

# Risk-based Machinery Management

API RECOMMENDED PRACTICE 691  
FIRST EDITION, JUNE 2017



AMERICAN PETROLEUM INSTITUTE

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## Introduction

The origins for the development of this recommended practice came from the recognition among responsible companies that more effective machinery risk management requirements are needed in view of:

- major accidents occurring within the industry;
- new manufacturing centers having difficulty in consistently achieving acceptable levels of quality;
- new applications and services that involve unproven design envelopes;
- larger fleets of aging machinery operating in process and pipeline facilities;
- limited experienced resources operating and maintaining machinery.

These and other drivers have influenced the content of the pages that follow, including understanding of the following.

- 1) Machinery risk is context dependent. It may be quite different among companies operating identical machinery within the same process service. Therefore, to be truly effective, the API Subcommittee on Mechanical Equipment (SOME) determined that prescriptive design requirements, as seen in machinery base standards, such as [API 610](#), could not be imposed upon the industry by API 691. Since every company has unique engineering specifications, process requirements, worker competencies, work processes, risk tolerances, etc., API 691 allows internal risk criteria and methodologies to be utilized by individual operating companies for the purpose of identifying and managing high-risk machinery applications within the context of their own operating regimes.
- 2) Machinery risk is systemic. As such, the recommended practice sets minimum requirements for operating companies, selected designated responsible parties (DRPs), and vendors. Depending on the companies within this system, risk levels may either rise or fall for any given machinery asset. Each company is encouraged to map the API 691 processes outlined herein to their internal work process to the extent possible. The vendor is required to maintain on file design failure mode and effects analysis (DFMEA) as specified by the operating company. They are also responsible to track the technology readiness levels (TRL < 7) of components and subcomponents whose failure may lead to a loss of containment and/or a loss of functionality that could lead to a potential process safety event and to define integrity operating window (IOW) as required. Any other risk management requirement placed upon the vendor is considered outside the scope of this recommended practice. The DRP is required to perform all tasks and activities required by the operating company to enable safe and environmentally compliant machinery.
- 3) Machinery risk is dynamic. It changes over time and, therefore, API 691 is organized by machinery life cycle phase, including feasibility and concept selection; front end engineering design; detailed design; installation and commissioning, and operations and maintenance. There are periodic risk assessments that are required in each of these phases. The recommended practice requires the operating company to put in place a management system to track and mitigate risks where required over time, develop machinery standard operating procedures, define safe operating limits (SOLs), and provide adequate training for operating and maintenance personnel working on high-risk machinery, hereafter referred to as “API 691 Machinery.”

While not required, the user of this recommended practice is encouraged to utilize the Informative annexes where internal requirements are either lacking or found to be insufficient. The operating company and/or their DRP will find that issuing both the base API machinery datasheet (e.g. the [API 618](#) datasheet) concurrently with the API 691 data sheet (Annex H) at the proposal stage is a useful way to define and communicate all API 691 requirements to ensure these are properly addressed and in the most timely manner.

A bullet ( • ) at the beginning of a section or subsection indicates that either a decision is required or further information is to be provided by the operating company. When such decisions and actions are taken, they may be specified in company documents (e.g. requisitions, change orders, datasheets, and drawings).

# Risk-based Machinery Management

## 1 Scope

### 1.1 General

**1.1.1** This recommended practice defines the minimum requirements for the management of health, safety, and environmental (HSE) risks across the machinery life cycle. It shall be applied to the subset of operating company and/or vendor defined high-risk machinery.

**1.1.2** Unless otherwise specified, the following criteria shall be used for initial risk screening to identify potential high-risk machinery for which this recommended practice will be applied:

- a) hazardous gas or liquid services as defined by jurisdiction, appropriate regulatory body, and/or operating company standards or specifications,
- b) services operating at temperatures  $>350^{\circ}\text{F}$  ( $177^{\circ}\text{C}$ ) and having design or specified off design operating pressures  $>80\%$  maximum allowable working pressure (MAWP),
- c) services operating at temperatures  $>400^{\circ}\text{F}$  ( $204^{\circ}\text{C}$ ),
- d) components and subcomponents having technology readiness levels (TRLs)  $< 7$  whose failure may lead to a loss of containment and/or a loss of functionality that could lead to a potential process safety event (see Table 1),
- e) liquid services operating at pressures in excess of 600 psig (41.4 bar),
- f) liquid services having specific gravities less than 0.5.

It is acknowledged that most operating companies and vendors may have existing risk management processes. This recommended practice is not written to replace or invalidate company practices but is meant to supplement them to provide safe working and living environments for facilities and surrounding communities. Operating companies (i.e. Sections 5, 6, 7, and 8 for design, installation, and operating purposes) or vendors [i.e. in Section 4 for research and development (R&D) and product development purposes] can use their own initial risk screening criteria where these have been found to be effective or the criteria recommended above.

NOTE 1 Typically only between 10 % and 20 % of machinery falling within any given initial risk screening will be considered API 691 Machinery. This can include a subset of “critical,” “unspared,” “special purpose,” “prototype,” and/or worst actor machinery. Risks can include loss of containment of hazardous fluids, loss of functionality, high energy releases, etc.

NOTE 2 Applicable international (e.g. GHS <sup>[1]</sup>) or national (e.g. OSHA 1910.119, [API 570](#) <sup>[2]</sup>, Class 1, etc.) hazardous service classifications are typically defined within operating company specifications.

NOTE 3 Operating companies and vendors can choose to apply this recommended practice to machinery not covered by existing API standards (e.g. hyper compressors).

**1.1.3** The following machinery protection and safety standards shall be applied to new API 691 Machinery where applicable:

- a) [API 670](#);
- b) IEC 61508-1, IEC 61508-2, and IEC 61508-3;
- c) IEC 61511 (Parts 1, 2, and 3) or ANSI/ISA-84.00-2004 (Mod IEC 61511);
- d) IEC 62061 or ISO 13849-1 and ISO 13849-2.

**1.1.4** Other standards and technical reports may be used to further assist in the application of this standard including:

- a) ISO 12100,<sup>[3]</sup>
- b) ISO/TR 14121,<sup>[4]</sup>
- c) VDMA 4315,<sup>[5]</sup>
- d) IEC 60812,<sup>[6]</sup>
- e) IEC 64244-3.<sup>[7]</sup>

**1.1.5** This recommended practice is intended to be used by operating companies, their designated responsible parties (DRP), and vendors that are identified as potentially operating at high risk. It is applicable to both new (Sections 4 to 8) and existing (Section 8) installations.

NOTE This can include some supporting process equipment, for example, knockout drums, instrumentation, etc. that are located off-skid.

## **1.2 Machinery Risk Management**

### **1.2.1 General**

The term “API 691 Machinery” is used in this recommended practice to identify machinery that warrants a comprehensive machinery risk management system. Using risk ranking to prioritize machinery for further study and/or action provides a focus that maximizes the risk reduction of ongoing activities and improves the effectiveness of machinery risk management systems.

### **1.2.2 Management System**

A management system to implement and sustain risk management programs for machinery should include:

- 1) procedures covering implementation, program maintenance, and reassessment (including reassessment triggers),
- 2) roles/responsibilities, training, and competence testing to ensure employment of qualified personnel,
- 3) documentation requirements of the risk analyses (e.g. scope, boundaries, assumptions, and mitigation actions),
- 4) data requirements including validation requirements,
- 5) acceptable risk limits and thresholds,
- 6) management of change (MOC) process,
- 7) program audit traceability requirements.

### **1.2.3 Risk Assessments**

Assessment of probability and consequence can be done by a variety of approaches at the operating company or vendor's option. Refer to Annex A for further information. This recommended practice allows flexibility in assessment approaches (various qualitative, semi-quantitative, or quantitative methods) and defines only the deliverables needed at each stage to determine appropriate mitigations.

### 1.2.4 Risk Mitigation

Risk mitigation is typically accomplished by:

- a) identifying risk levels above owner-defined limits,
- b) identifying both the probability of failure (POF) and consequence of failure (COF) to understand the risk drivers,
- c) identifying scenarios in sufficient detail to provide the specified deliverables at each life cycle stage,
- d) identifying potential mitigations for either or both probability and consequence,
- e) selecting and testing mitigations for sufficient risk reduction,
- f) documenting and implementing the selected mitigations.

NOTE All of the steps above may not be appropriate at every life cycle stage.

### 1.2.5 Integration with Other Risk Assessments

The risk assessment methodologies within this recommended practice encompass approaches that enhance those conducted as part of a typical process hazard analysis (PHA) or reliability centered maintenance (RCM) program, both of which tend to focus on only a portion of the equipment life cycle. Integration of the various methodologies across the machinery life cycle (and its organizational supply chain) is key to a successful machinery risk management program.

Operating companies or their designated responsible party (DRP) may perform initial screening of machinery as part of routine process safety management (PSM) and/or hazard and operability (HAZOP) studies. These may also be useful in providing information on risk (e.g. consequence and/or operating scenarios).

### 1.2.6 Risk Assessment and Mitigation Activities by Life Cycle Stage

#### 1.2.6.1 General

Risk assessment is used at different stages of the life cycle in different ways. These typically include two stages: a screening to identify machinery warranting further review and a more detailed assessment to identify needed mitigation.

For screening assessments, consequence alone may be used to trigger the need for further, more detailed risk assessments (e.g. better screening and evaluate risk management activities).

The following outlines the risk assessment and mitigation activities at each of the life cycle phases. It should be noted that API 691 Machinery can be declassified at any phase by the operating company if it is deemed that machinery or machinery components and subcomponents are not considered high risk and do not require mitigation.

#### 1.2.6.2 Feasibility and Concept Selection (Section 4)

A screening assessment is performed early to identify machinery with potential high risks principally in the research, development, new applications, or manufacturing activities. Technical risk categorization (TRC) and technical readiness level (TRL) assessments aid in risk assessment and the definition and application of mitigation in this phase.

#### 1.2.6.3 Front-end Engineering Design (FEED) (Section 5)

A preliminary risk assessment is performed in this stage to:

- a) identify API 691 Machinery with potential high risks,
- b) define a list of supplementary protective measures that should be within the scope for detailed design.

#### 1.2.6.4 Detailed Design (Section 6)

A more detailed risk assessment with the additional information available as design progresses (or as changes occur) is performed in this stage to:

- a) confirm that the risk level is high enough to warrant continued mitigation,
- b) define available mitigations in design or in operation and maintenance activities.

NOTE These would typically include detail to the maintainable item level for failure mode and effects analysis (FMEA) and task selection.

#### 1.2.6.5 Installation and Commissioning (Section 7)

This section covers requirements, recommendations, and considerations for the installation and commissioning phase including:

- a) use of [API 686](#) <sup>[8]</sup>,
- b) recommendations on the review of deviations in the process and/or the machinery,
- c) recommendations on the verification of mitigations (including functional safety tests),
- d) recommendations and considerations on commissioning operational tests,
- e) pre-start-up safety reviews (PSSRs),
- f) installation and commissioning documentation.

#### 1.2.6.6 Operation and Maintenance (Section 8)

An initial screen is performed to identify API 691 Machinery leveraging available HAZOPs, incident reports, and other HSE related documentation. A field risk assessment is then conducted for machinery found to meet specific criteria defined within the recommended practice. The results of the field risk assessment should provide actionable mitigation activities that, after technical review, are required to be implemented per this recommended practice.

#### 1.2.6.7 Guidelines for Risk Assessment Methodology (Annex A)

Annex A (informative) provides detailed background information and guidance on risk assessment and management methodologies.

### 1.3 Limitations

This recommended practice is based on machinery risk assessment methodologies commonly used within the petroleum, chemical, and gas industries.

Nonetheless, it will not compensate for:

- a) inaccurate or missing information,
- b) inadequate designs or faulty equipment installation,
- c) operating outside defined and acceptable limits,
- d) not effectively executing defined equipment activities,

- e) not employing or improper utilization of competent personnel,
- f) not applying good teamwork and/or communication principles,
- g) lack of utilizing recognized and generally accepted good engineering practice (RAGAGEP),
- h) not applying sound operational judgment,
- i) poor repair practices (e.g. materials, parts, workmanship),
- j) unknown or unidentified damage mechanisms,
- k) sabotage.

## 1.4 Work Process Overview

The recommended practice covers potential risk mitigation activities in the complete life cycle of the machinery, and as such it is organized for the sequential execution from the feasibility and concept selection phase of new facilities through the end of operations. Application to existing machinery installations is covered in Section 8. Figure 1 outlines the major work process steps and shows the starting points for both new and existing machinery.

