XX.- 4.- RISK-BASED MACHINERY MANAGEMENT

(Taken as per API RP 691, 1st Ed, June 2017)

1.- 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.

2 SCOPE

2.1 GENERAL

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.

2.2 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 °F (177 °C) and having design or specified off design operating pressures >80 % maximum allowable working pressure (MAWP),
c) services operating at temperatures >400 °F (204 °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 XX-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 for design, installation, and operating purposes) or vendors [i.e. in Section 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,” “un-spared,” “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) or national (e.g. OSHA 1910.119, API 570 [2], 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).

2.3 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.

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

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

2.5 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.

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

3.- MACHINERY RISK MANAGEMENT

3.1 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.

3.2 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.

3.3 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 XX-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.

3.4 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.

3.5 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).

4 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

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 XVIII-5.

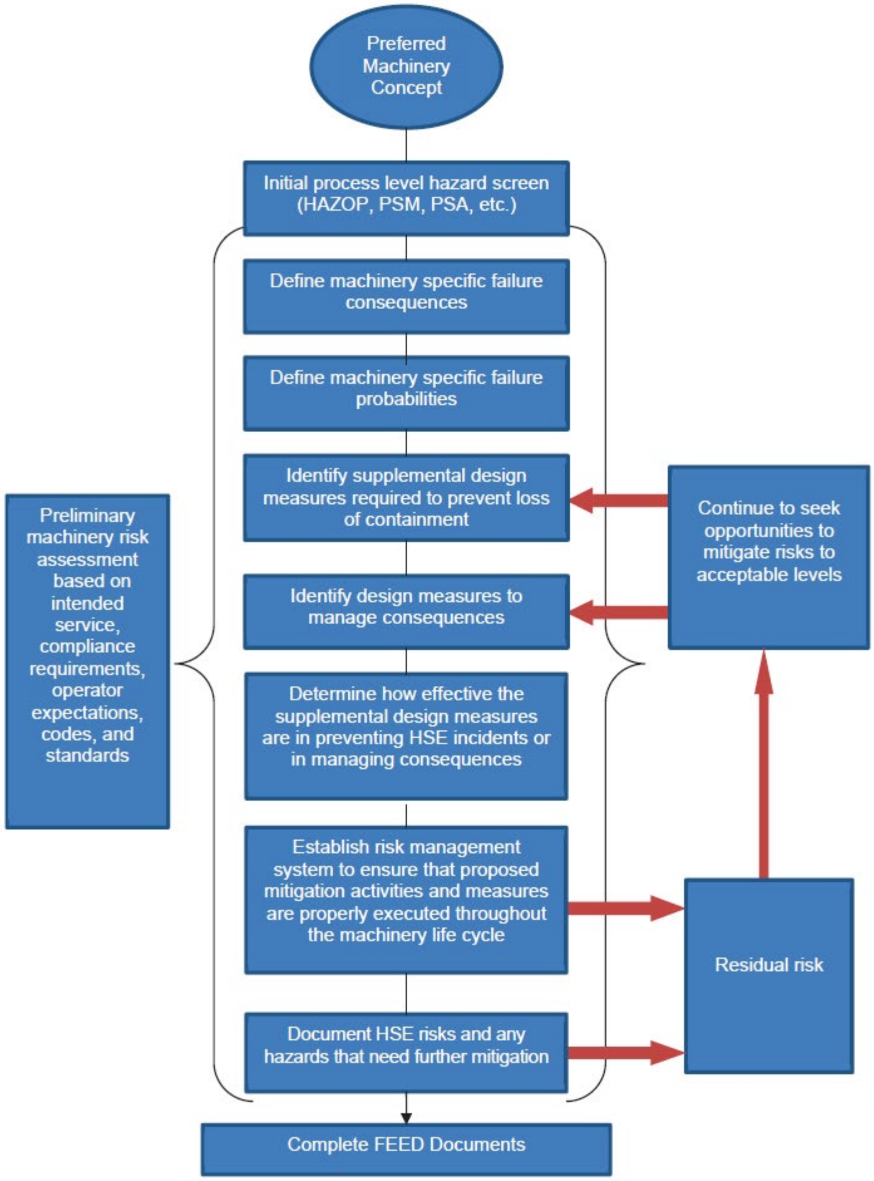


Figure XX-5—Preliminary Machinery Risk Assessment Process

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 XVIII-A.

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

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

NOTE 4 Annex XX-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 XX-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 XVIII-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 XX-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 XX-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 XX-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 XX-H may be used.

5.3 RELIABILITY, AVAILABILITY, AND MAINTAINABILITY ANALYSIS

The principal objectives of RAM analysis include **5.3.1** 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 XX-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 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 XX-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. Validation checklists found in XX-B.2 and XX-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 XX-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

It is the intent of this recommended practice to provide guidelines to address quality **5.7.1** 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 is recommended for establishing an effective implementation of processes, procedures, and information to ensure adequate vendor programs for risk-based integrity management of machinery.

API 691 Machinery shall be supplied by vendors having a quality management **5.7.2** system that is in accordance with ISO TS 29001, ISO 9000, 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 XX-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 XX-1, API 1FSC.

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 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 XVIII-2.

Table XX-2—Outline of Detailed Design

Hazard Identification/Hazard Operability Studies (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 [For API 691 Specified Machinery] (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 Engineering Specifications for API 691 Machinery	Detailed design project engineering specifications for API 691 Machinery will include: — qualification of manufacturing and design — safe operating limits (SOLs) — integrity operating windows (IOWs) — supplemental protection measures — risk-based installation and commissioning plans — 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
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

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 pre-commissioning 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.

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 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.

NOTE 1 PRDs are typically covered by site mechanical integrity procedures that are often broader in coverage and have additional requirements (e.g. for test facility qualification, documentation).

NOTE 2 Other API standards often apply if other equipment is protected by the same PRDs (e.g. API 510, API 570).

Auxiliary 7.3.5 Equipment

Risk mitigations that rely upon capacity, functionality or redundancy of auxiliary equipment should receive final testing in the as-built condition during commissioning prior to initial start-up. This testing would typically include auto-start of standby pumps, stroke checks of control valves including responsiveness to command signals, and overspeed trip checks.

In design of the test, special consideration should be given to transient and off design conditions likely to be seen by the device, and the test should be designed to sufficiently stress the device to validate the effectiveness of the risk mitigation.

7.3.6 Operating and Maintenance Procedures

7.3.6.1 Risk mitigations that rely upon processes and procedures should be validated during commissioning to ensure readiness to support initial start-up.

7.3.6.2 Operating procedures for high-risk machinery should be finalized prior to initial start-up to enable time for training and for operators to become familiar with the procedures. Training should include how the procedure relates to risk reduction. Procedures should be reviewed during commissioning and initial start-up to ensure they can be executed as written.

7.3.6.3 Work processes that relate to key mitigations identified in 6.4 (maintenance tasks, operator rounds, etc.) should be finalized prior to initial start-up to enable support functions to become familiar with the processes and to ensure that the processes are ready to support the equipment. Training should include how the process relates to risk reduction. Wherever practical, these processes should be initiated during the commissioning phase to test readiness prior to initial start-up.

7.4 PRE-START-UP SAFETY REVIEW

The operating company shall perform a PSSR, including any relevant input from the following:

a) PSA, PSM, and HAZOP studies,
b) preliminary risk assessment (5.2),
c) detailed risk assessment (6.2),
d) SOP,
e) MOC,
f) OEM guidelines and alerts,
g) competency and training needs (refer to Section 10).

7.5 OPTIONAL TESTS

7.5.1 General

Certain machinery operational testing can be performed during the commissioning phase to reduce risk of delay or failure during the initial start-up.

NOTE Operational tests during commissioning generally do not prove the full functionality of the assembled machinery package nor allow for performance validation.

7.5.2 Solo Run Testing

API 686 defines the procedures and precautions for steam turbine solo runs. Any special risk mitigations related to steam turbine control or protective systems should be tested prior to the solo run. Special operating procedures specific to the turbine and control design are typically needed during solo runs and during overspeed trip testing to limit steam energy and prevent sudden acceleration in the unloaded condition.

7.5.3 Motor Solo Run Testing

API 686 defines the procedures and precautions for motor solo runs. Any special risk mitigations related to motor controls or protective systems should be tested during the solo run. If the motor is equipped with a variable frequency drive (VFD), particular attention should be paid to field testing all of the VFD control and protective functions in all modes of motor operation.

7.5.4 Compressor Air and Inert Gas Testing

API 686 describes commissioning procedures and precautions for centrifugal and reciprocating compressors. Air and inert gas testing provide the opportunity to test valve sequencing and protective logic before start-up on process gas. Air and inert gas test procedures should include any precautions or limits identified by the vendor and those identified in detailed design reviews.

8 OPERATIONS AND MAINTENANCE

8.1 INTRODUCTION

8.1.1 General

This section defines the requirements that ensure acceptable risk management throughout the operations and maintenance phase of API 691 Machinery. The requirements herein apply to both newly installed and legacy machinery operating in existing facilities. The evaluation period should coincide with the operator's HAZOP schedule. The API 691 work process for the operations and maintenance phase is shown in Figure XX-8.

8.1.2 Identification of API 691 Machinery

The identification of high-risk machinery within an existing facility begins with a thoughtful review of the operating and design context in question. Facility machinery and safety engineers will typically have previously identified critical equipment using corporate best practices. The subset of critical machinery that poses high levels of HSE risks can best be identified through examination of previous HAZOP, PSA, PSM, root cause analysis (RCA), incident reports, etc. and with analysis of the following risk factors.

a) *Hazard of Process Service*—Operating companies may use their own initial screening criteria to identify process hazards or those defined in 1.1.2.

b) *Robustness of Machine Design*—To prevent loss of containment and/or a loss of functionality that could lead to a potential process safety event. Comparing individual legacy machines to the current API 600 series machinery standard design requirements are acceptable means to assess this robustness. In risk mitigation, users may choose to make upgrades to the features in current API machinery standards.

NOTE Gap assessments are generally performed against targeted design features affecting loss of containment and/or a loss of functionality that could lead to a potential process safety event.

c) *CM Inspection and Maintenance*—The level, quality of, and kinds of CM, inspection, and maintenance activity, and especially lack thereof, are important factors in risk. In risk mitigation, users generally choose to conduct more frequent machinery inspections and/or modify existing maintenance strategies to reduce risk.

NOTE Annex E outlines advanced CM approaches that may provide additional risk mitigation.

d) *Protection Systems*—The types of machinery protection systems, or lack thereof, are important factors in risk. In risk mitigation, users may choose to employ a variety of protection systems.

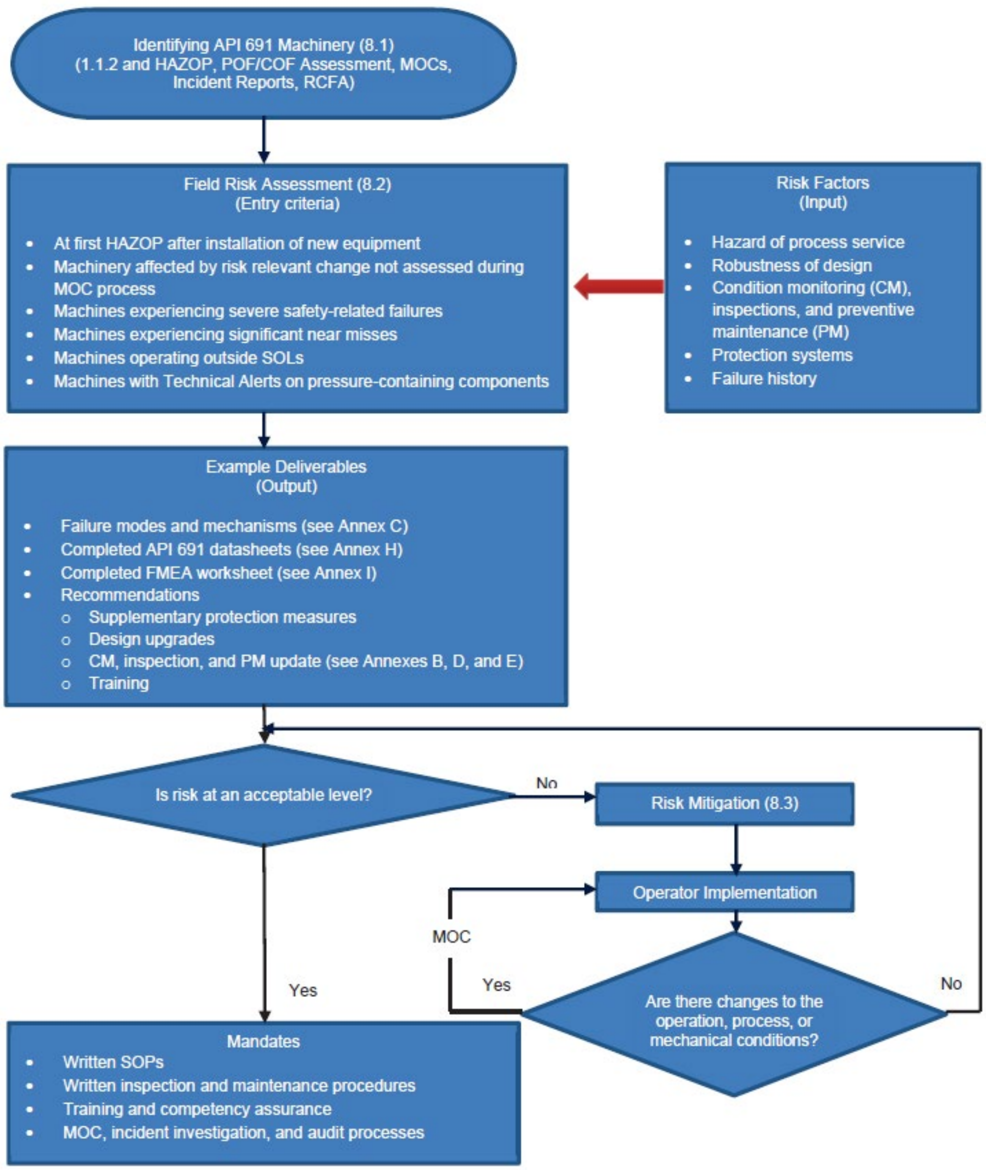


Figure XX-8—API 691 Work Process During the Operations and Maintenance Phase

e) *Post-lost-of-containment Systems*—Systems that isolate leakage points, for example, remotely actuated emergency block valves, or fire control/extinguishing systems or other means of containment, neutralization, or alarm—or lack of such systems—are risk factors. Users may choose to employ these types of systems to further mitigate risk.

f) *History*—Reliability and maintenance [e.g. mean time between failures (MTBF) or mean time to repair (MTTR)] data of legacy machines are essential to conducting accurate risk assessments by defining the POF and COF. Caution is warranted when using basic failure history results (e.g. MTBF) because it alone does not provide the causative factors on which the data are based and may not contain a worst-case COF. Details of failure history should be considered when performing risk assessment.

NOTE 1 Historical operations and maintenance data are often inputs to PHAs. PHAs provide additional information in identifying high-risk machinery. When history is used as a factor in establishing risk, the accuracy and completeness of data is critical.

NOTE 2 When no actual machine history is available, users may judiciously consider using the history of similar or identical machines in the application to assess risk.

8.2 FIELD RISK ASSESSMENTS

8.2.1 The field risk assessment is an evaluation of risk based on the process and machine conditions including installation, operation, inspection, and maintenance. The focus of this section is on identifying risks that may occur because of actual variances between intended design and actual operating conditions.

8.2.2 The purpose of the field machinery risk assessment is to identify any new or previously unidentified risks at the maintainable item level, such that specific, focused tasks or other actions can be taken to mitigate unacceptable (high) risks. The field machinery risk assessment also enables the operator to:

a) update the risk ranking of in-scope machinery within the operating facility,
b) identify and mitigate any changes in risk categorization or risk ranking since previous risk assessments,
c) determine whether the equipment is capable of performing its intended function.

