Recommended Practice on Subsea Equipment Qualification

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1 Scope

This recommended practice (RP) provides suppliers, contractors, and operators with process-level guidance to qualify equipment intended for use in subsea applications. This document is intended to provide high-level guidance only, so that the industry will have a common set of principles to follow for equipment qualification. It is not intended to replace existing company processes or procedures. The application of this recommended practice is dependent on the stakeholder companies (qualifier and end user) accepting its use. Although developed for application to subsea equipment, the process described by the RP can be applied to non-subsea equipment as well.

2 Normative References

The following referenced documents are required for the application of this recommended practice. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies:

API RP 17N, *Recommended Practice on Subsea Production System Reliability, Technical Risk, and Integrity Management*, 2nd Edition (2017)

3 Terms, Definitions, Acronyms, and Abbreviations

3.1 Terms and Definitions

For the purposes of this recommended practice, the following terms and definitions apply:

3.1.1
component
Collection of subcomponents which when brought together function as a unit. (e.g. connector, gate valve, pressure transducers).

3.1.2
cut set
Unique combination of component failures that can cause a system failure.

NOTE A system can have multiple, different cut sets.

3.1.3
environment
Internal, external, and operational conditions to which equipment is exposed.

NOTE This includes physical, chemical, biological, and usage conditions (i.e. seawater environment, water depth, seabed conditions, reservoir conditions, pressure, temperature, etc.).

3.1.4
failure mode
Effect by which a failure is observed on the failed item (i.e. the loss of a required functionality; e.g. the loss of containment).

3.1.5
field proven
Technology or equipment that has been through the entire qualification process and is classified as TRL 7.

NOTE See Table 1 for the definition of TRL 7.

3.1.6
first article
First of a product produced using the “normal processes” as will be used to make multiple numbers of the same product.

3.1.7
hazard rate
Instantaneous failure rate of a component.

NOTE When the hazard rate is constant, the hazard rate = failure rate.

3.1.8
limit state
State beyond which an item no longer satisfies the requirements.

NOTE The following categories of limit states are of relevance for structures: ULS = ultimate limit states, FLS = fatigue limit states, ALS = accidental limit states, SLS = serviceability limit states.

3.1.9
prototype
Trial product produced to test a concept or process.

3.1.10
production model
Product manufactured using the “normal processes” and intended for normal use.

3.1.11
qualification
Process of confirming, by examination and provision of evidence, that equipment meets the specified requirements for the intended use; the combination of verification and validation activities.

3.1.12
qualification FMECA
Q-FMECA
Integrated FMECA with the purpose of identifying and prioritizing qualification activities for a technology (see 5.6).

3.1.13
specification
Document in which function, performance, design, and operating requirements are defined, together with associated reliability and integrity goals and requirements.

3.1.14
standard qualification program
SQP
Qualification program that uses qualification activities prescribed within existing standards applicable to the technology (see 5.4).

3.1.15
technology
Component, product, physical process, or system used to perform specific functions and/or to achieve specific goals.

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3.1.16
technology qualification program
TQP
Qualification program that utilizes a Q-FMECA to identify qualification activities necessary to qualify the technology in line with the identified goals and requirements (see 5.4).

3.1.17
uncertainty
State of having limited knowledge where it is impossible to exactly describe the existing state or future outcome(s).

3.1.18
validation
Confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled.

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NOTE 1 Validation activities are intended to answer the following type of question:

— did we design/build the right thing? (i.e. confirmation that 'the thing' will work in a specific application)

— are we doing the right tests?

— did we build/use the right model with the right data?

NOTE 2 Design validation can include one or more of the following (this is not an all-inclusive list):

— prototype tests,

— functional and/or operational tests of production products,

— tests specified by industry standards and/or regulatory requirements,

— field performance tests and reviews.

— finite element analysis

— system reliability analysis

3.1.19
verification
Confirmation, through the provision of objective evidence, that the specified requirements have been fulfilled

NOTE 1 Verification activities are intended to answer the following type of question:

— did we design/build the thing right? (i.e. does 'the thing' conform to the specified requirements)

— did we undertake the test/analysis correctly?

NOTE 2 Design verification activities can include one or more of the following (this is not an all-inclusive list):

— confirming the accuracy of design results through the performance of alternative calculations,

— review of design output documents independent of activities of design and development,

— comparing new designs to similar proven designs.

3.2 Acronyms and Abbreviations

For the purposes of this recommended practice, the following acronyms and abbreviations apply:

ALT	accelerated life testing
CFD	computational fluid dynamics
ESS	environmental stress screening
FAT	factory acceptance testing
FEA	finite element analysis
FMECA	failure modes, effects, and criticality analysis
GOR	gas-to-oil ratio
HALT	highly accelerated life testing
HASS	highly accelerated stress screening
HPU	hydraulic power unit
MCS	master control station
MCTF	mean cycles to failure
MTTF	mean time to failure
RCFA	root cause failure analysis
R&D	research and development
RDT	reliability demonstration testing
RGT	reliability growth testing
RP	recommended practice
SIT	system integration test
SQP	standard qualification program
TQP	technology qualification program
TRC	technical risk categorization
TRL	technology readiness level

4 Document Outline and Application

4.1 Process Application

A qualification program is typically a multi-dimensional process that consists of a number of interrelated steps—from requirements setting, planning activities, executing tests and analyses, reviewing results against expectations, and preparing documentation. This recommended practice is written to simplify the qualification process and to align associated expectations within individual organizations and within the industry. It is recognized that there are many methods for qualifying technology and that each company may have specific motives or constraints preventing full adoption of the process described in this document. However, it is recommended to use as much of the process as possible to increase efficiency within the industry.

This recommended practice is not intended to replace the qualification and testing philosophies defined in existing standards (i.e. flexible pipe and ancillary equipment). Existing equipment standards shall be used for detailing qualification test plans, while this recommended practice can be used as a process guide to plan, execute and evaluate a qualification program.

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The document is organized based on the process described in 5.1. Section 5 is made up of subsections which represent each step of the process. Although the process is linear in nature, it does not necessarily mean that a qualification program must follow the steps in perfect sequence. Often, programs work on several steps at one time, or iterate between two steps until progress is made. The process is simply a guide for planning, executing, and evaluating a technology qualification.

This qualification process tailors recommendations depending on the assessed technology maturity and technical risk. Technology readiness levels (TRL) are used to assess technology maturity and the technical risk categorization (TRC) tool is used to assess the technical risk. TRLs are defined in this document in Section 6 and are a means of assessing and communicating the maturity of technology and equipment relative to a set of predefined criteria. TRCs are defined in API 17N and are a means of assessing technical risk across a set of change categories. The TRL and TRC are combined into a matrix to guide the user to the appropriate qualification activities for that specific phase of development. A key feature of the qualification process is to continually reassess the technology maturity and technical risk as the program progresses and the plan of the appropriate qualification activities for that stage based on the recommendations in this document.

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4.2 Equipment Applicability

4.2.1 General

This RP can be applied to all subsea oil and gas related equipment including:

— subsea equipment, including related control systems,

— non-permanently installed facilities and tools, and

— system interfaces (e.g. chemical injection interface with a production system).

4.2.2 Subsea Equipment

From wellhead equipment to the top of the riser, plus the hydraulic power unit (HPU)/master control station (MCS) (and other subsea-specific, surface equipment) and typically including: wellheads (both subsea and mud line casing suspension systems) and trees; pipelines, jumpers, flow lines, and end connections; processing equipment; controls, control lines, and control fluids; instrumentation; templates, manifolds, and production (including water injection) risers (both rigid and flexible).

4.2.3 Non-permanently Installed Facilities and Tools

Equipment and tooling required to install, commission, and operate subsea wells and equipment included in 4.2.2. Includes well access systems, drilling equipment, specialized tooling for facility intervention, etc.

4.2.4 System Interfaces

Hardware interfacing risks, especially those that also represent boundaries between different organizations, should be considered in equipment qualification programs.

4.3 Supplier and End User Role in Qualification Programs

The technology development and project development processes are often managed independently but are complementary in nature. Each has a distinct role within a qualification program and associated TRL progression. Figure 1 represents this relationship and how each process may interact with the other. Figure 1 depicts the role a supplier typically has in each process and the role the end user typically has in each process. The assumed role of a supplier in a technology/project development is to deliver TRL 4 rated component/equipment that may be assembled into an assembly or sub-system. The end user then typically takes that assembly/subsystem and integrates it with

their subsystems or systems to ensure broader interfaces are validated. A supplier may deliver a component or system to a TRL other than 4, depending on the product, end user needs, supplier strategic objectives, etc. The supplier can deliver a TRL 5 component if fully integrated into a supplier-delivered system.

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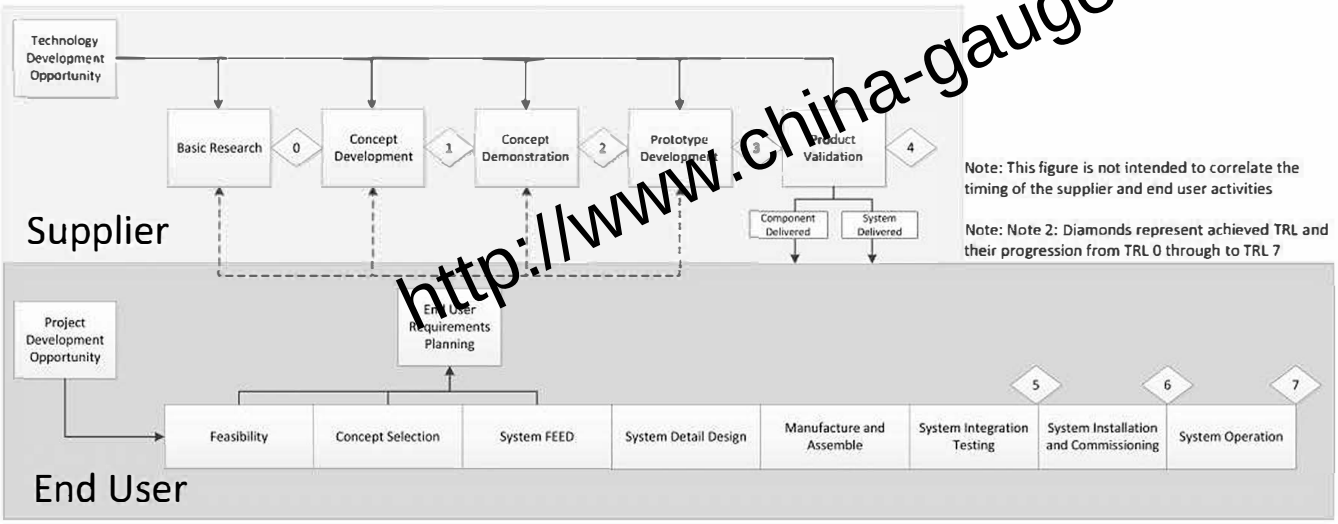

Figure 1—Example of Technology Development Link to End User Application/Project Development

NOTE A technology development is not always associated with a project development or specific field application. A technology development can be, and often is, undertaken as a standalone endeavor by a supplier and/or end user.

5 Qualification Program

5.1 General

It is recommended that all equipment to be used subsea, regardless of system design or application, be subject to qualification to ensure they meet defined reliability, integrity, and operational requirements. The need for executing a technology qualification should be assessed by performing a proper technology maturity assessment (see 5.4).

5.2 Overall Qualification Program Process

The overall aim of a qualification program is to provide evidence that a selected technology or equipment will meet functional and performance requirements, within specified operational limits, and with an acceptable level of confidence. Each step of the qualification program is a process in its own right. The overall qualification program process is shown schematically in Figure 2, described briefly below, and detailed in the following sections.

STEP 1 Requirements planning: The requirements planning process is undertaken early in the technology development program to define the goals and requirements for the technology and its application together with qualification requirements. If a specific application is unknown at the time of qualification, assumptions should be defined as part of the requirements planning process.

STEP 2 Technology maturity assessment: The technology maturity assessment uses TRC/TRL tools to (a) evaluate the technical risk and maturity of a concept in line with specified goals and requirements, (b) compare technologies, (c) determine if a research and development program is appropriate and, (d) identify the appropriate qualification path for the selected technology.

NOTE The level of detail in the technology maturity assessment depends on why the assessment is being conducted. If qualification is conducted as part of a field development, high-level assessments are often performed at an overall equipment level to assist with technology identification and concept selection, while detailed assessments at a component or part level are conducted to identify and focus qualification effort where it is needed.