## 2 Normative References

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

[API Recommended Practice 1FSC](#), *Facilities Systems Completion Planning and Execution*

[API Specification Q1](#), *Specification for Quality Management System Requirements for Manufacturing Organizations for the Petroleum and Natural Gas Industry*

[API 510](#), *Pressure Vessel Inspection Code: In-service Inspection, Rating, Repair, and Alteration*

[API Standard 541](#), *Form-wound Squirrel Cage Induction Motors—375 kW (500 Horsepower) and Larger*

[API Standard 546](#), *Brushless Synchronous Machines—500 kVA and Larger*

[API Standard 547](#), *General-purpose Form-wound Squirrel Cage Induction Motors—250 Horsepower and Larger*

[API Recommended Practice 571](#), *Damage Mechanisms Affecting Fixed Equipment in the Refining Industry*

[API Recommended Practice 576](#), *Inspection of Pressure-relieving Devices*

[API Recommended Practice 584](#), *Integrity Operating Windows*

[API Standard 600](#), *Steel Gate Valves—Flanged and Butt-welding Ends, Bolted Bonnets*

[API Standard 610](#), *Centrifugal Pumps for Petroleum, Petrochemical and Natural Gas Industries*

[API Standard 611](#), *General Purpose Steam Turbines for Petroleum, Chemical, and Gas Industry Services*

[API Standard 612](#), *Petroleum, Petrochemical, and Natural Gas Industries—Steam Turbines—Special-purpose Applications*

[API Standard 613](#), *Special Purpose Gear Units for Petroleum, Chemical and Gas Industry Services*

[API Standard 614](#), *Lubrication, Shaft-sealing and Oil-control Systems and Auxiliaries*

[API Standard 616](#), *Gas Turbines for the Petroleum, Chemical, and Gas Industry Services*

[API Standard 617](#), *Axial and Centrifugal Compressors and Expander-compressors*

[API Standard 689](#), *Collection and Exchange of Reliability and Maintenance Data for Equipment*

[API Standard 618](#), *Reciprocating Compressors for Petroleum, Chemical and Gas Industry Services*

[API Standard 619](#), *Rotary-type Positive Displacement Compressors for Petroleum, Petrochemical and Natural Gas Industries*

[API Standard 670](#), *Machinery Protection Systems*

[API Standard 676](#), *Positive Displacement Pumps—Rotary*

[API Standard 677](#), *General-purpose Gear Units for Petroleum, Chemical and Gas Industry Services*

[API Standard 682](#), *Pumps—Shaft Sealing Systems for Centrifugal and Rotary Pumps*

[API Standard 692](#), *Dry Gas Sealing Systems for Axial, Centrifugal, Rotary Screw Compressors and Expanders*

[ANSI <sup>1</sup>/ISA <sup>2</sup>-84.00-2004 \(Mod IEC <sup>3</sup> 61511\)](#), *Functional safety—Safety instrumented systems for the process industry sector (Parts 1, 2, and 3)*

[IEC 61508](#) *Functional safety of electrical/electronic/programmable electronic safety-related systems (Parts 1, 2, and 3)*

[IEC 61511](#), *Functional safety—Safety instrumented systems for the process industry sector (Parts 1, 2, and 3)*

[IEC 62061](#), *Safety of machinery—Functional safety of safety-related electrical, electronic and programmable electronic control systems*

[ISO 13849-1 <sup>4</sup>](#), *Safety of machinery—Safety-related parts of control systems—Part 1: General principles for design*

[ISO 13849-2](#), *Safety of machinery—Safety-related parts of control systems—Part 2: Validation*

[ISO 20815](#), *Petroleum, petrochemical and natural gas industries—Production assurance and reliability management*

[OSHA 1910.119 <sup>5</sup>](#), *Process safety management of highly hazardous chemicals*

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<sup>1</sup> American National Standards Institute, 25 West 43<sup>rd</sup> Street, 4<sup>th</sup> Floor, New York, New York 10036, [www.ansi.org](http://www.ansi.org).

<sup>2</sup> The International Society of Automation, 67 T.W. Alexander Drive, Research Triangle Park, North Carolina, 22709, [www.isa.org](http://www.isa.org).

<sup>3</sup> International Electrotechnical Commission, 3, rue de Varembé, 1st Floor, PO Box 131, CH-1211 Geneva 20, Switzerland, [www.iec.ch](http://www.iec.ch).

<sup>4</sup> International Organization for Standardization, 1, ch. de la Voie-Creuse, Case postale 56, CH-1211 Geneva 20, Switzerland, [www.iso.org](http://www.iso.org).

<sup>5</sup> U.S. Department of Labor, Occupational Safety and Health Administration, 200 Constitution Avenue NW, Washington, DC 20210, [www.osha.gov](http://www.osha.gov).

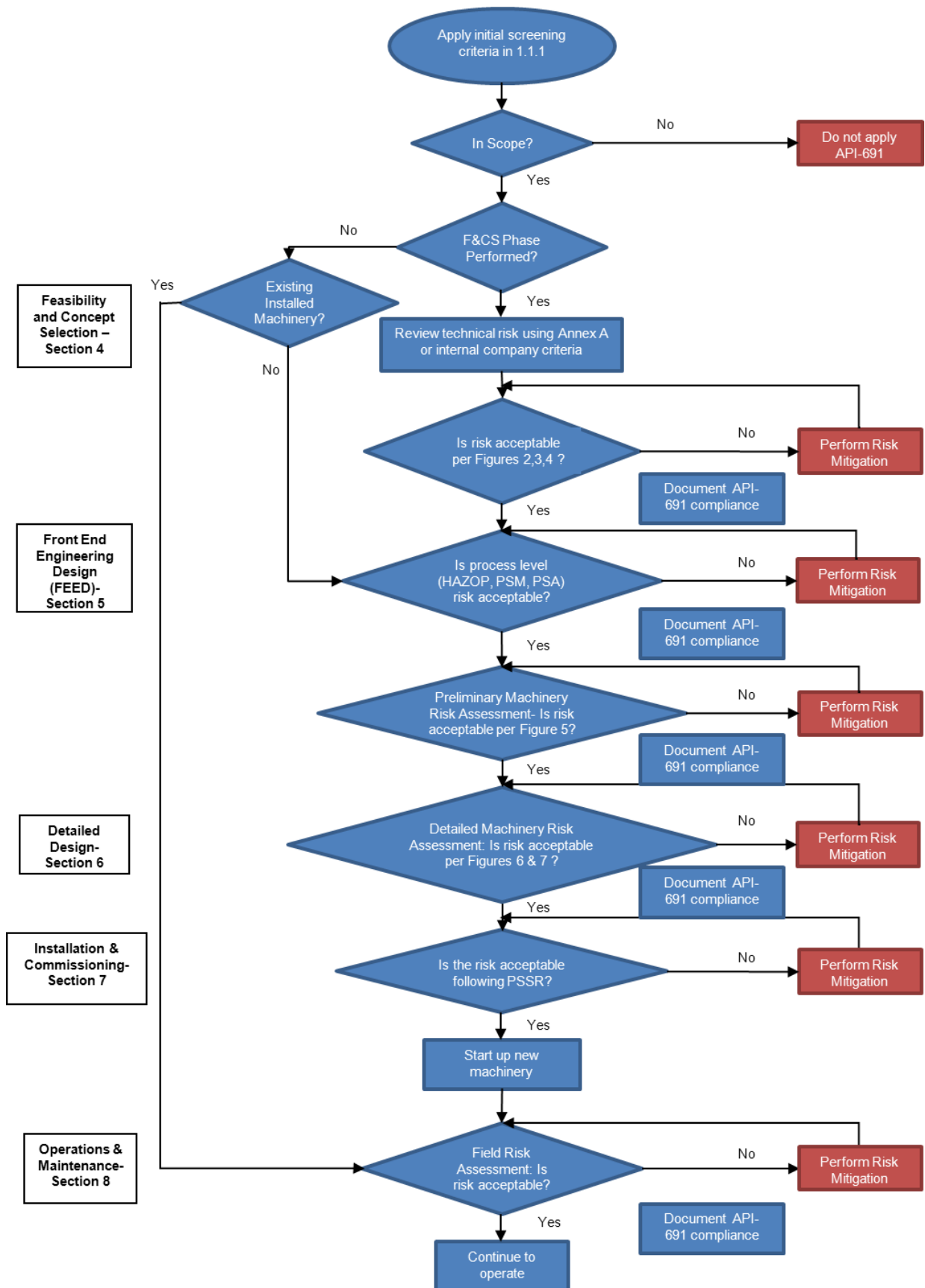


Figure 1—API 691 Work Process Overview

## 3 Terms, Definitions, Acronyms, and Abbreviations

### 3.1 Terms and Definitions

For the purposes of this document, the following definitions apply.

#### 3.1.1

##### **anomaly**

A state or transient that is a deviation from understood normality, which may or may not be indicative of failure.

#### 3.1.2

##### **API 691 Machinery**

API machinery and their auxiliaries falling in the scope of API 691 that have been assessed to be of potentially high risk at any phase in the equipment life cycle.

#### 3.1.3

##### **availability**

The ability of an item to be in a state to perform a required function in a defined operating context at a given instant of time, or on average over a given time interval, assuming that the required external resources are provided.

NOTE High availability can be achieved through high reliability (equipment rarely breaks down) or improved maintainability (when equipment breaks down it is repaired quickly), or a combination of both.

#### 3.1.4

##### **availability requirements**

Appropriate combination of reliability and/or maintainability performance characteristics that need to be achieved to meet project requirements.

#### 3.1.5

##### **condition-based tasks**

Preventive maintenance (PM) tasks driven by condition rather than time. The periodicity of “sampling” condition is determined by the potential failure (P-F) interval that sets the time base for the task.

#### 3.1.6

##### **condition monitoring**

##### **CM**

The process of monitoring condition indicators in machinery (vibration, temperature, etc.), in order to identify a significant change that is indicative of a developing fault.

NOTE Condition indicators can be inferred through age, usage, cyclic accumulation, and sensors of physical condition (including the direct effects of failure) or measurements of performance that infer condition.

#### 3.1.7

##### **condition monitoring tasks**

##### **CM tasks**

CM activities conducted to monitor data from assets to detect the onset of failure, determine condition, detect exceedance, and calculate prognostics to help decide the most opportune time to conduct condition-based preventative maintenance tasks.

#### 3.1.8

##### **corrective action**

An action carried out after fault recognition that is intended to restore the condition to a nominal state.

#### 3.1.9

##### **corrosion**

The gradual dissipation of metallic surfaces as the result of oxidation or other chemical reaction.

**3.1.10****downtime**

The time interval during which an item is unable to perform a required function due to a fault, or other activities, e.g. during maintenance.

**3.1.11****equipment unit**

Specific equipment unit within an equipment class as defined by its boundary (e.g. one pump).

**3.1.12****erosion**

Loss of material, or degradation of surface quality, through friction or abrasion from moving fluids, cavitation, or by particle impingements.

**3.1.13****failure**

Termination of the ability of an item to perform a required function.

NOTE 1 After failure initiation, the item has a fault.

NOTE 2 "Failure" is an event, as distinguished from "fault," which is a state.

NOTE 3 See also related definition for functional failure.

**3.1.14****failure cause**

Circumstances associated with the machine's environment, design, manufacture, installation, operation, and maintenance that have, or may, lead to a failure.

NOTE In the process of isolating a failure cause, each cause may have an effect, and each effect has causes, so the relationship is iterative.

**3.1.15****failure data**

Data characterizing the occurrence of a failure event.

NOTE Failure data can be plural in that many occurrences along with age at failure can be used to characterize the failure probability distribution.

**3.1.16****failure effect**

The consequence of a failure mode (e.g. loss of function, impact on safety, the environment, operational capability).

**3.1.17****failure finding task****FF task**

A routine maintenance task, normally an inspection or testing task, designed to determine whether an item or component has failed, where the failed state may not be apparent to the operating or maintenance crew undertaking their normal duties.

NOTE A failure finding (FF) task should not be confused with an on-condition task, which is intended to determine whether an item is about to fail. FF tasks are sometimes referred to as functional tests.

**3.1.18****failure mechanism**

A process (physical, chemical, human, or other) that leads to a failure.

NOTE Most failure mechanisms involve more than one process and occur as a chain of events and processes.

**3.1.19****failure mode**

The effect by which a failure is observed on the failed item (i.e. the loss of a required functionality, e.g. loss of containment).

**3.1.20****fault**

State of an item characterized by inability to perform a required function, excluding such inability during PM or other planned actions, or due to lack of external resources.

**3.1.21****frequency**

- a) Frequency is the number of occurrences of a specified event or class of events per unit time.
- b) The ratio of the number of times an event occurs in a series of trials of a chance experiment relative to the number of trials of the experiment performed.

Definition b) is equivalent to the definition of probability. In this recommended practice, Definition a) will be assumed wherever the term frequency is used, unless otherwise stated.

**3.1.22****function**

The intended purpose of an item to perform a specific task or capability in a defined operating context by asset stakeholders.

**3.1.23****functional failure**

A state in which an asset or system is unable to perform a specific function to a level of performance that is acceptable to its stakeholders.

**3.1.24****functional test**

FF task that involves testing of equipment or protective device functionality whose failure would otherwise be hidden to the operating and maintenance crew undertaking their normal duties.

**3.1.25****harsh service**

An inhospitable environment that can accelerate machinery degradation or affect performance.

**3.1.26****hazard**

Danger to personnel or the environment arising from an unplanned event such as a failure, fault, or accident.

**3.1.27****hidden failure**

Failure that is not immediately evident to operations and maintenance personnel undertaking their normal duties.

NOTE Equipment that fails to perform an “on-demand” function falls into this category. It is necessary that such failures be detected to be revealed.

**3.1.28****human error**

Human action or inaction that produces an unintended result, where the result is detrimental.

**3.1.29****incipient failure**

The early stages of a failure where the condition has not yet degraded to a point where stakeholder functions are not being met.

**3.1.30****indenture level**

A level of subdivision in any hierarchical representation of a system or object, indicating components that make up the whole. The hierarchies may refer to maintenance, physical equipment, organizations, etc.

**3.1.31****integrity**

The ability of a system of components to perform its required function while preventing or mitigating incidents that could pose a significant threat to life, health, and the environment over its operating life.

**3.1.32****integrity operating window****IOW**

Established limits for process variables (parameters) that can detrimentally affect the integrity of the equipment if the process operation deviates from the established limits for a predetermined amount of time (includes critical, standard, and informational IOWs).

**3.1.33****intrusive preventative maintenance tasks**

Time-based preventative maintenance tasks that require replacement of parts or disassembly to perform refurbishment or detailed inspection.

**3.1.34****life cycle**

The entire useful life of a product or service, usually divided into sequential phases, which include design, development, build, operate, maintain, and disposal (or termination).

**3.1.35****loss of containment**

An unplanned or uncontrolled release of any material from containment, including nontoxic and nonflammable materials (e.g., steam, hot condensate, nitrogen, compressed CO<sub>2</sub>, or compressed air).