Field risk assessment may be done in concert with other risk assessment processes (e.g. HAZOPs, MOC, risk-based strategies). The depth of review and methods used for a specific field risk assessment will be dependent on the complexity of the issues (e.g. machine type and operating context), level of potential risk, and what triggered the need for the assessment. Operators may use their own risk assessment methodologies.

In the absence of internal requirements, the use of PFMEAs is recommended (refer to Annex XX-A). For a short list of specific deliverables for a typical risk assessment, refer to 5.2.3.1.

8.2.3 The operating company or their DRP should gather the following information (if available) prior to performing a machinery risk assessment:

a) available process operating trends, both steady state and transient such as start-up, shutdown, upset, and other off-design conditions,
b) process flow diagrams (PFDs),
c) P&IDs,
d) HAZOP, PSM, or PSA documentation,
e) as-installed API datasheets,
f) machinery performance curves,
g) equipment failure history,
h) IOWs,
i) SOLs,
j) DFMEA,
k) PFMEA,
l) CM data,
m) safety integrity level (SIL) studies.

NOTE 1 Operating companies will also find the following information useful in performing a field risk assessment:

a) technical advisory alerts,

b) what-if studies,
c) RAM analysis,
d) redundancy study,
e) ALARP analysis,
f) bow tie analysis,
g) RCM,
h) RCA,
i) layer of protection analysis (LOPA).

NOTE 2 Information can be difficult to collect for legacy machinery. Paper copies of information for machinery that has been in operation over a long period of time is often discarded or misplaced. The intent of 8.2.3 is not to burden the operating company or the vendor in retrieving the listed data, analysis, etc. if it is missing; nor is it the intent to delay the timely completion of risk assessments. The lists above are offered as guidance to the operating company undertaking a machinery field assessment.

8.2.4 If materials of construction for pressure-containing components are unknown for legacy machinery operating in services outlined in 1.1.2, then positive material identification (PMI) should be determined by the operating company prior to conducting a field risk assessment.

NOTE The intent of this requirement is not to shut down machinery simply because there is no PMI on pressure-containing components but to confirm the PMI at the first available opportunity (overhaul, TA, etc.) if there exists no documentation on file.

8.2.5 Machinery meeting API 691 criteria shall have a field risk assessment if/when any of the following apply or occur.

a) Newly installed API 691 Machinery. The field risk assessment shall be made during the first HAZOP following installation.

NOTE Although risk mitigation requirements may have been implemented for all API 691 equipment for earlier phases of the equipment life cycle, the start of the operations and maintenance phase is often accompanied by unanticipated hazards. There exists uncertainty within the process, the machinery, and the work force within the newly built plant.

Process conditions may be very different than what designers had assumed during FEED or detailed design. These in some cases invalidate assumptions that can place greater stress on machinery causing failure. In other cases, the initial machinery design assumptions themselves can be proven to be incorrect, which without appropriate safeguards and training can prove to be catastrophic. There are unexpected component failures from infant mortality issues that can overwhelm an inexperienced work force who may still be learning their roles and responsibilities.

b) Machinery affected by a risk relevant change.

NOTE Machinery that has recently experienced a major change to the process, system, or components such as may occur during a TA, repair, rebuild, or upgrade. Such potential changes would include, for example, a change from sweet to sour service, change in pH, pumped abrasive content, temperature, pressure, hydrogen partial pressure, etc.

c) Machinery that has sustained moderate to severe safety failure consequences as defined by the operator.

NOTE Guidance can be found in API 689, First Edition, Table XX-C.1, Consequences I–IX.

d) Machinery that has experienced a significant near miss with potential for severe failure consequences as defined by the operator.

NOTE Guidance can be found API 689, First Edition, Table XX-C.1, Consequences I–V.

e) Machinery found to be operating outside of the SOL criteria.

f) Machinery that has received a technical alert issued by the vendor or sub-vendors that highlights component or subcomponent flaws that may lead to release of a highly hazardous material or other hazardous condition.

g) Machinery identified in 8.1.2 with potential high risk that has not previously had a risk assessment performed.

8.2.6 Field risk assessments may be conducted using a variety of approaches. See Annex XX-A for representative examples.

8.2.7 Companies may consider the need to implement this recommended practice across multiple facilities.

The following facility descriptions may be useful in determining the resource requirements required to successfully address risk-based machinery management across an organization.

a) New facilities that have performed the activities prescribed earlier in this recommended practice.
b) New facilities that have not performed all of the prescribed activities and/or do not have a clearly defined risk ranking or risk mitigation strategy.
c) Existing facilities that have an up-to-date risk analysis and risk-based strategy for operation and maintenance that were developed using methods other than those prescribed in this recommended practice.
d) Existing facilities without a representative and/or up-to-date risk categorization and risk management strategy.
e) Existing facilities that have undergone significant changes that may require a reevaluation of machinery risks.
f) Existing facilities that may be maturing or have aging equipment that may require additional activities to mitigate risks.
g) New or existing facilities that have programs such as RCM or total productive maintenance (TPM) but have plants where RCM studies have not been completed.

8.3 RISK MITIGATION

8.3.1 The field risk assessment determines whether mitigations are needed to achieve an acceptable level of risk and provides the operator with a list of recommended actions including their corresponding expected risk reduction (COF and POF) levels.

8.3.2 Risk mitigation may include one or more of the following:

a) reducing the hazard of the process (less hazardous chemicals, reducing the rates of degradation, mitigating damage mechanisms, etc.),
b) hardware upgrades to the machine proper (upgrades to features in the latest API machinery standards, upgrades that make the machine robust against loss of containment and/or a loss of functionality that could lead to a potential process safety event, etc.),
c) performing repairs per API 687 [17] where applicable to machine type,
d) predictive and preventative maintenance (refer to 6.4.2),
e) enhanced CM and diagnostics (Annex XX-E),
f) machinery prognostics (Annex XX-F),
g) protection systems, interlocks (such as used for lubrication, vibration, surge),
h) post loss-of-containment systems (remotely operated isolation valves, fire suppression and deluge, loss-of-containment monitor alarms),

i) reliability upgrades (upgrades that reduce POF such as moving machine design to better fit window of operation including all operational phases such as start-up, upsets, shutdown, improvements in bearing and seal lubrication quality),
j) increased inspection intervals and scope (refer to B.5.3 addressing additional pressure boundary inspections for machinery in corrosive, erosive, and harsh service),
k) risk-based maintenance activities (refer to Annex XX-B and Annex XX-D),
l) optional field testing on the process gas (refer to 5.9.6 and 8.3.6).

NOTE Jurisdictions may require that mitigation be carried out to ALARP and in some cases that the best available technology (BAT) be considered to achieve risk mitigation goals.

8.3.3 The operating company should consider performing data collection and analysis for API 691 Machinery in accordance with API 689, company overlay, or similar best practice.

8.3.4 The significance of the frequency, extent, and duration of IOW's excursions should be properly evaluated by the operating company. Risk mitigation actions addressing observed exceedances of process IOWs or machinery SOLs may include the following:

a) changing process set points,
b) modifying the process design,
c) revising SOPs,
d) reducing the time to the next inspection or overhaul,
e) improving inspection methods,
f) installing additional alarms/interlocks,
g) requiring additional operator training.

NOTE 1 Performing an engineering evaluation can expand the IOW and SOL range.

NOTE 2 For IOWs, the operator can evaluate the time weighted average of operation outside established ranges and windows. Occasional excursions outside preferred ranges may or may not pose a significant risk and should be evaluated on a case-by-case basis by the operating company.

8.3.5 The execution of all strategies and tactics to achieve risk mitigation for API 691 Machinery should be analyzed, documented, and stored as part of a continuous improvement process.

8.3.6 If specified, following initial start-up for new or rerated API 691 Machinery, the operating company shall conduct a field performance test to validate IOWs and risk reduction strategies developed and applied during FEED, detailed design phases, and/or operating and maintenance phases.

The field performance test also provides baseline operating data with the machine in the as-new condition to enable future CM.

NOTE The field performance test does not replace the factory performance test. If the field performance test is for contract guarantee purposes, additional instrumentation and procedural considerations may be necessary to achieve desired accuracy (refer to 5.9.6).

8.3.6.1 The extent of vendor participation depends on the purpose of the test and complexity of the machinery. Where multiple parties are involved (vendor, operating company, etc.), agreement on test purposes, procedures, safety requirement, and responsibilities should be reached prior to the commencement of testing. The following information provides input to the agreed procedures and operating targets:

a) factory acceptance test data (mechanical run test, performance test, string test);
b) process and instrumentation diagrams for all systems supporting the machine train;
c) OEM installation and operations manuals;

d) predicted performance curves (or existing test curves);
e) flow meter information: pipe internal diameter (ID), orifice bore or beta ratio (for orifice meter), K-factor (for turbine or vortex shedding meter), flow coefficient (for annubar or nozzle), and scaling frequency;
f) configuration log (for ultrasonic meter or to adjust turbine or mass flow meters);
g) performance data, such as factory test data and predicted performance;
h) piping geometry and test instrumentation.

8.3.6.2 The following items should be confirmed during the pretest checkout.

a) That the unit has been proven suitable for continuous operation.
b) If start-up strainer is installed in the inlet pipe, the strainer should be checked for cleanliness, either by use of a differential pressure gauge, direct inspection, or by borescope inspection.
c) All instrumentation should be calibrated in the range in which it will be operated during the test. Check all instrument readings for temperature, pressure, flow, torque, and speed to assure that the sensors are functioning properly.
d) Verify data acquisition system operation and setup prior to starting the field performance test. Data acquisition frequency should be consistent with analysis needs for validation of proper system response.

For example, very high frequency data should be captured during machine start-ups, shutdowns, load or speed transients, and surge testing. Lower frequency data are acceptable for steady state monitoring during the extended performance test.

8.3.6.3 At completion of the field performance test, the following should be performed:

a) All temporary infrastructure, instrumentation, etc. should be removed and machine prepared for unrestricted operation.
b) Data from the field performance test should be permanently archived in a format that will ensure availability to support future operation or risk assessment activities.
c) Results from field performance test data reduction and analysis should be produced and agreed upon by all affected parties (operating company, vendor, and DRP).

8.4 OPERATING COMPANY IMPLEMENTATION

8.4.1 The operating company shall implement risk mitigation measures identified in the field risk assessment to achieve the company defined acceptable risk level. To facilitate sustained risk mitigation over the remaining useful life (RUL) of the asset, the operating company should implement a management system meeting the requirements of 1.2.2. In addition, the following routine checks should be made on all API 691 Machinery:

a) verify written SOPs for start-up, operation, and shutdown are available,
b) review operating procedures to make sure they include steps necessary to mitigate risks and maintain SOLs/IOWs at all times,
c) confirm written maintenance procedures exist outlining preventive measures and system checks to ensure the proper functioning of protective shutdown devices,
d) ensure that current inspection, maintenance plans, and procedures are in place based on existing process and mechanical operating conditions,
e) verify that operating and maintenance personnel roles, responsibilities, training, and qualifications are clearly defined and managed for competency assurance,
f) investigate accidents, near misses, abnormal occurrences, and failures in accordance with company procedures or API 689, First Edition, Annex XX-C.1.10,
g) confirm that nonconformances are documented and corrective actions taken in accordance with company procedures,
h) confirm that an emergency response plan is in place to address loss-of-containment events,

i) ensure that appropriate documentation (datasheets, SOPs, inspection procedures, etc.) is current and revised in accordance with the operating company's MOC process.

NOTE Suggested practice for Items a) to d) above is to periodically review as changes occur in operations, process, and mechanical conditions (MOC trigger) and the company's HAZOP schedule.

ANNEX XX-A

A.2.4 ANALYZE MACHINERY RISKS

A.2.4.1 General

The identification of machinery risks is the first step in the analysis. Potential risks may be determined from a combination of several sources of hazard and failure knowledge and should include:

a) PHA studies, i.e. HAZOP;
b) potential failure modes checklists;
c) potential hazard checklists;
d) operating knowledge;
e) engineering studies.

Analysis of machinery risk involves the determination of the severity of the consequence of the hazard or failure and where possible the probability of the hazard or failure occurrence. This requires the user to review each hazard or failure mode associated with the machinery in a systematic process to identify the COF and POF.

An informative guide to each of the risk assessment methodologies stated in this document is provided in the following paragraphs. The user is referred to recognized industry standards for a detailed description and comprehensive application of these methods.

Table XX-A.3 identifies the relevant standards for reference related to each stage in the machinery life cycle.

A.2.4.3 What-if Analysis

A "what-if" analysis is a process that defines potential failure scenarios based on the experience of a team of experts in machinery. The risk assessment is a qualitative method and includes the following key steps.

a) Define the boundary of the system to be reviewed, which should be the machinery limits.
b) Determine which type of hazards are to be analyzed, which should include safety and environmental as a minimum.
c) Subdivide the system or equipment into components and subcomponents at an appropriate level.
d) Generate a list of "what-if" questions for each component or subcomponent.
e) Complete the risk assessment by answering the "what-if" question by identifying the consequences with no risk measures, possible safeguards, and mitigating recommended actions.

NOTE The method is a hazard assessment technique that relies on the creative thinking of a select team of specialist.

A.2.4.4 Hazard and Operability Analysis

HAZOP is a PHA method used primarily to identify major process hazards and operability issues. The method is defined in the standard IEC 61882 as an application guide for the identification of risk, risk analysis, and risk mitigation recommendations related to the process design.

In a HAZOP the terms of reference are established to determine which section of plant or system is to be examined. The following key process steps are facilitated by a HAZOP leader and applied to a single line or section on the P&ID reviewed.

a) Identify deviations from design intent using guide words on each element.
b) Identify the consequences and causes.
c) Determine whether significant problems exist.
d) Identify protection, detection, and indicating measures.
e) Identify possible remedial/mitigating measures.

This process is repeated for each element on the P&ID systematically until all risks have been documented for the system reviewed.

The results from the HAZOP review are risk-ranked causes of process parameter deviation from the design intent and associated recommendations for reducing risk through safeguards.

The analysis provides a mechanism to screen machinery within systems and identify API 691 Machinery. It also provides valuable hazard and potential failure information for further risk analysis such as FMEA and fault tree analysis (FTA).

HAZOP is a system centered approach compared to FMEA, which is a more component centered analysis.

A.2.4.6 Technical Risk Categorization

Design technical risk assessment is a checklist method in design used to evaluate and classify machinery risk considering reliability, technology, configuration, operating envelope, and organizational factors. The technical risk categories in Table XX-A.2 provide guidance to the user in identifying the particular risk category.

Category A machinery may be characterized by a high level of uncertainty, e.g. in terms of pressures and temperatures of produced fluids that are outside previous experience for development (suggesting a high level of new design and qualification may be required). Alternatively, the technology and environment may be relatively standard, but the project/product team may be inexperienced or located remotely from the primary technical resources of the company. This may include start-up company products or existing companies using new subvendors located in emerging regions of the world.

Category D machinery should be characterized by a high level of certainty in terms of environments very similar to existing projects, high likelihood of being able to use standard field proven equipment, and an experienced project team with a good understanding of technical requirements and an ability to produce a high-quality product.

The determination of machinery technical risk categories during the feasibility and concept selection stage allows both operating companies and vendors to focus their resources on high-risk machinery to satisfy the needs of the industry in ensuring a safe working environment.

Categorization should not be an onerous activity. The following ground rules should be used to facilitate the process.

a) If there is any doubt as to which technical risk category applies, select the higher risk category (and investigate the uncertainty).
b) The selected level of risk for each change factor should be accompanied with brief explanation/justification of the risk category to aid future understanding.

c) The overall category for the project/package/equipment is the highest of the categories for the individual risk change factors.
d) The definitions in Table XX-A.2 are general and are intended to be applied at project, package, and component levels. Some interpretation for each project stage and project scope may be necessary.

Vendors of equipment should be contacted to identify technical hurdles or barriers to implementation in order to establish cost and schedule to develop a qualified system. This should then be built into the preliminary project/product schedule with sufficient schedule flexibility to account for the information.