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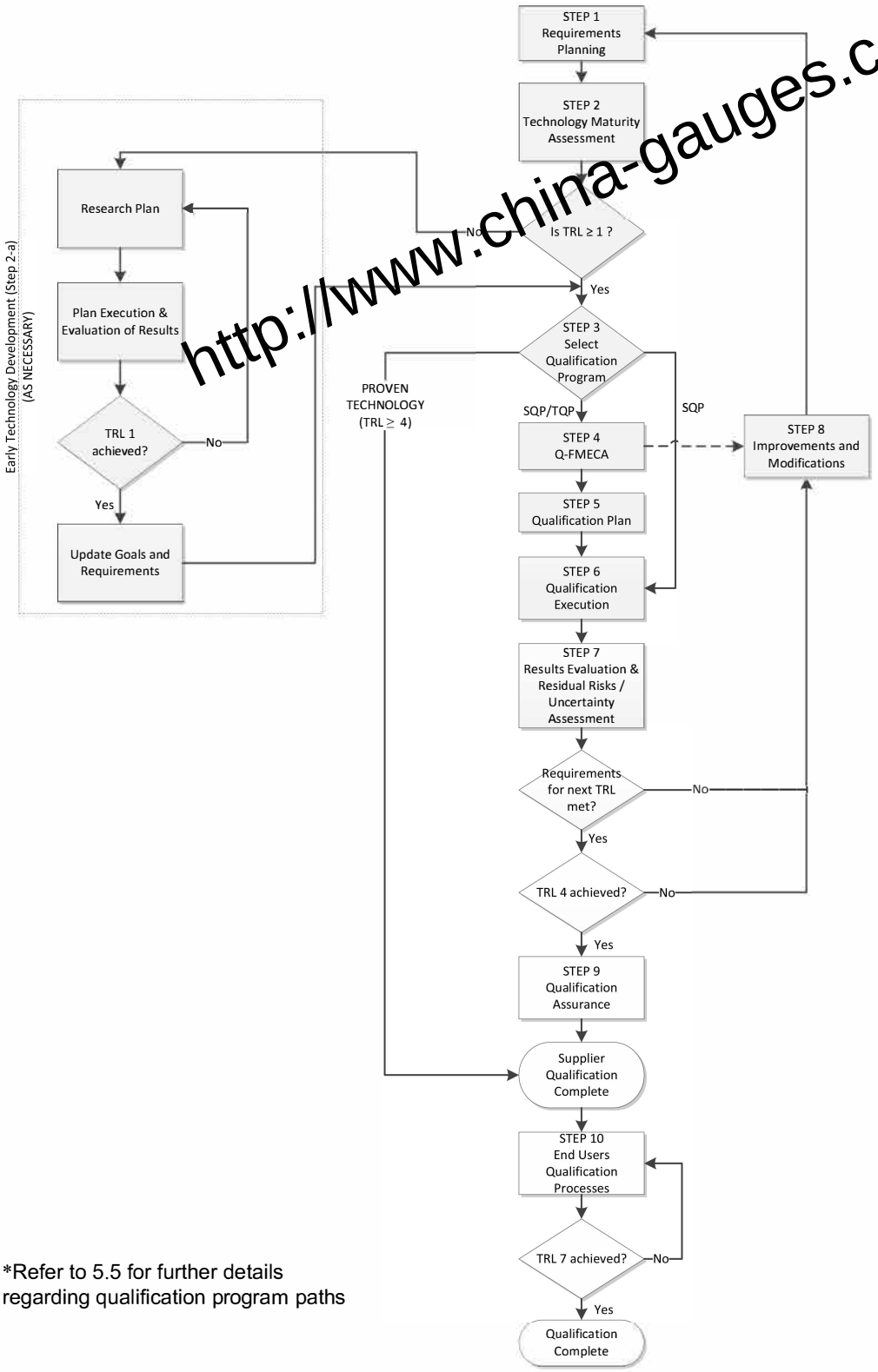

Figure 2—Overall Process for Qualification Programs
(Rectangle = Process; Diamond = Decision; Oval = End)

STEP 3 Select qualification program: The output from a technology maturity assessment is used to select one of three paths available for qualification:

— technology qualification program (TQP),

— standard qualification program (SQP), and

— proven in use (prior qualification program completed).

The recommendations for qualification path decision are described in 6.4. Which of the three paths is appropriate is dependent on the initial TRC and TRL assessed for the technology. It is recommended that a detailed maturity assessment be performed in advance of selecting the qualification program.

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STEP 4 Qualification FMECA (Q-FMECA) is a critical activity in the planning stages of a qualification. Its primary purpose is to support identification and development of the qualification plan (Step 5). The Q-FMECA output may also identify design improvements to be made before testing commences. Although a Q-FMECA is recommended for all qualification programs, organizations should consider mandating Q-FMECA where a TQP is selected at the end of Step 3.

STEP 5 Qualification Plan: A qualification plan is a document which comprises the activities required to qualify a technology to an acceptable level in line with the program goals and requirements. The plan should be directly informed by the Q-FMECA, as well as the detailed TRL assessment, industry standards, and other resources relevant to the subject technology. The plan generally includes a combination of physical testing activities and modelling and assessment activities. The plan should address the qualification activities to be undertaken at each TRL to achieve TRL 4.

STEP 6 Qualification Execution: The execution of qualification test plans typically involves running physical testing activities and performing modeling activities, including simulations, engineering analyses, and reliability/availability analyses in accordance with the plan and specified testing conditions. Qualification execution will generate results that provide the basis for evidence of function and performance. A key element of this stage is data analysis, which may require the application of statistical analysis techniques.

STEP 7 Results Evaluation: Following the qualification execution stage, the results of the tests and data analyses should be evaluated against the initial goals and requirements. If the qualification results indicate that the technology is not meeting the specified requirements for TRL advancement, then design improvements or modifications may be required (Step 8).

STEP 8 Improvements and Modifications: Design improvements or an evaluation of requirements can be performed at any point in the qualification program. It is most common to consider design improvements or requirement modification during the Q-FMECA (Step 4) or during results evaluation (Step 7). For example, if it is found during results evaluation that predicted reliability performance is less than specified, then design improvements may be necessary. The principle in Step 8 applies wherever the design is found not to meet the specification during qualification testing.

STEP 9 Qualification Assurance: The final step in the supplier qualification program is the qualification report. Assurance reports may be written at any stage in the qualification program but are specifically recommended once a technology achieves TRL 4. The qualification report is used to document the qualification claims together with associated arguments and evidence of qualification achievements throughout the technology qualification process.

STEP 10 End Users Qualification Program: The TQP steps outlined above are those generally undertaken by a technology developer or equipment supplier. Once equipment has achieved TRL 4, the technology is ready for an end user's application. The end users qualification program involves testing and monitoring to progress the equipment TRL through TRLs 5, 6 and 7. In addition to the guidance provided in this document, further considerations for this phase can be found in API 17N, Annex C.

5.3 Requirements Planning (STEP 1)

5.3.1 General

The definition of performance goals and requirements within a qualification program is the process which leads to the development of the application specification which typically includes goals, requirements and acceptance criteria. If a specific product application is unknown at the time of qualification, assumptions should be defined and agreed upon among stakeholders, and associated requirements should be developed based on these assumptions.

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The requirements planning process involves the following activities and procedures:

— develop a plan for identifying goals and requirements from stakeholders,

— elicit and validate goals and requirements,

— prepare a draft application specification document and issue to stakeholders for comment and approval,

— issue a final draft of the application specification with approved goals and requirements, and

— agreed-upon criteria for adapting the general TRL definitions to the specific technology to be qualified. Recommended only if the anticipated qualification scope warrants this level of detail.

The procedure is applicable for components, equipment and assemblies, which can be defined as new or modified technology.

5.3.2 Application Specification

The output of the requirements planning activity is the application specification which contains the goals, requirements, and technical risk acceptance criteria. The purpose of the application specification is to provide a common set of criteria against which all qualification activities should be assessed. The application of technology should be unambiguously and completely described through text, calculation data, drawings, and other documents. It is important that the functional and performance requirements and limitations of the technology are stated and that all relevant interfaces are clearly defined.

The application specification should be a living document which is updated as the technology maturity progresses and achievable goals and requirements become better defined.

The goals and requirements should address, but not be limited to, the following areas:

— regulatory requirements;

— function and performance requirements;

— technical requirements:

  — life cycle stages to be addressed;

  — design standards to be used;

  — operational and process conditions;

  — internal and external environmental conditions;

  — equipment life;

— reliability and integrity performance;

— limit states; and

— technology readiness level required for the program.

NOTE New technology may not be covered by established codes and procedures and thus it may not be clear how to qualify against existing standards or requirements. If this is the case, this document can be used to help guide the new technology development process.

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5.4 Technology Maturity Assessment (STEP 2)

5.4.1 General

There are various qualitative and semi-quantitative approaches to assess technology maturity. The tools described below—technical risk categorization (TRC) and technology readiness level (TRL)—are tools commonly used to compare technologies, to develop appropriate qualification plans, and to communicate the status of a specific technology as development programs are executed.

The TRCs and TRLs assigned during the technology maturity assessment are used to select the appropriate path for the technology qualification. Each of the available qualification paths makes specific recommendations suitable for the state of technology maturity indicated by the assessed TRC and TRL.

End users often perform technology maturity assessments in early stages of subsea development projects, specifically during feasibility studies and concept selection (see Figure 1). These assessments are typically preliminary and aid in technology identification, concept down-selection, and field development planning. It is not recommended to select a qualification path based solely on these high-level assessments.

A detailed technology maturity assessment is required to identify specific components and/or parts where qualification effort is needed. These detailed technology assessments are typically performed by suppliers (with end user participation) who possess the requisite knowledge of each technology and product. It is recommended that the detailed TRC and TRL assessments be conducted at a low enough level where discrete components and/or parts with low maturity for the specific application can be identified. This level of detail in the assessment ensures that qualification effort is focused only where it is needed and that qualification activities can be properly sequenced. For example, when qualifying assemblies, individual components may need to be qualified separately before the assembly can embark on its own qualification (i.e. a valve may be ready for final testing, assessed at TRL 3, except for a new seal design which is at TRL 1. If practical, the seal could be qualified independently of the valve until it reaches TRL 3 or 4). The qualifier should determine the appropriate level of detail to assess/qualify depending on component level maturity.

5.4.2 Technology Readiness Levels (TRLs)

Technology readiness levels (TRLs) are sets of defined levels of maturity to which technology and equipment can be assessed and their maturity clearly communicated. A TRL indicates a technology's current state of readiness, i.e. a "snapshot" in time, as intended for a specific application.

Performing TRL assessments, either on new technology or in response to a change to existing technology, helps clarify communication and facilitate qualification planning. The assessed TRL, when combined with an assessed TRC, determines the recommended qualification path for a specific technology. It is recommended to periodically reassess and track TRLs throughout a qualification program to monitor progress, communicate status, and adjust qualification activities. Monitoring and tracking TRLs is especially useful when multiple technologies are being qualified in a single program.

See Section 6 for TRL definitions and extended guidance on TRL assessments.

5.4.3 Technical Risk Categorization (TRC)

Technical risk categorization (TRC) is a critical step in the qualification process and should be utilized as early as possible to assess the qualification risk of the technology. The TRC assessment process should be used as often as needed to adequately define and address the risks in the qualification. Annex A of API 17N provides detailed context and guidance to perform and utilize the TRC process.

Within a qualification program, the TRC process serves several important purposes.

a) It facilitates technical discussion to evaluate what has changed in a technology and/or application to inform qualification requirements, often before detailed TRL assessments can be conducted.

b) It is the first formal opportunity to assess failure modes which will inform the qualification strategy.

c) It provides a comparative analysis to make decisions on which technology options to pursue.

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The assessed TRC, when combined with an assessed TRL, determines the recommended qualification path for a specific technology.

NOTE Other industry standards use alternative risk categorization schemes and may be used by some organizations instead of the TRC as defined in API 17N.

5.4.4 Research and Development

For new or modified technology categorized as TRL < 1, the TQP and SQP routes are unlikely to be practical. For example, at TRL 0, the technology is unlikely to be sufficiently defined to enable a FMECA to be performed. Consequently, to achieve TRL 1, a less formal, more flexible approach is required to explore the technology. The proposed qualification program stages have been simplified as shown in Figure 2. The proposed qualification stages are as follows:

— Research Plan - typically this is a document that comprises all activities required for a technology to achieve up to TRL 1, and it is in line with the program goals and requirements.

— Plan Execution and Evaluation of Results - this typically includes preliminary (high-level) engineering modeling activities and research and development (R&D) experimentation. It will generate results which will be evaluated against the initial goals and requirements and provide the basis for evidence that the technology has achieved TRL 1.

Following successful completion of an R&D program, the technology specification, goals and requirements should be updated, the technology maturity should be reassessed and further qualification activities should be determined as recommended in Step 3.

5.5 Qualification Program Selection (STEP 3)

5.5.1 General

This section describes the means of selecting a qualification program for new and modified equipment. Three qualification paths for a technology are available depending on the assessed TRC and TRL:

— TQP (described in 5.5.2);

— SQP (described in 5.5.2);

— proven technology (described in 5.5.3).

The TRC and TRL, as determined by the technology maturity assessment, are used to identify the type and sequence of qualification programs necessary for the technology. The recommended qualification program based on the assessed TRC and TRL is found in the TRC/TRL correlation matrix (see Figure 3). Each of the three paths (TQP, SQP, and proven technology) is described in the following sections.

NOTE Each TRL column identifies the recommended qualification program to achieve that column's TRL.