**3.1.36****maintainability**

Ability of an item under given conditions of use to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources.

**3.1.37****maintainable item**

Item that constitutes a part or an assembly of parts that is normally the lowest level in the equipment hierarchy indenture level during maintenance.

**3.1.38****maintenance**

Combination of all technical and administrative actions, including supervisory actions, intended to retain an item in, or restore it to, a state in which it can perform a required function in a defined operating context, required by its stakeholders.

**3.1.39****management of change****MOC**

The process of bringing planned change to an organization or set of physical assets. MOC usually means leading an organization through a series of steps to meet a defined goal. Synonymous with change management.

**3.1.40****mitigated risk**

A risk for which the probability and/or consequences have been either eliminated or minimized to an acceptable level.

**3.1.41****nonintrusive tasks**

Time-based PM tasks not requiring process or asset interruption, equipment shutdown, tag out, entry, or disassembly.

NOTE PM tasks typically reduce the likelihood of failure, but do not require significant replacement of parts, disassembly, or otherwise cause reintroduction of infant mortality failure risk.

**3.1.42****operational tests**

FF tasks that involve start-up and running of equipment to verify both initial ability to operate and long-term ability to continue to perform its function over a desired mission time.

NOTE Operational tests include cut in tests where redundant or spared equipment are checked to cut in and run as full duty equipment (i.e. routine equipment swapping).

**3.1.43****overhaul**

A comprehensive examination and restoration of an asset to an acceptable condition.

**3.1.44****package**

A named system, subsystem, or defined set of components considered as a single entity for the purposes of a design study or for procurement (e.g. subsea tree, control system).

**3.1.45****predictive tasks**

The analysis and trending of data obtained from CM tasks, so that the future ability of equipment to perform its desired function can be analyzed and predicted.

**3.1.46****preventive maintenance****PM**

Maintenance carried out at predetermined intervals or according to prescribed criteria with the intention to preserve the functions required of physical assets in a defined operating context by their stakeholders.

NOTE PM can have the effect of reducing the POF or the degradation of the functioning of an item.

**3.1.47****probability**

A number expressing the likelihood that a specific event will occur. It is usually expressed as the ratio of the number of actual occurrences to the number of possible occurrences.

**3.1.48****process**

An arrangement of tasks directed toward a specific objective.

**3.1.49****qualification**

The process of confirming, by examination and provision of evidence, that equipment meets specified requirements for the intended use.

**3.1.50****redundancy**

Existence of more than one means for performing a required function of an item.

**3.1.51****reliability**

The ability of an item to perform a required function under a defined operating context for a required time interval.

**3.1.52****reliability and maintainability data****RM data**

Data collected to support analysis of reliability, maintainability, and availability.

NOTE Reliability and maintainability (RM) data is the term applied by ISO 14224. ISO 20815 refers to reliability data instead.

**3.1.53****reliability, availability, and maintainability analysis****RAM analysis, RAM-1 and RAM-2**

Reliability, availability, and maintainability (RAM) analysis is the examination of equipment reliability, maintainability, and availability data to determine the optimum operation and maintenance strategies. RAM-1 is the initial analysis performed during the FEED stage and is focused at the system or process level. RAM-2 is the analysis performed during the detailed design stage and is used to validate the results of the RAM-1 analysis at the equipment level.

**3.1.54****risk**

The combination of the probability of some event occurring during a time period of interest and the consequence (generally negative) associated with the event.

NOTE Risk can be measured in several ways, e.g. as the probability of occurrence of an unwanted event during a given time or as the product of the frequency of occurrence of an adverse event and a numeric measure of the consequences of the event.

**3.1.55****risk assessment**

The determination of whether identified risks are acceptable or not.

**3.1.56****risk category**

A specific way to group risks under a common area, which provides a structured and systematic approach in identifying risks to a consistent level of detail.

**3.1.57****risk mitigation**

Process of selection and implementation of measures to modify risk. The term risk mitigation is sometimes used for measures themselves. Also called risk mitigating strategy.

**3.1.58****risk priority number****RPN**

A technique used for analyzing the risk associated with potential problems identified during an FMEA. Risk priority number (RPN) utilizes the following three rating scales.

- a) *Severity*—rates the severity of the potential effect of the failure.
- b) *Occurrence*—rates the likelihood that the failure will occur.

- c) *Detection*—rates the likelihood that the problem will be detected before the loss of stakeholder functions occur.

$$\text{RPN} = \text{severity} \times \text{occurrence} \times \text{detection}$$

### 3.1.59

#### **safe operating limit**

#### **SOL**

The value(s) that satisfies the most limiting of the prescribed operating criteria for a specified system configuration to ensure safe operation.

### 3.1.60

#### **specification**

The document in which functional, performance, design, and operating requirements are defined.

### 3.1.61

#### **surveillance tasks**

#### **SV tasks**

CM tasks that involve monitoring indications or other parameters or conditions to compare to established acceptance criteria.

NOTE Surveillance (SV) tasks are mainly manual and sometimes invasive. Includes operators conducting zonal checks.

### 3.1.62

#### **technical risk**

Risk associated with the achievement of a technical goal, criterion, or objective. It applies to the probability of and undesired consequences related to technical performance, human safety, mission assets, or environment.

### 3.1.63

#### **turnaround**

A scheduled shutdown of equipment, production lines, or process units to clean, change out components, make repairs, and if necessary, carry out capital projects.

### 3.1.64

#### **uncertainty**

A state of having limited knowledge where it is difficult or impossible to exactly describe the existing state or predict future outcome(s).<sup>[9]</sup>

### 3.1.65

#### **validation**

The process that substantiates whether technical data and engineering models are within the required range of accuracy, consistent with the intended application.

### 3.1.66

#### **verification**

The process that determines the extent to which a procedure, task, physical product, or model conforms to its specification.

## 3.2 Acronyms and Abbreviations

|       |                                |
|-------|--------------------------------|
| ALARP | as low as reasonably possible  |
| APV   | availability probability value |
| BAT   | best available technology      |
| CBM   | condition-based maintenance    |
| CFD   | computational fluid dynamic    |
| CM    | condition monitoring           |

|       |                                                                                |
|-------|--------------------------------------------------------------------------------|
| CMMS  | computerized maintenance management system                                     |
| COF   | consequence of failure                                                         |
| DFMEA | design failure mode and effects analysis                                       |
| DRP   | designated responsible party (e.g. engineering contractors, consultants, etc.) |
| EAM   | enterprise asset management                                                    |
| FEA   | finite element analysis                                                        |
| FEED  | front-end engineering design                                                   |
| FF    | failure finding task                                                           |
| FFT   | fast Fourier transform                                                         |
| FMEA  | failure mode and effects analysis                                              |
| FMECA | failure mode, effects, and criticality analysis                                |
| FOD   | foreign object damage                                                          |
| FTA   | fault tree analysis                                                            |
| GADS  | generating availability data system                                            |
| GPM   | general path model                                                             |
| HAZOP | hazard and operability (hazard and operability study)                          |
| HSE   | health, safety, and environment                                                |
| ID    | internal diameter                                                              |
| IGV   | inlet guide vane                                                               |
| IOW   | integrity operating window                                                     |
| IPF   | installation, potential failure, failure                                       |
| IPL   | independent protection layer                                                   |
| ITPM  | inspection test and preventive maintenance                                     |
| KPI   | key performance indicator                                                      |
| LOPA  | layer of protection analysis                                                   |
| MAWP  | maximum allowable working pressure                                             |
| MCM   | Markov chain model                                                             |
| MCS   | Monte Carlo simulation                                                         |
| MMS   | maintenance management system                                                  |
| MOC   | management of change                                                           |
| MTBF  | mean time between failures                                                     |
| MTTR  | mean time to repair                                                            |
| NCR   | nonconformance report                                                          |
| NDT   | nondestructive testing                                                         |
| NERC  | North American Electric Reliability Council                                    |
| NPSHR | net positive suction head required                                             |
| OC    | operating company supplied                                                     |
| ODR   | operator driven reliability                                                    |
| OEM   | original equipment manufacturer                                                |
| OG&P  | oil, gas, and petrochemical                                                    |

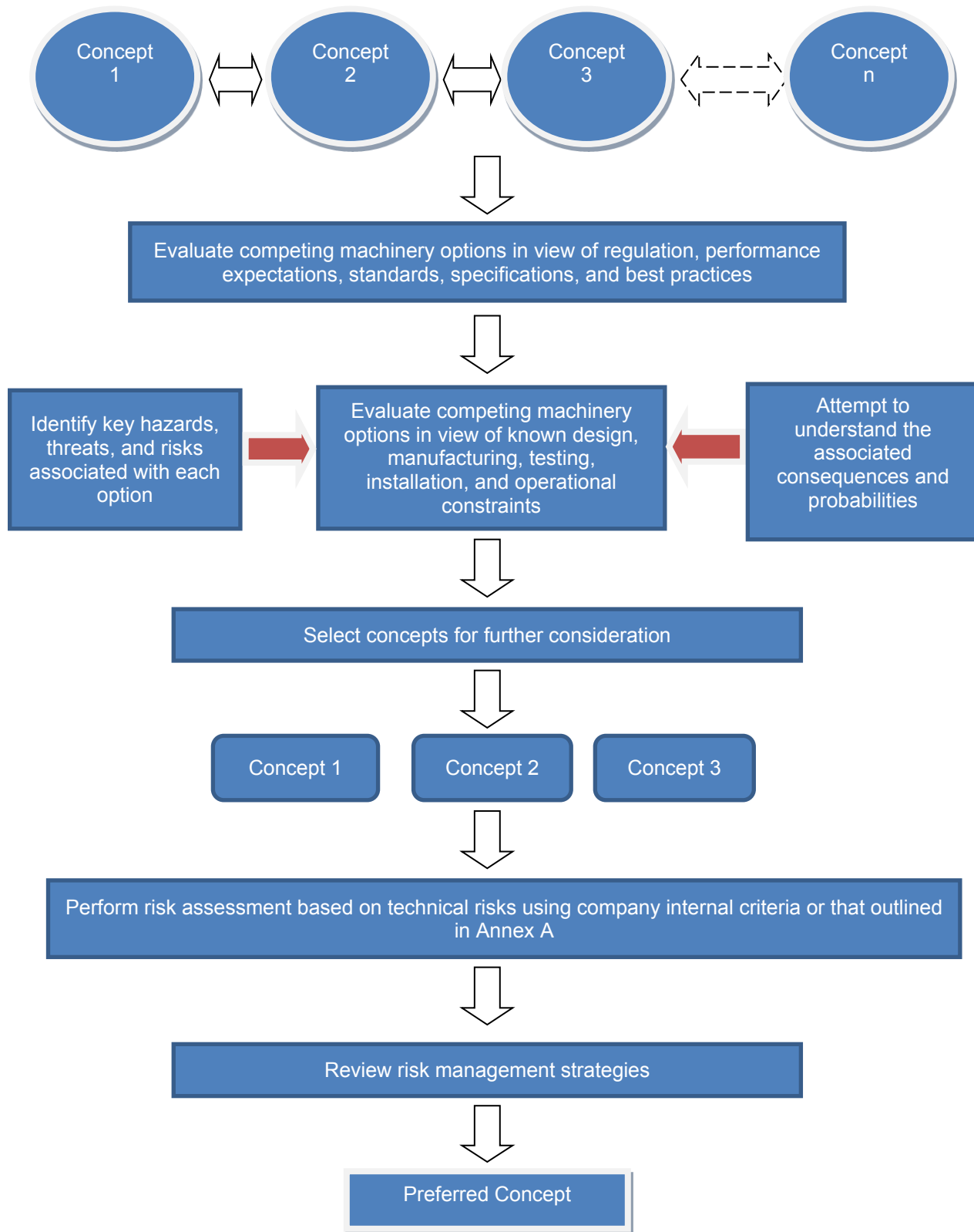
|         |                                                                 |
|---------|-----------------------------------------------------------------|
| ORAP    | operational reliability analysis program                        |
| OREDA   | offshore reliability data                                       |
| O/S     | operation surveillance                                          |
| PCA     | principal component analysis                                    |
| PDM     | predictive maintenance                                          |
| P-F     | potential failure                                               |
| PFD     | process flow diagram                                            |
| PFMEA   | process failure mode and effects analysis                       |
| PHA     | process hazard analysis                                         |
| PHM     | proportional hazard model                                       |
| P&ID    | process and instrument diagram                                  |
| PM      | preventive maintenance                                          |
| POF     | probability of failure                                          |
| PRD     | pressure-relief device                                          |
| PSA     | process safety analysis                                         |
| PSI     | process safety information                                      |
| PSM     | process safety management                                       |
| PSSR    | pre-start-up safety review                                      |
| PT      | penetration test                                                |
| PV      | pressure vessel                                                 |
| QA      | quality assurance                                               |
| QC      | quality control                                                 |
| RAGAGEP | recognized and generally accepted good engineering practice     |
| RAM     | reliability, availability, and maintainability                  |
| RBD     | reliability block diagram                                       |
| RCA     | root cause analysis                                             |
| RCFA    | root cause failure analysis                                     |
| RCM     | reliability centered maintenance                                |
| R&D     | research and development                                        |
| RM      | reliability and maintainability                                 |
| RPN     | risk priority number                                            |
| RUL     | remaining useful life                                           |
| SAFE    | Security Achieved Through Functional and Environmental (Design) |
| SCC     | stress corrosion cracking                                       |
| SIL     | safety integrity level                                          |
| SME     | subject matter expert                                           |
| SOL     | safe operating limit                                            |
| SOP     | standard operating procedure                                    |
| SV      | surveillance task                                               |
| TA      | turnaround                                                      |

|      |                                   |
|------|-----------------------------------|
| TDM  | transient data manager            |
| TPM  | total productive maintenance      |
| TRC  | technical risk categorization     |
| TRL  | technology readiness level        |
| UT   | ultrasonic testing                |
| V    | vendor supplied                   |
| VFD  | variable frequency drive          |
| WFMT | wet fluorescent magnetic particle |

## 4 Feasibility and Concept Selection

### 4.1 Introduction

Operating companies are tasked with developing pre-FEED scopes of work for major capital projects. In the majority of cases, these will duplicate similar facilities where the risk associated with processes and equipment may be adequately covered by company standards, procedures, etc. In certain cases, however, the engineering and manufacturing of previously proven machinery has been or is being relocated to unproven manufacturing locations. While a machinery vendor is responsible for meeting the product function and quality requirements, an operating company's early identification of probable machinery types, technologies, and manufacturing locations during the feasibility and concept selection stage may eliminate costly errors later on that can lead to HSE issues related to loss of containment and/or a loss of functionality that could lead to a potential process safety event. The API 691 feasibility and concept selection process is shown in Figure 2.



