ASME PCC-3–2007

Inspection Planning Using Risk-Based Methods

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Inspection Planning Using Risk-Based Methods

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ASME issues written replies to inquiries concerning interpretations of technical aspects of this Standard. The interpretations will be included with the above addenda service.

The American Society of Mechanical Engineers
Three Park Avenue, New York, NY 10016-5990

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FOREWORD

ASME formed an Ad Hoc Task Group on Post Construction in 1993 in response to an identified need for recognized and generally accepted engineering standards for the inspection and maintenance of pressure equipment after it has been placed in service. At the recommendation of this Task Group, the Board on Pressure Technology Codes and Standards (BPTCS) formed the Post Construction Committee (PCC) in 1995. The scope of this committee was to develop and maintain standards addressing common issues and technologies related to post-construction activities, and to work with other consensus committees in the development of separate, product-specific codes and standards addressing issues encountered after initial construction for equipment and piping covered by Pressure Technology Codes and Standards. The BPTCS covers non-nuclear boilers, pressure vessels (including heat exchangers), piping and piping components, pipelines, and storage tanks.

The PCC selects standards to be developed based on identified needs and the availability of volunteers. The PCC formed the Subcommittee on Inspection Planning and the Subcommittee on Flaw Evaluations in 1995. In 1998, a Task Group under the PCC began preparation of Guidelines for Pressure Boundary Bolted Flange Joint Assembly, and in 1999 the Subcommittee on Repair and Testing was formed. Other topics are under consideration and may possibly be developed into future guideline documents. The subcommittees were charged with preparing standards dealing with several aspects of the inservice inspection and maintenance of pressure equipment and piping.

This Standard provides guidance on the preparation and implementation of a risk-based inspection plan. Flaws that are identified during inspection plan implementation are then evaluated, when appropriate, using the procedures provided in the API 579-1/ASME FFS-1, Fitness for Service. If it is determined that repairs are required, guidance on repair procedures is provided in ASME PCC-2, Repair of Pressure Equipment and Piping.

This Standard is based on API 580, Risk-Based Inspection. By agreement with the American Petroleum Institute, this Standard is closely aligned with the RBI process in API 580, which is oriented toward the hydrocarbon and chemical process industries. In the standards development process that led to the publication of this Standard, numerous changes, additions, and improvements to the text of API 580 were made, many of which are intended to generalize the RBI process to enhance applicability to a broader spectrum of industries.

This Standard provides recognized and generally accepted good practices that may be used in conjunction with Post-Construction Codes, such as API 510, API 570, and NB-23.

ASME PCC-3–2007 was approved as an American National Standard on October 4, 2007.

ASME COMMITTEE ON PRESSURE TECHNOLOGY POST CONSTRUCTION

(The following is the roster of the Committee at the time of approval of this Standard.)

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C. D. Cowfer, *Contributing Member,* Consultant
E. Michalopoulos, *Contributing Member,* City of Kozani, Greece

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INSPECTION PLANNING USING RISK-BASED METHODS

1 SCOPE, INTRODUCTION, AND PURPOSE

1.1 Scope

The risk analysis principles, guidance, and implementation strategies presented in this Standard are broadly applicable; however, this Standard has been specifically developed for applications involving fixed pressure-containing equipment and components. This Standard is not intended to be used for nuclear power plant components; see ASME BPV, Section XI, Rules for Inservice Inspection of Nuclear Power Plant Components. It provides guidance to owners, operators, and designers of pressure-containing equipment for developing and implementing an inspection program. These guidelines include means for assessing an inspection program and its plan. The approach emphasizes safe and reliable operation through cost-effective inspection. A spectrum of complementary risk analysis approaches (qualitative through fully-quantitative) should be considered as part of the inspection planning process.

1.2 Introduction

This Standard provides information on using risk analysis to develop and plan an effective inspection strategy. Inspection planning is a systematic process that begins with identification of facilities or equipment and culminates in an inspection plan. Both the probability[1] of failure and the consequence of failure should be evaluated by considering all credible damage mechanisms that could be expected to affect the facilities or equipment. In addition, failure scenarios based on each credible damage mechanism should be developed and considered.

The output of the inspection planning process conducted according to these guidelines should be an inspection plan for each equipment item analyzed that includes

(a) inspection methods that should be used

(b) extent of inspection (percent of total area to be examined or specific locations)

(c) inspection interval (timing)

(d) other risk mitigation activities

(e) the residual level of risk after inspection and other mitigation actions have been implemented

[1] *Likelihood* is sometimes used as a synonym for *probability*; however, *probability* is used throughout this Standard for consistency.

1.3 Purpose

This Standard presents the concepts and principles used to develop and implement a risk-based inspection (RBI) program. Items covered are

(a) an introduction to the concepts and principles of RBI

1 Scope, Introduction, and Purpose
2 Basic Concepts
3 Introduction to Risk-Based Inspection

(b) individual sections that describe the steps in applying these principles within the framework of the RBI process

4 Planning the Risk Analysis
5 Data and Information Collection
6 Damage Mechanisms and Failure Modes
7 Determining Probability of Failure
8 Determining Consequence of Failure
9 Risk Determination, Analysis, and Management
10 Risk Management With Inspection Activities
11 Other Risk Mitigation Activities
12 Reanalysis
13 Roles, Responsibilities, Training, and Qualifications
14 Documentation and Record Keeping

1.4 Relationship to Regulatory and Jurisdictional Requirements

This Standard does not replace or supersede laws, regulations, or jurisdictional requirements.

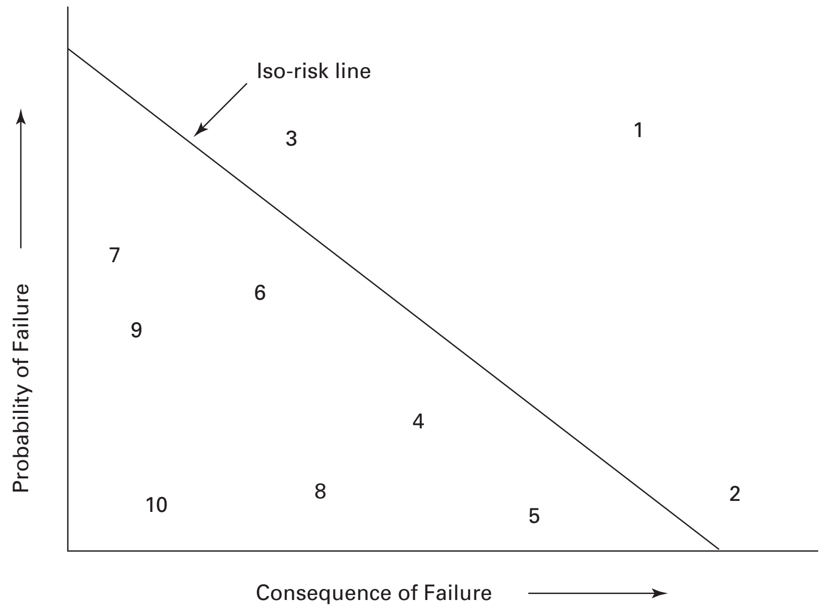
2 BASIC CONCEPTS

2.1 Risk

Everyone lives with risk and, knowingly or unknowingly, people are constantly making decisions based on risk. Simple decisions such as whether to drive to work or walk across a busy street involve risk. Bigger decisions such as buying a house, investing money, and getting married all imply an acceptance of risk. Life is not risk-free and even the most cautious, risk-averse individuals inherently take risks.