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			Technology Readiness Level (TRL)																	
			System Operation		System Installation / Commissioning		System Integration Testing		Product Validation		Prototype Development		Concept Demonstration		Concept Development		Basic Research			
			TRL 7 Achieved	7	TRL 6 Achieved	6	TRL5 Achieved	5	TRL4 Achieved	4	TRL3 Achieved	3	TRL2 Achieved	2	TRL1 Achieved	1	TRL 0 Achieved	0		
Technical Risk Categorization (TRC)	Very High	A	7	See Section 5.12	6	See Section 5.12	5	See Section 5.12	4	TQP	3	TQP	2	TQP	1	R&D	0	R&D		
	High	B	7		6		5		4	TQP / SQP	3	TQP / SQP	2	TQP	1	R&D	0	N/A		
	Medium	C	7		6		5		4	SQP	3	SQP	2	TQP / SQP	1	N/A		N/A		
	Low	D	7		6		5		4	N/A		N/A		N/A		N/A		N/A		

Figure 3—TRC/TRL Correlation Matrix

5.5.2 Technology Qualification Program (TQP) vs Standard Qualification Program (SQP)

For new or modified technology assessed as $1 \leq TRL < 4$, a technology has two possible qualification paths (i.e. TQP or SQP) depending on the TRC and project requirements.

TQPs utilize Q-FMECAs (see 5.6) to identify qualification activities necessary to qualify the technology in line with the identified goals and requirements. TQPs are typically necessary where the technology is novel or low maturity, where the environment or application is new or not well understood, and/or where no existing standard is applicable to the technology being developed. TQPs often require more effort and more complexity than comparable SQPs due to increased uncertainty in technology or environment.

SQPs utilize qualification activities prescribed within existing standards applicable to the technology. These may include but are not limited to, normative references in the API standards as well as normative and informative annexes to the API standards. These are typically associated with components, subassemblies, and assemblies of existing technologies that have been modified to meet an incrementally more stringent requirement, for instance, a change of operating depth from 1800 m to 2000 m. There are instances where, although a standard is applicable to a specific technology, it may not cover the required functional requirements to properly qualify the equipment. In this instance, it is recommended to utilize a Q-FMECA to address any potential gaps.

Guidance for selecting a TQP or SQP is based mainly on the assessed TRC (refer to the TRC/TRL correlation matrix in Figure 3):

— **TRC A**: any new technology categorized as TRC A should be qualified through a formal TQP (if TRL ≥ 1).

— **TRC B**: technology categorized as TRC B is likely to require a formal TQP to raise the readiness level from TRL 1 to TRL 4. However, in some cases, an SQP may be acceptable if the SQP is sufficiently well defined and provides all the necessary tests and analyses to demonstrate that the technology meets the specified goals and requirements for the technology.

— **TRC C**: a technology categorized as TRC C usually only requires an SQP. However, a TQP may be required to raise the readiness level from TRL 1 to TRL 3 or if an existing standard is not available.

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It is possible that a qualification program for a technology starts with a TQP and, as the TRL is advanced, the type of qualification program changes from TQP to an SQP. A reasonable justification for selecting a SQP in this case is that there is an existing standard that can cover prototype and product validation tests, but was not comprehensive for conceptual development or R&D activities.

The decision to use an SQP rather than a TQP should be formally documented in the qualification assurance document along with justification for why the chosen standard is appropriate and in line with the stated goals and requirements for the technology.

5.5.3 Proven Technology

Technology categorized 4 ≤ TRL < 7 can be classed as proven technology (note this is not the same as “field proven,” which is TRL = 7). Proven technology requires no further qualification activity at the component or part level, and the technology is ready for manufacture and project use. Typically the end user is responsible for raising the readiness level of the technology to TRL 7 during system integration and testing, commissioning and operations. See 5.12 for recommendations on end user qualification activities to achieve TRL 7.

Proven technology should meet the following criteria:

— the equipment is based on an existing design that has achieved TRL 4 or greater;

— the design has not been changed in any way, or there have been no modifications or alterations to form, fit or function which could have an impact on the performance of the equipment for the application being considered. A detailed assessment of component history and the supply chain may be needed to verify this criterion;

— products in service should have observed reliability and safety performance that meets the acceptance criteria associated with the specified performance goals and requirements;

— changes to the application, configuration, and/or operating environment in which the equipment is to be used should be:

  — of equal or lesser severity to previous applications and environments, or

  — not sufficient to impact on the performance of the technology.

Engineering judgment will likely be needed to determine the extent to which criteria 1 to 4 (above) are met. This requires expertise and broad background knowledge in the relevant subject area. Small modifications (to form, fit, function, or materials) can have significant impact on reliability performance. A high level of knowledge related to failure mechanisms and causes is generally needed to make informed judgments. For example, when the same component (i.e. exactly the same design with no modifications) is to be deployed in a new application or configuration, the TRL should be initially lowered to 3 until a more detailed assessment of the equipment can be

performed to determine whether the conditions of the new application or configuration has any effect on component performance. A detailed technology maturity assessment may then identify no impact to the ability to meet the specified requirements, and a TRL 4 and proven technology classification can be justified.

Equipment classified as proven technology may still require manufacture verification testing to be performed as per the relevant specification and/or standard covering that equipment. Examples of manufacture verification testing include ESS (environmental stress screening) or FAT (factory acceptance testing).

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5.6 Qualification Failure Modes, Effects, and Criticality Analysis (Q-FMECA)(STEP 4)

5.6.1 General

A key tool used to identify technology qualification activities is the qualification FMECA (Q-FMECA). The purpose of the Q-FMECA is to identify and prioritize qualification activities for a technology within a specified environment (application). A Q-FMECA will provide details regarding threats and weaknesses which should be used to define testing or analysis activities to demonstrate the technology's ability to meet specified requirements.

The format of the Q-FMECA is based upon existing FMECA types with a focus on identifying verification and validation activities for each identified failure mechanism. The Q-FMECA may require additional details to identify qualification actions. If an existing FMECA already covers the qualification performance requirements and qualification activities, then for the purposes of this RP, the existing FMECA can be considered a Q-FMECA.

5.6.2 Qualification Failure Modes, Effects, and Criticality Analysis (Q-FMECA) Contents

5.6.2.1 General

The Q-FMECA should be performed at a function level. The sections 5.6.2.2 through 5.6.2.7 describe a set of recommended columns for a standard Q-FMECA.

5.6.2.2 System Breakdown

Breakdown of the system to a level of detail required to discretely identify independent failure mechanisms. The breakdown should be based on the breakdown completed in the maturity assessment (from 5.4). To support the breakdown and function/criticality review, engineering documents for each component should be available.

System Breakdown			
Sub-System	Component	Current TRL	Required TRL

NOTE The system breakdown may also be used to identify combinations of items required for qualification testing as an assembly. This is useful where a specific failure mechanism only applies to an assembled unit or if it is not feasible to test items separately.

5.6.2.3 Function and Requirements

Identification of functions and performance requirements for each component (from 5.3) to correlate the identified qualification activities to a specific function and performance requirement. Identifying any changes between the proposed product and previous versions will assist in defining appropriate qualification activities. For example, a minor change in a performance requirement may require less onerous verification activities than a new product.

Function and Requirements		
Component Function	Component Functional Performance Requirements	Change Description (details of changes between this product and previous versions)

5.6.2.4 Failure Identification

Identification of all potential failure modes, mechanisms, and root causes for each functional entity examined, addressing potential deviations from performance expectations. The technical consequence should be documented to inform the criticality and risk assessments.

Failure Identification			
Failure Mode	Failure Mechanism	Failure Cause	Consequences (Local & Global)

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5.6.2.5 Criticality Assessment

Assessment of each potential failure mechanism to determine type of failure and means of failure detection.

Criticality Assessment			
Existing Safeguards	Fail Safe or Dangerous	Failure Detected or Undetected	Means of Failure Detection

5.6.2.6 Risk Assessment

A risk assessment should be performed for each identified failure mechanism to facilitate categorizing and prioritizing the qualification program.

Risk Assessment		
Likelihood	Consequence (by category)	Risk Score (by category)

NOTE The qualifier or end user risk matrix may be used to assign a severity level to the identified consequences.

Where underlying failure mechanisms and causes are not fully understood, Q-FMECA actions should include investigations including those involving testing and research, to improve knowledge and understanding of failure.

5.6.2.7 Qualification Activities

Identification of qualification activities needed to achieve the required TRL. Previous and current qualification evidence in relation to each failure mechanism should be identified and recorded in the Q-FMECA.

Qualification Activities		
Verification Activities	Validation Activities	Previous Qualification Activities and Evidence

NOTE The qualification activities identified in this section of the Q-FMECA should directly inform the qualification plan.

5.6.3 Other Qualification Failure Modes, Effects, and Criticality Analysis (Q-FMECA) Considerations

For modifications to existing technology:

— the system breakdown should identify all elements of the technology and be of sufficient granularity to identify which items are affected by the design or application changes, and

— items affected by changes to the design or application environment, additional granularity may be required. The level of granularity should be appropriate for the anticipated qualification activities.

The residual technical risks and uncertainties associated with each failure mechanism should be identified, noting that:

— for failure mechanisms classified as high risk, additional qualification activities should be undertaken to reduce the level of technical uncertainty and to identify design and development actions to reduce the likelihood of the failure mode occurring;

— for failure mechanisms classified as medium or low risk, additional qualification activities may be undertaken if there is a high degree of technical uncertainty or there is value in investing in improved reliability and integrity performance; and

— following implementation of identified qualification activities and follow-up actions, the technology assessment and FMECA should be updated and include an update of the residual technical risk associated with each failure mechanism.

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The Q-FMECA is intended to be a living document throughout the qualification process, and it should be updated as the technology advances in TRL.

5.7 Qualification Plan (STEP 5)

5.7.1 General

The inputs to the qualification planning stage are:

— Q-FMECA worksheets, and

— application specification:

  — technology goals and requirements, and

  — qualification requirements.

5.7.2 Input from Qualification Failure Modes, Effects, and Criticality Analysis (Q-FMECA) worksheets

The qualification planning stage builds on the output from the Q-FMECA risk assessments. Each element should have a set of actions and a qualification activity to be performed. The type of qualification activity is sensitive to the equipment's development stage and where it is positioned in the overall system hierarchy.

For elements still at the concept validation stage and not yet built as a prototype, the qualification activities may be restricted to materials testing activities. Some component reliability testing may not be possible until it has reached prototype development stage.

Function tests, cycle tests, and life tests for individual elements of the technology may be conducted on the elements as individual components, but in many instances, elements may need to be combined into a test rig with multiple elements or into the device as a whole. In some cases, the technology may have to be tested as a whole.

All technology qualification activities in the qualification plan should be based on and traceable to the Q-FMECA. The activities in the plan should be appropriate for the TRL of the technology. In this context, the plan may be considered a living document, which is updated as the technology develops.

5.7.3 Inputs from Application Specification

The technology requirements have a significant impact on the testing to be performed. For example, if the technology function has a pressure, temperature, and life requirement, the test plan should include function tests under the specified conditions for a time, such that there is confidence that the equipment can perform under those conditions

for the required life. Since qualification testing tends to be over a short period, life tests may need to be accelerated to demonstrate achievement of a long life within an acceptable time frame. Caution should be taken when planning for accelerated tests, so as not to introduce failure modes that would not be present in real operation. If the application specification includes a numerical reliability goal or requirement, then the qualification activities may need to include reliability demonstration tests and/or reliability modeling.

Relevant codes and testing standards may be used to support qualification testing activities where these are available and relevant. However for some technologies, where current codes and standards are not readily available or are inapplicable, bespoke tests should be specified or developed for the purpose of qualification.

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5.7.4 Preparation for Executing the Qualification Plan

The qualification actions to be included in the plan may include physical testing requirements or analysis/modelling requirements, or both. The choice depends on:

— the cost of physical testing relative to equivalent modeling approaches, and

— the relative confidence in the results from physical testing vs theoretical modeling results.

5.7.5 Contingency Planning

Qualification programs carry a certain level of risk that failure may occur. It is recommended to address these risks in a contingency plan which is agreed to among stakeholders in advance of a qualification. Often, implementation of a contingency plan requires forethought and upfront actions to be put in place. Considerations to include as contingency:

— schedule sufficient float in the program to allow for a given number of failed tests and re-tests,

— design variants of components pre-assessed and manufactured, available to be implemented,

— an already-proven technology available as an alternative for the application, and

— pre-agreement that certain specification could be relaxed.

5.8 Qualification Execution (STEP 6)

5.8.1 Qualification Analysis and Modeling

5.8.1.1 General

The analysis and modeling methods described in this section can be used to supplement physical testing. Using these methods as an alternative to physical testing should be in agreement with the goals and requirements defined in the application specification and agreed to among stakeholders. Use of analysis and modeling tools should not be considered an alternative to physical tests of a new technology/product. Such tools used to make predictions should be validated by test data and can also be used to design the parameters of a test or an experiment. Validated analysis tools and predictions can be used to supplement, or in some cases modify the requirements for testing, but only in circumstances that have been agreed upon by the relevant stakeholders.

The application of analysis and modeling methods should be made by technically experienced personnel with relevant knowledge of engineering principles, materials performance and failure mechanisms, industry standards, statistical data analysis and reliability technology.

5.8.1.2 Statistical Analysis of Test Data

Statistical analysis of test data may be included as part of the qualification program where there is a requirement to demonstrate reliability, availability, or other statistical requirements. Examples of tools which may be considered for this purpose include, but should not be limited to:

— chi-squared analysis (Appendix A),

— Weibull analysis, and

— reliability growth analysis.

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5.8.1.3 Engineering Analysis

Conventional engineering analysis tools may be used to support qualification activities. Two of the most common are:

— finite element analysis (FEA), and

— computational fluid dynamics (CFD).