Table XX-A.2—Machinery Technical Risk Classification

	Technical System Scale and Complexity			Operating Envelope	Organizational Factors
	Reliability	Technology	Configuration	Environment	Organization
Risk Level	— Machine type — Service — Blading/impeller design — Sealing design — Casing design — Bearing design — Speed	— Materials — Dimensions — Design life — Stress limits — Temperature limits — Corrosion — Duty cycle	— Layout complexity — Control systems — Driver size — Auxiliaries — Side streams — Shaft length	— Facility location — Pressure — Temperature — Flow rate — Fluid properties — Design point — Normal point — Process variability — Level of competence of field personnel	— Location — Company — Resources — Contractor — Supply chain — Experience — Machinery design competency — Manufacturing capabilities — Testing capabilities — QA/QC
A (Very High)	**Reliability improvements (technology change):** A significant reliability improvement requiring change to the technology involved.	**Novel technology or new design concepts:** Novel design or technology to be qualified during project.	**Novel applications:** Configuration has not been previously applied by vendor.	**New environment:** Project is pushing environmental boundaries such as pressure, temperature, etc., new part of the world, or limits of field expertise.	**Whole new team:** New project/product team, working with new vendors in new location.
B (High)	**Reliability improvements (design change):** A significant reliability improvement requiring change to the design but no change to the technology.	**Major modifications:** Known technology with major modifications such as materials changes, conceptual modifications, manufacturing changes, or upgrades. Sufficient time remains for time remains for qualification. Nonmature for extended operating environments.	**Orientation and capacity changes:** Significant configuration modifications such as size, orientation, and layout; changes fully reviewed and tested where viable. Large scale, high complexity.	**Significant environmental changes:** Many changes noted: extended and/or aggressive operating environment; risk requires additional review.	**Significant team changes:** Project team working with new vendor or with supply chain: key technical personnel changes from previous projects.
C (Medium)	**Minor reliable improvements:** Reliability Improvements requiring tighter control over quality during manufacture assembly and fabrication.	**Minor modifications:** Same vendor providing a copy of previous equipment with minor modifications such as dimensions or design life; modifications have been fully reviewed and qualifications can be completed.	**Interface changes:** Interface changes, equipment or control systems changes; where appropriate configuration has been tested and verified.	**Similar environmental conditions:** Same as previous project or no major environmental risk have been identified.	**Minor team changes:** Small or medium organization; moderate complexity; minor changes in contractor/vendor and project team.
D (Low)	**Unchanged reliability:** No reliability improvements required, existing QA and control is acceptable.	**Field proven technology:** Same vendor providing equipment of identical specification manufactured at the same location; provide assurance no changes have occurred through the supply chain.	**Unchanged:** Configuration is identical to previous specifications; interfaces remain unchanged, with no orientation or layout modification.	**Same environmental conditions:** Same as recent project.	**Same team as previous:** Same project team, contractors, vendors, and vendors supply chain; applies throughout project life cycle.

A.2.4.7 Failure Modes and Effects Analysis

FMEA is a method of risk assessment that can be applied at equipment, component, and subcomponent levels on API 691 Machinery.

The FMEA process is defined in IEC 60812 using a systematic approach to identify for each functional failure:

a) the potential failure modes,
b) the consequences or effects associated with each failure mode,
c) the potential causes of failure,
d) the controls or safeguards applied to mitigate failures,
e) the detectability of controls and how well they are expected to perform (refer to the Annex XX-I FMEA worksheet for example scale),
f) calculation of a RPN based on COF, POF, and detectability determination,
g) recommended mitigating actions.

The process is typically conducted using a FMEA form to structure the information gathering and analysis. A FMEA worksheet is included in Annex XX-I. An extension of the FMEA method to incorporate a quantification of risks associated with each failure mode is termed failure mode, effects, and criticality analysis (FMECA).

Several forms of FMEA exist, including functional, design, and process FMEA. Design FMEA (DFMEA) examines risk associated with equipment and component failures. Process FMEA (PFMEA) considers risk associated with work processes including failures, e.g. in the manufacturing or assembly process.

A.2.4.8 Layers of Protection Analysis for Machinery

LOPA is a structured risk analysis that normally follows a qualitative PHA such as HAZOP. The method is defined in IEC 61511 Part 3, Annex F (informative) for the process industries.

LOPA requires the user to determine and quantify the risk associated with various hazard events identified by the PHA using the severity of the consequences and the probability of the events being initiated. The residual risk after several layers of protection are considered is calculated to meet company risk reduction requirements. The LOPA risk assessment process is shown in Figure XX-A.3.

The following describes the basic steps of a LOPA:

a) *Determine the Hazardous Event*—The user determines the various hazardous events associated with operation of high-risk machinery. These events are typically those identified in the user's process safety analyses, along with any additional credible hazards identified by the user as potentially leading to
consequences that are above company defined risk thresholds.

b) *Determine Event Severity and Consequence*—The potential, undesirable consequences resultant from exposure to each hazardous event are identified. These consequences are typically used as identified in the user's process safety analyses. The appropriate COF category is assigned for any events not covered by the process safety analyses.

c) *Determine Initiating Causes*—All of the credible causes of the initiating event are then identified by the user. Causes are typically aligned with those identified in the user's process hazard analyses.

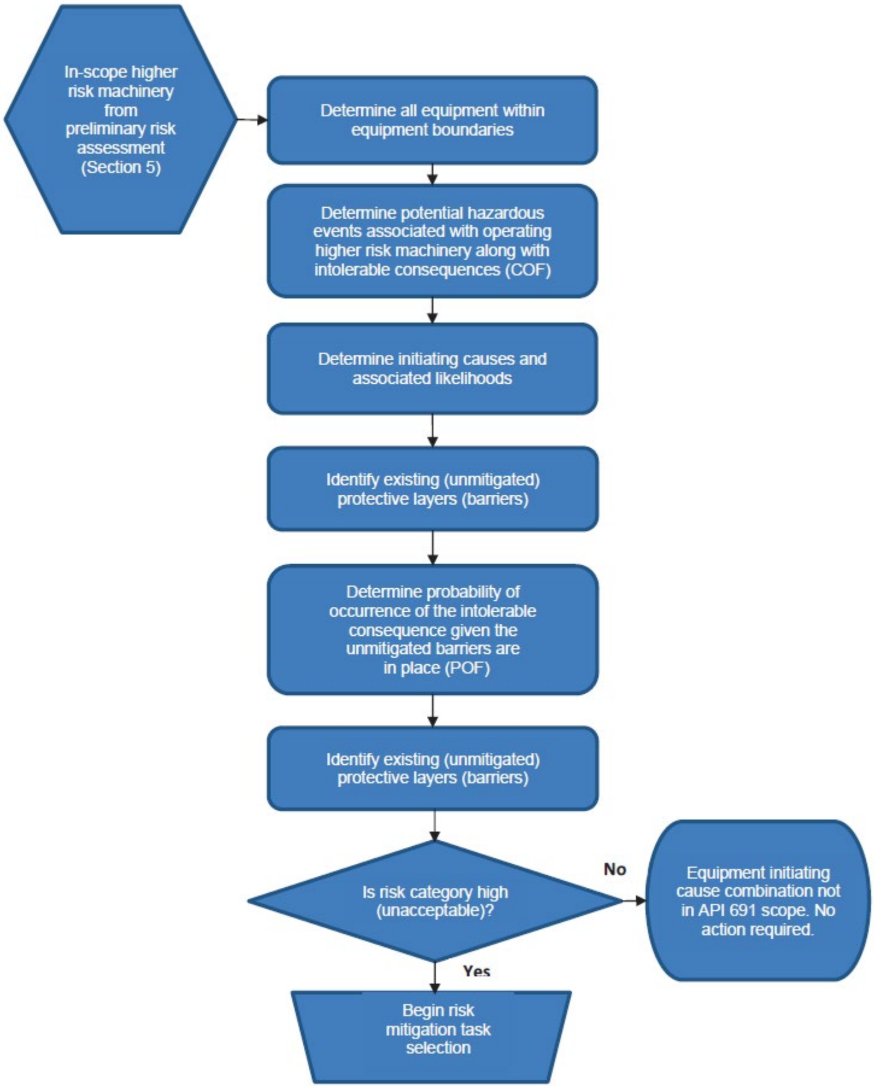


Figure XX-A.3—Detailed Risk Assessment Process Utilizing a LOPA

d) *Determine Likelihood of Initiating Causes*—An estimate of the probability of each initiating cause, POF.

NOTE The Center for Chemical Process Safety (CCPS) should be consulted for initiating event frequency information.

e) *Identify Existing Layers of Protection*—The independent protection layers (IPLs) such as mechanical devices, barriers, or protective instruments are identified for each hazard event. The level of protection provided by the IPL is quantified by the probability that it will fail upon demand.

f) *Determine the Requirement for Additional Mitigation*—Using the probability of the initiating cause, and the existing layers of protection IPL (unmitigated), the user determines the POF category, defined as the likelihood a given initiating cause will lead to an identified intolerable consequence.

LOPA is typically performed using an analysis worksheet.

A.2.4.9 Reliability, Availability, and Maintainability Analysis

A.2.4.9.1 The principal objectives of RAM analysis include the following.

a) Evaluate the ability of the system to operate at acceptable risk 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 availability probability value (APV), which can be an indicator of production capability. APV is often used in economic analysis to determine the impact of the present design on production, or it can be used to compare 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.
f) Maintenance policy such as number of repair teams, rig mobilization policy, spare parts management, and repair priority in case of simultaneous failures.

RAM analysis provides a forecast of equipment and/or facility (system, unit, refinery) production availability using statistical methods and is the means for quantifying the future performance of any system in terms of key performance indicators (KPIs) such as availability, production efficiency, utilized capacity, gross sales or profit, missed or late shipments, flaring events, etc. It addresses the production system performance and design improvement opportunities to close production deficiencies in a cost-effective manner.

A.2.4.10 Fault Tree Analysis

FTA is a method used in PHA to analyze complex system or component failures in which there are dependent failure modes or failure paths to an undesired event or hazard condition. Unlike other risk and failure analysis methods, including HAZOP and FMEA, the complex interdependencies in failure modes and causes can be combined and assessed. The method may be applied to machinery to perform failure analysis on machinery components, control systems, and controls logic, for example.

The FTA is a deductive, top-down process that analyzes the possible causes and combination of causes in Boolean logic that contribute to the top level hazard or undesirable event. Application guidance is provided in IEC 61025 [24]. Typically, a Boolean logic gate diagram (refer to Figure XVIII-A.6) is prepared to show the top level hazard and the multiple combinations of failure causes and events that can lead to the hazard. The probability of each failure cause/event can be quantified at each level to provide the overall likelihood of failure and each contributing failure cause.

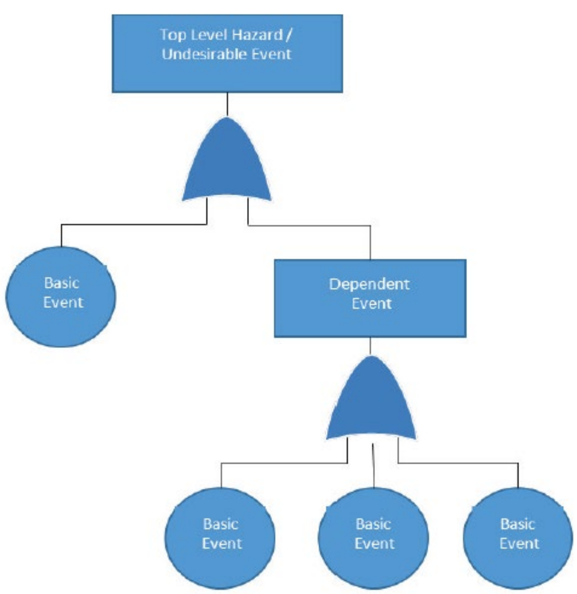


Figure XX-A.6—Typical Fault Tree Diagram

FTA can provide the following benefits to risk assessment in machinery:

a) an understanding of the path that can lead to the hazard/undesirable event,
b) overview of the complexity of the risk,
c) ability to prioritize focus on risk mitigating measures,
d) a basis to audit the safety and reliability performance of a system or component,
e) demonstrate compliance with design intent.

A.2.5 MACHINERY RISK RANKING

The process step of ranking the analyzed risks is important to the overall process. It provides a mechanism to prioritize risk mitigation review and actions based upon the level of risk to the machinery owner.

The level of risk to the owner is a key element and should be defined by the machinery owner. This is typically High, Medium, and Low risks or in some cases Intolerable, Tolerable, or Acceptable risks depending on the owners' criteria and corporate risk management definitions.

The result of machinery risk analysis is a quantitative or qualitative schedule of risks that may be shown on a risk matrix or calculated using RPNs. The risk matrix communicates those risks that are classified as High, Medium, and Low. The RPN method is based on the risk levels defined as ranges in RPN values for each level of risk.

The ranking and prioritization of these risks are then identified on the level of risk defined by the owner for risk mitigation treatment.

A.2.6 MACHINERY RISK MITIGATION

The risk mitigation measures following the risk assessment are described in the main sections of this document for each of the machinery life cycle stages.

This is an iterative process to determine if risk mitigating steps applied reduce residual risk to an acceptable level defined by the machinery owner.

ANNEX XX-B (INFORMATIVE)

B.- RISK-BASED MACHINERY VALIDATION CHECKLISTS

B.1 INTRODUCTION

This annex covers the minimum recommended validation checks to be carried out for API 691 Machinery throughout its life cycle.

a) Feasibility and concept design:

1) design validation reviews.

b) FEED:
1) P&ID validation reviews.

c) Detailed design:
1) equipment service condition checklist validation reviews.

d) Operations and maintenance:
1) pre-TA risk validation checklist reviews,
2) major overhaul risk validation checklist reviews,
3) additional pressure boundary inspections for machinery in corrosive, erosive, and harsh service.

B.2 FEASIBILITY AND CONCEPT DESIGN AND FEED VALIDATIONS

B.2.1 General

This section provides guidance on the design validation of machinery classified as API 691 Machinery during the feasibility and concept design and FEED phases of a project. The validation process should demonstrate that the machinery is capable of operating safely and reliably within the expected operating envelope.

B.2.2 Aerodynamic/Hydrodynamic Performance Attributes

Where applicable, the following aerodynamic/hydrodynamic performance attributes should be validated:

a) flow rate,
b) head,
c) efficiency,
d) net positive suction head required (NPSHR) (if applicable),
e) turndown performance,
f) preferred operating range,
g) allowable operating range,
h) best efficiency point.

B.2.3 Casing Design Attributes

Where applicable, the following casing design attributes should be validated:

a) pressure casing— include sealing and bolting arrangements,
b) attachments—instruments, inlet taps, outlet taps,
c) seal housing,
d) bearing housing,
e) end caps (if applicable).

B.2.4 Material Design Attributes

Where applicable, the following material design attributes should be validated:

a) necessary corrosion resistance,
b) necessary material strength,
c) wet material selections,
d) dry material selections,
e) nonmetallic material selections,
f) material compatibility with the process stream,
g) erosion resistance where process stream contains high levels of particulates,
h) mill test report.

B.2.5 Seal Design Attributes

Where applicable, the following seal design attributes should be validated:

a) sealing configuration,
b) seal type,
c) seal support plan (if applicable),
d) flush plan (if applicable),
e) seal quench plan (if applicable),
f) seal drain plan (if applicable),
g) seal face materials,
h) phase mapping (if applicable),
i) seal support system monitoring and protection instrumentation,
j) barrier and buffer fluids,
k) seal system fluid compatibility with process stream,
l) elastomer,
m) elastomer compatibility with seal system and process system constituents,
n) maximum seal temperature/pressure.

B.2.6 Rotor Dynamics Attributes

Where applicable, the following rotor dynamics attributes should be validated:

a) lateral critical speed study,
b) torsional analysis, where required,
c) separation margins,
d) amplification factors (resonances),
e) stability analysis,
f) steady state analysis,
g) transient analysis,
h) test vibration levels (if available),
i) surge (if applicable),
j) natural frequency of the rotor.