For example, when driving a car, an individual accepts the possibility that he or she could be killed or seriously injured. The risk is accepted because the probability of being killed or seriously injured is low while the benefit realized (either real or perceived) justifies the risk taken.

Fig. 2.1 Risk Plot



Influencing the decision is the type of car, the safety features installed, traffic volume and speed, and other factors such as the availability, risks, and affordability of alternatives (e.g., mass transit).

Risk is the combination of the probability of some event occurring during a time period of interest and the consequences (generally negative) associated with that event. Mathematically, risk should be expressed as

$$\text{risk} = \text{probability} \times \text{consequence}$$

Understanding the two-dimensional aspect of risk allows new insight into the use of risk analysis for inspection prioritization and planning. Figure 2.1 displays the risk associated with the operation of a number of equipment items. Both the probability and consequence of failure have been determined for ten equipment items, and the results have been plotted. The points represent the risk associated with each equipment item. An "iso-risk" line, representing a constant risk level, is also shown on Fig. 2.1. A user-defined acceptable risk level could be plotted as an iso-risk line. In this way the acceptable risk line would separate the unacceptable from the acceptable risk items (i.e., if the iso-risk line on the plot represents the acceptable risk, then equipment items 1, 2, and 3 would pose an unacceptable risk that requires further attention). Often a risk plot is drawn using log-log scales for a better understanding of the relative risks of the items assessed.

Risk levels or values may be assigned to each equipment item. This may be done graphically by drawing a series of iso-risk lines and identifying the equipment items that fall into each band or it may be done numerically. Either way, a list that is ordered by risk is a risk-based ranking of the equipment items. Using such a list, or plot, an inspection plan may be developed that focuses attention on the items of highest risk.

2.2 Overview of Risk Analysis

The complexity of a risk analysis is a function of the number of factors that can affect the risk and there is a continuous spectrum of methods available to assess risk. The methods range from a strictly relative ranking to rigorous calculation. The methods generally represent a range of precision for the resulting risk analysis (see para. 3.3.6).

Any particular analysis may not yield usable results due to a lack of data, low-quality data, or the use of an approach that does not adequately differentiate the risks represented by the equipment items. Therefore, the risk analysis should be validated before decisions are made based on the analysis results.

A logical progression for a risk analysis is

(a) collect and validate the necessary data and information (see section 5)

(b) identify damage mechanisms and, optionally, determine the damage mode(s) for each mechanism (e.g., general metal loss, local metal loss, pitting) (see section 6)

(c) determine the probability of failure over a defined time frame for each damage mechanism (see section 7)

(d) determine credible failure mode(s) (e.g., small leak, large leak, rupture) (see section 7)

(e) identify credible consequence scenarios that will result from the failure mode(s) (see section 8)

(f) determine the probability of each consequence scenario, considering the probability of failure and the probability that a specific consequence scenario will result from the failure (see section 9)

(g) determine the risk, including a sensitivity analysis, and review risk analysis results for consistency/reasonableness (see section 9)

(h) develop an inspection plan and, if necessary, other mitigation actions, and evaluate the residual risk (see sections 10 and 11)

If the risk is not acceptable, consider mitigation. For example, if the damage mode is general metal loss, a mitigation plan could consist of onstream wall thickness measurements, with a requirement to shut down or to repair onstream if the wall thickness measurements do not meet predetermined values or fitness-for-service acceptance criteria.

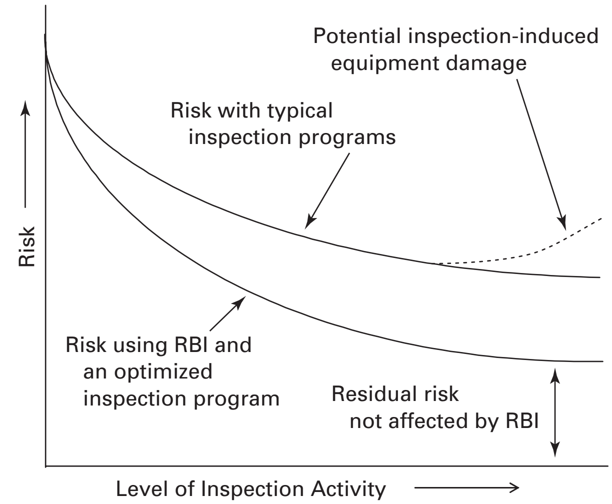
2.3 Inspection Optimization

When the risk associated with individual equipment items is determined and the relative effectiveness of different inspection techniques in reducing risk is estimated or quantified, adequate information is available for developing an optimization tool for planning and implementing an RBI program. Inspection affects perceived risk; physical actions such as mitigation activities performed as a result of an inspection affect actual risk.

Inspections may affect the calculated risk by reducing uncertainty. When there is uncertainty about the risk associated with operating equipment items, the default action should be to make reasonably adverse (conservative) or even "worst-case" assumptions resulting in relatively high calculated risk. For example, during an initial analysis one assumption may be that the only credible damage mechanism for a component is general corrosion (i.e., general metal loss). If inspection reveals that no measurable metal loss has actually occurred then the probability of failure may be reassessed to a lower level with a corresponding reduction in the calculated risk.

Figure 2.3 presents stylized curves showing the reduction in risk that should be expected when the degree and frequency of inspection are increased. The upper curve in Fig. 2.3 represents a typical inspection program. Where there is no inspection, there may be a higher level of risk, as indicated on the y-axis. With an initial investment in inspection activities, risk generally is significantly reduced. A point is reached where additional inspection activity begins to show a diminishing return and, eventually, may produce very little additional perceived risk reduction. Any inspection activity beyond this point may actually increase the level of risk. This is because invasive inspections in certain cases may cause additional damage (e.g., introduction of oxygen into boiler feedwater, water contamination in equipment with polythionic acid, damage to protective coatings or glass-lined vessels, or improper reclosing of inspection openings that may result in leakage of harmful fluids). This situation is represented by the dotted line at the end of the upper curve.

Fig. 2.3 Management of Risk Using RBI



RBI provides a consistent methodology for assessing the optimum combination of methods and frequencies. Each available inspection method may be analyzed and its relative effectiveness in reducing failure probability estimated. Given this information and the cost of each procedure, an optimization program may be developed. The key to developing such a program is the ability to assess the risk associated with each equipment item and then to determine the most appropriate inspection techniques for that equipment item. A conceptual result of this methodology is illustrated by the lower curve in Fig. 2.3. The lower curve indicates that, with the application of an effective RBI program, lower risks can be achieved with the same level of inspection activity. This is because, through RBI, inspection activities are focused on higher risk items and away from lower risk items.