NOTE The feasibility and concept selection stage is applicable to both operating companies engaged in capital project studies and machinery manufacturing companies involved in R&D programs. This section is useful in establishing common methods for assessing risk in a manner that is consistent with [API 17N](#)<sup>[10]</sup>.

**Figure 2—Feasibility and Concept Selection Process**

## 4.2 Technical Risk Categorization

**4.2.1** Risk-based machinery management begins with assessing the technical risk category for the machinery technologies being considered during feasibility and concept selection stage of a project or product development cycle (refer to Annex A). While only limited technical information is available at this time, the high-level information can be used to provide knowledgeable practitioners of machinery engineering the opportunity to identify more challenging assets (i.e. those that are more likely to pose a HSE risk later on during FEED). In the feasibility and concept selection stage, there are various methods of assessing risks of machinery technology. Operating companies and machinery manufacturing companies also have internal criteria for risk assessment. Table A.2 is one of the methods to be used to evaluate and classify machinery risks.

**4.2.2** Operating companies should identify the technical risk category of the machinery expected to operate in services outlined in 1.1.2 during the feasibility and concept selection stage of capital projects using internal criteria or that outlined in Annex A. The API datasheets in Annex H.1 may be used to define the risk category of the machinery in question.

**4.2.3** The identified technical risk category should be provided to the DRP prior to the start of a FEED study.

## 4.3 Technology Readiness Level

**4.3.1** When prototype machinery is being developed, or when proven machinery is applied to more severe operating service conditions, product qualification is necessary in order to manage the technical risks. One assessment method that can be used to underpin the qualification process is the TRL, which indicates the extent to which an item is “ready for use” given specified qualification factors/requirements. TRL indicates how far the processes in a technology qualification program for a particular technology have progressed. It should only be used with reference to a specific set of operating regime parameters and environmental conditions. If the operating regime or the planned environment changes, then the TRL may be downgraded for more demanding conditions or upgraded for less demanding conditions.

Eight TRLs have been defined, consistent with [API 17N](#) <sup>[10]</sup>, ranging from a minimum of 0, corresponding to an unproven idea, to a maximum of 7, corresponding to proven technology (installed and operating in the relevant conditions). These are shown in Table 1. The gap between the initial TRL and the required TRL will generally determine the qualification effort required within a project/product development program. The initial TRL is the qualification status of the equipment when it is first introduced to a project, whereas the required TRL is the qualification status required for entrance into operations. Both initial and required TRLs should be determined for a given project. In order for an item to be assigned with a particular TRL, all the required functional and performance activities and tests, as described in the TRL definition, are to be evaluated. The operating company and machinery company should agree on the required TRL level during the feasibility and concept selection phase of a capital project when considering a new technology and product for field installation and testing. If the current technology TRL level is less than the required TRL level, a qualification program should be in place to achieve the required TRL level within the cycle time requirement of the capital project. The qualification process described in 4.4.1 to 4.4.11 should be used to bring the product technology from initial TRL to the required TRL.

**4.3.2** The vendor shall identify in research proposals, inquiries, and/or requested feasibility studies any component and/or subcomponent having a TRL < 7 whose failure may lead to a loss of containment and/or a loss of functionality (see Note 2) that could lead to a potential process safety event.

**NOTE 1** It can be difficult to obtain the TRL for certain components that are provided by subvendors. However, it is important for the vendor having overall package responsibility to have an understanding of the readiness level of all components within their scope, particularly those that may result in loss of containment and/or a loss of functionality that could lead to a potential process safety event.

**NOTE 2** Functional failure of components that do not directly result in process safety incident can still cause a high consequence event if the overall system safety is dependent on the component working. For example, bearing failure on an unspared fire water pump could represent a loss of functionality that could lead to a process safety event, whereas a bearing failure on a potable water supply pump would not.

**NOTE 3** The API datasheets (Annex H.1) can be used to summarize the TRL of these prototype components and subcomponents.

**Table 1—Definition of Technology Readiness Levels**

|                         | TRL | Development Stage Completed                                                          | Definition of Development Stage                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|-------------------------|-----|--------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Concept</b>          | 0   | <b>Unproven Concept</b><br>(Basic R&D, paper concept)                                | Basic scientific/engineering principles observed and reported; paper concept; no analysis or testing completed; no design history                                                                                                                                                                                                                                                                                                                                                  |
| <b>Proof of Concept</b> | 1   | <b>Proven Concept</b><br>(Proof of concept as a paper study or R&D experiments)      | a) Technology concept and/or application formulated<br>b) Concept and functionality proven by analysis or reference to features common with/to existing technology<br>c) No design history; essentially a paper study not involving physical models but may include R&D experimentation                                                                                                                                                                                            |
|                         | 2   | <b>Validated Concept</b><br>Experimental proof of concept using physical model tests | Concept design or novel features of design is validated by a physical model, a system mock-up or dummy and functionality 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                                                                                                                                  |
| <b>Prototype</b>        | 3   | <b>Prototype Tested</b><br>(System function, performance and reliability tested)     | a) Item prototype is built and put through (generic) functional and performance tests; reliability tests are performed, including: 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<br>b) The extent to which application requirements are met are assessed and potential benefits and risks are demonstrated             |
|                         | 4   | <b>Environment Tested</b><br>(Preproduction system environment tested)               | Meets all requirements of TRL 3; designed and built as production unit (or full-scale prototype) and put through its qualification programming 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 prototype function and performance criteria can be met in the intended operating condition and external environment |
|                         | 5   | <b>System Tested</b><br>(Production system interface tested)                         | Meets all the requirements of TRL 4; designed and built as production unit (or full-scale prototype) and integrated into intended operating system with full interface and functional test but outside the intended field environment                                                                                                                                                                                                                                              |
| <b>Field Qualified</b>  | 6   | <b>System Installed</b><br>(Production system installed and tested)                  | Meets all the requirements of TRL 5; production unit (or full-scale prototype) built and integrated into the intended operating system; full interface and function test program performed in the intended (or closely simulated) environment and operated for less than 3 years; at TRL 6 new technology equipment might require additional support for the first 12 to 18 months                                                                                                 |
|                         | 7   | <b>Field Proven</b><br>(Production system field proven)                              | Production unit integrated into intended operating system, installed and operating for more than 3 years with acceptable reliability, demonstrating low risk of early life failures in the field                                                                                                                                                                                                                                                                                   |

## 4.4 Product Qualification

**4.4.1** The purpose of a product qualification program is for both operating companies and machinery vendors to successfully execute risk-based machinery management during the feasibility and concept selection phase. The key deliverables from a product qualification program for API 691 machinery should include the following:

- a) qualification basis including qualification targets and acceptance criteria,
- b) product and technology risk assessment,
- c) validation method selection and basis,

- d) validation plan,
- e) design review approval,
- f) product performance assessment and,
- g) application guide.

**4.4.2** The objective of the product qualification process is to:

- a) provide a structured methodology for managing risk of failure in capital projects and machinery technology R&D projects,
- b) demonstrate the extent to which new technology is ready for field piloting or use in a project,
- c) demonstrate the extent to which existing technology is ready for use in new applications or under extended operating conditions,
- d) increase confidence in the achievement of functional and performance requirements when new technology is applied in projects.

**4.4.3** The level of effort in the qualification of new machinery technology is commensurate with the level of uncertainty associated with the operating regime, the environment, and technology performance. Key considerations include the following:

- a) a greater uncertainty in the operating environment of the performance of the new machinery technology will require a higher margin against failure, more robust qualification methods, and a greater weight of evidence of performance achievement,
- b) the greater the COF (i.e. consequence caused by loss of containment and/or a loss of functionality that could lead to a potential process safety event), the greater the required confidence of reliable performance for the application and the greater the level of effort required in qualification,
- c) the level of effort required to reduce the risk depends on the extent to which a given technology is “ready” for use in a particular application and the preparedness of the operator to implement appropriate qualification procedures for such applications,
- d) the level of effort required to reduce the risk depends also on the extent of the vendor’s and industries’ experience and knowledge of the technology.

**4.4.4** A product qualification program is an iterative process whereby risk is diminished over time, typically progressing through concept development, preliminary engineering, and detailed engineering stages. Stage gate validation checks are conducted upon completion of each stage, wherein the product qualification team assesses the residual technical risks, evaluates the program progress against the product requirements, and makes “go” versus “no-go” decisions. These individuals may be internal to the manufacturing company or may also include external engineering experts or end users. Product qualification is achieved when the uncertainty of all performance metrics has been reduced to acceptable levels

NOTE During a new product qualification program, vendors do not commonly share internal design processes, methodology, and design criteria. However, operating companies can request to review validation plans, product performance assessments, and functional performance test results.

**4.4.5** The following activities are typically performed and documented prior to the conceptual development stage gate review meeting.

- a) Establishment of qualification targets and criteria at machinery system level including:
  - 1) the way the product will be used,

- 2) the environment in which the product is intended to be used,
  - 3) required functional specification,
  - 4) the design target and acceptance criteria.
- b) Perform feasibility study and initial risk assessment of the product and technology including the machinery system level failure modes and associated risks. Risk assessment may be conducted using company internal criteria or various methodologies outlined in Annex A.

**4.4.6** The following activities are typically performed and documented prior to the preliminary engineering stage gate review meeting.

- a) Refined product qualification targets and criteria. This may be accomplished by dividing machinery product into appropriate subsystems and components as well as driving the main function down to subfunctions.
- b) Updated risk assessment of the product and technology. Suggested aspects to be assessed include the following.
  - 1) The failure modes and associated risks by components and subsystems. Interfaces and interactions between the components should be included when evaluating the failure modes.
  - 2) Any physical and/or temporal constraints that will be critical to the success of the product qualification.
  - 3) Validation methods and development plans containing engineering activities to address the identified failure modes and risks.

**4.4.7** The following activities are typically performed and documented prior to the detailed engineering stage gate review meeting.

- a) Successful execution of analytical validation (see 4.4.10), including engineering analysis, assumptions, and the performance margins for the failure modes,
- b) Functional performance testing (see 4.4.11), including but not limited to material sample testing, component testing, prototype testing, pilot unit testing, and system testing. The purpose of the testing may include validating the product function, performance, and durability.
- c) Assessment of whether the results achieved meet qualification targets. In the final stage of the qualification program, the qualification is achieved once the product meets all its requirements and both the risk and the uncertainty have been reduced to acceptable levels. Final product specification and application guidelines should be documented based on the results of the assessments.

**NOTE** If some functional or performance requirements of the new product are not met, several actions can be taken:

- 1) redesign the product and identify further qualification activities to meet qualification targets;
- 2) limit the operating envelope for the new product and increase inspection and maintenance requirements to collect evidence.

**4.4.8** Providing there is full disclosure of the qualification status, the machinery vendor may elect to offer prototype technology to the operating company before completion of the product qualification process. In addition to the aforementioned stage gates, the machinery vendor should pass an approval stage gate before entering the market for field application to determine that:

- a) the residual technical risks of new technology can be mitigated within a reasonable time frame for field piloting or use in a project,
- b) the residual technical risks of existing technology can be mitigated within a reasonable time frame in new applications or under extended operating conditions.

**4.4.9** The approval stage gate for a new technology or product should clearly state the operating envelope for which it has been analytically validated and/or functionally tested.

**4.4.10** A key element of the product qualification process is analytical validation, which provides the vendor a quantitative basis for design.

**4.4.10.1** Component and subcomponent designs identified in 4.3.2 shall be subjected to analytical validation in accordance with Figure 3. Suggested validation methods include the following.

- a) Analytical methods based on existing procedures, handbook solutions, and mathematical formulas,
- b) Numerical methods such as finite element analysis (FEA), computational fluid dynamic (CFD) analysis, dynamic modeling, etc.
- c) Empirical correlation and statistical analysis.
- d) Engineering judgments based on previous experience with similar equipment and operating conditions.

**4.4.10.2** Following the analytic validation for the component or subcomponent, a risk analysis should be conducted. Any designs that are assessed to have high residual risk, as defined in Figure 3, should undergo functional performance testing.

NOTE 1 Machinery manufacturing companies can use company internal criteria or various methodologies outlined in Annex A for risk assessment of the design.

NOTE 2 ISO 12100<sup>[3]</sup> can also be used to provide guidance to vendors in how risk assessments and reduction may be conducted and documented.

- **4.4.10.3** If specified, machinery that is identified as having high residual risk by the vendor or the operating company during the feasibility and concept selection stage shall be validated within its expected operating envelope. The extent of design validation shall be agreed upon between the vendor and operating company.

NOTE Annex B.2 lists commonly considered machinery attributes to be validated as part of product qualification.

**4.4.11** Functional testing is the most common approach to reduce uncertainty during the product development cycle and product qualification program.

