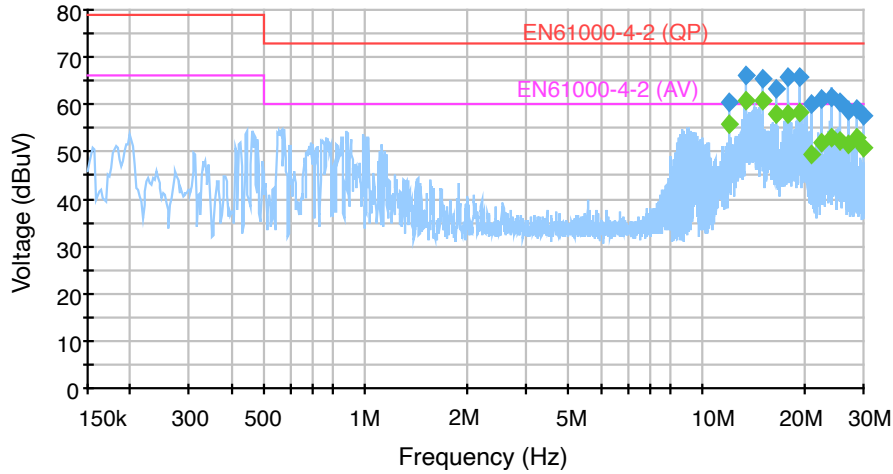


Figure 8: Conducted Emission result on the Live line using the Voltage Probe – SEM is powered ON with 595 V_{AC} and loads are connected with all SEM's interfaces. Red and purple traces represent respectively the Quasi-peak and Average peak limits set in the standard. Blue trace represents the actual emission level in dB μ V of the live line of the SEM. Blue and Green diamonds represent the Quasi-peaks and Average peaks respectively.

Table 3
Conducted Immunity Test Parameters.

Frequency Range	150 kHz to 80 MHz
Amplitude Modulation Frequency	1 kHz
Dwell Time per Momentary Frequency	3 sec
Test Voltage	10 V_{rms}
Test Voltage Mains Supply Cables	10 V_{rms}
Test Voltage Signal/Control Cables	10 V_{rms}
Step Increment	1 % of momentary frequency

communication interfaces, therefore, the SEM achieves performance criteria-A for this test. It is concluded that the SEM is immune to transient phenomena because there are no signs of malfunction during this test. The EMC and functional tests are successfully completed on all interfaces of the SEM and it is concluded that SEM is EMI compatible.

5. Conclusion

The extraction of uninterrupted hydrocarbons from the sea bed is relying on the reliable and robust production and process systems. That is only possible if the deployed products in these systems are rigorously tested for the subsea harsh environment. In this context, the proposed TQP life cycle laid out the various phases of the comprehensive technology qualification program to ensure that the final product performs as expected without any operational failures. In the proposed TRL4 qualification process, the compliance (physical) testing and the analytical assessment are the fundamental parts of technical quality assurance of the subsea products in terms of overall system functional performance, electrical operations, and reliability while operating on the seabed.

The proposed technology readiness level 4 test methods are applied to the Subsea Electronics Module (SEM). The modified thermal and vibration test methods guarantee that the product is scrutinized at adequate stress. Furthermore, Electromagnetic compatibility of the SEM against the proposed EMC standards is successfully exercised on the SEM's power and communication interfaces, thus the SEM withstands the electromagnetic interference. Although physical testing is the most robust, it is also an expensive route for the qualification in terms of both time and cost of conducting the tests. Thus, the proposed analytical assessments of the product assist to expedite the qualification process and reduce the cost of qualification. The proposed analytical assessment methods, i.e., FEA, thermal, structural, FMECA, power/signal, and communication analyses are successfully conducted on the SEM using the available tools and

Table 4

SEM functional test during Thermal, Vibration and EMC testing. SEM successfully passed all tests.

no.	Test Description	Test Details
1.	SEM Power Up	Apply AC Voltage.
2.	Solenoid Board	• Correct operation of all solenoid driver channels is verified. • $23.23V_{DC}$ is measured on the voltage delivered to solenoid loads. • Fail-safe drive holding voltage $9V_{DC}-11V_{DC}$
3.	Analogue Input Board	• All channels on the analogue simulator send the correct read-back current of 4 mA, 12 mA and 20 mA.
4.	Electrical Isolated Routing Switch	• Ethernet traffic generator transmit 4,380,00 bytes without any error between the PC and all other active devices on the network.
5.	Ethernet Electrical Modem	• Ethernet traffic generator to transmit continuous packets on all channels of the topside and SEM modems and no errors occur.
6.	Serial RS485 Interface	• Fully loaded serial communication link between the SEM serial channels of Serial PCB and third party devices simulated by a terminal server. All channels are tested both on 19200 kbps and 9600 kbps.
7.	CAN Board	• No error on the CAN Bus for all low-speed fault tolerant channels.

software. This comprehensive qualification test program is successfully completed on various subsea electrical and electronic products, which boost the confidence of the clients on the products and help the manufacturer to declare the products fit for use for the subsea production systems.

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