Not all risks are affected by inspection. Table 2.3 shows seven categories of factors that have contributed to loss of containment events resulting in major insurance losses in petrochemical process plants.

Table 2.3 shows that, in a typical petrochemical plant, only about half of the causes of loss of containment can be influenced by inspection activities (the 41% of mechanical failures plus some portion of the "unknown" failures). Other mitigation actions should be used to manage the other factors contributing to risk.

As shown in Fig. 2.3, risk cannot be reduced to zero. Residual risk factors include, but are not limited to, the following:

(a) human error

(b) natural disasters

(c) external events (e.g., collisions or falling objects)

(d) secondary effects from nearby units

Table 2.3 Factors Contributing to Loss of Containment

Category of Failure	Contribution to Losses
Mechanical failure	41%
Operational error	20%
Unknown	18%
Process upset	8%
Natural hazard	6%
Design error	4%
Sabotage/arson	3%

(e) consequential effects from associated equipment in the same unit
(f) deliberate acts (e.g., sabotage)
(g) fundamental limitations of inspection method
(h) design errors
(i) unknown mechanisms of damage

3 INTRODUCTION TO RISK-BASED INSPECTION

In most facilities, a large percentage of the overall risk is concentrated in a relatively small number of equipment items while a large percentage of the equipment items may pose minimal risk. The equipment items having higher risk will require more attention in an inspection plan based on a risk analysis (commonly referred to as risk-based inspection or RBI) and the associated increased inspection costs may be offset by reducing or eliminating inspection of equipment items that pose minimal risk. RBI will allow users to

(a) define, measure, and use risk for managing important elements of facilities or equipment
(b) manage safety, environmental, and business-interruption risks in an integrated, cost-effective manner
(c) systematically reduce the overall facility risk by making better use of inspection resources and timely follow-up action

3.1 Items RBI Will Not Compensate for

RBI is based upon sound engineering and management principles; however, RBI will not compensate for

(a) inaccurate or missing information
(b) inadequate design or faulty equipment
(c) improper installation and/or operation
(d) operating outside the acceptable design envelope
(e) not effectively implementing the inspection plan
(f) lack of qualified personnel or team work
(g) lack of sound engineering or operational judgment
(h) failure to promptly take corrective action or implement appropriate mitigation strategies

3.2 Consequence and Probability for Risk-Based Inspection

The objective of a risk analysis should be to determine what incident would occur (consequence) in the event of an equipment failure, and how likely (probability) it is that the incident could happen. For example, if a pressure vessel subject to damage from corrosion under insulation develops a leak, or if a crack in the heat-affected zone (HAZ) of a weld results in a rupture, a variety of consequences could occur. Some possible consequences are

(a) formation of a vapor cloud that could ignite, causing injury and equipment damage
(b) release of a toxic chemical that could cause health problems
(c) a spill that could cause environmental damage
(d) a rapid release of superheated steam that could cause damage and injury
(e) a forced unit shutdown that could have an adverse economic impact
(f) minimal safety, health, environmental, and/or economic impact

Combining the probability and the consequence of each applicable scenario will determine the risk to the operation. Some failures may occur relatively frequently without significant adverse safety, environmental, or economic impacts. Similarly, some failures have potentially serious consequences, but the probability of the incident is low. In either case, the risk may not warrant immediate action; however, if the probability and consequence combination (risk) is high enough to be unacceptable, then mitigation action(s) to reduce the probability and/or consequence of the event should be implemented. In addition, some failures that occur frequently may accumulate a high economic impact when examined over time.

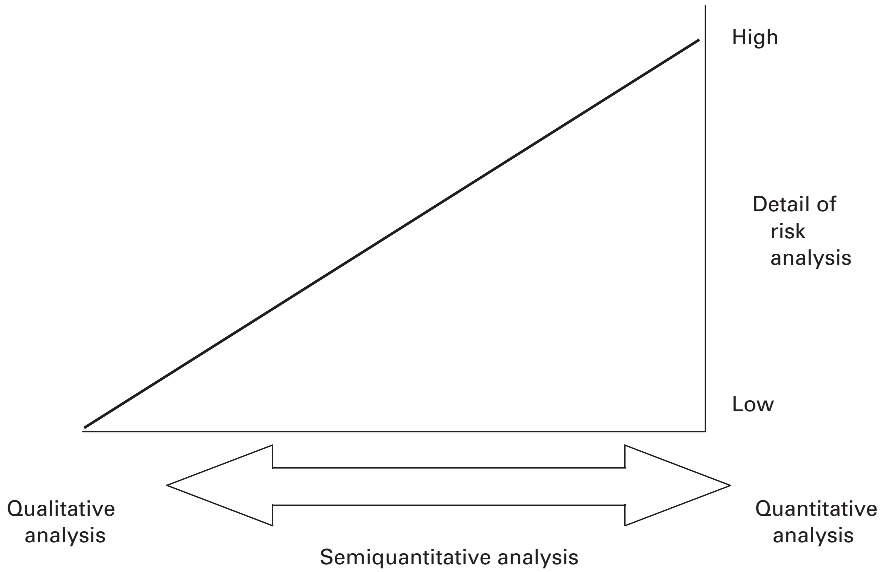
Past inspection planning methods have traditionally focused solely on the consequences of failure or on the probability of occurrence without systematic efforts to tie the two together. They have not considered how probable it is that an undesirable incident will occur. Only by considering both factors can effective risk-based decision making take place. Typically, acceptance criteria should be defined recognizing that not every failure will lead to an undesirable incident with serious consequence (e.g., water leaks) and that some serious consequence incidents have very low probabilities.

3.3 Risk Analysis Methodology

The risk analysis that supports the RBI program may be qualitative, quantitative, or a combination of the two. In each case, the risk analysis approach should be used to systematically screen for risk, identify areas of potential concern, and develop a prioritized list for more in-depth inspection or analysis. Use of expert opinion will typically be included in most risk analyses. The choice of approach depends on many factors such as

(a) objective of the analysis
(b) number of facilities and equipment items to assess
(c) available resources

Fig. 3.3.1 Continuum of RBI Approaches



(d) analysis time frame
(e) complexity of facilities and processes
(f) nature and quality of available data

The chosen approach may be selected at the beginning of the analysis process and carried through to completion, or the approach may be changed (i.e., the analysis may become more or less quantitative) as the analysis progresses. If the risk determined using any approach is below the acceptance criterion specified by the management of the organization conducting the analysis, no further analysis, inspection, or mitigation steps are required within the analysis time frame as long as the conditions and assumptions used in the analysis remain valid.

The spectrum of risk analysis should be considered to be a continuum with qualitative and quantitative approaches being the two extremes of the continuum and everything in between being a semiquantitative approach (see para. 3.3.4).