**4.4.11.1** The functional test logic is illustrated in Figure 4. The design of the test program should be based on a detailed understanding of the failure mechanisms expected for the operating conditions to which the product will be exposed.

NOTE It has to be considered that many machines for process applications are tailored for the specific service conditions. Prototype testing or environment testing is typically only done for critical parts at a component level. System testing an entire package is usually only conducted in alpha/beta versions for machinery with high system level risk incorporating significant developmental advances.

**4.4.11.2** Following the functional testing for the component or subcomponent, a risk analysis should be conducted. Any designs that are assessed to have high residual risk, as defined in Figure 3, should be rejected. A modified or alternative design concept should be considered for qualification.

- **4.4.11.3** If specified, an operator may elect to pilot test emerging technology in a field application before roll-out across multiple facilities. The field testing scope, acceptance criteria, and documentation requirements shall be mutually agreed upon between the operator and the vendor.

- **4.5 API 691 Feasibility and Concept Selection Facility Audit**

If specified, an API 691 facility and concept design audit shall be conducted using company internal criteria or the methodologies outlined in Annex G.

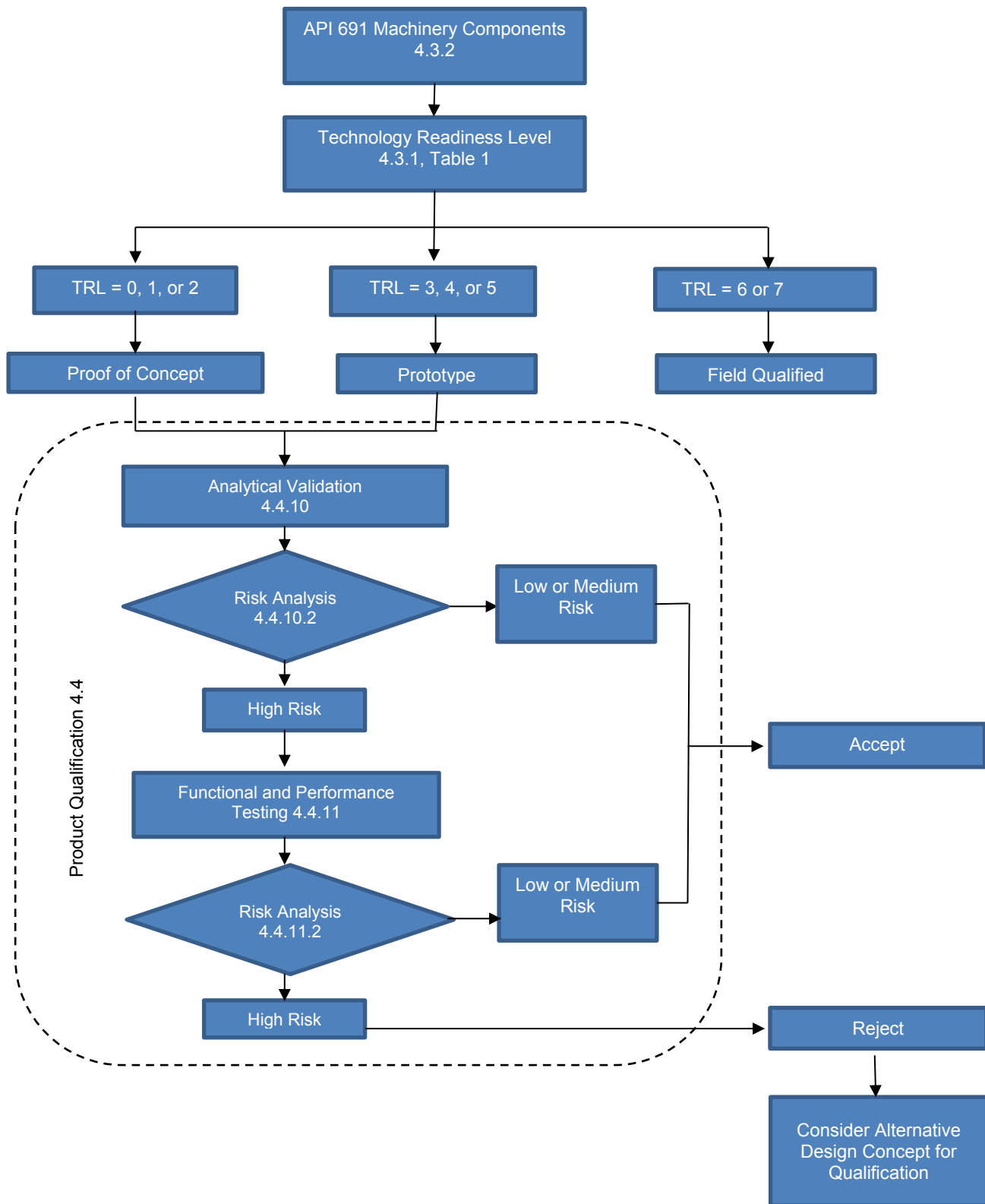


Figure 3—Technology Readiness Process Flowchart

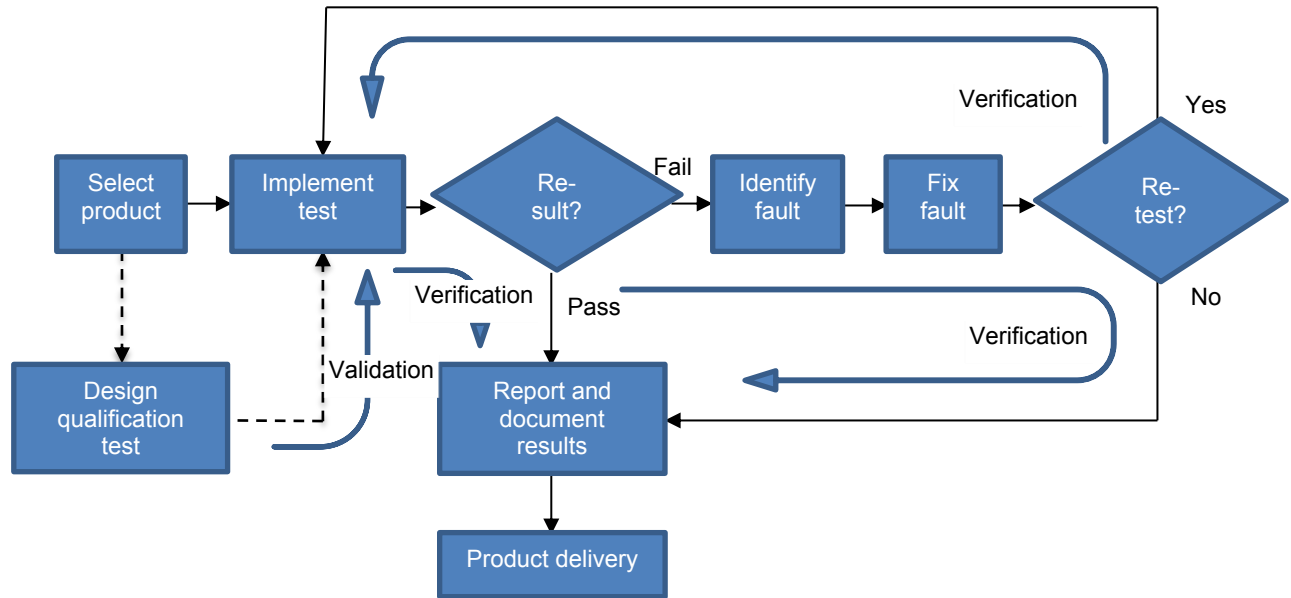


Figure 4—Functional Performance Test Logic Flowchart

## 5 Front-end Engineering Design

### 5.1 Introduction

FEED involves the identification of machinery technologies that are deemed capable of meeting operational and performance targets addressing:

- a) health,
- b) safety,
- c) environmental compliance,
- d) process availability,
- e) production capacity,
- f) turnaround (TA) cycle frequency equipment and facility design life.

While base API standards are considered the foundation upon which machinery selection is made, the majority of operating companies apply additional engineering specifications, practices, and overlays that enable appropriate technologies to be successfully applied to machinery for specific processes and applications.

The purpose of this section is to define requirements for risk-based machinery management during FEED to address HSE risks associated with loss of containment and/or a loss of functionality that could lead to a potential process safety event.

Preliminary machinery risk assessment process during FEED is shown in Figure 5.

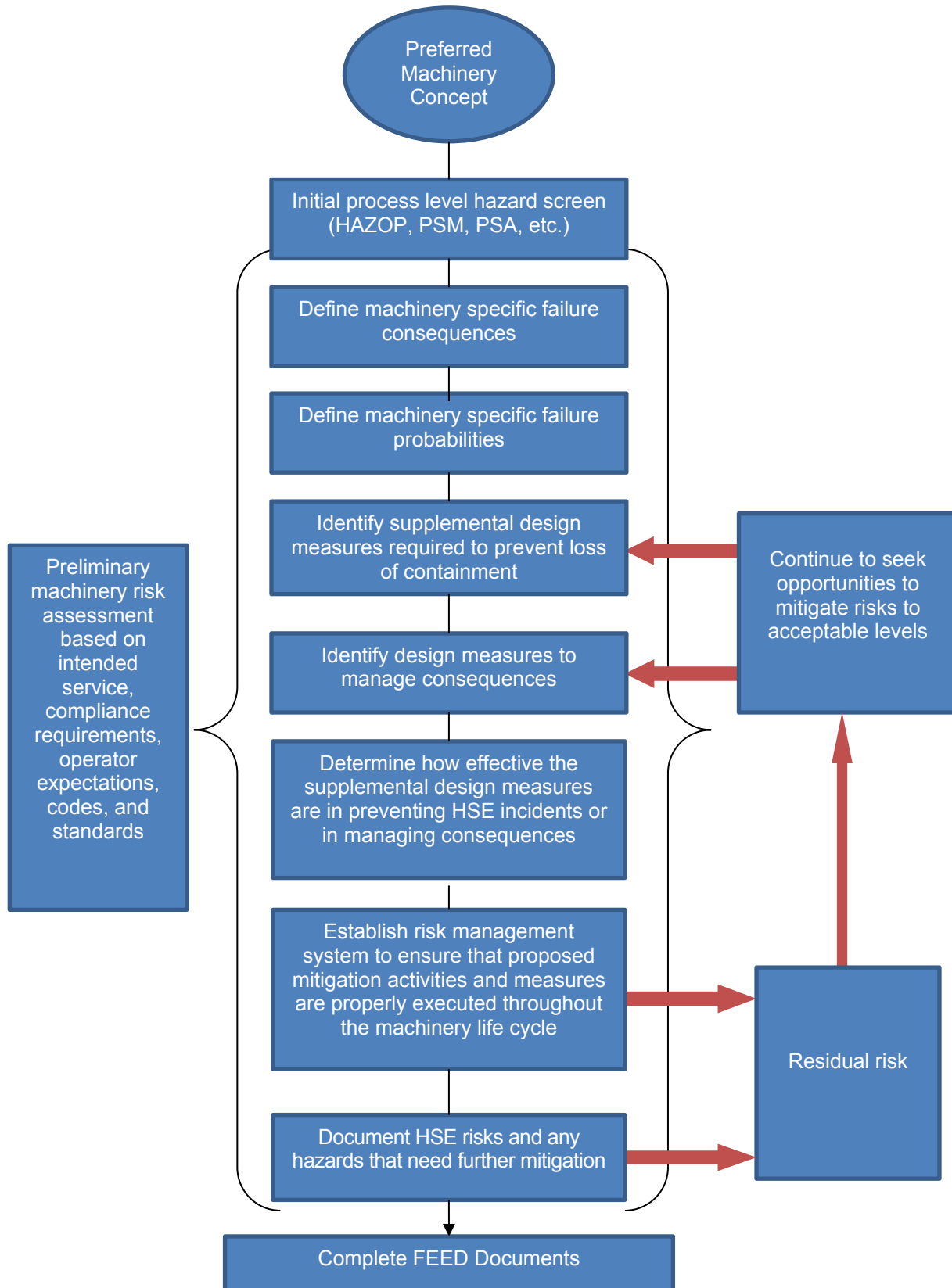


Figure 5—Preliminary Machinery Risk Assessment Process

## 5.2 Preliminary Machinery Risk Assessment

### 5.2.1 Purpose

The purpose of the preliminary machinery risk assessment is to identify all “large-scale” potential hazards in order to later assess the associated risks and provide targeted mitigations to be included within the final FEED documents.

**5.2.2** Process safety and environmental hazards are first addressed during HAZOP, PSM, or process safety analysis (PSA) studies that are part of early design activities. Initial screening at the process level may be conducted to identify machinery warranting more rigorous evaluation.

**5.2.3** Unless otherwise specified, the operating company or DRP shall perform a PFMEA on all API 691 Machinery to:

- a) confirm that the risk level is within company defined limits,
- b) identify most appropriate risk mitigation options.

NOTE 1 Risk assessments can be conducted using a variety of approaches outlined in Annex A.

NOTE 2 IEC 60812 is a useful guide when performing PFMEAs.

NOTE 3 The API 691 datasheets (Annex H) can be used to specify the preferred methodology.

NOTE 4 Annex I (API 691 FMEA worksheet) can be used to perform an API 691 PFMEA.

NOTE 5 DFMEA can be useful in completing an API 691 PFMEA (refer to 6.3 below).

**5.2.3.1** The deliverables from the preliminary machinery risk assessment include:

- a) a completed risk assessment defining unmitigated risk in terms of both POF and COF with sufficient detail to define the mitigation options,
- b) defined machinery boundaries,
- c) a list of relevant high-level failure modes (at the asset or equipment level) that were considered (refer to Annex C),
- d) defined risk mitigations potentially affecting process design, or equipment selection (refer to 1.2.3),
- e) risk ranking list identifying the highest to lowest risks of concern.