B.2.7 Impeller/Blade Design Attributes

Where applicable, the following impeller/blade design aspects should be validated:

a) stresses,
b) Security Achieved through Functional and Environmental Design (SAFE) diagram, Modified Goodman diagrams, Campbell Goodman diagrams, etc.
c) interference fits.

B.3 P&ID REVIEWS DURING FEED

B.3.1 General

This section provides guidance on the recommended minimum level of validation of pipework and instrumentation systems supporting machinery classified as API 691 Machinery during the FEED phase of a project. The validation process should demonstrate that the systems outlined in the P&IDs are capable of providing safely and reliable operation within the expected operating envelope of the machinery. The validation of P&IDs can extend into the detailed design phase of the project.

B.3.5 API 616—Gas Turbines

Where applicable, the following items on P&IDs should be validated:

a) instrumentation, alarms, and shutdowns provided in API 613, API 614, API 616, and API 670 where applicable and as noted on the equipment datasheets,

b) governor system,
c) flameout protection,
d) venting, purging provision,
e) fire and gas protection,
f) inlet and exhaust systems,
g) fuel valve,
h) fuel system venting,
i) overspeed trip protection controls,
j) turbine wash connections and piping,
k) lubricating oil system.

B.4 VENDOR QUALIFICATION DURING FEED AND DETAILED DESIGN

B.4.1 General

This section provides guidance on the qualification of a vendor to manufacture machinery classified as API 691 Machinery. The qualification process should demonstrate that the vendor has manufactured machinery of an identical type that has successfully operated under equivalent operating conditions. The critical areas relative to equivalent service conditions that should be demonstrated are included below.

B.4.5 API 616—Gas Turbines

Where applicable, the following critical items relative to equipment service conditions should be validated:

a) inlet air system,
b) exhaust system,
c) starting system,
d) site rated firing temperature,
e) inlet air filtration system,
f) emissions,
g) acceptable Wobbe index range,
h) base/peak loads,
i) fuel system,
j) lubrication system,
k) post FAT borescope inspection prior to shipping.

For API 616 gas turbine packages, the vendor should have manufactured an identical gas turbine (model number) of comparable design context, speed, power rating, etc. to that of the intended duty. The vendor should demonstrate their experience on an individual component and service condition basis, as listed below.
Experience need not be concentrated in a single reference, but may be spread through several operating referenced designs.

NOTE The Wobbe index range is a gauge of the OEM allowable range of change in heating value of fuel gas. It is the ratio of the lower heating value (LHV) of the fuel gas divided by the square root of the specific gravity (SG) of the fuel gas:

Wobbe index = LHV SG

The “modified” Wobbe index range can also be used, which takes into account absolute fuel temperature (TFA):

modified Wobbe index = LHV SG´ TFA

B.5 OPERATIONS AND MAINTENANCE MACHINERY CHECKLISTS

B.5.1 PRE-TURNAROUND CHECKLISTS

B.5.1.1 General

Machinery classified as API 691 Machinery should be evaluated for inclusion in any planned shutdown activities. Risk is dynamic and changes during operation. As a general rule, machinery that frequently operates outside IOWs should be considered for special attention and activities during shutdown activities.

Operator risk tolerance and the checklists outlined below have been provided to assist with the inclusion decision. These lists are not comprehensive in terms of machinery types or specific checks.

B.5.1.4 API 616—Gas Turbines

This list is provided to assist with the TA scope inclusion decision for API 616 gas turbines classified as API 691 Machinery. Gas turbines have life-limited combustion and hot gas path components that require time-based inspections, which are usually determined from historical findings in past inspections, metallurgy of components, fired hours of service, fuel quality and type, operational mode, environmental conditions, and firing temperatures. OEM recommendations and/or past inspection history are used to set frequencies of combustion inspections, hot gas path inspections, overhauls, and rotor breakdown inspections.

a) Check equipment condition history.
b) Check performance of axial compressor and turbine sections, including a comparison of inlet and outlet temperatures and pressures to normal conditions.
c) Check guide vanes for excessive looseness in linkages and for proper operation.
d) Check operation of inlet gas and gas ratio valves and responses to signal changes and load changes.
e) Review the last inspection and repair reports.
f) Any known issues that arose since the last inspection/repair or issues that were not addressed during the last inspection/repair [Item e)].
g) Any concerns with extending gas turbine operation to another TA cycle, taking into consideration the special note above.

B.5.2 MACHINERY OVERHAULS

B.5.2.1 General

The scope of both minor and major overhauls are typically defined by the severity of failure events, degree of observed performance deficiencies, or the results of asset specific health checks routinely performed on high-risk machinery. To the extent possible, operating companies will typically schedule overhauls to coincide with scheduled turnarounds with greater preference given to those scope activities that result in the greatest risk mitigation.

The success of overhauls following unplanned (forced) outages is often dependent on prior field risk assessments that have considered the availability of skilled personnel, preapproved repair procedures, and spare parts. Depending on the extent of the overhaul, close coordination may be required with vendors to ensure safe and reliable operation following critical repairs and/or inspections.

Unless otherwise specified, operating companies should follow the vendor's repair or replacement, procedures, practices, and recommendations for any components or subcomponents that mitigate the risks of failure.

However, as a minimum, the following additional checks, inspections, and maintenance tasks should be considered within the overhaul scope using approved SOPs.

NOTE The checks listed are not comprehensive and do not constitute complete overhaul scope for listed machinery types.

B.5.2.4 API 616—Gas Turbines

The following list is provided to assist with compiling the overhaul scope tasks for API 616 gas turbines classified as API 691 Machinery.

a) Perform cold side and hot gas path inspections as required.
b) Check alignment.
c) Survey pipe supports/hangers, expansion joints.
d) Clean instrument taps.
e) Inspect, calibrate surge protection system.
f) Inspect, calibrate vibration monitoring system.
g) Check integrity of trip system.
h) Inspect, calibrate inlet gas and gas ratio, IGVs, discharge control valve, vent control valve, capacity/pressure control system.
i) Inspect coupling(s).
j) Borescope inspection of flame tubes and transition ducts.
k) Visually inspect valve seats.
l) Visual inspection, gear tooth check, and check/clean of lubrication spray nozzle.
m) Thoroughly examine system protective devices.
n) Calibrate fire extinguishing system.
o) Weigh fire suppression cylinders.
p) Check condition of bearings.
q) Check oil and other fluid systems for leaks.
r) Check cleanliness of filters and coolers.

B.5.3 ADDITIONAL PRESSURE BOUNDARY INSPECTIONS FOR MACHINERY IN CORROSIVE, EROSIVE, AND HARSH SERVICE

Based on machinery condition and other factors, more detailed inspections and CM activities should be considered as well as adjustments to maintenance tasks and frequencies for equipment in corrosive, erosive, and harsh service.

The operator should consider performing the following inspections (may be tied to site TA schedule).

a) NDT of any welded connections for nozzles.
b) Visual inspection of sealing surface areas to identify any pitting or mechanical damage.
c) Internal dimension measurements to identify material loss through corrosion, erosion, or wear. Thickness readings may be taken using UT in cases where component geometry prevents use of conventional measuring methods.
d) External examination of the casing to identify material loss through corrosion.
e) Examination of casing drain connections.
f) Baseplate integrity check.
g) Visual inspection of driven and driver mounting foot.
h) Visual inspection of the external piping including piping used for auxiliary systems in lube oil, sealing, and cooling systems.
i) Inspection of auxiliary system orifice plates as applicable.

j) Fatigue life and residual life estimation.
k) Pipe strain/pipe alignment.
l) Visual inspection for excessive pipe misalignment resulting in excessive nozzle.
m) Leak point inspections on split lines, flanges, balance lines, recycle lines, drains, etc.

Table XX-B.4 — Example of aero gas turbine faults matched to measurement parameters and techniques

Machine type: Aero gas turbine	Symptom or parameter change											
Examples of faults	Compressor temperature	Compresor pressure/ Pressure ratio	Air flow	Fuel pressure/ Fuel flow	Speed	Gas generator temperature	Pressure/ Pressure ratio	Power turbine temperature	Exhaust temperature	Vibration	Oil debris	Oil leakage/ consumption
Air inlet blockage	•	•	•		•							
Compressor fouled	•	•	•	•	•	•	•	•	•	•	•	
Compressor damaged	•	•		•	•	•	•	•	•	•	•	
Compressor stall					•		•			•		
Fuel filter blockage		•		•	•		•					
Seal leakage						•	•				•	•
Combustion chamber holed				•	•				•			
Burner blocked				•	•		•					
Power turbine dirty	•	•	•		•		•	•		•		
Power turbine damage	•	•	•		•		•			•	•	
Bearing wear/ damage										•	•	•
Gear defects										•	•	
Unbalance										•		
Misalignment										•		

• Indicates symptom could occur or parameter could change if fault occurs.

Table XX-B.5 — Example of industrial gas turbine faults matched to measurement parameters and techniques

Machine type: Industrial gas turbine	Symptom or parameter change											
Examples of faults	**Compressor temperature**	**Compressor pressure**	**Air flow**	**Fuel pressure/ Fuel flow**	**Speed**	**Exhaust tempera-ture**	**Vibration**	**Output power**	**Compressor efficiency**	**Turbine efficiency**	**Oil debris/ contamination**	**Oil consumption**
Air inlet blockage		•	•		•			•				
Compressor fouled	•	•	•	•	•			•	•			
Compressor damaged	•	•	•	•	•		•	•	•		•	
Fuel filter blockage		•		•	•			•				
Combustion chamber holed				•	•			•				
Burner blocked				•	•	•		•				
Power turbine damaged					•	•	•	•		•	•	
Bearing wear							•				•	•
Unbalance							•					
Misalignment							•					
• Indicates symptom could occur or parameter could change if fault occurs.												

ANNEX XX-C (INFORMATIVE)

C.- MACHINERY FAILURE MODES, MECHANISMS, AND CAUSES

C.1 INTRODUCTION

Benchmarking efforts within the industry have ambitiously attempted to classify failures under a single set of codes intended to be applicable for all equipment types, operating conditions, and processes.

More focused industry work that has identified failures applicable to a single type of equipment have proven to be of greater value in the prevention of HSE incidents throughout the industry. API 571 (*Damage Mechanisms Affecting Fixed Equipment in the Refining Industry*), for example, has enabled operators to have greater clarity in developing inspection programs, fitness-for-service assessments, and risk-based inspection applications.

Similarly, this recommended practice is intended to aid the operator in better understanding:

a) failure modes, mechanisms, and causes of machinery failures,
b) affected materials prone to some machinery mechanisms,
c) critical factors that affect certain mechanisms (i.e. rate of damage),
d) appearance or morphology of mechanisms—a description of the failure mechanism, with pictures in some cases, to assist with recognition of the condition.

The value of this annex is in assisting the operator in developing machinery specific PFMEAs (Annex A) for the purpose of preventing or mitigating risks by more effectively designing and optimally selecting maintenance tasks that target the most dangerous and relevant failure mechanisms associated with API 691 Machinery.

NOTE While failure modes, mechanisms, and causes are both equipment and process specific, there are, however, several areas of overlap with equipment types operating within a similar or identical process. The PFDs highlighted in API 571 show some of the areas within the unit where many of the primary failure mechanisms can be found. The reader should be advised that this is not intended to be an all-inclusive list of the failure mechanisms for a given process, but should serve as a starting point for reference and information.

While this annex is intended to cover most failure mechanisms for API specified machinery, there may be other special-purpose machinery whose failures are not adequately described. The user is encouraged to seek guidance from the OEM or independent lab to determine the root cause and in these cases should gather information specific to these unique assets. Identification of credible damage mechanisms is essential to the quality and effectiveness of risk analysis. The user should be knowledgeable about these unique assets.

C.2 FAILURE OBSERVATIONS

C.2.1 Failures can manifest themselves in a variety of ways. The way they are found can vary depending on who is working with or around the equipment. People (operators, mechanical, and electrical technicians, CM technicians, e.g. vibration and thermography) that work with and around machinery may observe failures in different ways.

C.2.2 Table XX-C.1 summarizes common observations with machinery failure mechanisms.

Table XX-C.1—Observations Associated with Common Machinery Failure Mechanisms

Ref.	Mechanism	Component Failure	Discoloration	External Leak	Loose Parts	Loss of Output	Noise/Sound	Output Change—Flow	Output/Input Change—Pressure	Output/Input Change—Temperature	Loss of Performance (e.g. Flow, Pressure)	Product Quality	Seized Part	Stops	Vibration	Will Not Start	Loss of Barrier Fluid (e.g. Level, Pressure)	Visual Damage/Degradation	Lubrication (Contamination)	Bearing Temperature	Borescope—Deposits	Borescope—Distortion	Borescope—Impact Damage	Borescope—Metal Loss	Oil Analysis	Sometimes Observes Movement	Thermography Hot Spot	Beach Marks	Blown Fuse	Burnt Part	Color Variations	Cracks	Distortion	External Corrosion	Fractured Part	Impeller Damage	Internal Corrosion	Loose/Broken Wire	Metal Loss—Thinning	Pitting	PM Checks	Tripped Breaker
1	Brittle fracture	X			X	X	X						X																						X							
2	Cavitation	X					X		X	X	X				X					X																X			X	X		
3	Circuit failure													X		X											X		X	X												X
4	Corrosion (uniform, pitting, oxidation, sulfidation, etc.)			X															X		X			X	X							X					X			X		
5	Deformation														X	X		X															X									
6	Electrical discharge																	X							X															X		
7	Environmental cracking— stress corrosion cracking (SCC) (e.g. ammonia, caustic, chloride, hydrogen, sulfide)	X	X	X																												X	X									
8	Erosion—(e.g. droplets, solids, corrosion)			X							X	X								X																			X			
9	Fatigue, contact	X					X						X	X	X	X		X	X	X					X							X							X			
10	Fatigue (mechanical/thermal/ corrosion-fatigue)	X		X	X	X	X						X		X			X							X			X				X			X			X				
11	Faulty or no power/voltage											X		X		X											X		X									X			X	X
12	Faulty or no signal/indication/alarm											X		X		X						X	X	X														X			X	
13	Foreign object damage	X					X				X			X	X			X				X	X	X																		
14	Fouling/contamination							X	X	X	X				X				X	X	X																					
15	Fretting/wear	X	X		X								X		X					X					X	X													X			
16	Seal failure	X	X	X			X					X		X			X		X																		X			X		
17	Selective leaching (dealloying)			X							X																				X								X			
18	Temper embrittlement	X				X							X																			X			X							

C.3 FAILURE MODES

Failure mode is the general manner by which a failure of an item and its impact on equipment/system operation becomes evident.

Failure modes should normally relate to the equipment-class level in the hierarchy. At the equipment unit level, failure modes would typically align with specific functional failures (e.g. fails while running, fails to deliver specified flow and pressure).

Failure modes may be hidden, at least until they are observed during a FF task.

According to API 689 and ISO 14224, failure modes can be categorized into three types:

a) desired function is not obtained (e.g. failure to start, fails while running),
b) specified function lost or outside accepted operational limits (e.g. fails to deliver specified flow and pressure, spurious stop, high output),
c) failure indication is observed, but no immediate and critical impact on the equipment-unit function (degraded or incipient conditions),

Table XX-C.2 summarizes common failure mode descriptions used within the industry for machinery.

Table XX-C.2—Failure Mode Descriptions

Failure Mode Code	Description	Examples
AIR	abnormal instrument reading	false alarm, faulty instrument indication
BRD	breakdown	serious damage (seizure, breakage, etc.)
ERO	erratic output	oscillating, hunting, instability, etc.
ELF	external leakage of supplied fuel	external leakage of fuel, gas or diesel
ELP	external leakage of process medium	oil, gas, water, etc.
ELU	external leakage utility	lubricant, cooling water, etc.
FTS	failure to start on demand	does not start when required
HIO	high output	overspeed, flow, pressure, etc. impacting output
INL	internal leakage	leakage internally of process or utility fluids
LOO	low output	flow, pressure, etc. impacting output
NOI	noise	abnormal noise
PDE	parameter deviation	monitored parameter exceeding limits, e.g. high/low alarm
PLU	plugged/choked	flow restrictions
SER	minor in-service problem	discoloration, loose items, etc.
STD	structural deficiency	material damages
STP	failure to stop	does not stop when required
UST	spurious stop	unexpected shutdown
OTH	other	failure nodes not covered above

C.4 FAILURE MECHANISMS

Failure mechanisms are the apparent physical, chemical, electrical, thermal, or other processes that technical deduction concludes led to the failure. They will normally be related to a lower indenture level (subunit or maintainable-item level). Table XX-C.3 summarizes the most common failure mechanisms associated with machinery.