3.3.1 Qualitative RBI Analysis. Data inputs based on descriptive information using engineering judgment and experience as the basis for the analysis of probability of failure and consequence of failure are used. Inputs are often given in data ranges instead of discrete values. Results are typically categorized as high, medium, and low, although numerical values may be associated with these categories. The value of a qualitative analysis is that it enables completion of a risk analysis in the absence of detailed quantitative data. The accuracy of a qualitative analysis is dependent upon the background and expertise of the analysts. A qualitative analysis is represented by the left end of Fig. 3.3.1.

Although the qualitative approach is less precise than more quantitative approaches, it is effective in screening out units and equipment with low risk. The qualitative approach may be used for any aspect of inspection plan development; however, the conservatism inherent in this approach should be considered when making final mitigation and inspection plan decisions.

3.3.2 Quantitative RBI Analysis. Quantitative risk analysis integrates into a uniform methodology the relevant information about facility design, operating practices, operating history, component reliability, human actions, the physical progression of accidents, and potential safety, health, and environmental effects.

Quantitative risk analysis uses logic models depicting combinations of events that could result in severe accidents and physical models depicting the progression of accidents and the transport of hazardous material to the environment. The models are evaluated probabilistically to provide both qualitative and quantitative insights about the level of risk and to identify the design, site, or operational characteristics that are the most important to risk. Quantitative risk analysis is distinguished from the qualitative approach by the analysis depth and integration of detailed analysis.

Quantitative risk analysis logic models generally consist of event trees and fault trees. Event trees delineate initiating events and combinations of system successes and failures, while fault trees depict ways in which the system failures represented in the event trees can occur. These models are analyzed to estimate the probability of each accident sequence. Results using this approach are typically presented as risk numbers (e.g., cost per year). Nonmandatory Appendix D provides more information on quantitative analysis.

A fully-quantitative analysis is characterized by the use of all possible numeric data to develop a probability and consequence of failure and all the inputs should be expressed as distributions. Probabilities and consequences should be combined in a mathematically rigorous process so that the axioms of probability theory and decision theory are followed.

3.3.2.1 Quantitative Risk Analysis (QRA). Quantitative risk analysis (QRA) refers to a prescriptive methodology that has resulted from the application of risk analysis techniques at many types of facilities. An RBI analysis shares many of the techniques and data requirements of a QRA. If a QRA has been prepared for a process unit, the RBI consequence analysis may borrow extensively from this effort.

The QRA is generally comprised of five tasks

(a) systems identification
(b) hazards identification
(c) probability assessment
(d) consequence analysis
(e) risk results

A properly implemented QRA may be used for an RBI analysis.

3.3.3 Semiquantitative RBI Analysis. A semiquantitative analysis is an analysis that includes aspects of both qualitative and quantitative analyses.

3.3.4 Continuum of Approaches. In practice, a risk analysis typically uses aspects of qualitative and quantitative approaches. These approaches should not be considered as competing but rather as complementary. For example, a high-level qualitative approach could be used at a facility level to find the unit within the facility that poses the highest risk. Systems and equipment within the unit then may be screened using a qualitative approach with a more quantitative approach used for the higher risk items. Another example could be to use a qualitative consequence analysis combined with a semiquantitative probability analysis.

The risk analysis process, shown in the simplified block diagram in Fig. 3.3.4, depicts the essential elements of inspection planning based on risk analysis. This diagram is applicable to Fig. 3.3.1 regardless of which approach is applied, i.e., each of the essential elements shown in Fig. 3.3.4 are necessary for a complete analysis regardless of approach (qualitative, semiquantitative, or quantitative).

3.3.5 Data Inputs. The data required for risk analyses should usually be drawn from plant and/or industry databases, interviews, and/or engineering models. For quantitative analyses, the data required may be drawn from probabilistic expert opinion elicitations and/or probabilistic engineering analysis models. It may be necessary to rely on the collective memory of subject matter experts and competent, experienced plant personnel, since records are often incomplete. In addition, it may be especially useful to interview subject matter experts to obtain information supplemental to the written records. In almost all cases, information in databases should be reviewed and interpreted by knowledgeable individuals to ensure that the probability and consequence values and distributions are realistic.

3.3.6 Precision Versus Accuracy. Accuracy is a function of the analysis methodology, the quality of the data, and consistency of application, while precision is a function of the selected metrics and computational methods. Risk presented as a numeric value is not inherently more accurate than risk presented as a matrix, though it may be more precise. Regardless of how accurately the analysis is conducted, it may not perfectly model reality because of factors that were not fully taken into account during the analysis.

The precision with which the probability of failure and the consequence of failure are determined will vary with the application. The probability of failure and the consequence of failure need not be determined with the same precision. However, it should be noted that the precision of the resulting risk is a function of the precision of both the probability and the consequence.

Insufficient precision may not support required decisions, while excess precision may be both time consuming and costly. Also, if the uncertainty in the probability of failure or consequence of failure is greater than the precision required, more research or a different approach will be required.

Quantitative analysis uses logic models to calculate probabilities and consequences of failure. Mathematical models used to characterize damage to equipment and to determine the consequence of failures only approximate reality. Therefore, results from these models should be reviewed by experts and the reasons for any disagreements between the model and the experts should be resolved.

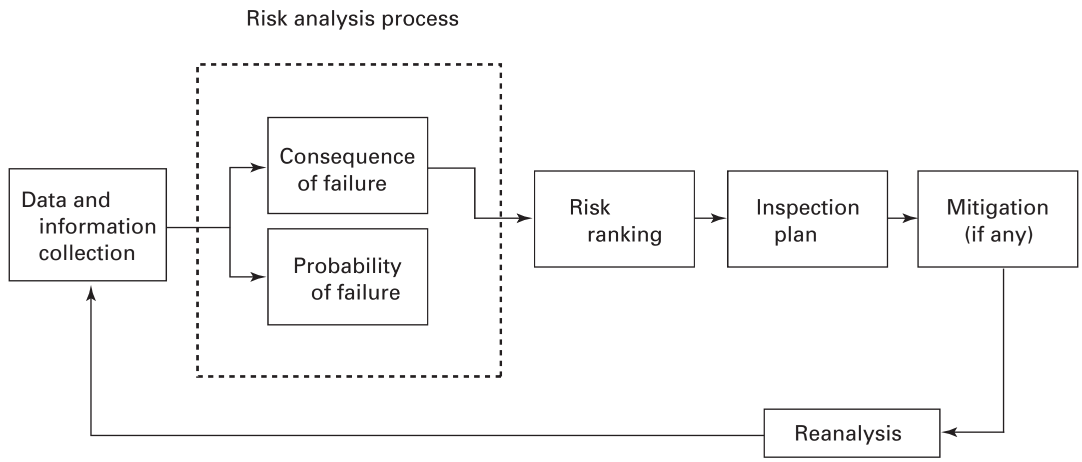
The accuracy of any type of risk analysis depends on using a sound methodology, quality data, and knowledgeable personnel.