NOTE 1 The API 691 datasheets (Annex H) can be used to specify the appropriate risk assessment steps, methods, and deliverables for FEED.

NOTE 2 Corporate process safety and risk management groups will typically have methodologies and practices covering aspects of these assessments. It is the intent of this recommended practice that these methodologies can be utilized to the extent possible.

NOTE 3 Assessments can be conducted using a variety of approaches outlined in Annex A.

### 5.2.4 Supplementary Protective Measures

As applicable, operating companies and/or their DRP shall identify supplementary protective measures that are required to attain acceptable risk from loss of containment and/or a loss of functionality that could lead to a potential process safety event for design conditions and credible off design conditions such as:

- a) improved sealing,

- b) backup protective control devices,
- c) relief valves and venting (e.g. blowdown),
- d) greater factors of safety in design,
- e) enhanced CM (see Annex E),
- f) additional inspections,
- g) secondary containment,
- h) remotely operated isolation valves,
- i) machinery vibration, bearing temperature, and axial position monitoring system,
- j) bearing bracket upgrades,
- k) machinery upgrades (e.g. obsolete equipment),
- l) improved lubrication systems,
- m) deluge and firefighting systems,
- n) gas release alarms,
- o) pressure boundary material upgrade,
- p) machinery prognostics (see Annex F),
- q) emergency stop functionality,
- r) evacuation procedures.

**5.2.5** The identified supplementary protective measures shall be included in the company issued preliminary design specifications and or equipment (e.g. [API 610](#)) datasheets. Alternatively, API 691 datasheets in Annex H may be used.

### **5.3 Reliability, Availability, and Maintainability Analysis**

**5.3.1** The principal objectives of RAM analysis include the following.

- a) Evaluate the ability of the system to operate at acceptable production levels.
- b) Support the definition of the maintenance or intervention support strategy.
- c) Represent the combined reliability analysis and modeling effort in operational terms.
- d) Determine the mean availability to evaluate the present design or to compare it against two or more competing options. The economic model is derived from plant inputs or estimates of the capital, procurement, installation, disposal, operating, and maintenance costs.
- e) Identify and rank the contributors to production losses and potential unplanned flaring that may result in significant HSE events.
- f) Assess maintenance policy such as number of repair teams, rig mobilization policy, spare parts management, and repair priority in case of simultaneous failures.

- **5.3.2** If specified, RAM-1 analysis shall be conducted during FEED in order to establish:

- a) probability of unplanned flaring events,

- b) buffer sizing and location,
- c) process unit redundancy and sizing,
- d) process technology,
- e) major utility needs,
- f) equipment redundancy,
- g) first pass spares analysis for major equipment.

NOTE Additional guidance on performing RAM analysis can be found in Annex A (A.2.4.9).

## 5.4 Machinery Design and Selection

**5.4.1** During FEED, blanket assumptions are often made regarding pressure losses across process exchangers, vessels, control valves, etc., which can vary significantly from individual losses as defined in the vendor's specifications. Certain license processes will also recommend that a +10 % margin on flow be added to accommodate uncertainty during operation. Operating companies are encouraged to closely audit assumed standard pressure losses and design margins used by engineering and procurement contractors to ensure they are consistent with company specifications, industry standards and recommended practices, and license process requirements. Excessive process engineering and mechanical design margins may result in off design operation that can impact reliability<sup>[11]</sup> and increase the risk of safety, health, and environmental events.

**5.4.2** Selection of machinery during FEED shall follow a detailed review of all process assumptions along with various process operating scenarios. The operating company or DRP should ensure that adequate operational flexibility exists in the selected machine frame size to accommodate potential process changes during detailed design.

**5.4.3** Process optimization changes affecting equipment selection should be thoughtfully reviewed by machinery engineers to ensure that final selections meet necessary operating ranges including turndown and ensure safe and reliable start-up and shutdown sequences.

**5.4.4** For API 691 Machinery, the vendor shall identify all components and subcomponents having a TRL < 7 whose failure may lead to a loss of containment and/or a loss of functionality that could lead to a potential process safety event. The API datasheets in Annex H.1 may be used to summarize the TRL of these prototype components and subcomponents.

**5.4.5** The operating company or DRP should conduct a design and reliability evaluations validating proposed machinery designs<sup>[12]</sup>. Validation checklists found in B.2 and B.4 may be helpful in making appropriate technical selections.

## 5.5 Process and Instrument Diagram (P&ID) Reviews

Safe operation of machinery covered by this recommended practice depends on comprehensive review of piping and instrument diagrams.

NOTE Annex B.3 can be used to ensure that appropriate and thorough design checks are made during FEED.

## 5.6 Long Lead Machinery

In order to meet overall project requirements, it is recognized that some API 691 Machinery may need to be procured during FEED due to long lead times from original equipment manufacturers (OEMs). In these cases, the requirements specified in Section 6 (Detailed Design) shall be performed during FEED.

## 5.7 Vendor Qualification

**5.7.1** It is the intent of this recommended practice to provide guidelines to address quality assurance (QA) and quality control (QC) features necessary to ensure the integrity of API 691 Machinery. For the purpose of

this recommended practice, ISO TS 29001<sup>[13]</sup> is recommended for establishing an effective implementation of processes, procedures, and information to ensure adequate vendor programs for risk-based integrity management of machinery.

**5.7.2** API 691 Machinery shall be supplied by vendors having a quality management system that is in accordance with ISO TS 29001, ISO 9000<sup>[14]</sup>, or equivalent. The quality management system shall be third-party certified.

**5.7.3** Risk-based machinery management is dependent upon the machinery vendor's supply chain, internal engineering and manufacturing processes, and agreements with operating company organizations to gather and share data between responsible parties. The design and development of these processes shall ensure free flow of information. Information shall be available in electronic formats to enable uniform transmittal, use, and storage of shared data.

**5.7.4** The vendor shall provide evidence to demonstrate effective management of documentation and data relative to identified API 691 Machinery. The ability to share relevant information is considered essential. Demonstration of effective management of data should include:

- a) the ability to demonstrate reasons specific subvendors were selected for particular components and or services,
  - b) the ability to demonstrate measurement and monitoring of subvendors of products and services,
  - c) the ability to demonstrate processes utilized for verification and validation of product characteristics,
  - d) the ability to demonstrate subvendor communication/data sharing processes relative to subcomponents of the final machinery delivered to customers,
  - e) the ability to demonstrate communication/data sharing processes with customers/users of machinery,
  - f) the ability to demonstrate processes to identify customer complaints and specific actions taken to resolve noted issues,
  - g) the ability to demonstrate processes to identify warranty claims and specific actions taken to resolve noted issues,
  - h) corrective and preventive action to mitigate machinery failures,
  - i) the ability to provide spare parts support,
  - j) the ability to provide on-site/offsite service and repair support.
- **5.7.5** If specified, an API 691 FEED audit shall be conducted using company internal criteria or the methodologies outlined in Annex G.

## **5.8 Operations, Maintenance, and Facilities Strategies**

**5.8.1** Operating companies or their designated representatives shall develop operations and maintenance strategies that address the following key items:

- a) spare parts requirements,
- b) predictive maintenance (PDM) and PM services,
- c) site-wide lubrication strategies,
- d) safe operating limits (SOLs),
- e) IOWs,
- f) emergency response,

g) training.

**5.8.2** Operating companies or their designated representatives should consider the FEED planning and executing activities listed in Table 1, [API 1FSC](#).<sup>[15]</sup>

## **5.9 Optional Field Testing**

### **5.9.1 General**

Optional field testing can be performed either during the installation and commissioning phase (5.9.2 to 5.9.5) or during the operations and maintenance phase (5.9.6) for the purpose of reducing the risk of unexpected delays or failure that may lead to HSE impacts.

**NOTE** Typical testing performed during commissioning generally does not prove the full functionality of the assembled machinery nor allow for accurate performance assessments based on the actual operating conditions.

### **5.9.2 Steam Turbine Solo Run Test**

- If specified, steam turbine solo run testing shall be performed during commissioning in the field.

### **5.9.3 Motor Solo Run Test**

- If specified, motor solo run testing shall be performed in the field.

### **5.9.4 Centrifugal, Axial, and Screw Compressor Inert Gas Test**

- **5.9.4.1** If specified, compressor inert gas testing shall be performed during commissioning.

**NOTE** Inert gas testing runs offer the following benefits to successful initial start-up:

- a) verification of process (yard) valve sequencing,
- b) verification of start logic,
- c) partial verification of alignment in running condition,
- d) verification of machinery bearing and vibration equipment functionality,
- e) verification of machine integrity with an inert gas—any leakage will be nonflammable,
- f) additional process piping clean-up and ability to clean strainers without time-consuming gas-free operations.

**5.9.4.2** Plans for inert gas testing should be thoughtfully coordinated between the operating company, DRP, and the vendor. The process coolers supporting most compressors are not designed to remove the heat of compression associated with nitrogen; therefore, to prevent potentially damaging discharge temperatures, inert gas test runs with nitrogen are usually of a short duration or at a reduced speed. As an alternative and if available, inert gas testing with helium provides for longer test runs. In all cases, the vendor should confirm that the compressor design is capable of running on the inert gas and all auxiliaries and instrumentation are appropriately selected to achieve the desired accuracy. Significant differences in gas molecular weight can effect differential pressure style flow measurements.

**5.9.4.3** Performance curves for inert gas testing should be provided by the vendor.

**5.9.4.4** The inert gas test plan should include considerations for the anti-surge valve(s) and spillback piping. Procedures should ensure sufficient cooling of the gas and protection from over temperature. Considerations can include replacing the anti-surge valve(s) with spools or removal of valve trim, to allow unobstructed flow through the anti-surge loop. After test run, the anti-surge valve internals should be inspected to ensure it has not been plugged or damaged from debris.

### 5.9.5 Reciprocating Compressor Inert Gas Test

- If specified, reciprocating compressor inert gas testing shall be performed.

### 5.9.6 Field Performance Test on Process Gas

- **5.9.6.1** If specified, API 691 Machinery shall be field performance tested on process gas during the operating and maintenance phase. The operating company or DRP shall specify the required scope, and design (e.g. instrumentation to accurately measure pressure, temperature, flow rate, and gas composition).

NOTE Field performance testing using process gas can typically only occur once the plant has been fully commissioned and all process units have been started up. Generally this happens after mechanical completion certificates have been signed and the operations and maintenance phase has commenced (refer to 8.3.6).

- **5.9.6.2** If specified, both the DRP and vendor shall be present during this post-commissioning testing.

NOTE Appropriate ASME Power Test Codes can be used to specify the necessary field test instrumentation to achieve the required accuracy for performance assessments.

## 6 Detailed Design

### 6.1 Introduction

Once the efforts of FEED are completed, detailed design commences with the validation of the process design. It is not unusual for detailed design contractors to identify improved methods, technologies, or more accurate process conditions that influence machinery designs. This may in certain cases change the risk classification of machinery previously evaluated in FEED. It may also result in machinery that had not been previously specified or evaluated. As more accurate technical information becomes available, machinery engineers are better able to assess risk and determine the correct risk mitigation activities and strategies to be applied throughout the equipment life cycle. The focus of detailed design from a risk-based machinery management perspective is to develop purchase quality design specifications that sufficiently reduce the future probability and/or consequence of HSE events while meeting other business objectives. The key requirements for the detailed design phase are outlined in Table 2.

### 6.2 Detailed Machinery Risk Assessment

#### 6.2.1 General

The purpose of the detailed machinery risk assessment is to validate the preliminary risk assessment, identify any new hazards, and assess risk for all equipment within the boundary of the selected machinery package, such that specific, focused tasks or other actions can be identified to mitigate unacceptable (high) risks to an acceptable level. As mentioned in Section 5, many operating companies possess and utilize existing corporate methodologies for the analysis of risk. This recommended practice does not prescribe the use of a specific risk assessment methodology. Whenever applicable, users may utilize existing methodologies, and/or supplement them, as deemed necessary. A risk assessment methodology employed in detailed design should:

- a) consider POF and COF, whether qualitative or quantitative, in determining risk,
- b) assess unmitigated risks at the failure mode level for all equipment within the defined machinery boundary limits,
- c) assess mitigated risks for the various tasks and other actions proposed,
- d) confirm that the mitigated risk is acceptable,
- e) provide sufficient documentation of the risk assessment to allow life cycle management of risk, per the requirements of Section 8.