FEA and CFD are widely used software tools to assess mechanical behaviour (FEA) and fluid flow (CFD) in complex engineering equipment. For example, FEA may be used to identify localized hot spot stresses and to demonstrate the ability to withstand complex loading in structures and mechanical devices. Although these are useful tools for engineering assessment, their use for reliability assessment is limited, since these are deterministic and cannot readily address uncertainties. However, with the increasing power of computers, it is now possible to perform probabilistic FEA and CFD to determine the probability of exceeding limit states and hence the probability of failure in complex structures. As an alternative to probabilistic FEA or CFD, the Q-FMECA can be used to define any varying or uncertain parameters to be further assessed in subsequent detailed FEA or CFD models. Examples of variable or uncertain parameters for use in probabilistic FEA include: dimensional tolerances, material min / max properties, min /max loads and environment.

5.8.1.4 Probabilistic Engineering Analysis Tools

A number of models can be used to perform probabilistic engineering calculations, including:

— probabilistic damage accumulation and limit state model,

— stress strength interference model,

— probabilistic fatigue, and

— probabilistic FEA and CFD.

5.8.1.5 Systems Reliability Assessment Models

For systems involving a number of subsystems and components, systems reliability analysis should be performed. The purpose of these assessments is to determine the system cut sets (system failure modes) which can be used to assess, for example, the impact of redundancy on reliability performance. Some of the assessment tools presently available to industry to facilitate an analysis of the reliability of a system include the following:

— reliability block diagrams,

— fault tree analysis,

— event tree analysis, and

— state space Markov modeling.

5.8.2 Physical Qualification Testing

5.8.2.1 General

Physical qualification testing takes many forms; the identification of tests to qualify the technology depends on the technology itself, the functional and performance requirements of the technology, the type of evidence required, and the current stage within the qualification process. The decision on what, how and when to test should be made by technically experienced personnel with relevant knowledge of engineering principles, materials performance and failure mechanisms, test engineering, technology qualification protocols, industry standards, statistical data analysis, and reliability technology. This recommended practice is not intended to replace the qualification and testing philosophies defined in existing subsea (i.e. flexible pipe and ancillary equipment) standards. Existing subsea equipment standards shall be used for detailing qualification test plans.

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Examples of physical testing that may be considered for hardware are briefly introduced below and include:

— function and performance testing,

— reliability demonstration testing,

— cycle testing,

— reliability growth testing,

— life testing,

— accelerated life testing,

— highly accelerated life testing,

— national and international standards tests, and

— stress screening.

5.8.2.2 Function and Performance Testing

Demonstrates in a test environment the capability to deliver a function and/or a performance level; for example, demonstrate that a valve can open or close on command within a specified time limit. There may be no attempt to demonstrate how function or performance varies with time.

5.8.2.3 Reliability Demonstration Testing (RDT)

Testing a number of components (replicates) over a specified time interval or cycles in a defined test environment. This is usually followed by statistical analysis of the number of failed or working components following the test (see chi-squared reliability demonstration test). See Annex B for more information on RDT.

5.8.2.4 Cycle Testing

Testing a demand-based component, such as a safety shut-off valve, over a number of demanded cycles (e.g. open and close cycles) and recording whether the component fails or survives the test. A chi-squared reliability demonstration test can be applied to cycle testing to assess reliability performance on the test.

5.8.2.5 Reliability growth testing (RGT)

This follows a similar approach to reliability demonstration testing but with a fix and retest stage. The intent of the fix action is to prevent or reduce the likelihood of failure. Reliability growth occurs if the test-fail-fix-test cycle leads to gradually increasing time between failures on the test.

5.8.2.6 Life testing

Components are tested in a simulated operating environment until failure. Where replicates are used, all components are tested to failure. Statistical analysis tools such as Weibull analysis can be applied to determine reliability or probability of failure as a function of time. Testing to failure may not always be practical when considering the schedule and financial constraints of some qualification programs.

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5.8.2.7 Accelerated life testing (ALT)

ALT is essentially life testing using an aggressive test environment which accelerates the rate of deterioration and reduces the time to failure. For example the test may be conducted at elevated temperatures. This approach is particularly useful for reducing test time and hence the cost of testing. Estimates of expected life under normal operating conditions may be possible by the extrapolation of results from accelerated conditions to normal conditions. Caution should be taken in planning and executing accelerated life testing so that failure modes are not introduced that would not be present in real operation.

5.8.2.8 Highly accelerated life testing (HALT)

HALT is not a technique for estimating the life of equipment but rather a method for increasing the robustness of the equipment through a sequence of test-fail-fix-retest cycles. HALT is only of value if the qualification plan accounts for iterative testing. Any test cycle that does not create a failure results in an increase “stress” in the test. The term stress in this context refers to any variable that increases the likelihood of failure, including temperature, pressure, flow, mechanical load, corrosivity of environment, etc. For electronic components, stress variables are typically temperature, mechanical vibration, and humidity.

5.8.2.9 National and international standards tests

National and international standards tests are the tests described in such standards as API 6A, 17D, 17B, 17J, etc. The tests described in such documents help provide context and testing methods to ensure a new product of similar type can meet the demands required of it. Standards tests also provide a means by which to define the ultimate goals and delivery condition of equipment past the technology qualification stage. Governing equipment specifications may provide normative validation requirements and means by which these qualification results are delivered. For delivery of equipment and validation of equipment, these standards take precedence over this document.

5.8.2.10 Stress Screening

Stress screening is a short test performed on a product following manufacture but before shipping, to enable discovery of any process faults and/or defects remaining in the product and hence prevent delivery of a defective product to the customer.

The test procedure typically involves the application of stresses, such as vibrations, shock loads, humidity, and thermal cycling, applied combined or sequentially, at a level intended to reveal any defects present in the product by forcing failure. The applied stresses and durations are critical. If the stresses are too low, defects may not be discovered, whereas if the stresses are too high, defect-free products may be damaged by the test, and their lives reduced.

There are two common approaches: environmental stress screening (ESS) and highly accelerated stress screening (HASS). The primary difference between the two methods is that the stresses applied in ESS tests are largely defined in standards, whereas HASS tests are preceded by a HALT program to optimize the applied stresses such that latent

defects can be revealed without damaging or significantly reducing the life of the product. In this context, HASS is considered to be a more rigorous process than ESS.

5.9 Results Evaluation and Residual Risk/Uncertainty (STEP 7)

The results of the qualification analysis and physical testing should be reviewed for conformance to the defined performance goals and requirements. It is recommended that this evaluation be conducted as a standalone step in the process to ensure a thorough evaluation is performed. This is the stakeholders' opportunity to identify any gaps in the results against the goals and requirements so that the requirements can be modified or the design can be improved.

In addition to the results evaluation, an assessment of the residual technical risk and its uncertainty should be performed following the achievement of each TRL. As qualification progresses, the uncertainty associated with the reliability and hence the technical risk of the technology should reduce. However, there will always be some remaining residual risk.

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Reliability and residual risk uncertainty assessments apply to all failure modes of equipment being qualified and consist of:

— an estimate of the most likely frequency of failure, together with an estimate of its uncertainty, and

— an estimate of most likely consequences of failure, together with an estimate of its uncertainty.

The Q-FMECA already contains the potential failure modes associated with the technology, together with their likelihood and consequences. The uncertainty around the likelihood and consequences needs to be understood, estimated, and addressed such that the risk can be appropriately managed.

Monte Carlo Simulation may be considered to support the residual uncertainty assessment to assess, for example, the impact of uncertainty of component failure rates on overall uncertainty of system performance in a system reliability model.

Uncertainty can be managed through further data gathering, analysis, or testing. If the uncertainty cannot be further reduced, the worst case risk would need to be assumed.

5.10 Implement Improvements and Modifications (STEP 8)

Improvements and modifications to the product or technology can occur at any point in the qualification program. It is most common to consider changes to the product or technology during development of the Q-FMECA (Step 4) or during results evaluation and residual risk/uncertainty assessment (Step 7).

If the specified goals, requirements, and/or acceptance criteria have not been met or if a modification of the product is considered appropriate, the product or technology should be returned to Step 1 (as shown in Figure 2) where requirements can be reevaluated or changes can be implemented.

Identification of strategies and processes for performance improvement may include but should not be limited to:

— design for reliability and integrity,

— design for maintainability,

— design for obsolescence management,

— continuous improvement,

— redundancy, and

— component de-rating.

After improvements and modifications are implemented, the qualification program is then repeated, taking into account the changes being made. All existing aspects of the qualification program should be reviewed and verified for applicability to the revised technology or product.

5.11 Qualification Assurance (STEP 9)

5.11.1 Documentation Requirements

The overall objective of the qualification report is to summarize the evidence of the extent to which the specified performance goals and requirements have been achieved during the qualification process. The qualification report should cross-reference to other documents where details can be found, on an as-needed basis, rather than producing a large, complex document.

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5.11.2 Example Contents for the Qualification Report

Industry best practice is to treat the qualification report as a live document that is continuously updated as the qualification program progresses. Typically the qualification report includes the following:

— a technology description;

— a summary of the application specification, goals and requirements and acceptance criteria;

— a summary of the qualification plans undertaken at each technology development stage;

— a summary of the qualification claims in relation to the specified goals and requirements;

— a summary of the evidence to support the claims with links to documentation:

  — FMECA,

  — system reliability studies,

  — model/analysis results, and

  — test results;

— improvements arising from qualification testing and assessment; and

— potential system and component weaknesses, and residual risks and uncertainty.

5.11.3 Independent Program Review

The need/requirement for an independent review of the qualification program and results should be agreed upon among stakeholders as part of Step 1. The intent of the review is to independently validate that the qualification program was planned, executed, and produced results in accordance with the specified goals and requirements. The independent program review can be conducted by an internal group not involved with the qualification or by a third-party company. If a third-party review is required by the qualifying company, other stakeholder companies, or by legislative requirements for the region in which the technology will be deployed, this requirement should be defined at the onset of the program.

If it is identified as a requirement, independent program review may include:

— validation of models and associated data to be used for analyses and simulations,

— verification that analysis has been performed in accordance with relevant standards and best practice,

— validation and witnessing of physical tests,

— verification that testing has been performed in accordance with the agreed-upon test procedure, and

— validation of each analysis, simulation, or test against its goals and requirements.

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5.12 End User Qualification Process (TRL 5–7) (STEP 10)

5.12.1 Technology Readiness Level (TRL) 5 Qualification program

5.12.1.1 General

A TRL 5 qualification program addresses the function and performance of the technology, as the technology is connected to and integrated with the wider system, but without operation.

A TRL 5 qualification program has the following objectives:

— to demonstrate that the technology will function and perform reliably once later installed as part of the wider system,

— to ensure that all continuity connections can be made safely and reliably and that interfaces are reliable over the required number of connect and disconnect events.

— to determine the residual technical risk and its uncertainty, and

— identification and specification of the qualification tests to be included in the SIT, for the test unit, and the subsequent production items.

A TRL 5 qualification program should include the integration of the technology product into the intended system. However, it is not a requirement for the operating environment to also be replicated at this stage, as this might constrain the testing that can be performed at this stage for some types of equipment (e.g. a multi-phase flowmeter).

As part of the integration with the intended system, the TRL 5 qualification program should ensure that all interfaces and functions are tested, including but not limited to mechanical, hydraulic, optical, electronic, software, ROV/tooling, and human interfaces.

An interface FMECA should be performed or updated to identify potential or additional failure modes and causes associated with interfaces with the wider system. Output from the FMECA should be used to support identification of tests to be included in the TRL 5 qualification.

All functions of the technology, including primary, secondary, and auxiliary functions, that may be required during the lifecycle, should be identified and included in the TRL 5 system qualification. For modified technology, testing may be limited to only those functions affected by the change.

Testing should demonstrate that if the technology is connected to the wider system, its functions do not adversely affect the wider system functions, performance, or reliability (e.g. it should ensure that there are no unexpected outputs or stresses from the product that prevent the wider system from conforming to the wider system functional or performance requirements). Testing should also demonstrate that the wider system does not adversely affect the technology function, required performance, and reliability (e.g. the wider system does

not impose unanticipated or unexpected stresses on the product that prevent the product from conforming to function or performance requirements).

5.12.1.2 Technology Readiness Level (TRL) 5 Assessment and Validation of System Reliability

A TRL 5 qualification program also should include the assessment and/or update and the validation of system reliability to verify that the predicted system reliability can be achieved.

Assessment and validation should examine the impact of the technology on the wider system reliability together with the impact of the wider system on the technology reliability.

Assessment and validation should include:

— a review of the system cut sets to see if these have changed, particularly in relation to any potential single point failures, and

— a review of potential common cause failures to identify any additional potential for a single event to cause multiple failures in the systems.

An estimation of the residual technical risk and its uncertainty, including practical limitations of system and interface tests performed, should be provided on completion of the TRL 5 qualification.

5.12.2 Technology Readiness Level (TRL) 6 Qualification Program

A TRL 6 program addresses the installation, hookup, and commissioning of the technology, together with the procedures covering the installation, hookup, and commissioning for the technology product. A TRL 6 qualification should include the integration of the technology product into the intended system in the intended operating environment.

As part of the subsea integration with the intended system, a TRL 6 qualification program should be used to verify that all interfaces and functions are tested to demonstrate that:

— the technology product is able to work as intended;

— the reliability of the technology product has not been compromised by the installation, hookup, and commissioning process; and

— the required in-service monitoring sampling and inspection can be performed.