3.4 Understanding How RBI Helps to Manage Operating Risks

The mechanical integrity and functional performance of equipment depends on the suitability of the equipment to operate safely and reliably under the normal and abnormal (upset) operating conditions to which the equipment is exposed. In performing a risk analysis, the susceptibility of equipment to damage by one or more mechanisms (e.g., corrosion, fatigue, and cracking) should be established. The susceptibility of each equipment item should be clearly defined for the current operating conditions (see para. 4.4.2) including

(a) normal operation
(b) upset conditions
(c) normal start-up and shutdown
(d) emergency shutdown and subsequent start-up

Fig. 3.3.4 Risk-Based Inspection Planning Process



3.4.1 Variables Considered for Each Operating Condition. The following process variables should be considered for each operating condition:

(a) process fluid, contaminants, and aggressive components

(b) pressures, including cyclic and transient conditions

(c) temperatures, including cyclic and transient conditions

(d) flow rates

The above information, together with equipment design information, operating and inspection history, and the current condition of the equipment will determine the probability of failure of the equipment from one or more damage mechanisms. This probability of failure, when coupled with the associated consequence of failure will determine the risk associated with the equipment item, and therefore the need for any additional analysis or mitigation such as repair, inspection, change in operating conditions, or equipment modification.

3.5 Inspection Plan

Once the risk associated with individual equipment items is determined and the relative effectiveness of different inspection techniques and other mitigation actions in reducing risk is established, an optimized risk-based inspection plan can be developed.

A fully integrated inspection planning process should include inspection activities, inspection data collection and updating, and continuous improvement of the system. Risk analysis is state of knowledge specific, and since the processes are changing with time, a risk analysis only reflects the situation at the time the data were collected. As knowledge is gained from inspection and testing programs and the database improves, uncertainty in the program will be reduced resulting in reduced uncertainty in the calculated risk.

When an inspection identifies damage beyond predetermined limits, it should be evaluated using appropriate flaw evaluation (fitness-for-service) methods such as those contained in ASME and API standards. Based on the evaluation, decisions may be made to repair, replace, or continue to operate. The knowledge gained from the inspection, engineering evaluation, and corrective action should be captured and used to update the plant database. The new data may affect the risk analysis and risk ranking for the equipment item. For example, a vessel suspected of operating with stress corrosion cracks could have a relatively high risk ranking. After inspection, repairs, and change or removal of the adverse environment, the risk calculated for the vessel would be significantly lower, moving it down in the risk ranking and allowing a revised risk-based inspection plan to focus on other equipment items.

3.6 Management of Risks

3.6.1 Risk Management Through Inspection. Inspection reduces the uncertainty of the risk associated with pressure equipment primarily by improving knowledge of the damage state. This knowledge may improve the predictability of the probability of failure. Although inspection does not reduce risk directly, it is a risk management activity that may lead to risk reduction. Inservice inspection is primarily concerned with the detection and monitoring of damage. The probability of failure due to such damage is a function of four factors

(a) damage mechanism

(b) rate of damage

(c) probability of identifying and detecting damage and predicting future damage states with inspection technique(s)

(d) tolerance of the equipment to the type of damage

3.6.2 Using RBI to Establish Inspection Plans and Priorities. The primary product of a risk analysis effort is an inspection plan for each equipment item evaluated. The inspection plan should detail the risk related to operation of the equipment items prior to implementing any mitigation activities. For equipment items with an unacceptable level of risk, the plan should refer to the mitigation actions that are recommended to reduce the risk to acceptable levels.

For those equipment items where inspection is a cost-effective means of risk management, the plans should describe the type, scope, and timing of inspection/examination. Ranking of equipment items by risk allows users to assign priorities to the various inspection/examination tasks. The risk level should be used to evaluate the urgency for performing an inspection.

3.6.3 Other Risk Management. It should be recognized that some risks cannot be adequately managed by inspection alone. Examples where inspection may not be sufficient to manage risks to acceptable levels are

(a) equipment nearing retirement

(b) failure mechanisms (such as brittle fracture, fatigue) where avoidance of failure primarily depends on operating within a defined pressure/temperature envelope

(c) high-consequence, low-probability events

In such cases, noninspection mitigation actions such as equipment repair, replacement, or upgrade, equipment redesign, or maintenance of strict controls on operating conditions may be the only appropriate measures that can be taken to reduce risk to acceptable levels.

3.7 Relationship Between RBI and Other Risk-Based and Safety Initiatives

The risk-based inspection methodology is intended to complement other risk-based and safety initiatives. The output from several of these initiatives can provide input to the RBI effort, and RBI outputs may be used to improve safety and risk-based initiatives already implemented by organizations. Examples of some initiatives are

(a) OSHA Process Safety Management Programs

(b) EPA Risk Management Programs

(c) ACC Responsible Care

(d) ASME Risk Analysis Publications

(e) CCPS Risk Analysis Techniques

(f) Reliability-Centered Maintenance

(g) Process Hazards Analysis

(h) Seveso II Directive in Europe

The relationship between RBI and several initiatives is described in paras. 3.7.1 through 3.7.3.

3.7.1 Process Hazards Analysis. A process hazards analysis (PHA) uses a systemized approach to identify and analyze hazards in a process unit. The risk analysis may include a review of the output from any PHA that has been conducted on the unit being evaluated. Hazards identified in the PHA should be specifically addressed in the RBI analysis.

Potential hazards identified in a PHA will often impact the probability of failure side of the risk equation. The hazard may result from a series of events that could cause a process upset, or it could be the result of process design or instrumentation deficiencies. In either case, the hazard may increase the probability of failure, in which case the RBI procedure should reflect the same.

Some hazards identified would affect the consequence side of the risk equation. For example, the potential failure of an isolation valve could increase the inventory of material available for release in the event of a leak. The consequence calculation in the RBI procedure should be modified to reflect this added hazard.

Likewise, the results of an RBI analysis may significantly enhance the overall value of a PHA.

3.7.2 Process Safety Management. A strong process safety management (PSM) system can significantly reduce risk levels in a process plant (refer to OSHA 29 CFR 1910.119). RBI may include methodologies to assess the effectiveness of the management systems in maintaining mechanical integrity. The results of such a management systems evaluation should be factored into the risk determinations.

Several of the features of a good PSM program provide input for a risk analysis. Extensive data on the equipment and the process are required in the RBI analysis, and output from PHA and incident investigation reports increases the validity of the risk analysis. In turn, the RBI program may improve the mechanical integrity aspect of the PSM program. An effective PSM program includes a well-structured equipment inspection program. The RBI system will improve the focus of the inspection plan, resulting in a strengthened PSM program.

Operating with a comprehensive inspection program should reduce the risks of releases from a facility and should provide benefits in complying with safety-related initiatives.

3.7.3 Equipment Reliability. Equipment reliability programs may provide input to the probability analysis portion of an RBI program. Specifically, reliability records may be used to develop equipment failure probabilities and leak frequencies. Equipment reliability is especially important if leaks can be caused by secondary failures, such as loss of utilities. Reliability efforts, such as reliability-centered maintenance (RCM), may be linked with RBI, resulting in an integrated program to reduce downtime in an operating unit.