**Table 2—Outline of Detailed Design**

|                                                                                                                |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
|----------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Hazard Identification/Hazard Operability Studies<br>(Process Level)                                            | Having performed HAZID and HAZOP during FEED—further work along these lines is only likely to be required during the detailed design phase if there are major changes occurring in process designs, operating conditions, standard operating procedures, etc.                                                                                                                                                                                                                                                                                                                                                                                                          |
| Detailed Machinery Risk Assessment<br>[For API 691 Specified Machinery]<br>(Machinery Failure Mechanism Level) | Updating the preliminary machinery risk assessment to include detailed design data allows for the completion of a detailed machinery risk assessment at the failure mechanism level for all equipment within the detailed machinery boundary (see Annex C). The operating company should provide guidance on the risk criteria and methodologies to be used whether internal or those outlined in Annex A. The recommended practice requires a vendor provided design failure modes and effects analysis (DFMEA), which can optionally be incorporated into a process failure modes and effects analysis (PFMEA) constructed by the operating company and/or their DRP |
| Risk Mitigation                                                                                                | The risk mitigation includes design upgrades identified in the detailed machinery risk assessment. While these will largely have been implemented during FEED, further improvements may be possible for specific operating services depending on the process design, operating experience, selected machinery vendor, and the content of operating company internal engineering specifications                                                                                                                                                                                                                                                                         |
| Detailed Design Project<br>Engineering Specifications for API 691 Machinery                                    | Detailed design project engineering specifications for API 691 Machinery will include: <ul style="list-style-type: none"> <li>— qualification of manufacturing and design</li> <li>— safe operating limits (SOLs)</li> <li>— integrity operating windows (IOWs)</li> <li>— supplemental protection measures</li> <li>— risk-based installation and commissioning plans</li> <li>— preventative maintenance tasks targeting failure mechanisms that might lead to a loss of containment and/or a loss of functionality that could lead to a potential process safety event</li> </ul>                                                                                   |
| Standard Operating Procedures for API 691 Machinery                                                            | The operating company is required to develop machinery standard operating procedures that ensure to the extent possible that machinery is operated within the established SOLs and IOWs using checklists, guidelines, controls, alarms, shutdowns, and demonstrated operator competency                                                                                                                                                                                                                                                                                                                                                                                |

### 6.2.2 Unmitigated Risk

Companies have varying levels of risk mitigation measures already designed into their internal requirements. For the purposes of API 691, unmitigated risk is that process and machinery risk that has not already been adequately addressed for a given service by or within:

- a) company overlays to API standards,
- b) project engineering specifications,
- c) upgraded materials selections,
- d) supplemental layers of protection included in design specifications,
- e) automated CM or machinery protection,
- f) basic operator walk-through surveillance and response to installed alarms.

NOTE Unmitigated risk typically does not include:

- a) preventative maintenance,
- b) PDM.
- c) specific SV or CM tasks beyond basic walk-throughs.

### 6.2.3 Documentation Requirements

The detailed machinery risk assessment builds upon the results of the preliminary risk assessment conducted in Section 5 and should utilize the following information:

- a) finalized process conditions,
- b) finalized P&IDs,
- c) assessment of individual assets within the defined boundaries of the API 691 Machinery,
- d) completed API datasheets (e.g. [API 610](#)),
- e) special design requirements of the selected machinery vendor [e.g. comments and exceptions to the API standards, baseplate layouts, piping arrangements, input received on loss of containment and/or a loss of functionality that could lead to a potential process safety event, and critical failure mechanisms from the design failure mode and effects analysis (DFMEA) (refer to 6.3)],
- f) potential HSE events identified from RAM-2 modeling, if specified (refer to 6.5),
- g) SOLs,
- h) IOWs,
- i) manufacturing, testing, or design experience limitations of the vendor for similar or identical machinery.

Figure 6 depicts the fundamental detailed risk assessment process.

### 6.2.4 Allowable Methodologies

- Unless otherwise specified, the operating company or DRP shall develop a PFMEA.

NOTE 1 Risk assessments can be conducted using a variety of approaches outlined in Annex A; however, the PFMEA is the most common conducted throughout the industry.

NOTE 2 The API 691 datasheets (Annex H) can be used to specify the preferred methodology.

NOTE 3 Annex I (691 FMEA worksheet) can be used to perform an API 691 PFMEA.

NOTE 4 DFMEA can be useful in completing an API 691 PFMEA (refer to 6.3 below).

### 6.2.5 Declassifying API 691 Machinery

Some machinery, including equipment, components, and subcomponents within the selected boundary limits, may not require risk mitigation and are therefore not subject to further requirements of this recommended practice. Operating companies may at their discretion declassify equipment previously defined during FEED as API 691 Machinery should risk levels be reassessed to be tolerable based on:

- a) changes in process conditions,
- b) relocation to unmanned locations,
- c) deletion of scope,
- d) changes in design,
- e) errors found in earlier risk assessments.

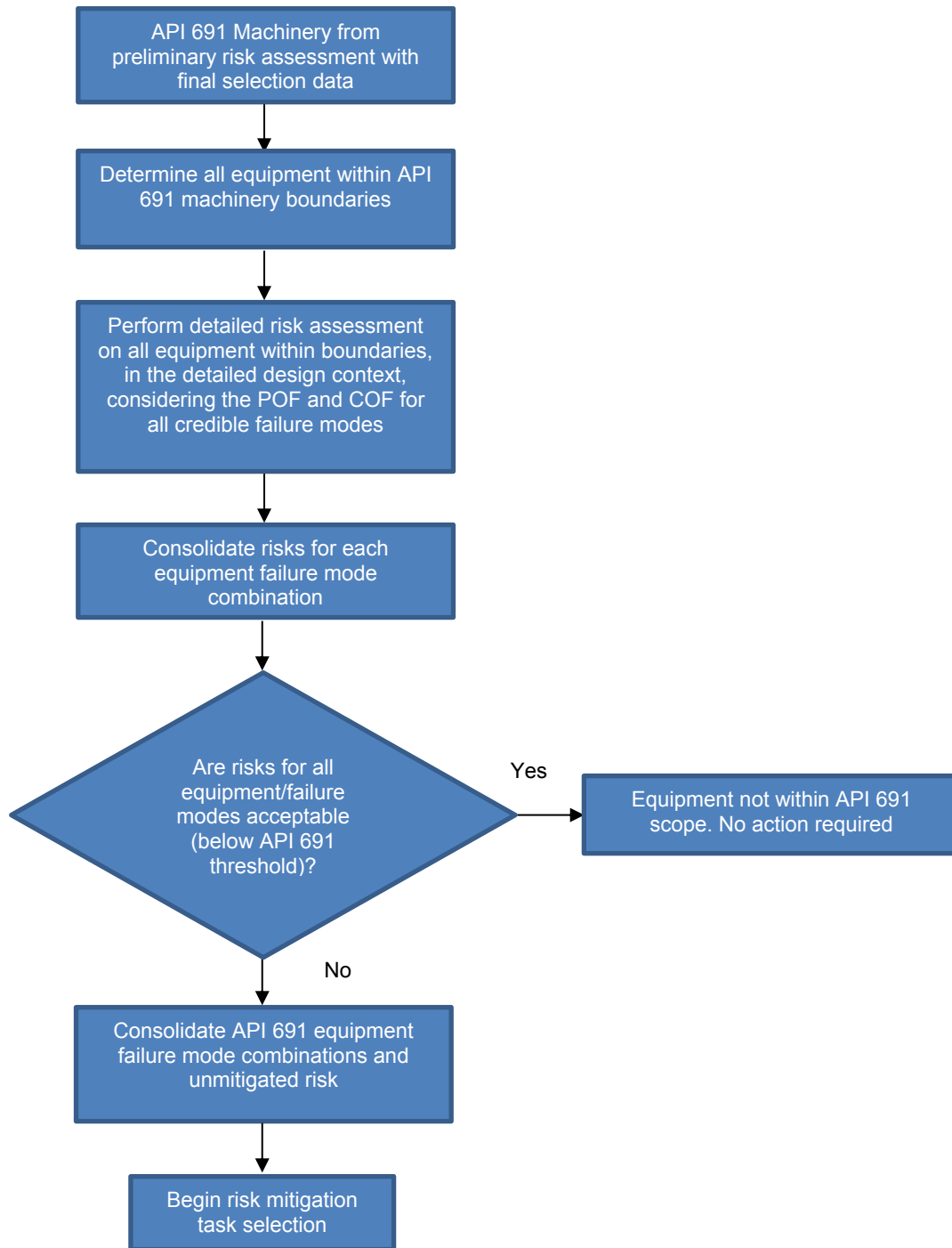


Figure 6—Fundamental Detailed Risk Assessment Process

### 6.3 Design Failure Mode and Effects Analysis

**6.3.1** DFMEAs often contain useful information that may allow users of machinery to better understand potential failure mechanisms. The data the vendor provides with the DFMEA shall include where applicable:

- a) assumptions made as to machinery operating context,
- b) installation specifications,

- c) limits of operation (e.g. IOWs assumed in the design and/or assumed to meet functional requirements),
- d) routine maintenance activities that are assumed for the DFMEA results to remain valid,
- e) preservation maintenance tasks recommended and assumed to be performed in the period from machinery delivery to commissioning and initial start-up,
- f) HSE requirements associated with operations and maintenance of equipment.

NOTE For additional information on constructing a DFMEA, refer to Annex A.

**6.3.2** For API 691 specified machinery, the vendor shall provide a DFMEA addressing failure modes related to a loss of containment and/or a loss of functionality that could lead to a potential process safety event.

- **6.3.3** If specified, the vendor shall provide a complete DFMEA for all failure modes and failure mechanisms that may result in HSE events. The DFMEA shall include POF and COF data based on collected, calculated, or assumed values. It is not required that a unique DFMEA be developed for each specific order, but rather that the vendor have on file a complete analysis for machinery covering the model, type, and/or design being offered.

NOTE 1 The API 691 FMEA worksheet (Annex I) can be used as a reference in developing the DFMEA.

NOTE 2 POF data can be found from sources referenced in A.2.4.9.7.

## 6.4 Risk Mitigation—Task Selection Process

**6.4.1** Following the detailed risk assessment, tasks and strategies shall be assigned to ensure that adequate mitigation is achieved. The process outlined below and depicted in Figure 7 is focused on efficient and effective mitigation of risks associated with API 691 Machinery. The API 691 datasheets in Annex H.3 may be used to summarize the required tasks to achieve necessary risk reduction.

**6.4.2** When considering tasks to prevent or mitigate the identified failure mechanisms, the following may be considered.

- a) CM:
  - 1) SV tasks,
  - 2) predictive tasks,
  - 3) CM tasks.
- b) PM:
  - 1) nonintrusive PM tasks,
  - 2) intrusive PM tasks.
- c) FF tasks:
  - 1) functional tests,
  - 2) operational tests.
- d) Design modifications (e.g. improved sealing and containment, or implementation of protective systems).
- e) Annex C provides a list of failure modes and failure mechanisms and causes. It is recognized that users may have other failure coding systems and formats that are at an appropriate level of detail to be used to assess risk and determine mitigation strategies. Therefore, it is not the intent of this recommended practice to prescribe a failure coding format.

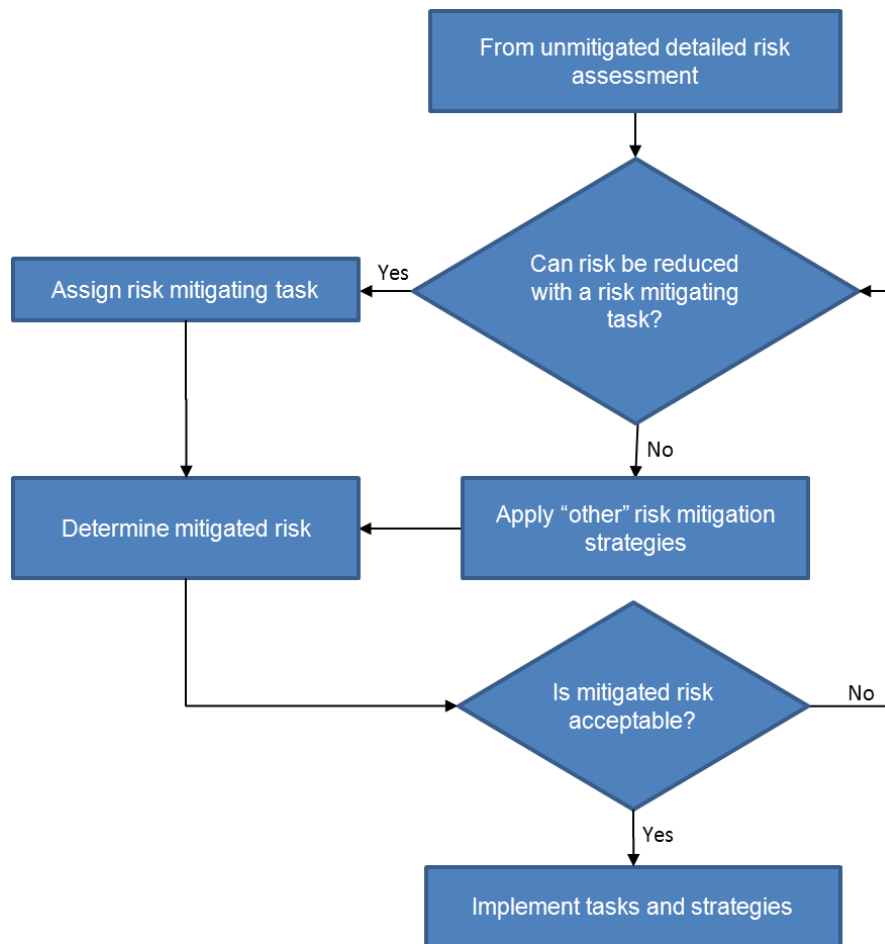


**Figure 7—Fundamental Risk Mitigation Task Selection Process**

- f) In addition to assessment of machinery condition and prediction of future performance, CM tasks should focus on the assurance that API 691 Machinery is operated within its SOLs and IOW. Section 6.6 provides further guidance on SOLs and IOWs.
- g) Annex D provides guidelines on the applicability and frequency of risk mitigation maintenance task types in addressing various failure modes and mechanisms. Annex D also provides example templates containing fundamental risk mitigation tasks by API 691 Machinery type. This is not meant to be an exhaustive list, nor should these be considered always applicable. For API 691 Machinery, enhanced CM and other potential tasks beyond those in the Annex D templates should be considered. If the task selection process is unable to effectively reduce the risk to an acceptable level, other risk mitigation strategies should be considered in order to sufficiently do so. These can include process modification, spare parts strategies, improved inspection methods, etc. These types of recommendations will often require revisiting design or other nonmaintenance aspects of the machinery application.