C.5 FAILURE CAUSES

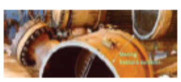
Failure causes are the initiator of the process by which deterioration begins, ultimately resulting in failure. In other words, failure causes are what initiate the failure mechanism (from the user/owner's perspective, where the defects manifested themselves)—failure being the termination of the ability of an item to perform a required function. Examples of failure causes are:

a) design (can relate to the design of the machinery/system itself or to the initial specification of the requirements for the machinery/system),
b) manufacturing quality (e.g. variation in quality of "identical" products from same vendor, but from different manufacturing locations, or reverse engineered components from parts replicators),
c) installation,
d) maintenance (technical actions, intended to retain an item in, or restore it to, a state in which it can perform a required function),
e) use or operation (in user/owner's process or application, at specific location),
f) operating context changes (e.g. changes in the raw materials or manufacturing process that can make a good design become a bad one),
g) management (administrative actions),
h) miscellaneous (e.g. weather, natural disasters).

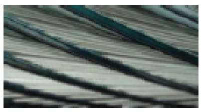
Failure causes will also normally be related to a lower indenture level (component/maintainable item or part level).

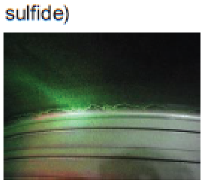
Table XX-C.4 summarizes common machinery failure causes.

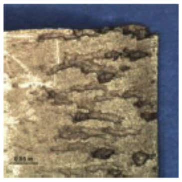
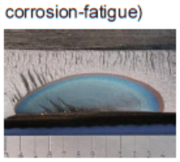
Table XX-C.3—Machinery Failure Mechanisms

Ref.	Mechanism	Category	Degradation Type	Observations By			Definition
				Operator	CM Tech	Mechanic/ Electrician	
1.	Brittle fracture  Brittle fracture of 2.2 in. wall C-0.5 Mo exchanger channel during hydrotest	Material	Metallurgical degradation	Loss of output, component failure, leak, noise, loose and seized parts		Fractured part	Brittle fracture is the sudden rapid fracture under stress (residual or applied) where the material exhibits little or no evidence of ductility or plastic deformation. Carbon steels and low alloy steels are of prime concern, particularly older steels. 400 series stainless steels are also susceptible. For a material containing a flaw, brittle fracture can occur. Following are important factors to consider with this failure mechanism: a) the material fracture toughness (resistance to crack like flaws) as measured in a Charpy impact test; b) the size, shape, and stress concentration effect of a flaw; c) the amount of residual and applied stresses on the flaw; d) susceptibility to brittle fracture may be increased by the presence of embrittling phases; e) steel cleanliness and grain size have a significant influence on toughness and resistance to brittle fracture; f) thicker material sections have a lower resistance to brittle fracture due to a higher constraint that increases triaxial stresses at the crack tip; g) in most cases, brittle fracture occurs only at temperatures below the Charpy impact transition temperature (or ductile-to-brittle transition temperature), the point at which the toughness of the material drops off sharply.

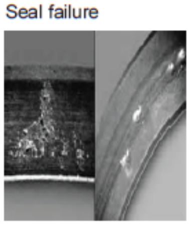
Ref.	Mechanism	Category	Degradation Type	Observations By			Definition
				Operator	CM Tech	Mechanic/ Electrician	
2.	Cavitation  Cavitation pitting on the low-pressure side of a stainless steel pump impeller	Material	Metal loss	Performance problem, noise, vibration	Vibration, noise	Impeller damage	Cavitation is a form of erosion caused by the formation and instantaneous collapse of innumerable tiny vapor bubbles. The collapsing bubbles exert severe localized impact forces that can result in metal loss referred to as cavitation damage. The bubbles may contain the vapor phase of the liquid, air, or other gas entrained in the liquid medium. Cavitation is best prevented by avoiding conditions that allow the absolute pressure to fall below the vapor pressure of the liquid or by changing the material properties. Examples include the following. a) Streamline the flow path to reduce turbulence. b) Decrease fluid velocities. c) Remove entrained air. d) Increase the suction pressure of pumps. e) Alter the fluid properties, perhaps by adding additives. f) Use hard surfacing or hardfacing. g) Use of harder and/or more corrosion resistant alloys.
3.	Circuit failure	Electrical		Stops/alarms/trips, will not start		Blown fuse, burnt part	Open or short circuit
4.	Corrosion (Uniform, pitting, oxidation, sulfidation, etc.)  Corrosion caused by poor steam chemistry (Photograph compliments of M&M Engineering Assoc.)	Material	Metal loss	Leaks, discoloration		Internal/ external corrosion, pitting	The deterioration of metal caused by chemical or electrochemical reaction of a metal with its environment, resulting in metal loss. The loss can take many forms, including general uniform metal loss, localized metal loss in the form of pitting, high temperatures causing oxidation, etc. Sulfidation occurs in piping and equipment in high temperature environments where sulfur-containing streams are processed. Common areas of concern are the crude, FCC, coker, vacuum, visbreaker, and hydroprocessing units. Corrosion in boiler feedwater and condensate return systems is usually the result of dissolved gases, oxygen, and carbon dioxide, which lead to oxygen pitting corrosion and carbonic acid corrosion, respectively. Critical factors are the concentration of dissolved gas (oxygen and/or carbon dioxide), pH, temperature, quality of the feedwater, and the specific feedwater treating system.
5.	Deformation  Tube failure by bulging and rupture due to short-term overheating	Mechanical	Distortion	Vibration	Vibration, noise	Distortion	Deformation is the bending, twisting, distorting, bowing, or warping of a metal component that prevents the proper operation of a piece of equipment.

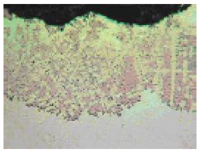
Ref.	Mechanism	Category	Degradation Type	Observations By			Definition
				Operator	CM Tech	Mechanic/ Electrician	
6.	Electrical Discharge  Spark tracking on an outer oil seal ring  Frosted gear teeth on a speed increaser gear (Photographs compliments of Dresser Rand)	Material	Metal loss	Vibration, excessive seal oil flow	Oil analysis	Pitting	A pitting mechanism caused by passing electrical currents between two surfaces. If current is high enough, very localized melting can occur. Electrica discharge is also referred to as "frosting" or "spark tracking." Here the names relate to the observations of the damaged parts. Common sources of electrical discharge are steam turbines especially those with wet steam running through the latter stages, and electric motor driven trains. Degradation or lack of grounding brushes, couplin electrical insulation, motor bearing insulation, and sound overall equipment grounding are typical causes for the appearance of electrical discharge damage. Certain combinations of lube oil and oil filter materials can also create static in the lube an or seal oil. Here the damage is typically confined t the filter elements.

Ref.	Mechanism	Category	Degradation Type	Observations By			Definition
				Operator	CM Tech	Mechanic/ Electrician	
7.	Environmental cracking—SCC (e.g. ammonia, caustic, chlorides, hydrogen, sulfide)  SCC of turbine disk caused by caustic carryover in steam (Photograph compliments of M&M Engineering Assoc.)	Material	Crack	Leaks, discoloration, component failure		Cracks	Environmental cracking is a common term applie to the cracking of metals under the combined act of tensile stress and a specific corrodant. For example, 300 series stainless steel is susceptible chlorides, while copper is susceptible to ammoni Even steels are susceptible to anhydrous ammonia. Most steels (carbon to low alloy to stainless) are susceptible to caustic. Cracking ha been reported down to ambient temperatures wi some amines. Increasing temperature and stress levels increases the likelihood and severity of cracking.

Ref.	Mechanism	Category	Degradation Type	Observations By			Definition
				Operator	CM Tech	Mechanic/ Electrician	
8.	Erosion (e.g. droplets, solids, corrosion)  Trailing edge erosion caused by recirculation flow of water droplets on last stage steam turbine blades (Photograph compliments of M&M Engineering Assoc.)	Material	Metal loss	Leaks, performance problem, product quality		Metal loss—thinning, grooving	Erosion is the accelerated mechanical removal of surface material as a result of relative movement between, or impact from, solids, liquids, vapor, or any combination thereof. Corrosion can also contribute to erosion by removing protective films or scales, or by exposing the metal surface to further corrosion under the combined action of erosion and corrosion. Erosion and erosion-corrosion are characterized by a localized loss in thickness in the form of pits, grooves, gullies, waves, rounded holes, and valleys. These losses often exhibit a directional pattern. Failures can occur in a relatively short time.
9.	Fatigue, contact	Material	Crack	Vibration	Oil analysis, vibration	Cracks, metal loss	Cracking and subsequent spalling of metal subjected to alternating Hertzian (contact) stresses.
10.	Fatigue (mechanical, thermal, vibration, corrosion-fatigue)  Fatigue failure of a compressor blade in a gas turbine (Photograph compliments of M&M Engineering Assoc.)	Material	Crack	Leak, component failure, vibration	Vibration	Cracks	Fatigue cracking is a mechanical form of degradation that occurs when a component is exposed to cyclical stresses for an extended period, often resulting in sudden, unexpected failure. The signature mark of a fatigue failure is a "clam shell" type fingerprint that has concentric rings called "beach marks" emanating from the crack initiation site. Thermal cycles can cause thermal stresses leading to thermal fatigue. If a corrosive atmosphere is present along with the cyclic stresses, corrosion fatigue can occur. Key factors affecting thermal fatigue are the magnitude of the temperature swing and the frequency (number of cycles). Time to failure is a function of the magnitude of the stress and the number of cycles and decreases with increasing stress and increasing cycles. Start-up and shutdown of equipment increase the susceptibility to thermal fatigue. There is no set limit on temperature swings; however, as a practical rule, cracking may be suspected if the temperature swings exceeds about 200 °F (93 °C).
11.	Faulty or no power/voltage	Electrical		Stops, will not restart		Loose/ broken wire or tripped breaker, blown fuse	The intermittent or permanent loss of electrical power—AC or DC or excessive or inadequate electrical power.
12.	Faulty or no signal/indication/ alarm	Instrument		Stops/alarms/trips product quality, cannot start		PM checks	A loss of, defective or errant signal leading to a failure.

Ref.	Mechanism	Category	Degradation Type	Observations By			Definition
				Operator	CM Tech	Mechanic/ Electrician	
13.	Foreign object damage (FOD)  FOD damage on first stage impeller	Material	Distortion	Performance problem/vibration, sound	Borescope—see deformation, impact damage, metal loss		Damage caused by foreign objects impacting the rotating and stationary parts of rotating equipment.
14.	Fouling/ contamination  Steam turbine fouled from steam chemistry upset (Photograph compliments of M&M Engineering Assoc.)	External	Unwanted deposits/ chemicals	Performance problem/vibration, pressure, temperatures, flow	Vibration, borescope—observe deposits		The buildup of deposits or introduction of contaminants that prevent the proper function of equipment.

Ref.	Mechanism	Category	Degradation Type	Observations By			Definition
				Operator	CM Tech	Mechanic/ Electrician	
15.	Fretting/wear  Severe bearing wear from inadequate lubrication (Photograph compliments of M&M Engineering Assoc.)	Material	Metal loss		Oil analysis, vibration, discoloration debris, sometimes movement	Metal loss	Wear that occurs between tight-fitting surfaces subjected to oscillation at very small amplitude. This type of wear can be a combination of oxidative wear and abrasive wear. Abrasive wear is the removal of material from a surface when hard particles slide or roll across the surface under pressure. The particles may be loose or may be part of another surface in contact with the surface being abraded.
16.	Seal failure  Face blistering on a mechanical seal (Photograph compliments of Maintenance World Magazine)	Material		Leaks		Leak	Degradation or cracking of a seal that allows the fluid being sealed to leak.

Ref.	Mechanism	Category	Degradation Type	Observations By			Definition
				Operator	CM Tech	Mechanic/ Electrician	
17.	Selective leaching (dealloying)  Cross section of a silicon-brass alloy C87500 pump impeller from stagnant firewater service	Material	Metallurgical degradation	Performance problem, leak		Metal loss, color variations	Dealloying is a selective corrosion mechanism in which one or more constituents of an alloy are preferentially attacked leaving a lower density (dealloyed) often porous structure. Component failure may occur suddenly and unexpectedly because mechanical properties of the dealloyed material are significantly degraded. Factors that influence dealloying include the following. a) The composition of the alloy and exposure conditions including temperature, degree of aeration, pH, and exposure time. b) Dealloying occurs with several different alloys but is usually limited to very specific alloy-environment combinations. c) Exact conditions under which dealloying occu are often hard to define and damage may occ progressively over many years in service.

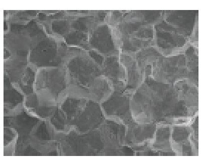
Ref.	Mechanism	Category	Degradation Type	Observations By			Definition
				Operator	CM Tech	Mechanic/ Electrician	
18.	Temper embrittlement  Sample of fractured steel that had been embrittled by improper heat treatment in the embrittling temperature range. The "rock candy" appearance of the fracture is typical of intergranular cleavage. (Photograph compliments of M&M Engineering Assoc.)	Material	Metallurgical degradation	Loss of output, component failure, seized parts		Fractured part	Temper embrittlement is the reduction in toughne due to a metallurgical change that can occur in so low alloy steels as a result of long-term exposure the temperature range of about 650 °F to 1100 °F (343 °C to 593 °C). This change causes an upwa shift in the ductile-to-brittle transition temperature measured by Charpy impact testing. Although the loss of toughness is not evident at operating temperature, equipment that is temper embrittled may be susceptible to brittle fracture during start-u and shutdown. 885 °F (475 °C) embrittlement is a form of temper embrittlement that can occur in all containing a ferrite phase, as a result of exposure the temperature range 600 °F to 1000 °F (316 °C 540 °C). Affected materials are as follows. a) Primarily 2.25Cr-1Mo low alloy steel, 3Cr-1M (to a lesser extent), and the high-strength low alloy Cr-Mo-V rotor steels. b) Older generation 2.25Cr-1Mo materials manufactured prior to 1972 may be particula susceptible. Some high strength low alloy steels are also susceptible. c) The C-0.5Mo, 1Cr-0.5Mo, and 1.25Cr-0.5Mo alloy steels are not significantly affected by temper embrittlement. However, other high temperature damage mechanisms promote metallurgical changes that can alter the toughness or high temperature ductility of the materials. d) Weld materials are generally more affected than today's low-impurity base materials.

Table XX-C.4—Machinery Failure Causes

Ref.	Cause	Cause Category
1.	Design error	Design
2.	Improper material—selected	Design
3.	Insufficient lubrication—inadequate	Design
4.	Operating outside limits—incorrectly specified limits	Design
5.	Software or controls failure	Design
6.	Vibration—harmonics/resonance	Design
7.	Manufacturing or fabrication error	Manufacturing
8.	Installation error—installed backwards, wrong torque loads	Installation
9.	Alignment failure	Maintenance
10.	Clearance, fit, or tolerance failure	Maintenance
11.	Improper handling—damage during handling	Maintenance
12.	Improper material—replaced	Maintenance
13.	Unbalance—installation	Maintenance
14.	Insufficient lubrication—wrong oil, etc.	Maintenance
15.	Maintenance error	Maintenance
16.	Operating outside limits—improper parts	Maintenance
17.	Vibration—misassembly issues	Maintenance
18.	Unbalance—fouling/wear	Operation
19.	Loss of power	Operation
20.	Operating error	Operation
21.	Operating outside design limits—operating beyond limits	Operation
22.	Vibration—off limits operation	Operation
23.	Documentation error	Management
24.	Expected wear and tear	Management
25.	Improper material—purchased	Management
26.	Management error	Management
27.	Management of spares—improper storage	Management
28.	Operating outside limits—MOC process	Management
29.	Process stream composition upset	Miscellaneous
30.	Extreme environmental conditions, earthquake, 500-year flood	Miscellaneous
31.	Other cause	Miscellaneous

ANNEX XX-D (INFORMATIVE)

GUIDELINE ON RISK MITIGATION TASK SELECTION

D.1 PURPOSE

D.1.1 General

This informative annex provides guidelines on the applicability and frequency of risk mitigation maintenance task types in addressing various failure modes and mechanisms. Each task selected should be based on the identified failure mechanisms and causes leading to the intolerable unmitigated risk. 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 also be considered, as they may provide more effective overall risk mitigation.