3.8 Relationship With Jurisdictional Requirements

In jurisdictions that have adopted post-construction rules and regulations governing inspection practices and intervals, the jurisdictional rules may supersede some of the results of an RBI plan. However, the fact that jurisdictions have some definitive time-based rules on inspection intervals does not preclude the user from gaining significant benefits from the application of RBI.

4 PLANNING THE RISK ANALYSIS

4.1 Getting Started

A risk analysis should be a team-based process that starts with defined objectives. Screening focuses the effort and boundary limits should be identified to determine what is vital to include in further analysis (see Fig. 3.3.4). The process of screening risks, determining priorities, and identifying boundaries improves the efficiency and effectiveness of the analysis.

(a) At the facility level, risk analysis may be applied to all types of operations including but not limited to

(1) oil and gas production, processing, and transportation

(2) refineries

(3) petrochemical and chemical

(4) pipelines and pipeline stations

(5) liquefied gas processing

(6) power generation

(7) pulp and paper

(8) storage facilities

(9) pharmaceutical facilities

(10) food and beverage processing facilities

(11) catalyst and other solids-handling facilities

(b) At the beginning of the analysis, the following should be defined:

(1) Why is the analysis being done?

(2) How will the analysis be carried out?

(3) What knowledge and skills are required for the analysis?

(4) Who is on the team?

(5) What are the roles of the team members in the process?

(6) Who is responsible and accountable for what actions?

(7) Which facilities, process units, systems, equipment, and components will be included?

(8) What data are to be used in the analysis?

(9) What codes and standards are applicable?

(10) When will the analysis be completed?

(11) How long will the analysis remain in effect and when will it be updated?

(12) How will the results be used?

4.2 Outcome of the Planning Portion of the Process

At the conclusion of the planning portion of the development of the RBI program, the following should have been completed:

(a) Establish the objectives of the risk analysis.

(b) Identify the physical boundaries.

(c) Identify the operating boundaries.

(d) Develop screening questions and criteria consistent with the objectives of the analysis and identified physical and operating boundaries.

Once this portion of the RBI planning process has been completed, the required data and information should be identified (see section 5). It may be necessary to revise the objectives, boundaries, screening questions, etc., based upon the availability and quality of the data and information.

4.3 Establish Objectives

A risk analysis should be undertaken with clear objectives that are fully understood by all members of the analysis team and by management.

See paras. 4.3.1 through 4.3.8.

4.3.1 Understand Risk. An objective of the risk analysis may be to ascertain the risk of operating a facility, process unit, system, or component and to better understand the effect inspection, maintenance, and other mitigation actions have on the risk.

By understanding the risk, a program may be designed that optimizes the use of inspection and other resources.

4.3.2 Define Risk Criteria. A risk analysis will determine the risk associated with equipment items within the scope of the analysis. The risk analysis team and management may wish to judge whether the individual equipment item and cumulative risks are acceptable.

Establishing risk criteria to judge acceptability of risk could be an objective of the analysis.

4.3.3 Manage Risks. When the risks have been identified, inspection and/or other mitigation actions that reduce risk to an acceptable level may be taken. These actions may be significantly different from those performed during a statutory or certification type inspection program.

By managing and reducing risk, safety is improved and loss of containment incidents and commercial losses are reduced.

4.3.4 Reduce Costs. Costs reduction is not usually the primary objective of a risk analysis, but it is frequently a side effect of inspection optimization. When the inspection program is optimized based on an understanding of risk, one or more of the following cost-reduction benefits may be realized:

(a) Ineffective, unnecessary, or inappropriate inspection activities may be eliminated.

(b) Inspection of low-risk items may be eliminated or reduced.

(c) Online or noninvasive inspections may be substituted for invasive inspections that require equipment shutdown.

(d) More effective and less frequent inspections may be substituted for less effective and more frequent inspections.

4.3.5 Meet Safety and Environmental Management Requirements. Risk management based upon a risk analysis may complement other risk and safety initiatives (see para. 3.7). By focusing efforts on areas with the greatest risk, an RBI program provides a systematic method to guide a user in the selection of equipment items to be included and the frequency, scope, and extent of inspection activities to be conducted in order to meet safety and environmental requirements.

4.3.6 Identify Mitigation Alternatives. The risk analysis may identify actions other than inspection to manage risks. Some of these mitigation actions include but are not limited to

(a) modification of the process to eliminate conditions driving the risk

(b) modification of operating procedures to avoid situations driving the risk

(c) chemical treatment of the process to reduce damage rates/susceptibilities

(d) alteration of components to reduce probability of failure

(e) removal of unnecessary insulation to reduce probability of corrosion under insulation

(f) reduction of inventories to reduce consequence of failure

(g) upgrading safety, detection, or monitoring systems

(h) changing to less flammable or toxic fluids

4.3.7 New Project Risk Analysis. It is usually more economical to modify a process or alter equipment when a facility is being designed than when it is operating. A risk analysis made on new equipment or a new project while in the design stage may yield important information on potential risks. This may allow risks to be minimized by design prior to installation.

4.3.8 Develop Facilities End-of-Life Strategies. Facilities approaching the end of service life are a special case where application of RBI may be very useful for gaining the maximum remaining economic benefit from an asset without undue personnel, environmental, or financial risk.

End-of-life strategies focus the inspection efforts directly on high-risk areas where the inspections will provide a reduction of risk during the remaining life of the plant. Inspection strategies may be developed in association with a fitness-for-service analysis and inspection activities that do not impact risk during the remaining life may be eliminated or reduced.

The risk analysis should be reviewed if the remaining plant life is extended after the remaining life strategy has been developed and implemented.

4.4 Initial Screening

The screening process focuses the analysis on the most important equipment items so that time and resources are effectively utilized.

4.4.1 Physical Boundaries. The physical boundaries [facilities, process units, systems, equipment, and components (see Fig. 4.4.1)] should be identified and be consistent with the objectives of the risk analysis. The amount and detail of data and information to be reviewed and the resources available to accomplish the objectives directly impact the extent of equipment items that can be assessed. The scope of a risk analysis may vary from an entire facility to a single component; however, a risk analysis typically includes many equipment items (e.g., an entire process unit) rather than a single component.

4.4.1.1 Facility Screening. Screening at the facility level may be done by a simplified qualitative risk analysis. Screening at the facility level could also be done by

(a) asset or product value

(b) history of problems/failures

(c) PSM/non-PSM facilities

(d) age of facilities

(e) proximity to the public

(f) proximity to environmentally sensitive areas

(g) next scheduled outage

4.4.1.1.1 Key Questions at the Facility Level. Key questions to answer at the facility level before considering RBI should be as follows:

(a) Is the facility located in a regulatory jurisdiction that will accept modifications to statutory inspection intervals based on risk analysis?

(b) Is the management of the facility willing to invest the necessary resources to achieve the benefits of RBI?

(c) Does the facility have sufficient resources and expertise available to conduct the risk analysis?

4.4.1.2 Process Unit Screening. If the facility is a multiprocess unit facility, then the first step should be screening entire process units to rank relative risk. The screening identifies areas higher in risk (priority) and suggests which process units to begin with. It also provides insight about the level of analysis that may be required for systems, equipment, and components in the various process units.