**6.4.3** The risk mitigation task selection process defines the strategies to effectively reduce risk of operating API 691 Machinery (as designed) to an acceptable level. The primary means to do this is through proactive maintenance, operations, and/or engineering. However, virtually no strategy can completely eliminate the possibility of failure, and for some equipment failure modes and mechanisms, failures simply cannot be prevented. In these cases, the overall strategy may include contingencies for mitigation of the COFs (e.g. preexisting rapid repair and replacement strategies). This includes detailed procedures, parts identification, and skills/manpower requirements. Having API 691 Machinery repairs preplanned and proceduralized can provide significant mitigation of potential failure consequences by significantly reducing the mean time to repair (MTTR), while increasing work quality.

**6.4.4** As part of the risk mitigation task selection process, requirements for machinery preservation should be evaluated. These preservation tasks should be placed into the project mechanical completion plan and executed as required. Proper execution of required preservation tasks should be documented so they can be reviewed and validated as part of the commissioning processes described in Section 7.

## 6.5 RAM-2 Analysis

- If specified, RAM-2 analysis shall be conducted. The primary purpose of the RAM-2 analysis, developed in detailed design, is to validate that the actual installed machinery, including all associated auxiliaries, still meets final design basis requirements. This is accomplished by building on the RAM-1 with enhanced equipment detail. In addition to the validation of as-built design, the RAM-2 analysis can also be utilized in the detailed design process as a tool to assist in decisions such as:
  - a) the effect of maintenance strategy on equipment availability,
  - b) finalization of other design details such as buffer sizing, utility requirements, equipment redundancy, etc.,
  - c) minimizing impacts of failed equipment at the plant level.

The final RAM-2 analysis and final model delivered from the detailed design effort should reflect the as-built design such that it can be used in the future to make informed decisions regarding operational changes and end of life criteria. As such, the RAM-2 analysis and model should be continually updated as design is finalized. Further use of the RAM model is presented in Section 8.

Although the scope of this recommended practice only includes development and expansion of a RAM-2 (if specified) to cover primary and supporting equipment within the defined boundaries of API 691 Machinery, users may elect to develop a more comprehensive RAM model covering other details in support of achieving plant performance targets.

NOTE Additional guidance on performing RAM analysis can be found in Annex A (A.2.4.9).

## 6.6 Safe Operating Limits and Integrity Operating Windows

**6.6.1** For API 691 specified machinery, the vendor shall define IOW critical levels and limits. The operator shall use this information to determine SOLs, which may include the following:

- a) maximum allowable vibration,
- b) maximum allowable suction pressure,
- c) minimum allowable suction pressure,
- d) maximum allowable casing pressure,
- e) maximum allowable inlet temperature,
- f) maximum allowable speed,
- g) minimum continuous stable flow,
- h) maximum allowable solids concentration,
- i) maximum allowable corrosive limits,
- j) maximum allowable bearing temperature,
- k) minimum lube oil pressure,
- l) minimum seal gas flow.

**6.6.2** The DRP shall clearly define all IOWs impacting API 691 Machinery. The vendor should review IOWs and positively verify that operation within the defined IOW levels and limits will not invalidate assumptions made within their DFMEA. The operator shall approve final SOLs. [API 584](#) provides guidelines for determining IOWs, focused primarily on mechanical integrity and prevention of loss of containment and/or a loss of functionality that could lead to a potential process safety event. In addition, operating envelopes should be defined to sustain safe and reliable operation.

## **6.7 Qualification of Manufacturing and Design**

**6.7.1** For API 691 specified machinery, the vendor shall identify all components and subcomponents having a TRL < 7, whose failure may lead to a loss of containment and/or a loss of functionality that could lead to a potential process safety event in accordance with 4.3.2.

**6.7.2** For major repairs defined by ASTM on pressure-containing components, the vendor shall obtain approval from the operating company.

- **6.7.3** If specified, applicable welder qualification records, weld repair procedures, and photographs shall be provided to the operating company for review and approval.

**6.7.4** API 691 Machinery should be supplied by facilities qualified by experience in manufacturing the units proposed. Verification of this experience should form part of the vendor/vendor proposal. Annex B (B.4) provides guidance on the qualification of API 691 Machinery. The qualification process should demonstrate that the vendor has manufactured machinery of a similar or identical type that has successfully operated under equivalent operating conditions. The unit should be manufactured at a facility meeting the quality requirements of [API Q1](#)/ISO TS 29001, ISO 9000, or equivalent.

- **6.7.5** If specified, an API 691 detailed design audit shall be conducted using company internal criteria or the methodologies outlined in Annex G.

## **6.8 Start-up and Commissioning Plans**

**6.8.1** Commissioning activities should be thoughtfully planned to ensure that API 691 Machinery is prepared for installation and commissioning. Commissioning plans should ensure availability of temporary facilities to support commissioning and timely mobilization of specialty support personnel. It should define major activities and sequence of events required for precommissioning, commissioning, testing, mechanical completion, and initial start-up of API 691 Machinery and associated support systems.

**6.8.2** A control and protective system narrative should be provided that describes all machinery control and protective functions including logic and should accompany a finalized cause and effect matrix. The narrative should be used by the DRP to prepare a machinery control and protection test procedure for use during commissioning.

## **6.9 Machinery Standard Operating Procedures**

**6.9.1** Improper operation, and other related human error, is a major root cause of equipment failure. This is especially true in the case of machinery, which is typically more sensitive to changes in operating conditions and excursions outside of defined IOWs. For API 691 Machinery, standard operating procedures (SOPs) shall ensure to the extent possible that machinery is operated within the established SOLs and IOWs using checklists, guidelines, controls, alarms, shutdowns, and demonstrated operator competency. SOPs shall also provide clear guidance as to actions required if/while operating outside the defined SOLs and IOWs.

**6.9.2** API 691 SOPs shall address the following machinery operating modes:

- a) initial start-up,
- b) normal start-up,
- c) normal shutdown,
- d) emergency shutdown and operations,
- e) any other expected nonroutine operation.

**6.9.3** API 691 SOPs may be developed as standalone procedures or contained within integrated system or unit operating procedures. In any case, the requirements contained in this recommended practice shall be met.

**6.9.4** API 691 SOPs should be reviewed to verify that operation will not invalidate assumptions made in the DFMEA or otherwise allow operation outside of the vendor's defined SOLs.

## **6.10 Facilities Completion Planning and Execution**

**6.10.1** Operating companies or their designated representatives should consider the detailed design planning and execution activities listed in Table 1, [API 1FSC<sup>\[15\]</sup>](#).

## **6.11 Implementation of Risk Mitigation Tasks and Strategies**

**6.11.1** In order to assure the desired outcomes result from the decisions made in the risk mitigation task selection process, tasks and other strategies should be fully implemented into work management systems, such that they are properly poised for execution after plant start-up. Operating company guidelines should be followed to develop proactive maintenance work orders (PMs) and job plans that address what work is to be done and what materials and labor (including skills) are required.

**6.11.2** Given the variability in work management systems employed by users, this recommended practice prescribes only the minimum requirements for proper implementation of tasks and strategies. The implementation of PMs and other tasks identified as key HSE risk mitigations in 6.4 should adhere to the following:

- a) work instructions for tasks should be written to a level of detail commensurate with the skill levels of the workforce who will be executing the tasks, as well as the risk associated with the equipment being maintained, monitored, or tested;
- b) the proper parts and materials necessary for execution of the tasks should be clearly defined such that the risk of use of the wrong parts or materials is minimized to as low as reasonably possible (ALARP);
- c) for tasks that are of a level of complexity that special skills are required, formal maintenance procedures should be developed to an appropriate level of detail to control the quality of work and assure adequate management of this risk;
- d) work instructions and formal maintenance procedures should contain and clearly indicate appropriate cautions and warnings based on critical quality checkpoints and other risk criteria identified in the vendor's DFMEAs, API 691 detailed risk assessments, and defined SOLs and IOWs;
- e) work instructions and formal maintenance procedures should include clear indication of data that needs to be captured as part of work execution and closeout of the task (e.g. as-found/as-left condition, clearances, material cause of failure, parts failed/replaced, other action taken based on inspection), and this data should be organized for inclusion in the required processes described in Section 8.

**6.11.3** Some API 691 risk mitigation tasks may be managed outside of a computerized maintenance management system/enterprise asset management (CMMS/EAM) system. Examples are tasks managed in systems such as operator activity systems, PDM systems, advanced CM systems, etc. Similar to the tasks implemented through the CMMS/EAM, these tasks should be detailed, packaged, and formatted appropriately, per the implementation requirements of the target work management systems and/or analysis tools.

**6.11.4** API 691 risk mitigation tasks and strategies should be tracked through implementation. A detailed implementation plan should, therefore, be developed to accomplish this. This plan should also include defined actions to reevaluate required risk mitigation tasks or strategies, should any recommendations be determined to be not practical to implement as originally scoped. Changes that are proposed following initial start-up should be governed by the processes described in Section 8.

**6.11.5** Implementation plans should also identify the process and enabling tools that will manage the tasks [CMMS, PDM, operator driven reliability (ODR) tools, etc.]. Included, as well, should be resource requirements and required training for personnel to be able to properly execute the tasks and strategies associated with API 691 Machinery.

## 7 Installation and Commissioning

### 7.1 Introduction

**7.1.1** Following the detailed design phase, the operating company or their installation contractor will be tasked with ensuring that high-risk machinery are installed and commissioned in accordance with applicable manufacturing guidelines, API standards, company specifications, and prevailing national and local codes. Successful completion depends on thoughtful planning to ensure that the machinery, including instrumentation, controls, and auxiliaries, are fully functional at process start-up. An important step is functional testing of hardware and software during commissioning to achieve the risk reduction identified during FEED and detailed design. Work begins with a comprehensive review of the commissioning procedures and test program that were completed during detailed design. The operating company or their installation contractor shall confirm the acceptability of the following:

- a) installation and commissioning or decommissioning and decontamination schedule,
- b) installation and commissioning or decommissioning and decontamination procedures,
- c) the sequence in which the various elements are integrated,
- d) the criteria for acceptance of safety related systems through functional testing,
- e) procedures to resolve nonconformances falling outside of specified requirements.

NOTE 1 This section is not intended to provide a comprehensive guide for proper machinery installation, commissioning, and start-up. It is assumed the operating company and DRP execute good installation, commissioning, and start-up practices normally associated with special-purpose machinery.

NOTE 2 TRL 6 and below machinery, components, and subcomponents can require additional support for the first 12 to 18 months in the field.

**7.1.2** The operating company or their DRP should consider the recommended precommissioning and commissioning activities outlined in [API 1FSC](#).

### 7.2 Installation

- **7.2.1** If specified, API 691 Machinery shall be installed in accordance with [API 686](#) <sup>[8]</sup>.

**7.2.2** Any deviations or changes to the process and machinery design including auxiliaries, controls, and instrumentation should be implemented under an MOC process to assure changes are properly reviewed, communicated, and documented and resulting actions are tracked to completion.

All changes to design should be considered in the context of any PFMEA that may have been developed during the detailed design phase. Any impact on residual risk should be documented, accepted, and approved by the owner.

### 7.3 Commissioning, Decommissioning, and Decontamination

#### 7.3.1 General

Risk mitigations identified by PFMEA conducted during FEED or detailed design should be assessed, to extent practical, for functionality and effectiveness during commissioning.

Verification of risk mitigations during commissioning or decommissioning and decontamination is important for components/systems where functionality and effectiveness have been assumed to reduce risk but where functionality and effectiveness of the complete and integrated system have not been proven during factory acceptance tests.

### 7.3.2 Commissioning, Decommissioning, and Decontamination Procedures

**7.3.2.1** Procedures should be developed to specifically address API 691 Machinery including associated auxiliary and support systems; machinery control, protective, and monitoring systems; and other functioning systems or components that are part of the risk reduction strategy.

**7.3.2.2** Procedures should:

- a) include validation that preservation tasks have been properly performed,
- b) contain appropriate caution and warning statements and controls to prevent operation outside of the IOWs or other SOLs,
- c) capture and acceptance of CM results as part of overall acceptance criteria,
- d) capture baseline data and confirm action levels for risk mitigation tasks,
- e) include validation of proper set points in machinery control, protective, or monitoring systems,
- f) include activities to confirm the proper function of all support equipment.

**7.3.2.3** Procedures should be reviewed by the vendor. Vendors should verify that execution of the procedures will not invalidate assumptions made within DFMEA or otherwise allow operation outside of the assumed SOLs.

### 7.3.3 Field Functional Safety Testing

**7.3.3.1** Risk mitigations that rely upon instrumentation and controls to provide protective functions should be functionally tested during the commissioning phase prior to the initial start-up.

**7.3.3.2** Functional testing preparation for instrument and controls should include the following.

- a) Verify that the final approved version of machinery control and protective software has been installed. Any logic changes made since factory testing should be reviewed with vendor.
- b) Confirm any temporary modifications made to the machinery control and protective software or the unit control panel during factory acceptance testing have been removed.

**NOTE** The items mentioned are not exhaustive and the operating manuals may provide other items to consider in preparation for functional test of instrumentation and controls.

**7.3.3.3** Changes to the logic, set points, cause-and-effects matrix, or control variables for machinery protective functions made during installation and commissioning should be reviewed by the vendor and approved within an MOC system. A log of these changes should be included in the turnover documentation along with any necessary changes to PFMEA assumptions made during detailed design.

Instrument and control function testing should be performed with the final configuration of field device, cabling, intermediate signal conditioning hardware, terminations, and logic.

**7.3.3.4** The test procedure should provide a structured, sequential testing methodology based on the cause and effects matrix for all protective functions. Interlocks and permissives should be tested in both the “OK” and the “prohibited” conditions in such a way that both the instrument loop and the logic are tested.

### 7.3.4 Process Safety Valves

Pressure-relief devices (PRDs) mitigating high-risk failure modes should be tested prior to initial start-up per [API 576](#). Documentation and testing of process safety valves should be accomplished per [API 576](#) or operating company's procedures.