The design FMECA should be reviewed and updated to verify technology in-service monitoring, sampling, and inspection requirements, including collection of data to:

— confirm function;

— measure the relevant process conditions (e.g. temperature, GOR, pressure, and flowrates);

— measure performance achievement (e.g. the timing of valve closure);

— measure or estimate the deterioration of in-service performance; and

— estimate failure rates and restoration rates.

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Additionally, a process FMECA should be performed for the installation and hookup process, to identify any potential failure modes in the technology product being installed or in the wider system arising from the technology product installation or hookup procedures. Appropriate mitigation procedures should then be included in the installation, hookup, and commissioning procedures.

An estimation of the residual technical risk and its uncertainty, including the risks identified in the updated design FMECA, should be provided on completion of the TRL 6 qualification.

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5.12.3 Technology Readiness Level (TRL) 7 Qualification Program

A TRL 7 qualification program involves establishing that the technology product functions and performs reliably in the intended operating (production) environment. Achievement of TRL 7 should be dependent on the technology product operating with the required reliability in the actual field environment for the required maintenance or failure-free operating period.

If a failure of the technology product occurs in-service or a failure of the wider system occurs as a result of application of the technology product:

— an RCFA should be performed to determine the root cause and contributing causes of the failure;

— results of the RCFA should be used to implement appropriate improvements or corrective measures;

— the subsequent qualification period required to achieve TRL 7 should be reviewed and, if necessary, reset to zero and the TRL 7 qualification restarted following implementation of the required improvement or corrective measures; and

— data and lessons learned should be fed back to technology development teams, project design teams, and equipment vendors, as applicable.

6 Assessing Technology Readiness

6.1 Technology Readiness Levels (TRL)

This section describes the definition and intent of each TRL and provides a guide to the types of qualification activities typically carried out at each TRL.

Each TRL is achieved by performing qualification activities that meet the technical and functional performance requirements and the reliability/integrity goals and requirements. These requirements are the most important in identifying the specific tests and/or analyses to be undertaken. However, these qualification activities that are identified should also be consistent with the types of qualification actions appropriate for the current TRL of the equipment.

Table 1 provides guidance on the types of qualification action to be considered at each TRL, from TRL 0 to TRL 7, respectively, for hardware. In practice, the initial TRL depends on the extent to which the equipment has been modified or changed.

The generic TRL ladders described in Table 1 should be reviewed and where necessary adapted into a technology-specific TRL ladder, with technology-specific expectations at each TRL stage.

6.2 Performing the Technology Readiness Level (TRL) Assessment

The technology assessment process makes use of basic systems engineering principles to break down complex systems into less complex elements that can be more accurately assessed. The assessment begins at the lowest

Table 1—TRL Definition, Descriptions, Supporting Information, and Achieved Level

TRL	Development Stage	Definition of Development Stage	Supporting Information (Evidence) Performed
0	**Basic Research** (Basic R&D, paper concept)	Basic scientific/engineering principles observed and reported; paper concept; no analysis or testing completed; no design history.	Basic Research activities to achieve TRL 0 typically include: a) identify fundamental objectives and requirements; b) undertake R&D conceptual studies; c) sketch out basic form (shape, dimensions, etc.) and function; d) identify basic principles; e) back of the envelope type calculations; f) lessons learned review for similar technologies; and g) identifying key technical risks.
1	**Concept Development** (Development of concept as a paper study or R&D experiment)	Meets all the requirements of TRL 0 and: a) technology concept and/or application formulated; b) concept and functionality proven by analysis or reference to features common with/to existing technology. No design history; essentially a paper study not involving physical models, but may include R&D experimentation.	Concept development activities to achieve TRL 1 typically include: a) extend research to formulate concept and potential applications; b) formulate concept and demonstrate functionality by analysis; c) preliminary assessment of fit (physical interfaces, etc.); d) engineering drawings with some engineering calculations; and e) review and update key technical risks.
2	**Concept Demonstration** (Experimental proof of concept using physical model tests)	Meets all the requirements of TRL 1 and: concept design or novel features of design is validated by a physical model, a system mock up or dummy, and functionally tested in a laboratory environment; no design history; no environmental tests; materials testing and reliability testing is performed on key parts or components in a testing laboratory prior to prototype construction	Concept demonstration activities to achieve TRL 2 typically include: a) demonstrate functionality—physical models/lab “mock-up”; b) perform initial Q-FMECA; c) laboratory scale material testing of degradation mechanisms; d) engineering studies to specify function/performance/ reliability; e) identify reliability drivers; f) all interfaces identified; g) consider feasibility of manufacture / assembly / transit / storage / installation; h) specify RAM requirements for technology overall / key components; and i) review and update key technical risks.

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Table 1—TRL Definition, Descriptions, Supporting Information, and Achieved Level (Continued)

TRL	Development Stage	Definition of Development Stage	Supporting Information (Evidence) Performed
3	**Prototype Development** (Prototype functional, performance and reliability tested)	Meets all the requirements of TRL 2 and: a) item prototype is built and put through (generic) functional and performance tests; reliability tests are performed, including where relevant: reliability growth tests, accelerated life tests and robust design development test program in relevant laboratory testing environments; tests are carried out without integration into a broader system; and b) the extent to which application requirements are met has been assessed and potential benefits and risks are demonstrated.	Prototype development testing activities to achieve TRL 3 typically include: a) perform detailed Q-FMECA; b) visualize / demonstrate form, fit and functional capability; c) physical prototype testing in factory or test laboratory; d) virtual prototype analysis / simulation; e) performance, durability and life tests; f) system reliability analysis; g) establish / confirm operating / destruct limits and degradation limits and degradation rates; h) all interfaces addressed; i) all FEA and hand calculations complete; j) address risks from the manufacture / assembly / transit / storage / installation; k) identify required in-service monitoring; and l) estimate reliability and residual technical risks and uncertainty.
4	**Product Validation** (Product validated and tested)	Meets all requirements of TRL 3 and, designed and built as a production unit (or full scale prototype) and put through its qualification program in a simulated environment (e.g. hyperbaric chamber to simulate pressure) or actual intended environment (e.g. subsea environment), but not installed or operating; reliability testing limited to demonstrating that functional and performance criteria can be met in the intended operating and environmental condition, where practical.	Product validation activities to achieve TRL 4 typically include: a) manufacture a specification for production items; b) review and update Q-FMECA; c) establish a performance data collection system; d) product testing in a simulated or actual subsea environment; e) degradation of function / performance within acceptable limits; f) acceptability of the manufacturing / assembly process; g) manufacture / assembly defects removed by stress screening; and h) estimate reliability and residual technical risks and uncertainty.
5	**System Integration Testing** (System interface tested)	Meets all the requirements of TRL 4 and, designed and built as a production unit and integrated into the intended operating system with full interface and functional test but outside the intended field environment	System integration testing activities to achieve TRL 5 typically include: a) review and update Q-FMECA; b) test function / performance when connected / integrated with wider system; not necessarily in a subsea environment; c) address mechanical, hydraulic, optical, electronic, software, ROV/tooling and human interfaces; d) confirm product SIT requirements; e) initiate performance / reliability data collection; f) update system reliability assessment; and g) estimate reliability and residual technical risks and uncertainty.

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Table 1—TRL Definition, Descriptions, Supporting Information, and Achieved Level (Continued)

TRL	Development Stage	Definition of Development Stage	Supporting Information (Evidence) Performed
6	**System Installation and Commissioning** (System installed and tested)	Meets all the requirements of TRL 5 and, production unit built and integrated into the intended operating system; full interface and function test program performed in the intended (or closely simulated) environment. A TRL 6 new technology equipment normally requires extended testing during the commissioning stage to verify function and performance requirements.	System installation and commissioning activities to achieve TRL6 typically include: a) review and update Q-FMECA; b) installation / hook-up / testing / commissioning with wider production system—not operating with production fluids; c) confirm product is able to work as intended / reliability is not compromised by installation / hook-up / commissioning processes; d) define detailed in-service inspection / monitoring / sampling; e) verify inspection / monitoring / sampling functionality; f) define preparedness response; g) complete interface / function qualification testing; and h) Identify remaining technical risks to be managed by operations.
7	**System Operation** (System field proven)	Meets all the requirements of TRL 6 and, unit integrated into intended operating system, operating for a sufficient length of time (or number of operations) to demonstrate achievement of early life and through life reliability and integrity goals and requirements. Appropriate justification should be prepared to support the defined "sufficient length of time." NOTE The length of time (or number of operations) required to demonstrate reliable performance depends on the population of components, intended design life and the failure rate of the equipment and will vary from system to system. To promote a consistent approach for defining "sufficient length of time," generally, permanently installed production systems can be considered to achieve TRL 7 after three years of continuous service.	System operation activities to achieve TRL 7 typically include: a) implement in-service monitoring, sampling and inspection; b) collect and analyze reliability and integrity performance data; c) review and update Q-FMECA with in-service performance data; d) undertake RCFA for failed / underperforming items; e) implement reliability improvements for failed / underperforming items; f) establish product functions in its operating environment with the required reliability for the required maintenance or failure free operating period; and g) feedback performance to projects / suppliers.

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level in the breakdown and proceeds up the hierarchy in a bottom-up approach. This system breakdown and bottom-up TRL assessment approach is visualized in Figure 4.

The TRL for each element in the system breakdown is equal to or lower than the minimum TRL of its constituents. For example, the systems TRL is equal to or lower than the minimum TRL of each of its subsystems. Similarly, the subsystems TRL is equal to or lower than the minimum TRL of each of its components. When considering the TRL for a subsystem or system, the user should consider the state of integration between components, as the TRL of integration may be lower than the TRL of each of the components themselves.

For subsea production systems, the TRL is evaluated at the component level, since it is typically components that are developed, tested, manufactured, and integrated as cohesive units throughout a field development project. However, a TRL assessment may be performed at any level deemed necessary to effectively and accurately communicate technological maturity. The level of detail in the breakdown structure is often dependent on an organization's desired degree of visibility into the development project. For example, a manufacturer may focus on the TRL of key design features or component parts when developing a new product, whereby an end user may focus on the TRL of component assemblies and/or subsystems when planning for a new field development.

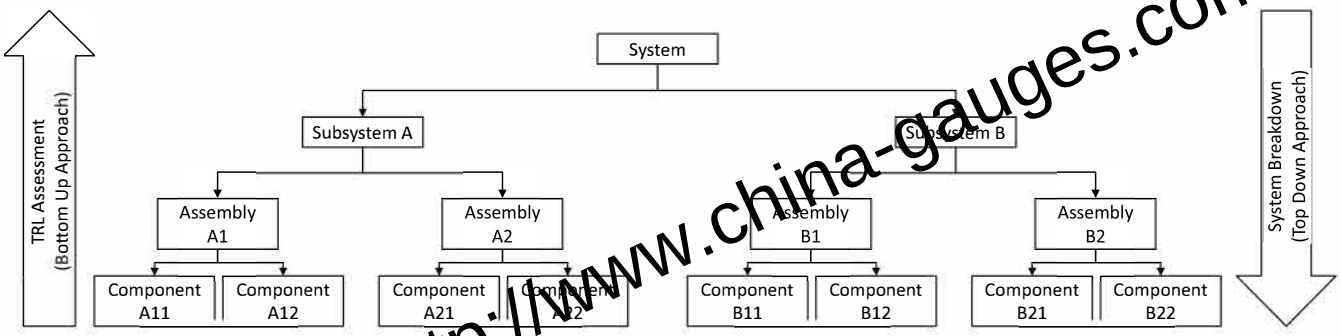

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Figure 4—Top Down System Hierarchy and Bottom Up TRL Assessment

When assessing TRLs, the definition of TRLs listed in Table 1 should be used. A TRL assessment is only valid for a particular application, defined by a set of reliability, integrity, and/or operational requirements. If the requirements change, the TRL must be reassessed.

A useful approach to performing the TRL assessment is to consider the past performance and current requirements in terms of form, fit, and function, and to determine if that performance satisfies the requirements for the relevant application. For guidance on this initial TRL assessment, refer to Figure 5.

Assessing the TRL requires due diligence on the part of the assessor to evaluate all the differences between past performance and current requirements in order to provide sufficient evidence and justification for each TRL achieved. Supporting evidence in the form of design documentation, test reports, and/or service records should be recorded along with the TRL.

Annex B of this document provides an example of a TRL assessment.

Discussion between qualifiers and end users is often required to adapt the generic TRL ladder for new technology and to agree on more specific definitions, i.e. when is a component/assembly considered a prototype, how similar are the environments, how much time is sufficient to achieve TRL 7, etc.

NOTE Figure 5 must be used in conjunction with the guidance provided in 6.1 and 6.2

6.3 Risks in Advancement of Technology Readiness Level (TRL)

6.3.1 Planning Phase Risk Evaluation

The difficulty of advancing through TRLs, particularly at higher TRLs, should be carefully assessed throughout a qualification program. Although TRLs and TRCs are useful tools for categorizing technologies, not all technologies will require equal effort and resources to advance. In addition to TRL and TRC assessments, it is recommended to assess each technology's difficulty of advancement, with a focus on effort/resources/schedule so that appropriate, non-technical decisions can be made.