Priorities may be assigned based on one or more of the following:

(a) relative risk of the process units

(b) relative economic impact or value of the process units

(c) relative consequence of failure of the process units

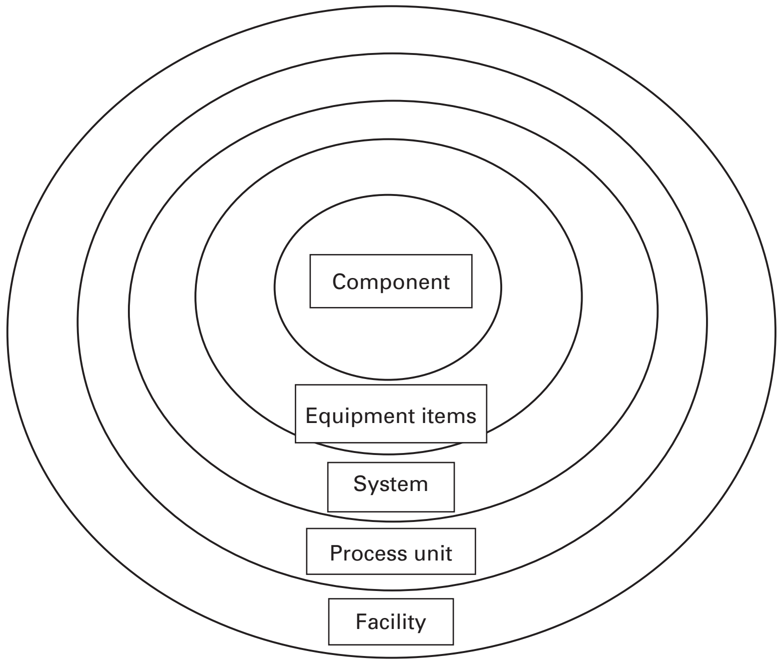
(d) relative probability of failure of the process units

(e) turnaround schedule

(f) experience with similar process units

4.4.1.2.1 Selection of Process Units. Selection of process units to be included should be based on meeting the objectives of the risk analysis (see para. 4.3). Key

Fig. 4.4.1 Relationship Among Component, Equipment, System, Process Unit, and Facility



questions to answer at the process unit level before considering RBI should be as follows:

(*a*) Does the process unit have a significant impact on the operation of the facility?

(*b*) Are there significant risks involved in the operation of the process unit and would the effect of risk reduction be measurable?

(*c*) Do the operators of the process unit see that some benefit may be gained through the application of RBI?

(*d*) Are sufficient resources and expertise available to conduct the risk analysis?

4.4.1.3 Systems Screening. It is often advantageous to group equipment within a process unit into systems (circuits) where common environmental and operating conditions exist based on process chemistry, pressure, temperature, metallurgy, equipment design, and operating history. By dividing a process unit into systems, the equipment can be screened together, saving time compared to treating each piece of equipment separately.

A common practice utilizes block flow or process flow diagrams for the process unit to identify the systems. Information about metallurgy, process conditions, credible damage mechanisms, and historical problems may be identified on the diagram for each system.

When a process unit is identified for a risk analysis and overall optimization is the goal, it is usually best to include all systems within the unit; however, limitations such as resource availability may necessitate that the risk analysis be limited to one or more systems within the process unit. Selection of systems may be based on

(*a*) relative risk of the systems

(*b*) relative consequence of failure of systems

(*c*) relative probability of failure of systems

(*d*) relative expected benefit from applying RBI to systems

When screening systems, site-specific questions should be developed. The information developed should form the basis of the subsequent risk analysis.

4.4.1.4 Equipment Item Screening. In most facilities, a large percentage of the total risk will be concentrated in a relatively small percentage of equipment items. These potentially high-risk equipment items should receive greater attention in the risk analysis. Screening of equipment items may be conducted to identify the higher risk equipment to be carried forward for more detailed risk analysis.

A risk analysis may be applied to the pressure boundary components of the following equipment items:

(*a*) piping
(*b*) boilers
(*c*) pressure vessels
(*d*) reactors
(*e*) heat exchangers
(*f*) furnaces
(*g*) storage tanks
(*h*) pumps
(*i*) compressors
(*j*) pressure relief devices
(*k*) block valves
(*l*) control valves

4.4.1.4.1 Selection of Equipment Items. Selection of equipment items to be included should be based on meeting the objectives of the risk analysis (see para. 4.3). Key questions to answer at the equipment level should be as follows:

(a) Will pressure containment be compromised by damage mechanisms?

(b) Which equipment has a history of failure?

(c) Which equipment has the highest consequence of failure if there is a loss of containment?

(d) Which equipment is subject to the most damage that could affect pressure containment?

(e) Which equipment has lower design margins and/or lower corrosion allowances that may affect pressure containment?

When screening equipment items, site-specific questions should be developed. The information developed should form the basis of the subsequent risk analysis.

4.4.1.5 External Systems, Utilities, and Emergency Systems. Whether or not external systems, utilities, and emergency systems should be included depends on the planned use of the risk analysis and the current inspection requirements of the facility. Possible reasons for inclusion of external systems, utilities, and emergency systems are

(a) the risk analysis will be the basis for an overall optimization of inspection resources and environmental and business consequences of failure should be included.

(b) there is a specific reliability problem in a utility system. An example would be a cooling water system with corrosion and fouling problems. An RBI approach could assist in developing the most effective combination of mitigation actions including inspection, monitoring, repair, and treatment for the entire facility.

(c) reliability of the process unit is a major objective of the risk analysis.

When emergency systems (e.g., flare systems, emergency shutdown systems) are included in the risk analysis, the systems should be assessed based on all expected service conditions (i.e., routine, test, and emergency operation should all be considered).

4.4.2 Operating Boundaries. Similar to physical boundaries, operating boundaries for the risk analysis are established consistent with the objectives, level of data to be reviewed, and resources. The purpose of establishing operational boundaries should be to identify key process parameters that may impact damage. The risk analysis normally includes review of both probability of failure and consequence of failure for normal operating conditions. Start-up and shutdown conditions as well as emergency and nonroutine conditions should also be reviewed for their potential effect on probability of failure and consequence of failure. The operating conditions used for the risk analysis, including any sensitivity analysis, should be recorded as the operating limits for the analysis.

Operating within the operating boundaries is critical to the validity of the risk analysis as well as good operating practice. Key process parameters should be monitored to determine whether operations are maintained within the operating boundaries.

4.4.2.1 Start-Up and Shutdown. Process conditions during start-up and shutdown may have a significant effect on risk especially when the conditions are more severe (likely to cause accelerated damage) than normal conditions. A good example is stress corrosion cracking by polythionic acid formed when a vessel surface laden with iron sulfide in hydrocarbon service is exposed to air and moisture during a shutdown. The probability of failure for susceptible components is controlled by whether mitigation measures are applied during shutdown procedures. Start-up lines should often be included within the process piping and their service conditions during start-up and subsequent operation should be considered.