The intent is to select tasks that are the most effective as well as efficient in achieving required risk reduction, by addressing the target failure mechanisms/causes. If the task selection process is unable to effectively reduce the risk to an acceptable level, other risk mitigation options should be considered in order to sufficiently do so. These can include process modification, spare parts strategies, or other one-time or recurring actions. These types of recommendations will often require revisiting design or other non-maintenance aspects of the machinery application.

D.1.2 Task Selection Guidelines

D.1.2.1 General

The mitigation task selection process is described in 6.4. Typically the specific task is selected based on FMEA (see 6.3) and/or RCM. The selected tasks are deemed effective in the mitigation, prevention, or detection of the failure. Typically, multiple competing tasks may target a single failure mechanism and often the operating company will perform a cost-benefit analysis to determine the most effective tasks to mitigate risks to acceptable levels. If no applicable task exists, then run to failure strategies might be considered providing the failure mode or mechanism is not safety related.

D.1.2.2 Task Type Applicability

The following provides guidance on the applicability of task types.

a) For CM tasks to be applicable, it should be possible to detect reduced failure resistance for a specific failure cause/mechanism, a specific task should be able to detect a potential failure condition, and there should be a reasonable, consistent amount of time between the first indication of potential failure and the actual failure (i.e. indication and detection are not so close, or coincident with failure so that there is some benefit from performance of the task).
b) For time-based PM tasks to be applicable, there should be an identifiable age at which the component displays a rapid increase in the conditional POF, a large proportion of the same equipment type should survive to that age, and it should be possible to restore the original, or near-original, failure resistance to the equipment through servicing, rebuild or overhaul, or replacement. Random failure mechanisms/causes can seldom be effectively addressed with time-based PM.
c) For FF tasks or operational tests to be applicable, the equipment should be subject to a failure cause/mechanism that is not evident to personnel during normal plant operations (hidden failure).

D.1.2.3 Task Selection Priorities

In the risk-based approach the selected mitigation tasks should be prioritized. This can be achieved by detailed FMEA (see Annex I). FMEA can be supplemented by using a concept of RPN. The RPN is a product of three rating parameters: occurrence, detection, and severity. Occurrence is a rating value corresponding to the estimated expected frequencies of failures for a given failure cause. Detection is a rating corresponding to the likelihood that proposed task will detect a specific failure mode to prevent consequence. Severity is a rating indicating the seriousness of the effect of a potential failure mode the task is attempting to address. The goal is to reduce RPN.
There is no uniform RPN scale available across industry; therefore, each FMEA result that uses this concept is unique.

D.1.2.4 Task Frequency Consideration

Also part of the task selection process is the assignment of frequencies for the selected tasks. Frequency considerations vary with the type of task, but in general, the issues that should be addressed concerning task frequency can be summarized in the following questions.

a) How frequently would the failure mechanism that the task addresses be expected to occur?
b) Does the likelihood of the failure mechanism increase over time (age-related), or is it fairly constant for the vast majority of equipment life (random)?
c) How much time elapses between equipment failure initiation and functional failure?
d) Is there an adequate mechanism to measure the failure progression or component degradation?

When determining the frequency for condition-monitoring tasks, the frequency should be consistent with the time interval between the first indication of potential failure (a “threshold value”) and the actual time of failure.
Scheduling should be a consideration for monitoring multiple pieces of equipment (vibration rounds, lube oil sampling, etc.). Operator round frequencies should also be considered to enable packaging of routine tasks (shift, daily, weekly, etc.).

In determining frequency for time-based tasks, past failure history and/or maintenance experience on similar equipment should be consulted, as should OEM input. Normally, the frequency will be based on the expected MTBF or the time between incidences of unacceptable degradation. Frequency consideration should also take into account level of risk exposure and needed risk mitigation.
When determining frequency for FF tasks, consideration should be given to expected frequency of demand, failure rate, and tolerability of failure on actual demand. Also, it should be remembered that performing the FF task may increase the amount of wear or degradation in the equipment and/or may place the system in an unsafe or abnormal condition.

D.1.3 Inspection Test and Preventive Maintenance (ITPM) Templates

D.1.3.1 Benefits and Limitations

The use of these templates will help in defining specific tasks for both minor and major maintenance activities in a cost-effective manner to manage and minimize risk.
The use of these maintenance templates to develop machinery specific maintenance plans will not compensate for:

a) inaccurate or missing information,
b) inadequate designs or faulty equipment installation,
c) operating outside the acceptable IOWs,
d) not effectively executing the plans,
e) lack of qualified personnel or teamwork,
f) lack of sound engineering or operational judgment.

The ITPM plans should be based on the following:
a) age of the machinery,

b) design of the machinery,
c) facility experience with the machinery,
d) industry best practices,
e) machinery risk level as determined in the previous sections of this recommended practice,
f) machinery service, i.e. continuous, intermittent, or standby,
g) OEM recommendations,
h) process conditions and variables,
i) relative condition of the machinery.

D.1.3.2 Fine Tuning of ITPM

Initial content of the ITPM should be considered as a starting point and to improve quality of ITPMs a continuous improvement feedback loop is required. This will help identify gaps and shortcomings of the initial ITPMs and allow ITPMs to be fined tunes to improve effectiveness.
There is a need for a balance between automated CM tasks and human supervision (operator rounds) to ensure the correct level of equipment CM against identified risks.

D.1.3.3 In the following tables (XX-D.1–XX-D.7), the task type descriptions are defined.

Table XX-D.3—Gas Turbines

ID	Type	ITPM Tasks
1.	SV	Perform four senses (look, smell, touch, hear) inspection and report unusual findings
2.	FF	Instrument testing and calibration Verify readiness/start-up of aux lube oil pump
3.	CM	Monitor inlet and outlet temperatures and pressures, axial compressor and turbine sections
4.	CM	Obtain vibration trend data for gas turbines
5.	CM	Measure and record bearing housing temperature
6.	SV	Draw sample of lube/seal oil. Perform visual inspection for water, contaminants, etc.
7.	CM	Perform lube/seal oil sample analysis including ferrography, establish action levels, trend results
8.	PM	Replace lube/seal oil filters, clean and inspect filter housing
9.	SV	Survey condition of machine supports, shims, baseplate, grout, foundation
10.	PM	Replace inlet air filters
11.	PM	Overhaul lube/seal oil reclaimer
12.	PM	Perform operation surveillance (O/S) test—mechanical and electrical
13.	PM	Drain lube oil reservoir, clean, flush, refill
14.	PM	Drain seal oil reservoir, clean, flush, refill
15.	PM	Perform hot gas path inspection
16.	PM	Perform combustion inspection

ANNEX XX-E (INFORMATIVE)

E.- GUIDELINE ON CONDITION MONITORING AND DIAGNOSTIC SYSTEMS

E.1 INTRODUCTION

This annex provides practical guidance on the specification of CM and diagnostic systems for API 691 Machinery. Key to identifying the diagnostic needs that support effective maintenance task selection is conducting a PFMEA (Annex XX-A) to accurately define the CM technology, parameters, data, collection frequency, etc. in order to provide the earliest detection of machinery faults.

NOTE ISO 17359 may be useful to operators developing a CM program.

E.2 THE BASIC PRINCIPLES OF CONDITION MONITORING

E.2.1 This section includes the attributes that need to exist before any type of on-condition maintenance, including manual inspection and basic and condition monitoring, can be applied. Not all failure modes will be applicable to CM, and so CM (whether it is labeled predictive or advanced technology) will always be a subset of the overall maintenance regime if CM tasks are chosen.

E.2.2 Figure XX-E.1 provides a pictorial view of the progression of incipient failure and how this degrades toward a point of functional failure showing all of the salient points important in on-condition maintenance. The point of detectability is when a potential failure can be detected with the technologies being utilized in the operational context of the observed machine. The P to F (potential to functional) time is that which may be used to take action to avoid the functional failure consequences.

The P-F interval will have a natural variance between different failure events of the same type, and variance may also be influenced by differences in operating regime and the operating environment.

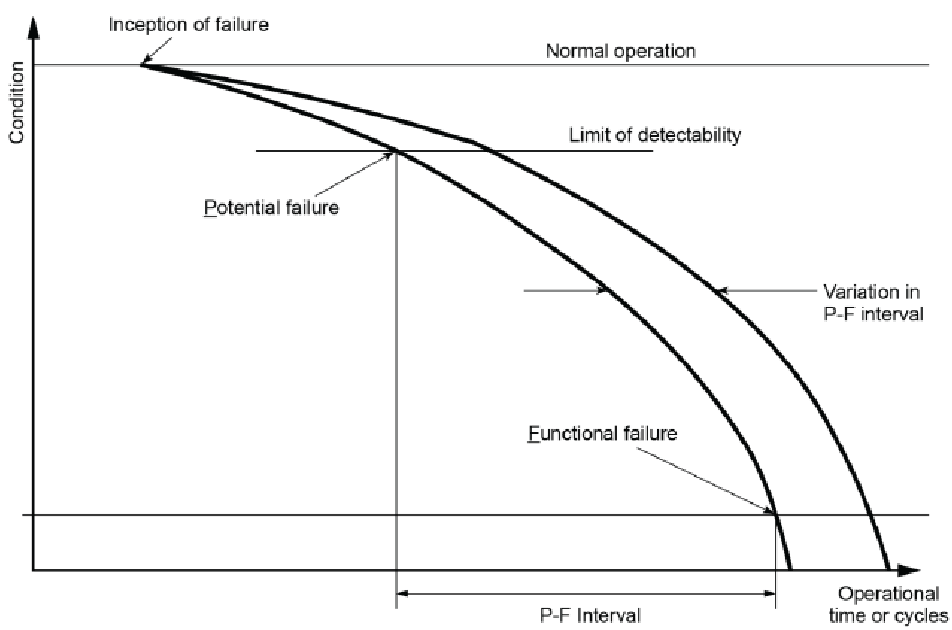


Figure XX-E.1—Illustration of the Basic Principles of Condition Monitoring

The normal acceptable operating band may also have variance and may change over time (especially as components gradually wear). The observed variance may also be due to noise in the sampled data.

The identification of what is the functional failure line is obvious in some cases; however, in other cases the difficulty in agreeing this should not be underestimated. Reference to other standards should be used.

The inception of failure may start as soon as a machine is introduced into its operating environment (e.g. exposure to corrosion) or may be an initiating event that can happen at any time in operational life (e.g. a bearing failure may be initiated by a shock load condition).

E.2.3 Required Prerequisites for Condition Monitoring

The following list outlines the behaviors of the failure modes and conditions that need to exist before any type of practical and effective on-condition maintenance may be applied.

a) Sensors and data exist that are able to be used to detect a precursor condition or symptoms that are indicative of a failure mode.
b) Suitable data shall be accessible in a timely manner.
c) There shall be sufficient time between the diagnosis (detection) and the point of functional failure to allow practical and cost-effective remedial action to be taken (see Figure XX-E.2).
d) The variation in P-F interval for different instances of the same failure mode should be reasonably small, such that the calculation of time to functional failure (RUL) has an acceptable degree of certainty.
e) The standard for and levels of functional failure needs to be agreed and defined with the asset stakeholders, such that the P-F interval may be determined.
f) The application of CM is practical and cost-effective.

For CM to be considered as a risk-mitigating task in the API 691 PFMEA, then the above criteria need to be applied to each failure mode and then calculated to determine the overall value of the CM system.

E.2.4 The prerequisite list above also needs to include two considerations when considering the acquisition and specification of a CM system. For all failure modes covered by a CM task:

a) how much warning time does CM need to deliver to:

1) allow planning and predisposition of resources to effect the fastest and most effective recovery,
2) identify the best time to shut down the machinery to have minimum impact on production or product quality;

b) what is the level of granularity of isolating fault conditions and failure modes required given the requirement to accurately identify the correct spares, the depth of machinery strip, and the likelihood of other induced damage, for the most effective and efficient recovery of the machinery back into service.

These considerations may influence what CM techniques are applied, in order to deliver the required warning time and granularity of fault isolation criteria.

E.2.5 Consideration of Operating Context and Environment

It is also important to understand that the impact and likelihood of failure may be significantly influenced in variations of build, operating context and environments. These variations need to be fully taken into account when specifying a CM solution. The following diagram outlines these major factors, which should be applied to the FMEA studies.

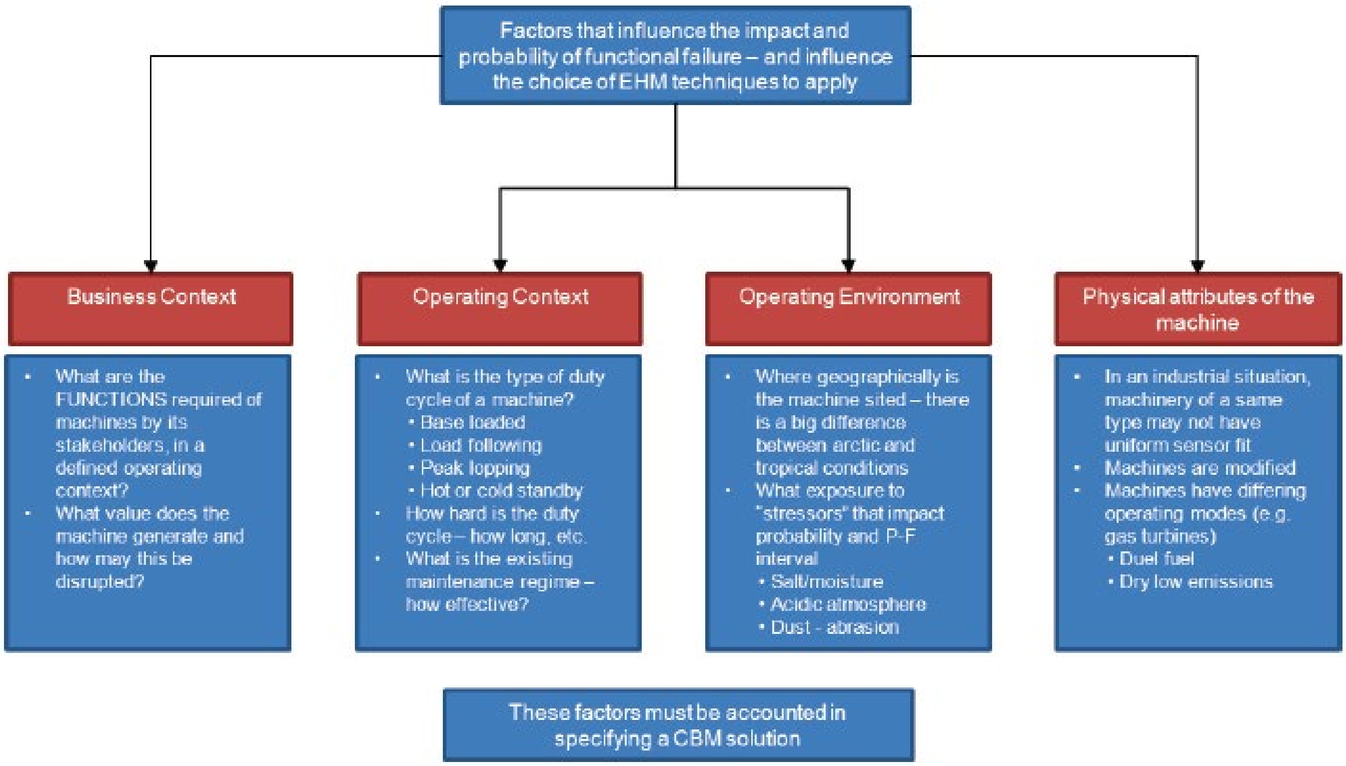


Figure XX-E.2—Influences on Functional Failure and Condition Monitoring Specifications