6.3.2 Execution Phase Risk Evaluation

There is a possibility that a failure is identified during qualification testing/analysis, installation, commissioning or operation such that the technology does not meet performance and reliability requirements. This situation could arise from unaccounted for loading conditions, environmental interactions, material properties, etc. In such a situation, an

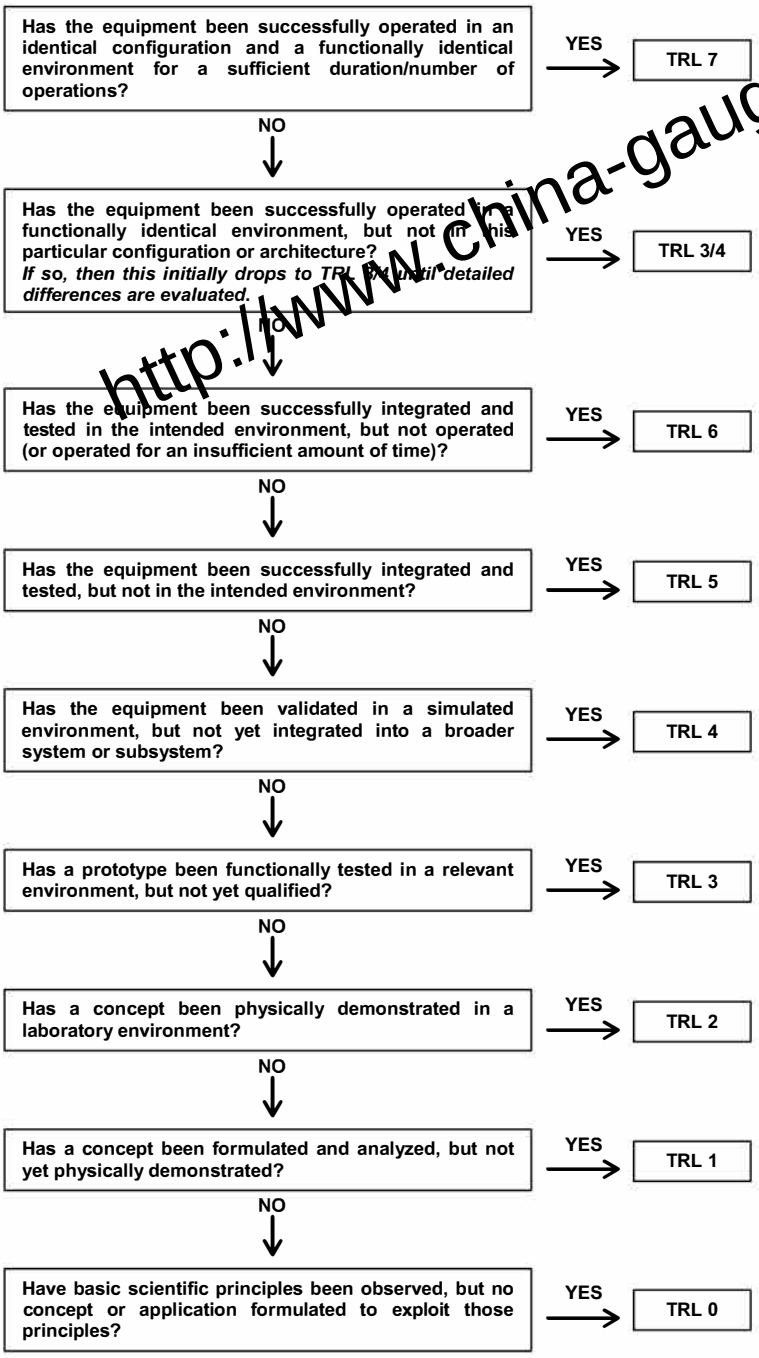

Figure 5—TRL Assessment Question Sequence

RCFA should be conducted to understand the potential causes and to develop an action plan to remediate the issue. Depending on the failure type, the RCFA action plan may result in a design change. During or after the RCFA process, the stakeholders should re-perform a technology maturity assessment (see 5.3) on the impacted system(s). The previous TRL/TRC may justifiably decrease, in which case, the process defined in Section 5 should apply to determine if additional qualification is required.

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Annex A
(informative)

Statistical Analysis of Test Data

NOTE The following examples are merely examples for illustration purposes only. Each company should develop its own approach. They are not to be considered exclusive or exhaustive in nature. API makes no warranties, express or implied for reliance on or any omissions from the information contained in this document.

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A.1 Annex Purpose

This annex provides example methods for estimating the failure rate of equipment from performance verification test data.

NOTE It is not appropriate to use this method in reverse to determine the level of testing needed to achieve a failure rate performance requirement.

A.2 Application of Test Statistics to Continuously Operating Equipment

A.2.1 General

During new technology qualification programs, it is often necessary to place equipment items or components on test to demonstrate how long they can be expected to function without failure. If the test environment is similar or equivalent to those expected in service, the performance measured on the test will be a useful demonstration of the expected performance in the field.

This section demonstrates how the reliability of a device can be estimated from tests conducted in conditions equivalent to those expected in operation from a sample number of components. The same techniques may be applied to time to first failure data obtained in operation, e.g. during the early life of the operation.

Recorded times to failure are generally subjected to a number of statistical tests with the objective of:

— validating the failure pattern, and

— estimating the reliability parameters (e.g. the mean time to failure).

Table A.1 provides a sample data set for the purposes of this example. It is assumed that twenty items were tested under the expected operating conditions, and the test was concluded when the final item failed. This type of test is known as test to failure. All failures are assumed relevant.

Table A.1—Example of Sorted Failure Data

Failure Number	Time to Item Failure (Yr)	Failure Number	Time to Item Failure	Failure Number	Time to Item Failure
1	0.08015	8	1.43274	15	2.38448
2	0.12863	9	1.63482	16	3.14187
3	0.30204	10	1.64809	17	3.25363
4	0.32808	11	1.77079	18	3.6551
5	0.53285	12	1.8526	19	4.29491
6	0.80301	13	1.85436	20	7.8356
7	0.98767	14	1.89738		

A.2.2 Test for Validating Failure Pattern

Much of the published reliability data are in the form of failure rates, which are assumed to be constant over time. In practice, failure rate may vary with time.

NOTE The instantaneous failure rate is more correctly referred to as the hazard rate. When the hazard rate is constant, the hazard rate is called the failure rate. The hazard rate is constant if failures occur randomly over time and hence conform to the exponential distribution.

For non-repairable equipment in which data are independently and identically distributed (IID), probability plotting methods can be used to estimate time-to-failure parameters. Probability plotting can be manually implemented using probability plotting papers, which can be easily downloaded from the internet. However, parameter estimation can be readily implemented using computer software.

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The Weibull distribution is arguably the most common distribution used for assessing the failure pattern and is given by:

$$F(t) = 1 - e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \quad \text{(A.1)}$$

where

$F(t)$ is the cumulative failure distribution function;

η is the characteristic life (time to failure);

β is the shape parameter; and

γ is the location parameter.

NOTE The location parameter, γ, is zero for 2-parameter Weibull distribution and non-zero for 3-parameter Weibull distribution.

By fitting the observed time-to-failure data to this expression, it is possible to determine from the value of the shape parameter, β, whether the hazard rate is increasing ($\beta > 1$), decreasing ($\beta < 1$), or constant ($\beta = 1$). When $\beta = 1$, the value of η is the mean time to failure, and the failure rate is $\lambda = 1/\eta$.

NOTE A 3-parameter Weibull distribution cannot be represented by a straight line on a Weibull plot. More details on Weibull analysis and other life data analyses can be found in Reference [1] in the bibliography.

Weibull analysis has been performed on the data presented in Table A.1. The data were fitted to the 2-parameter Weibull distribution. The results are shown in Figure A.1. The derived distribution parameters from Figure A.1 are $\beta = 1.009$ and $\eta = 2.103$ with $\rho = 98.7$ %, where ρ, the correlation coefficient, is a measure of how well the model fits the data. Since $\beta \approx 1$, these data may be considered to exhibit a constant hazard rate.

A.2.3 Estimating the Failure Rate for Components with Constant Hazard Rate

If the failure pattern conforms to a constant hazard rate or if there is an expectation that the hazard rate will be constant, the failure rate can be estimated from a knowledge of the number of failures (r) and the total accumulated time of components on test T^*.

A point estimate of the failure rate, $\hat{\lambda}$, is given by:

$$\hat{\lambda} = \frac{r}{T^*} \quad \text{(A.2)}$$

To calculate the failure rate to a given level of confidence (CL) from tests (see A.2.3), the uncertainty in the data can be modeled using the χ^2 distribution, with the statistic $2\lambda T^*$ from which λ can be estimated as:

$$\lambda = \frac{\chi^2(1 - CL), df}{2T^*} \quad \text{(A.3)}$$

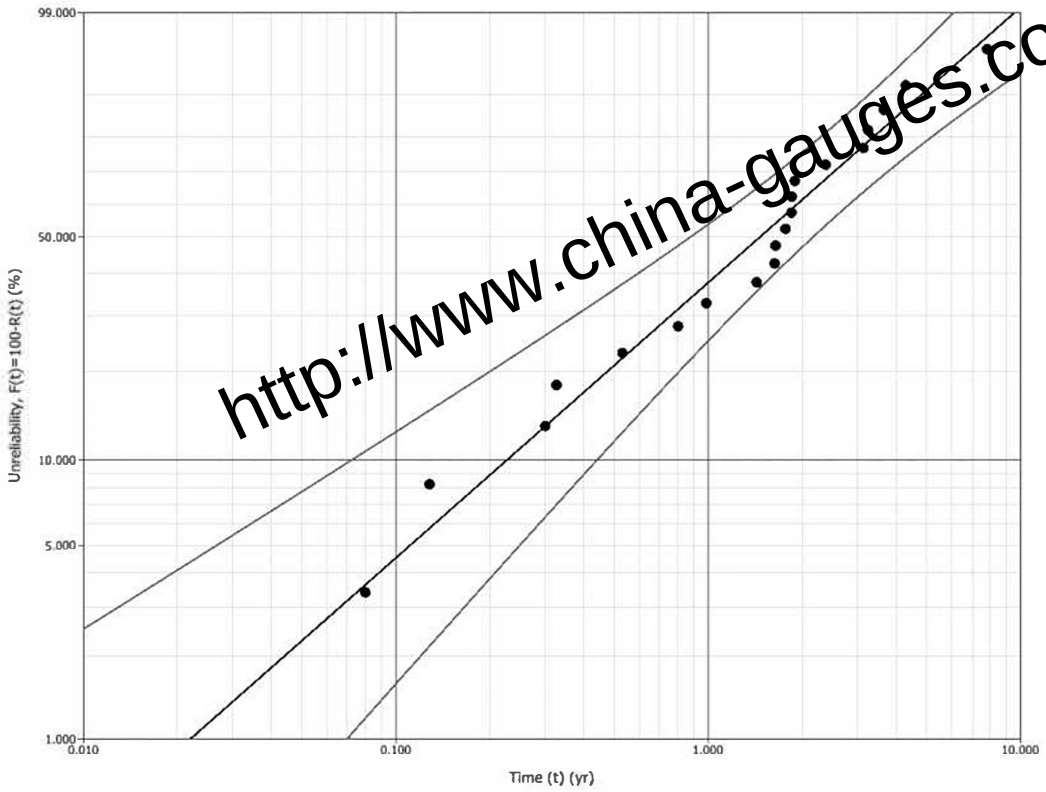

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Figure A.1—Weibull Probability Plot with 2-sided 90 % Confidence Interval (Data from Table A.1)

where

$df = 2r$ is the number of degrees of freedom for failure-terminated tests.

A.2.4 Confidence Level

A.2.4.1 General

The confidence level is a statistical variable which is the complement of the acceptable risk of error. Lowering the confidence level (i.e. increasing the acceptable risk of error) gives more optimistic (higher) values for the lower limit of the mean cycles to failure (MCTF). A high confidence level (i.e. lowering the acceptable risk of error) will generally result in a more conservative estimate for the lower limit of MCTF. Table A.2 provides a correlation between the confidence levels and the chi-square values corresponding to the time-truncated case (see Equation (A.8)).

NOTE 1 When assessing confidence levels, it is the lower bound on MCTF or mean time to failure (MTTF) which is normally required, or the upper bound on the failure rate.

To calculate the upper and lower bound (confidence levels), it is first necessary to specify a confidence interval and the degrees of freedom, related to the number of observed failures r.

The lower limit of the failure rate, λ_L, is calculated as:

$$\lambda_L = \frac{\chi^2(\alpha/2, 2r)}{2T^*} \tag{A.4}$$

Table A.2—Confidence Levels vs Chi-Square Values

Confidence Level $Px\ (1-\alpha)$	α	$\chi^2(\alpha, 2r+2)$		
		$r=0$	$r=1$	$r=2$
P_{10} (10 %)	0.9	0.211	1.064	2.204
P_{20} (20 %)	0.8	0.446	1.649	3.070
P_{25} (25 %)	0.75	0.575	1.923	3.455
P_{30} (30 %)	0.7	0.713	2.195	3.828
P_{40} (40 %)	0.6	1.022	2.752	4.570
P_{50} (50 %)	0.5	1.386	3.357	5.348
P_{60} (60 %)	0.4	1.833	4.045	6.211
P_{70} (70 %)	0.3	2.408	4.878	7.231
P_{75} (75 %)	0.25	2.773	5.385	7.841
P_{80} (80 %)	0.2	3.219	5.989	8.558
P_{90} (90 %)	0.1	4.605	7.779	10.645
P_{99} (99 %)	0.01	9.210	13.277	16.812

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The corresponding upper limit of the failure rate for failure-terminated tests, λ_U, is calculated as:

$$\lambda_U = \frac{\chi^2(1-\alpha/2, 2r)}{2T^*} \tag{A.5}$$

where

$CL = 1-\alpha$, and

where

α is the acceptable risk of error.