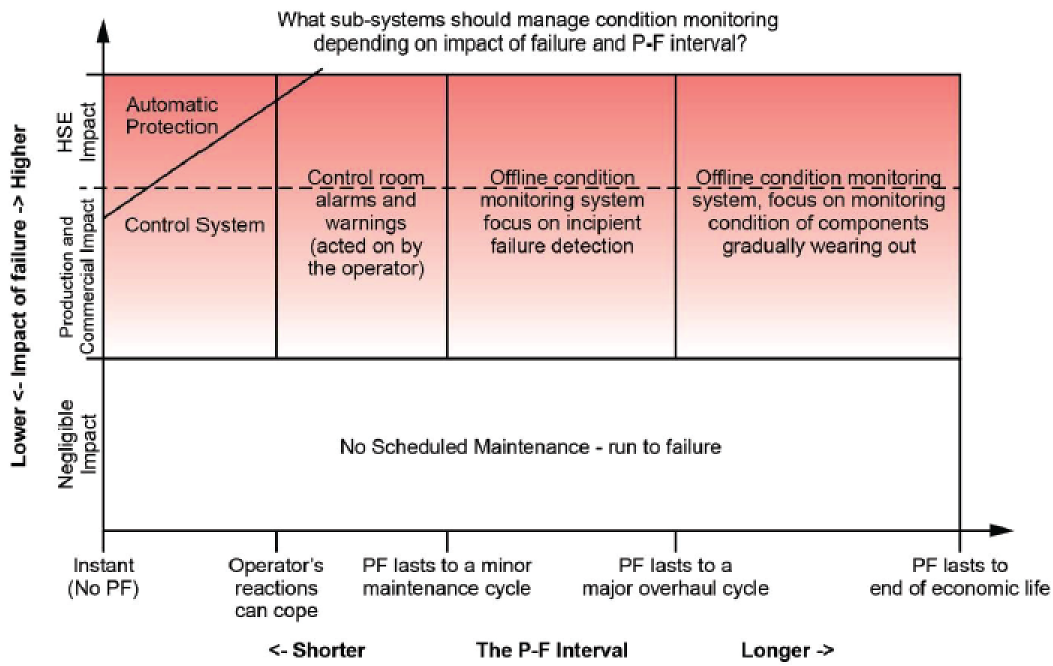


Figure XX-E.3—Subsystem Boundary Guidance for the Assignment of CM Tasks

E.2.6 Determination of Subsystems to Assign Condition Monitoring

A further consideration to assign subsystems to assign CM tasks is by comparing the natural P-F interval of a machine's failure modes to the impact of failure of the machine in its operating context. Any critical machine may have components that may or may not be HSE critical, and there may be considerable economic benefit in applying CM tasks to mitigate failures with operational production or economic impacts. Figure XVIII-E.3 illustrates where CM functions should be applied. The boundaries drawn in the following diagram are for illustrative purposes and the actual boundaries and rules for assigning CM tasks will need to be conducted by individual organizations.

E.3 CONDITION MONITORING APPROACHES AND TECHNIQUES

E.3.1 General

This section provides a basic breakdown of common CM approaches and associated techniques that can be applied when developing a maintenance regime. This is not an exhaustive list.

The following commonly applied approaches will be covered:

a) vibration analysis (this would include acoustic analysis),
b) tribology, particularly oil and oil debris analysis,
c) chemical monitoring,
d) performance analysis (uses process data),
e) electrical monitoring,
f) thermography,
g) stress or duty cycle counting.

E.3.2 Machinery Faults Matched to Condition Monitoring Techniques

Table XX-E.1 shows primary and secondary techniques that are commonly applied today for API machinery and a selection of their most common failure modes. As part of risk mitigating task section described in 6.4, it may be desirable to consider the application of several CM techniques to improve certainty of risk reduction.

This table is not exhaustive and some of the choices of whether particular techniques can be subjective. The table does represent a consensus view from a number of CM experts. The first section of the table includes common faults that are seen on the majority of all rotating machines.

Table XX-E.1—Machinery Faults Matched to Condition Monitoring Technology

Machine Type	Condition Monitoring Technology (P—Primary; S—Secondary)							
Examples of Faults	Vibration Analysis	Acoustic Analysis	Performance Analysis	Tribology Analysis	Chemical Monitoring	Electrical and Magnetic Waveform Analysis	Thermography	Stress or Duty Cycle Counting
Common Rotating Machinery Faults (Driven Asset)								
Bearings (rolling)	P	S		S		S	S	
Bearings (thrust)	P	S	S	S		S		
Bearings (fluid film)	P	S		S		S		
Gears	P	P		P		S		
Out of balance	P	S				S		
Shaft misalignment	P	P				S		
Loose foundation	P	P				S		
Coupling wear	P	P				S		
Belt slippage	P	P				S	S	
Corrosion					P			
Cooler—heat exchangers		S	P				S	
Structural—containment		S			S	P		
Inefficient operation			P			P		
Pump Specific Faults								
Damaged/impacted impeller	P		S			P		
Cavitation	P		P			P		
Eccentric impeller, blocked impeller	P					P		
Seal damage/leakage	S		P			S	S	
Gas Turbines (Industrial)								
Air inlet blockage	P		P					
Compressor fouled	P		P					
Compressor damaged	P		P					S
Fuel filter blockage			P					
Combustion chamber holed			P					
Burner blocked	P		P					
Power turbine damage	P		P					

Machine Type	Condition Monitoring Technology (P—Primary; S—Secondary)							
Examples of Faults	Vibration Analysis	Acoustic Analysis	Performance Analysis	Tribology Analysis	Chemical Monitoring	Electrical and Magnetic Waveform Analysis	Thermography	Stress or Duty Cycle Counting
Gas Turbines (Aero-derivative)								
Air inlet blockage			P					
Compressor fouled	P		P					
Compressor stall	P		P					
Fuel filter blockage			P					
Combustion chamber holed			P					
Burner blocked	P		P					
Power turbine dirty	P		P					
Blade/vane fatigue life	P							P
Hot end thermal coating dissipation			S					P
Power turbine damage	P		P					
Steam Turbine Specific Faults								
Damaged rotor blade	P		S					
Centrifugal Compressor								
Damaged impeller	P		S			P		
Damaged seals	P		P			S		
Eccentric impeller	P					P		
Cooling system fault			P					
Valve fault	P		P			P		
Reciprocating Compressor								
Inlet blockage	P					S		
Piston ring wear			P					
Flywheel damage	P							
Mounting fault	P					S		
Cylinder valves flutter			S			P		
Discharge line resonance	P							
Discharge valve leakage		P	S					
Connection rod wear	P			P		P		

Machine Type	Condition Monitoring Technology (P—Primary; S—Secondary)							
Examples of Faults	Vibration Analysis	Acoustic Analysis	Performance Analysis	Tribology Analysis	Chemical Monitoring	Electrical and Magnetic Waveform Analysis	Thermography	Stress or Duty Cycle Counting
Electrical Generators								
Rotor windings, uneven rotor-stator gap						P		
Stator windings						P		
Eccentric rotor	S					P		
Brush(es) fault						P		
Insulation deterioration						P		
Loss of output power phase	S					P		
AC Electrical Motors								
Caged rotor bar cracks	S					P		
Grounded or shorted field windings			S			P		
Rotor-stator air gap eccentricity						P		
VFD improper performance						P		
High resistance terminals/joints						S	P	
Fans								
Damaged impeller	P					P		
The following international standards may be useful to understanding and implementing the condition monitoring technologies noted above: c) ISO 13373-1, [27] d) ISO 13373-2, [28] e) ISO 13373-3, [29] f) ISO 22096, [30] g) ISO 13380, [31] h) ISO 14830-1, [32] i) ISO 18434-1. [33]								

E.5 ADVANCEMENTS IN CONDITION MONITORING

Table XX-E.2 suggests some distinctions between regular traditional approaches to CM and those more advanced approaches that have emerged in recent years. The term advanced condition monitoring is not meant to be a hard definition, because it is a qualitative judgment on aspects of CM, and what is advanced today will be mainstream tomorrow.

However, CM is in a state of rapid technical development, and this section emphasizes the point that asset managers would be wise to understand what is state of the art and what disruptive changes (that may challenge deeply held assumptions and value in the industry) are emergent from the CM domain.

Table XX-E.2—Comparison of Basic CM to Advanced CM

Basic CM	Advanced CM
Relies on human experts to interpret raw or semi-processed data to diagnose and prognose. Calculations may be manual. Tends to use single standalone techniques. Fusion of information is done manually.	Tends to be highly automated using signal processing, applied machine learning, artificial intelligence, and statistical methods applied to diagnostics and prognostics. Automatically fuses several techniques and data from other influencing systems. The presentation of symptoms may occur at different times from different techniques that the advanced CM system uses as further diagnostic information.
Tends to use steady state analysis, even when extracting information from dynamic behavior (such as vibration) analysis.	Exploits both steady and transient state analysis, augmented by dynamic behavior analysis.
Tends to use single variables that indicate a change or departure from normal behavior. Diagnosis of failure modes is routinely conducted by a human expert.	Uses multivariable approach, using patterns of "features" from several variables that uniquely indicate failure modes. Diagnosis is routinely automated.
May be restricted to higher levels of machinery breakdown, may only detect symptoms that need further troubleshooting.	Provides more granular information that results in more effective preventative correction. Allows the detection of more complex evidence to isolate faults at component levels and identify causal failure mechanisms.

ANNEX XX-F (INFORMATIVE)

F.- GUIDELINE ON MACHINERY PROGNOSTICS

F.1 INTRODUCTION

F.1.1 Machinery prognostics use historic, current, and forecasted operational and maintenance data to predict the RUL of the machine and proactively manage pending loss of function or failures. The objective is to give those responsible for asset management additional tools to deliver consistent machinery operation, reduce lost production, lower maintenance cost, optimize equipment spares investment, and improve safety through proactive maintenance, maximizing equipment performance.

The random occurrence of failures is a result of variations in equipment degradation rates, which makes it difficult to predict when the accumulation of degradation will lead to equipment failure. These variations occur for a number of interactive reasons such as:

a) current equipment condition,
b) running hours,
c) cycle times,
d) operating conditions,
e) process operating windows,
f) variation in equipment loading,
g) contamination of operating material,
h) maintenance strategies and actions.

Prognostic models use automated methods to observe the degradation process of equipment and predict the RUL of the equipment with some confidence on that prediction. Where possible, actual feedback on current conditions will improve the accuracy of the prediction as this information may provide an understanding of the physical degradation process.

F.1.2 Remaining Useful Life

In order to address the deterministic nature of the installation, potential failure, failure (IPF) approach, a mechanism is needed to convert failures in time to POF over time with confidence intervals on these answers.

This is what is known as remaining useful life (RUL), and an example of these curves can be seen in Figure XX-F.1. This figure illustrates that additional quality information obtained within the context of consistent operations may improve the results.

RUL distributions frame the answer around the likelihood of reaching a specific point in time before the failure occurs with a given confidence. This approach addresses the problem that occurs when the subject matter expert (SME) makes his/her best estimate, by providing a more realistic view of the POF.

The first illustration of this can be seen by observing the solid red line in Figure XX-F.1. In this case, the simplest answer given by the SME would be, “I have an 80 % confidence that it will be at least 33 days before this failure occurs.” This approach is a significant change from traditional thinking and provides flexibility in the exact time the failure will occur because, by definition, some failures will occur earlier and some will occur later than the identified failure point.

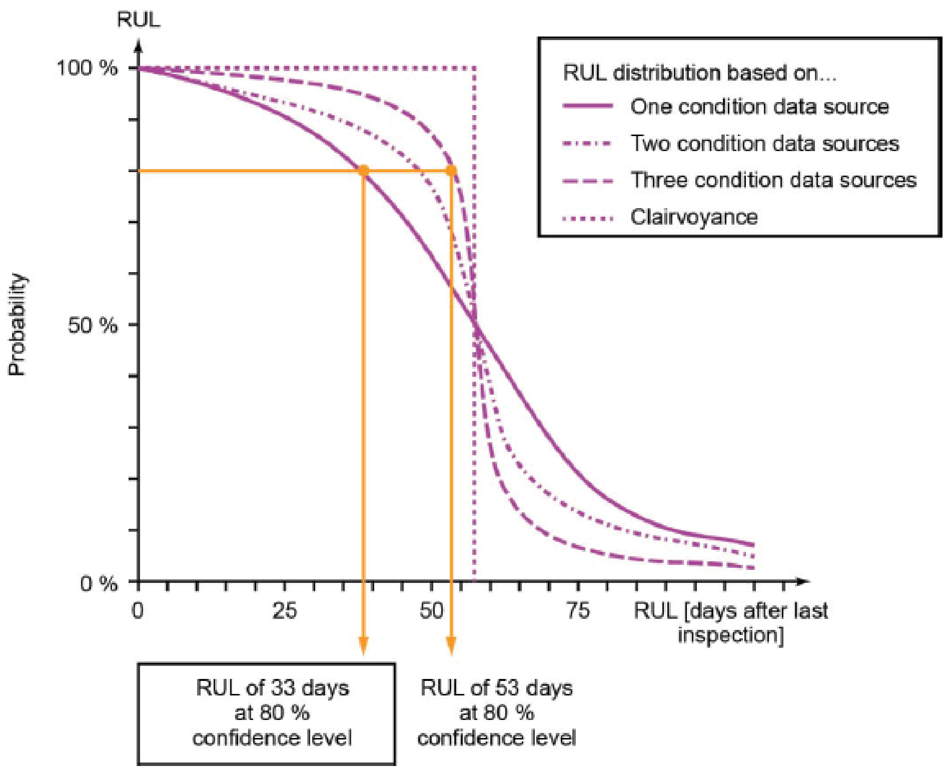


Figure XX-F.1—RUL Curves

F.1.3 Advanced Predictive Systems

The application of diagnostics and predictive technologies, known as predictive maintenance, has become the mainstay of many asset strategies (refer to Figure XX-F.3, Type 1 and 2.). This approach provides a significant improvement in the cost of maintenance and, when applied correctly, knowledge that equipment is on the P-F portion of the IPF curve and that a failure(s) is impending.

This is of great value to the operators of industrial facilities who can take preemptive corrective action before the functional failure has occurred, thereby avoiding unexpected downtime that reduces the risk of HSE events associated with unplanned shutdowns and the lost production impacts that often accompany these.

Despite the benefits of PDM, when compared to time-based preventive systems, the application is limited because of the following.

a) Predictive technologies are a backward looking equipment monitoring function only finding an impending failure after the equipment has entered the P-F portion of the failure curve. Vibration monitoring, for example, can detect high axial vibration on a thrust bearing when deviations from baseline are observed, but may not be able to shut down the machine before failure has occurred due to the failure degradation rate (i.e. the P-F interval).

b) The ability to extend the useful life of the equipment is limited by the detection time of the abnormality, the SME’s cognitive ability to diagnose the fault, and the frequency of observation. For example, lube oil contamination for a given machine may occur within the sampling frequencies and therefore bearing failure may be unavoidable without additional detection methodologies.

F.1.4 Definition of Prognostics

Prognostics are a class of mathematical models, statistical and physical, that are used in the monitoring of equipment and producing an estimate of the RUL of the equipment, systems, or components. A wide range of models have been developed and some of the more common ones are:

a) failure time distribution,
b) proportional hazard model (PHM),
c) Markov chain model (MCM),
d) shock models,
e) general path model (GPM),
f) exploration models,
g) models combining different techniques.