NOTE 2 For time terminated tests, with/without replacements, the upper bound on failure rate is obtained by setting $= 2(r+1)$.

When predicting reliability in performance verification tests such as those found in API Specification 17D, Table B-2, or API Specification 6A, Annex F, the analysis should include the associated confidence level.

A.2.4.2 Calculation of Accumulated Time

The calculation of accumulated time is sensitive to practical testing constraints, such as time allowed for testing, the number of failures that occur on test, and the number of components on test. The following are common testing constraints:

1) Time terminated (or truncated) tests, and

2) Failure-terminated (or truncated) tests.

A.2.4.2.1 Time Terminated Tests

For time terminated testing ($0 \le r < n$), n components are placed on test at the same time, and if, after time T, there are r out of n failures, the total accumulated time, T^* can be calculated as:

$$T^* = (n-r)T + \sum_{i=1}^{r} t_i \tag{A.6}$$

where

n is the number of samples in the test

r is the number of failed items in the test sample

t_i is the time of the i^{th} failure

T is the total test time

The term $(n-r)\mathrm{T}$ represents the time accumulated by those components still working at the end of a test of duration T. The second term $\sum_{i=1}^{r} t_i$ represents the time accumulated in the working state by those items that fail before the end of the test time T.

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NOTE For testing in which test specimens fail and are subsequently repaired and put back on test, Equation (A.6) reduces to $\mathrm{T}^* = n\mathrm{T}$.

For example, for the data in Table A.1 if the test had been terminated after the 10th failure, $n = 20$ and $r = 10$:

$$\mathrm{T}^* = (n-r)\mathrm{T} + \sum_{i=1}^{r} t_i = (20-10)1.64809 + 7.87808 = 24.334323$$

A.2.4.2.2 Failure-Terminated Tests

For failure-terminated testing ($r = n$), the test is run until all components placed on test have failed. In this case, equation (A.6) simplifies to:

$$\mathrm{T}^* = \sum_{i=1}^{r} t_i \qquad \text{(A.7)}$$

For tests terminated after the 20th failure, $n = 20$ and $r = 20$:

$$\mathrm{T}^* = \sum_{i=1}^{r} t_i = 39.8188$$

With the example data provided in Table A.1, the point estimate of failure rate (failures per year) is calculated as:

$$\hat{\lambda} = \frac{20}{39.8} \approx 0.5$$

This corresponds to a mean time to failure of 2 years. Assuming that a 90 % confidence interval is required between the upper and lower bound estimates (i.e. $\alpha = 0.1$), the lower limit of the failure rate, λ_L, is calculated as:

$$\lambda_L = \frac{\chi^2(\alpha/2, 2r)}{2\mathrm{T}^*} = \frac{\chi^2(0.05, 40)}{79.64} = \frac{26.51}{79.64} = 0.33,$$

which corresponds to a mean time to failure of 3 years.

The upper limit, λ_U, is calculated as:

$$\lambda_U = \frac{\chi^2(1-\alpha/2, 2r)}{2\mathrm{T}^*} = \frac{\chi^2(0.95, 40)}{79.64} = \frac{55.76}{79.64} = 0.70,$$

which corresponds to a mean time to failure of 1.43 years.

A.3 Application of Test Statistics for Non-Continuous Operation

A.3.1 General

The performance verification tables published in existing industry standards, such as API Specification 6A, Annex F and API Specification 17D, Table 3, are performance verification test requirements and are intended to validate non-continuous operation components (cycle life) for an assumed design (or operating life). Cycle tests are used here to demonstrate performance verification for an assumed design life.

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NOTE The term MCTF is used to represent mean cycles to failure where cycle tests have been performed, and MTTF is used to represent mean time to failure. MTTF can be calculated from MCTF if the number of cycles per unit time is known.

Often, the specified number of components to be tested are insufficient to determine the statistical distribution. However, the chi-square (χ^2) distribution method, outlined below, may be used to estimate MCTF, and hence reliability, with small test sample populations, even populations as low as one, provided that the test failure occurrence can be accepted as random. This method is also applicable to any number of failures on test, including zero failures.

NOTE If this assumption is invalid, the use of equation (A.8) and (A.9) below could lead to errors in the estimate of the MCTF, i.e. the value of the lower limit of the MCTF may not be as conservative as implied by the method.

Calculating the lower confidence level on an MCTF is given by one of the following equations:

For a time-truncated test:

$$\mathrm{MCTF} \geq \frac{2\mathrm{C}}{\chi^2(\alpha, 2r+2)} \tag{A.8}$$

For a failure-truncated test:

$$\mathrm{MCTF} \geq \frac{2\mathrm{C}}{\chi^2(\alpha, 2r)} \tag{A.9}$$

where

C = the total number of cycles a component sees during a test.

Where replicate tests are practicable, it is recommended that these are included to check that the distribution conforms to constant hazard rate (CHR), or to improve confidence in the lower bound MTTF estimate. A minimum of four tests would normally be necessary to check conformance to CHR.

Once the lower limit is established for a given number of failures and confidence level, the component's reliability can be estimated using the following equation:

$$\mathrm{RFT} = \exp\left(-\frac{\text{field cycles}}{\mathrm{MCTF}}\right) \tag{A.10}$$

where

RFT is the reliability of the component, estimated from tests, for a given number of field cycles and

MCTF is the mean cycles to failure.

The lower bound on MCTF may be used in Equation (A.10) if required to give a more conservative estimate of reliability.

The term RFT (reliability from test) has been introduced here to emphasize that the reliability is estimated from test(s) rather than historical field failure performance. The value of reliability obtained from tests may have different value from that derived from historical failure data and is sensitive to the test conditions. Test conditions should therefore be made explicit.

A.3.2 Example Calculations of Mean Cycles to Failure (MCTF) and Mean Time to Failure (MTTF)

EXAMPLE 1 Consider a choke stepping actuator's cycle testing completing a 1,000,000 cycle test with no failures ($r = 0$). What is its reliability, for a 50 % confidence ($\alpha = 0.5$), as a function of field cycles for the field unit?

The calculation method can be performed in terms of MCTF and then converted to mean time to failure if the cycle rate (number of cycles per unit time) is known or can be estimated.

$$\text{MTTF} = \frac{\text{MCTF}}{\text{cycle rate}}$$

Using the above table to look up the value of chi-square corresponding to $\alpha = 0.5$ and $r = 0$, the 50 % confidence level for MCTF is given by the following equation:

$$\text{MCTF} \geq \frac{2\text{C}}{\chi^2(\alpha, 2r+2)} = \frac{2(1{,}000{,}000)}{\chi^2(0.5, 2)} = \frac{2{,}000{,}000}{1.386} \approx 1{,}443{,}000 \text{ cycles}$$

Interpretation: "There is 50 % confidence that the MCTF of the actuator is equal to or greater than 1,443,000 cycles."

$$\text{MCTF} = 1{,}443{,}000 \text{ cycles}$$

Applying the exponential reliability equation:

$$R(\text{cycles}) = e^{-(\text{field cycles}/1{,}443{,}000)}$$

The results at 50 % confidence can be found in Figure A.2 below.

Assuming that the actuator performs 500 cycles per year:

$$\text{MTTF} = 1{,}443{,}000/500 = 2886 \text{ years}$$

EXAMPLE 2 Consider a valve cycle test-to-failure program in which there are 723 cycles before it malfunctions ($r = 1$). What is its mean MCTF, for a 90 % confidence?

Number of Field Cycles	Reliability
0	1
5000	0.997
10,000	0.993
15,000	0.99
20,000	0.986
25,000	0.983
30,000	0.979
50,000	0.966
100,000	0.933

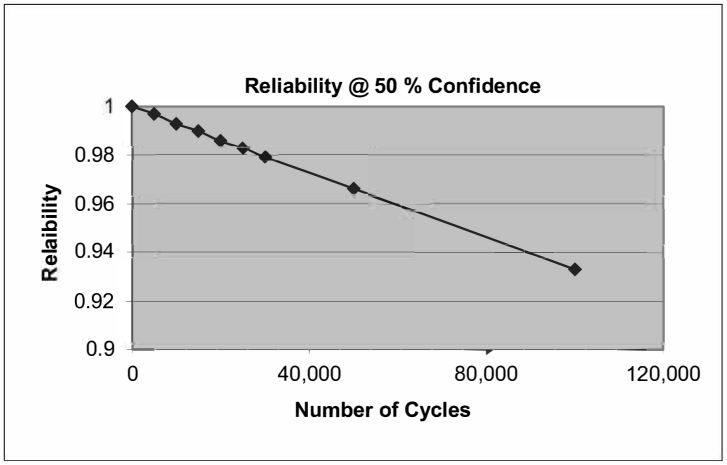

Figure A.2—Results of Example at 50 % Confidence

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In this case, the 90 % confidence level for MCTF is given by the following equation:

$$\text{MCTF} \geq \frac{2\text{C}}{\chi^2(\alpha, 2r)} = \frac{2(723)}{\chi^2(0.1, 2)} = \frac{2(723)}{4.605} \approx 314 \text{ cycles}$$

Interpretation: "There is 90 % confidence that the MCTF of the valve is greater than or equal to 314."

$$\text{MCTF} = 314 \text{ cycles}$$

Assuming that the valve performs 12 cycles per year:

$$\text{MTTF} = 314/12 = 26.2 \text{ years}$$

The MTTF values obtained from this method should only be considered a starting point value and should be followed up by a risk assessment process to determine if additional scope of qualification testing is needed to meet specific reliability requirements such as described in this document.

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A.4 Reliability Demonstration

A.4.1 Estimating Test Sample Size

A test in which failure is undesirable is commonly referred to as test to success. This type of test is often accelerated and it aims to represent an equivalent to *one service life* which the product is expected to complete without failures. The binomial distribution is often used to describe success run test statistics in test situations with two possible outcomes, i.e. pass or fail. The probability of product survival (based on the binomial cdf) can be estimated as follows:

$$\text{CL} = 1 - \sum_{i=0}^{k} \frac{N!}{i!(N-i)!} R^{N-i}(1-R)^i \tag{A.11}$$

where:

R = unknown reliability;

CL = confidence level;

N = total number of test samples;

k = number of failed items.

With $k = 0$ (i.e. no failures) and solving for the (test) sample size N, equation (A.11) can be rearranged to give:

$$N = \frac{\ln(1-\text{CL})}{\ln(R)} \tag{A.12}$$

Equation (A.12) can be used to estimate the number of test samples required, assuming no failures occur on the test for the equivalent product service life. Alternatively, it can be used to assess the confidence level given a specified reliability, R, and the number of tests, N, conducted.

If failures occur (i.e. $k > 0$), Equation (A.11) is difficult to solve for reliability R. In this case, an approximation using the chi-square formula may be used instead of Equation (A.11).

$$N = \frac{\chi^2(1-\text{CL}, 2k+2)}{2\ln(R)} \tag{A.13}$$

A.4.2 Correlating Test Duration and Test Sample Size

Producing multiple test samples for reliability demonstration testing may significantly impact project costs and schedule. In some situations, it is possible to extend the test duration in order to reduce test sample size using the parametric binomial model. In cases with limited test capacities, reducing the number of test samples at the expense of longer testing may be beneficial.

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Lipson and Sheth (1973) [2] developed the following relationship to extend test duration in order to reduce test sample size:

$$\frac{N_2}{N_1} = \left(\frac{t_1}{t_2}\right)^{\beta} \tag{A.14}$$

where:

β = Weibull slope for primary failure mode (known or assumed);

N_1, N_2 = test sample sizes;

t_1, t_2 = test durations.

If t_1 is equivalent to one mission life, then:

$$t_2 = Lt_1 \tag{A.15}$$

where L is the life test ratio.

Combining Equations (A.12) and (A.15) and solving for L yields the following:

$$L = \left(\frac{\ln(1-\mathrm{CL})}{N\ \ln(R)}\right)^{\frac{1}{\beta}} \tag{A.16}$$

NOTE Equation (A.16) can only be used for cases where there are no failures, i.e. $k = 0$. For situations in which undesirable failure occurs, an approximation using the chi-square formula can be used instead by combining Equations (A.13) and (A.15) as follows:

$$L = \left(\frac{\chi^2(1-\mathrm{CL}, 2k+2)}{2N_1\ \ln(R)}\right)^{\frac{1}{\beta}} \tag{A.17}$$

EXAMPLE A product is to be tested at the specified test temperature for 5000 hours, corresponding to its service life. The required reliability is 95 %, with a 50 % confidence level.

a) Calculate the required number of test samples for reliability demonstration assuming all samples can be tested at the same time and temperature and that the components exhibit constant failure rate:

   The number of test samples can be calculated using either Equation (A.12) or (A.13):

$$N = \frac{\ln(1-\mathrm{CL})}{\ln(R)} = \frac{\ln(1-0.5)}{\ln(0.95)} = 14$$

   Therefore, the required test sample size for $R = 0.9$ and $\mathrm{CL} = 0.5$ is 14.

b) If the temperature chamber can only accommodate 10 test samples, calculate the test time required to meet the above reliability and confidence level. Assume the Weibull slope $\beta = 2$ (i.e. increasing failure rate).