F.1.5 The Relationship of Prognostics to Condition-based Maintenance

Condition-based maintenance (CBM) is a maintenance program that recommends actions based on information collected through CM. This is an important development in maintenance strategy development as equipment deteriorates over time. The rate of degradation may vary based on operating conditions, usage shock, materials, operating conditions, etc., and this process is often nonlinear. By using information that can be collected on equipment health and operating decisions, more informed maintenance decisions can be made. The CBM process has three steps:

a) data acquisition,
b) data processing,
c) maintenance decision making.

Predictive maintenance technology, diagnostics, and prognostics are all part of a robust CBM program (refer to Figure XX-F.3, Type 3). While diagnostics are a posterior event analysis and prognostics are a prior event analysis, there is an important relationship between the two. This is because prognostics often rely on diagnostic outputs as inputs and these should be considered together. This relationship is illustrated in Figure XX-F.2 shown below.

Prognostics are integral to any CM. This may be generalized into a number of regimes, two of which may be the following.

a) *Regime 1—Incipient Failure Detection*. This is where a failure may be initiated at any time in the service life of a machine, and once the CM has diagnosed that the asset is in the potentially failed state, prognosis of the RUL may then be undertaken.

b) *Regime 2—Monitoring Long-term Degradation*. Many assets start to deteriorate as soon as they are introduced to their operating environment; there is no discrete inception of failure as seen in incipient failure detection. Many of these deterioration factors define the trigger for major maintenance or overhaul, or define the end of asset economic life. Prognostics has the task of accurately monitoring the conditional deterioration and accurately forecasting RUL, where major maintenance is due, or the asset needs to be retired.

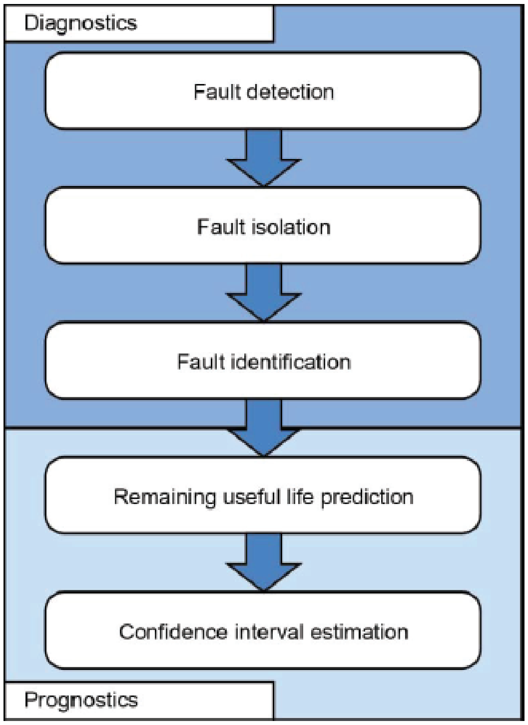


Figure XX-F.2—Relationship Between Diagnostics and Prognostics

F.2 PROGNOSTIC MODELS CLASSIFICATION

F.2.1 Introduction

Prognostic models endeavor to present a future state of equipment health by utilizing RUL as discussed earlier. Some prognostic approaches integrate multiple data sources and modeling techniques to provide a more accurate prediction of equipment health and is illustrated in Figure XX-F.1 as a dashed line.

In this case, additional data improve the accuracy of the prediction. Luo et al. developed an interacting multi-model approach to model-based prognostics.

A basic methodology for prognostics can be summarized as follows.

a) Collect historical data.
b) Perform FMEA to identify the failure modes of greatest interest.
c) Develop any additional data as necessary, e.g. failure testing.
d) Clean and select the data.
e) Identify and develop the appropriate class of prognostic model.
f) Validate prognostic model.
g) Implement prognostic model.

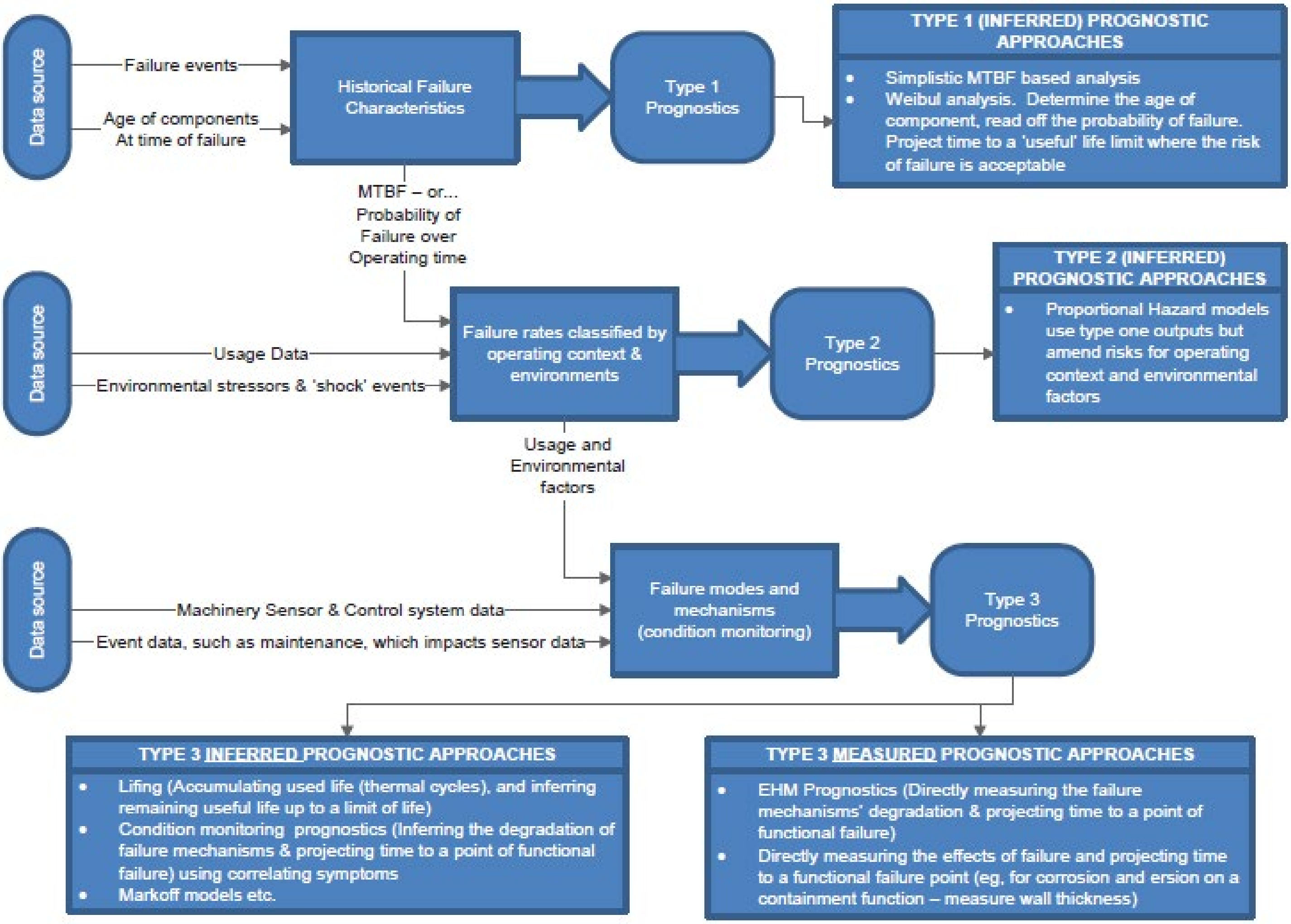


Figure XX-F.3—Prognostics Classification Approaches

NOTE ISO 13381-1 may be useful to the operator in understanding and implementing this technology.

F.2.2 Failure Mode Specific Models

Each failure mode may require its own prognostic model as mentioned in XX-F.1.4.
Garvey and Hines have classified prognostic models into three types as outlined below.

F.2.3 Type I—Traditional Reliability Analysis

This class of models uses parametric and nonparametric models to estimate failure density functions. These models assume that past usage and degradation will be indicative of future conditions. Hazard rates are assumed to follow the bathtub curve shown in Figure XX-F.4, which describes a decreasing, constant, and increasing failure rate corresponding to infant mortality, random failure, and equipment wear-out.

The most widely used model for describing the failure distribution over time is the Weibull distribution. The Weibull distribution is very flexible and by varying the parameters of the distribution a good approximation of the bathtub curve can be achieved. A rigorous discussion of the application of the Weibull can be found in *The New Weibull Handbook*.

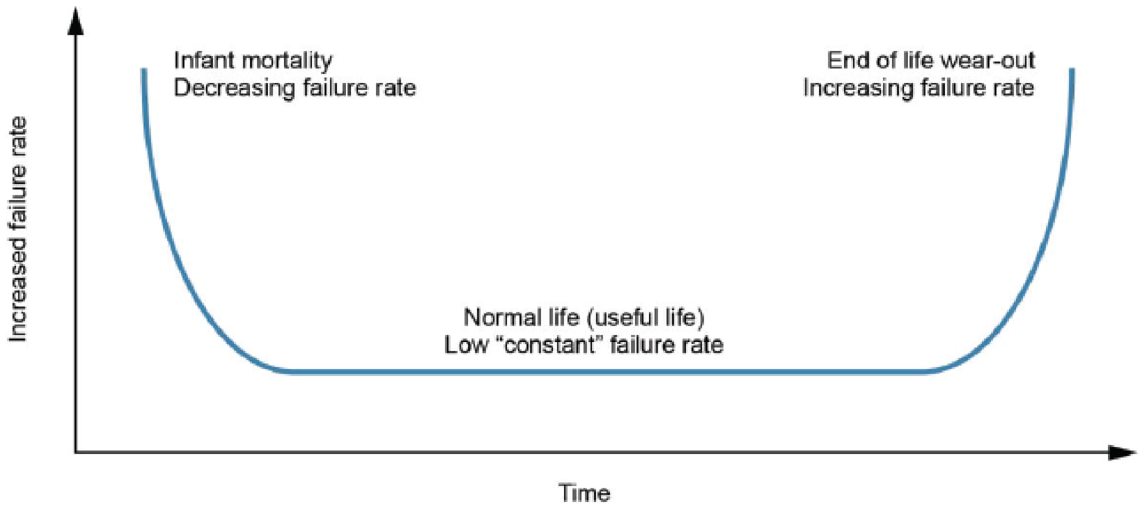


Figure XX-F.4—Bathtub Curve

F.2.4 Type II—Stress Based

A distinguishing characteristic for this class of prognostic models is the consideration of operating conditions such as operational load and/or environmental conditions and the impact of these elements on the system or component being modeled. This is important because the degradation rate of the equipment may vary based on these conditions.

These models provide a RUL of the average equipment under review for a given set of operating conditions. Type II models include PHMs and MCMs. PHM was introduced by Cox and is a technique that combines failure data and stress data. The model may use a baseline hazard rate with a covariate multiplicative factor that yields a new hazard rate.

Markov chain modeling is a process that consists of a finite number of states with some known probabilities to move from one state to another (the transition probability). This process is independent of all previous states, and only the current state has any bearing on the transition probabilities.

MCMs are discrete in the time domain and degradation measure domain and provide a mechanism to account for equipment damage. This damage degradation is represented in units of damage and the probability of damage occurring. This is related to the operating conditions, environmental conditions, and the duty cycle load. The model is formulated as a probabilistic simulation of past and future degradation. At each step in time, specific parameters can be estimated from historical data:

a) probability of damage (degradation) in a duty cycle,
b) the amount or magnitude of the damage,
c) the POF at the current degradation level,
d) other factors such as the probability that personnel will find and repair the degradation before failure can be considered.

Some additional examples of physical stress-based models include:

a) Paris’ law of crack growth modeling,
b) Forman’s equation of crack growth modeling,
c) fatigue spall initiation and progression model,

d) contact analysis for bearing prognostics,
e) stiffness-based damage rule model.

F.2.5 Type III—Condition Based

F.2.5.1 General

This class of prognostic models is more advanced and uses measurements such as equipment parameters, process data, system health data, etc., directly from the operating system to develop the RUL for the components being modeled. The degradation measure can be a function of several variables measured directly or as an empirical model. These models develop cumulative damage based on the number of duty cycles the damage accumulates and grows toward the failure threshold. Cumulative damage models were proposed by Bogdanoff and Kozin.

F.2.5.2 General Path Model

The GPM developed by Lu and Meeker proposed that degradation measurements over time may contain useful information about reliability. They developed statistical and nonlinear estimation methods for using degradation measures to estimate the time-to-failure distribution for degradation models and used Monte Carlo simulation (MCS) to estimate confidence intervals for reliability. GPM models have proven to very useful prognostic tools.

F.2.5.3 Incorporating Prior Information via Bayesian Methods

Bayes' theorem is most commonly expressed as:

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

The learning process in Bayesian inference involved modifying the initial probability statements about parameters before observing the data or posterior knowledge that combines both prior knowledge and the data at hand; that is to say, the theorem links the degree of belief in a proposition before and after accounting for evidence. This evidence has already taken place and is known as priori information.

This information is used in prognostic models to obtain a posterior estimate of degradation parameters. This estimate then becomes known as the new prior distribution in the next estimate of the degradation parameters.

The relative influence of the prior data on updated beliefs depends on how much weight is given to the prior based on the confidence that the data contains relevant information.

F.2.5.4 Data-driven Prognostic Models

The data-driven prognostic approach uses CM data directly to model RUL (refer to Figure XX-F.2). These models are based on statistical and learning techniques related to pattern recognition. This approach can be problematic in that it relies on past data patterns for analysis and may use techniques such as exponential smoothing and autoregressive models. Over time the patterns may change and new failure modes may introduce completely new data patterns. However, this approach is simple and where data patterns are consistent over time they can provide insight into RUL.

These models can be divided into two categories: statistical and artificial intelligence. Statistical approaches include multivariate analysis, principle component analysis, partial least squares, linear vector quantization, state space models, etc. Sikorska, Hodkiewicz, and Ma do an excellent job of classifying the modeling options for RUL estimation, and the reader is encouraged to review that material directly.

ANNEX XX-I (INFORMATIVE)

I.- API 691 FMEA WORKSHEET

I.1 INTRODUCTION

The purpose and intent of the API 691 FMEA worksheet is to provide a suggested methodology and template for machinery. Companies may use their own format.

The FMEA worksheet can be used in a DFMEA or PFMEA as outlined in Annex XX-A and can be used in conjunction with the failure modes, mechanisms, and cause codes provided in Annex XX-C.

I.2 API 691 FMEA WORKSHEET

The API 691 FMEA worksheet is shown in Figure XX-I.1. Definitions for each of the FMEA worksheet data fields are shown in Figure XX-I.2.

Figure XX-I.1—API 691 Machinery FMEA Worksheet

					REMARKS:
energy API			JOB NO.		
			ITEM NO.		
RISK-BASED MACHINERY MANAGEMENT API 691 ANNEX I: PROCESS FAILURE MODES AND EFFECTS ANALYSIS (PFMEA) WORKSHEET			PURCHASE ORDER NO.		
			SPECIFICATION NO.		
			REVISION NO.		
			DATE		
FOR			MANUFACTURER		
SITE			MODEL		
UNIT			SERIAL NUMBER		
SERVICE	☐	CONTINUOUS	TAG NO.		
	☐	INTERMITTENT	P&ID SHEET NO.		
	☑	STANDBY	NO. REQUIRED		

PRE-MITIGATED RISK ASSESSMENT									COF					MITIGATED RISK ASSESSMENT			COF				
Item #	Functional Performance Standard	Functional Failure/Loss of Performace	Failure Mode	Failure Effect(s)	Failure Cause(s)	Failure Mechanism(s)	Existing Safeguards	Detection	Safety	Environment	Other	POF	RPN	Mitigating Actions	Action Owner/Due Date	Detection (Rate 1-5)	Safety	Environment	Other	POF	RPN

Figure XX-I.2—API 691 Machinery FMEA Worksheet Definitions