To determine the new test duration (i.e. based on 10 test samples instead of the original 14), it is necessary to first calculate the life test ratio.

The life test ratio can be calculated using either Equation (A.16) or (A.17):

$$L = \left(\frac{\ln(1-\mathrm{CL})}{N\ln(R)}\right)^{\frac{1}{\beta}} = \left(\frac{\ln(1-0.5)}{10\ln(0.95)}\right)^{\frac{1}{2.0}} \approx 1.162$$

Therefore the original test duration (t_1) should be extended to:

$$t_2 = Lt_1 = 1.162 \cdot 5000 \approx 5812 \text{ hours}$$

Although this approach has been previously used to both extended and reduced life testing, there are limitations in its application. It is recommended that the test times not change by more than ±50 %. Since Equations (A.16) and (A.17) use the Weibull slope, significantly extending the test time may result in tests being performed in a range where the value of β may not be constant. For example, using the example above, if the original test time is extended by more than 50 %, the value of β may be changing to values greater than 2. This would then violate the assumptions implicit in the parametric binomial model. The converse is also true: reducing the test time by more than 50 % could violate the binomial model assumptions, since it may affect the failure probability by shifting the failure pattern from the wear-out phase to the useful life, i.e. the β-value may be closer to 1 over that time range.

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Annex B
(informative)

Example Technology Maturity Assessment

NOTE The following examples are merely examples for illustration purposes only. Each company should develop its own approach. They are not to be considered exclusive or exhaustive in nature. API makes no warranties, express or implied for reliance on or any omissions from the information contained in this document.

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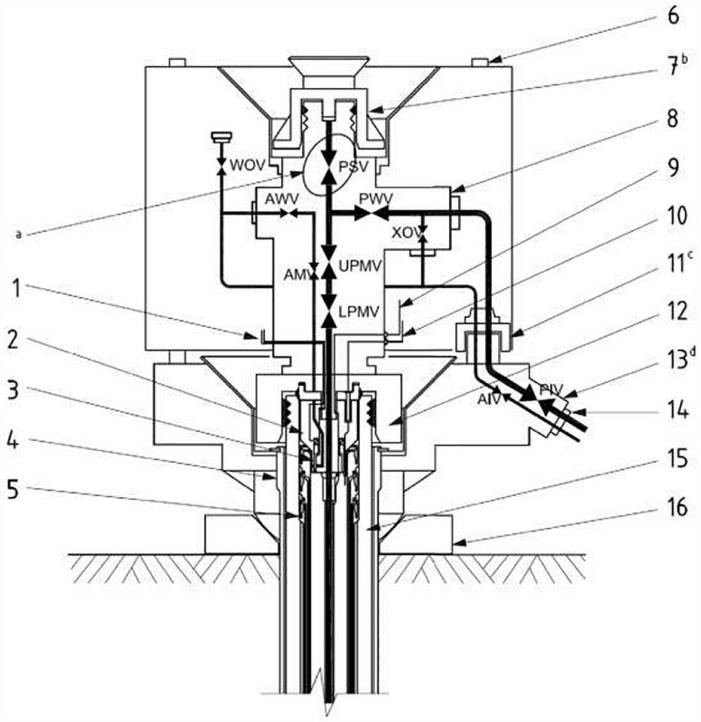
B.1 Example Technology Maturity Assessment Introduction

The following is an example of a TRL assessment of a new 15,000 psi, 350 °F-rated subsea vertical xmas tree (VXT), depicted in Figure B.1. An initial TRL assessment of each component of the VXT is performed to identify any gaps in technology when compared with the overall program goals and requirements. A detailed assessment of one of the components is then performed to assist with qualification planning.



Key

1 annulus access shift valve control line
2 tubing hanger (TH)
3 annulus access sliding sleeve
4 conductor housing
5 casing hangers and seal assemblies
6 guideposts
7 XT cap
8 Xmas tree (XT)
9 DHPTT monitoring line
10 SCSSV control line
11 flow line connector
12 XT connector
13 guidebase
14 flow line/tie-in spool connector
15 wellhead
16 drilling guidebase or template slot

[a] PSV may be substituted with plug.
[b] XT cap may be pressure-containing or non-pressure-containing.
[c] Flowline connection shown connected to production guidebase, but may also be connected directly to XT.
[d] Production guidebase shown (allows connection of flowlines).

Figure B.1—Diagram of a Vertical Xmas Tree with Key

B.2 Example Breakdown and Technology Maturity Assessment

The assessment of the VXT system begins with a system breakdown to testable components. An example breakdown is shown in Figure B.2.The level of detail in the system breakdown depends on the purpose of the technology maturity assessment. For this example, a supplier is performing an assessment of the VXT system to identify low-maturity components that will need qualification.

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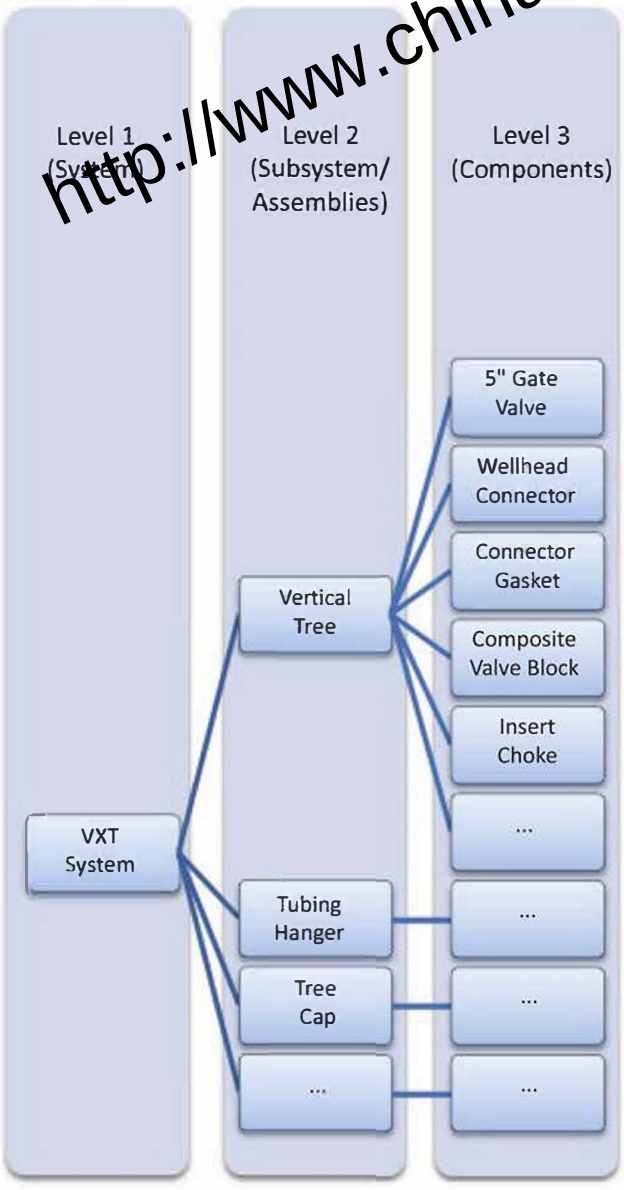

Figure B.2—System Breakdown Example for 15K 350F VXT

The components from the system breakdown are evaluated according to the TRC assessment criteria and assigned a TRL. Tables B.1 and B.2 show an example technology maturity assessment for the gate valve and the connector gasket.

Table B.1—Technology Maturity Assessment for a Gate Valve

Component: Gate Valve

The intended application is in 8900 feet of water and has a maximum wellhead shut-in pressure of 13,000 psi and a maximum temperature of 320 °F.

The gate valve has been qualified to 10,000 ft of water with a maximum pressure of 15,000 psi and a maximum temperature of 350 °F.

The gate valve has been installed and operated in several different fields over the last five years, all of them in less than 5000 ft of water and with shut-in pressures less than 11,000 psi.

Technical Risk Category	Rating	Justification
Reliability	D	No reliability improvements are required. Existing quality assurance and control is acceptable based on previous project success.
Technology	D	Same supplier providing equipment of identical specification. Gate valve qualification meets project requirements.
Architecture/ Configuration	D	Architecture/configuration is identical to previous specifications. No interface changes to VXT or control system identified.
Environment	C	Previous projects have only been installed and operated in up to 5000 feet of water. Gate valve qualification meets project requirements but has not been installed and operated at this water depth. Shut-in pressures are slightly higher than previous projects but are still within specification.
Organization	D	Same organization and supply chain as previous projects.
Highest TRC	**C**	
Technology Readiness Level (for this application)	**5**	The gate valve has been qualified and successfully integrated into an identical system, but has never been installed/commissioned (TRL 6) and operated (TRL 7) at the required water depth and shut-in pressures. For this application, the gate valve has a TRL of 5.

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Table B.2—Technology Maturity Assessment for a Connector Gasket

Component: Connector Gasket

The intended application is in 8900 ft of water and has a maximum wellhead shut-in pressure of 13,000 psi and a maximum temperature of 320 °F.

The supplier does not have a connector gasket rated for these application requirements, and would need to develop a new gasket.

The new connector gasket would be based on a previous design rated for 10,000 ft of water, and maximum wellhead shut-in pressure of 10,000 psi, and a maximum temperature of 250 °F.

Technical Risk Category	Rating	Justification
Reliability	B	Historical reliability has been acceptable; however, reliability performance is unknown in the new environment and may require a major design improvement
Technology	B	Known gasket technology that will be scaled up but is non-mature for the more severe environment. A new material may be required.
Architecture/ Configuration	B	Significant changes to the connector gasket interfaces are expected in terms of size and layout.
Environment	B	Significant changes to the environment. Higher pressure and temperature than previous gasket designs.
Organization	D	The same organization and supply chain as previous projects.
Highest TRC	**B**	
Technology Readiness Level (for this application)	**1**	The connector gasket has been assessed a TRL of 1. The gasket concept is based on common features with previous gasket designs. Preliminary sizing has been completed by analysis. Material change may be required. The concept has not been functionally tested for the higher pressure/temperature.

Based on Figure B.3, the connector gasket, assessed at a TRC B and TRL 1, should go through a TQP. Similarly, since the gate valve was assessed at TRL 5, it can be implemented into the end user qualification program (see 5.11) and further component level qualification work is not required.

The technology maturity assessment for the VXT system would continue until all of the components have been assessed. Once all components have been assessed, the TRL for the VXT system can be determined based on the lowest TRL of all the components or integration of the components. For this example, the lowest TRL of the components was determined to the connector gasket at a TRL of 1. The VXT system TRL is therefore also TRL 1 for this application.

A more detailed assessment of the components can be performed as input to a Q-FMECA by breaking down each of the components to the part or design feature level. Figure B.3 shows a breakdown of the gate valve to the part level. Each of the parts can then be evaluated against the application requirements to help focus detailed qualification efforts where needed.

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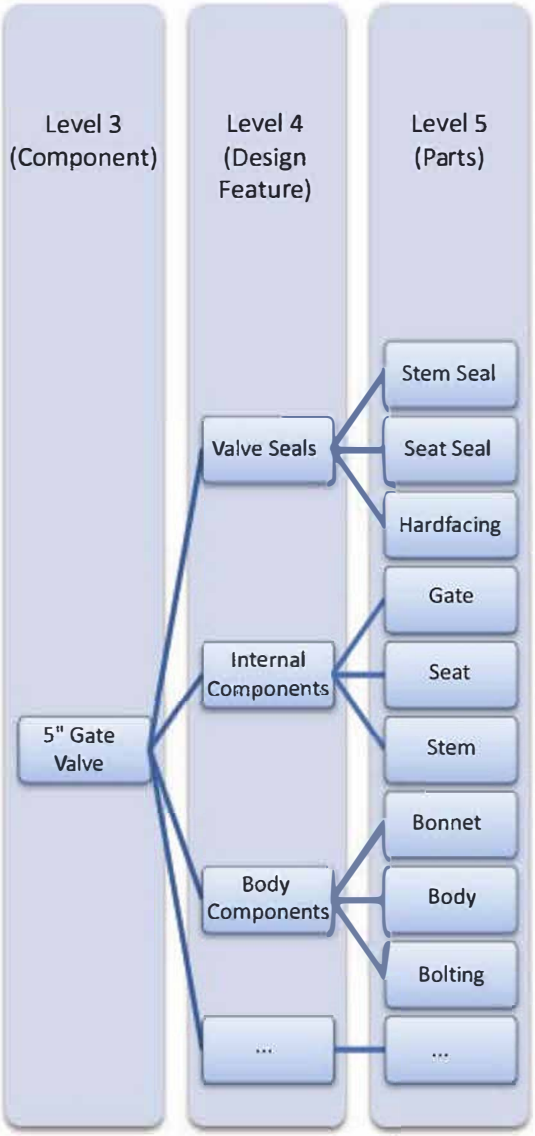

Figure B.3—Component Breakdown Example for 5" Gate Valve

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