4.4.2.2 Normal, Upset, and Cyclic Operation. The normal operating conditions may be most easily provided if there is a process flow model or mass balance available for the facility or process unit. However, the normal operating conditions found on documentation should be verified as it is not uncommon to find discrepancies that could substantially impact the risk analysis results. The following data should be obtained:

(a) operating temperature and pressure including variation ranges

(b) process fluid composition including variation with feed composition ranges

(c) flow rates including variation ranges

(d) presence of moisture or other contaminants

Changes in the process, such as pressure, temperature, or fluid composition, resulting from abnormal or upset conditions should be considered in the risk analysis.

Systems with cyclic operation, such as reactor regeneration systems, should consider the complete cyclic range of conditions. Cyclic conditions could impact the probability of failure due to some damage mechanisms (e.g., fatigue, thermal fatigue, corrosion under insulation).

4.4.2.3 Operating Time Period. The target run length of the selected process units/equipment should be considered. The risk analysis may include the entire operational life, or may be for a selected period. For example, process units are occasionally shut down for maintenance activities and the associated run length may depend on the condition of the equipment in the unit. A risk analysis may focus on the current run period or may include the current and next projected run period. The time period may also influence the types of decisions and plans that result from the analysis, such as inspection, repair, alteration, replacement, or other mitigation actions. Future operational projections are also important as part of the basis for the operational time period.

4.5 Selecting a Risk Analysis Approach

Selection of the type of risk analysis will be dependent on a variety of factors (see para. 3.3) and a strategy should be developed matching the type of analysis to the expected or evaluated risk. For example, process units that are expected to have lower risk may only require simple, fairly conservative methods to adequately accomplish the objectives, whereas process units expected to have a higher risk may require more detailed methods. Another example would be to evaluate all equipment items in a process unit qualitatively and then evaluate the identified higher risk items more quantitatively.

4.6 Estimating Resources and Time Required

The resources and time required to conduct a risk analysis will vary widely among organizations depending on a number of factors including

(a) implementation strategy/plans

(b) knowledge and training of personnel involved in the analysis

(c) training time and cost for personnel involved in the analysis

(d) availability and quality of data and information

(e) availability and cost of resources needed for the analysis

(f) number of facilities, process units, systems, equipment, and components to be evaluated and the detail of analysis applied to equipment items

(g) degree of complexity of risk analysis

(h) degree of precision required

(i) time and resources to evaluate risk analysis results and develop inspection and other mitigation action plans

5 DATA AND INFORMATION COLLECTION

5.1 Introduction

Utilizing the objectives, boundaries, level of approach, and resources identified in section 4, the objective of this section is to provide an overview of the data that may be necessary to develop a risk-based inspection plan.

The data collected will provide the information needed to assess potential damage mechanisms, potential failure modes, and scenarios of failure that are discussed in section 6. Additionally, it will provide much of the data that will be used in section 7 to assess probabilities, the data used in section 8 to assess consequences, and also data that will be used in section 10 to assist in the inspection planning process.

5.2 General

Examples of data sources are

(a) design and construction records

(b) inspection and maintenance records

(c) operating and process technology records

(d) hazards analysis and management of change records

(e) materials selection records, corrosion engineering records, and library/database

(f) cost and project engineering records

The precision of the data should be consistent with the risk analysis method used. The individual or team should understand the precision of the data needed for the analysis before gathering it. It may be advantageous to combine risk analysis data gathering with other risk/hazard analysis data gathering [see para. 5.3(a)] as much of the data may be the same.

5.3 Data Needs and Common Types of Data

The following data that relate to the equipment being considered should be obtained as needed and to the extent available. In some cases additional data may be needed. Where data are not available, input from inspection, maintenance, and operations personnel should be combined with the engineering judgment of appropriate subject matter experts.

(a) Hazard Analysis

(1) Process Hazards Analysis (PHA)

(2) Hazard and Operability Study (HAZOP)

(3) Failure Mode and Effects Analysis (FMEA)

(4) Process Safety Management (PSM) and Reliability-Centered Maintenance (RCM) data or reports

(b) Inspection, Maintenance, and Repair/Alteration Records

(1) current schedules and scope of inspection (including NDE methods employed)

(2) repairs and alterations

(3) positive material identification (PMI) records (base material and deposited weld metal)

(4) inspection results (including baseline inspection records)

(5) management of change records

(6) incident investigation reports

(7) preventive maintenance records

(c) Costs

(1) availability, cost, and proximity of critical spare parts

(2) equipment repair or replacement costs (including repainting, reinsulating)

(3) environmental remediation costs

(4) engineering costs

(5) business interruption costs, including lost opportunity

(d) Phases of Operation (Both Current and Anticipated During Time Period Under Consideration)

(1) start-up

(2) shutdown

(3) normal operation

(4) temporary operation

(5) process upset (including deflagration)

(6) recovery

(7) emergency (external upset)

(8) restart after emergency shutdown

(e) Process Data (Both Current and Anticipated During Time Period Under Consideration)

(1) fluid composition, including contaminants and aggressive components

(2) changes in fluid composition and flow rates

(3) maximum pressures and coincident temperatures, including details of cyclic and transient conditions

(4) maximum temperatures and coincident pressures, including details of cyclic and transient conditions

(5) minimum temperatures and coincident pressures, including details of cyclic and transient conditions

(6) normal operating pressure and temperatures

(7) operating logs and process records

(8) fluid inventory

(9) heat and material balance

(f) Design and Construction Records/Drawings

(1) unique equipment identification and piping identifiers

(2) piping and instrument diagrams, process flow diagrams, etc.

(3) piping isometric drawings

(4) block/process flow diagrams

(5) equipment, piping, paint, and insulation specifications

(6) description of heat tracing if any

(7) materials of construction records

(8) construction records

(9) equipment design data

(10) applicable codes and standards[2]

(11) protective instrument systems

(12) leak detection and monitoring systems

(13) isolation systems

(14) equipment capacity

(15) emergency depressurizing and relief systems

(16) safety systems

(17) fireproofing and firefighting systems

(18) plant layout

(19) equipment orientation and exposure

(20) description of cathodic protection system if provided

(g) Failure Data, Damage Mechanisms, and Damage Rate Information. The best information will come from operating experience where the conditions that led to the observed damage rate could realistically be expected to occur in the equipment under consideration. Other sources of information could include databases of plant experience or reliance on expert opinion. The latter method is often used since plant databases, where they exist, do not always contain sufficiently detailed information. Other sources include

(1) generic failure frequency data — industry and/or in-house

(2) industry-specific failure data

(3) plant, material, and equipment-specific failure data

(4) reliability, inspection, and equipment monitoring records

(5) leak data

(6) historical information on damage mechanisms and rates

(7) industry information and recommended practices on applicable damage mechanisms and rates

(8) laboratory testing

(9) in situ testing and inservice monitoring

(10) publications on damage and damage mechanisms

(a) WRC 488, Damage Mechanisms Affecting Fixed Equipment in the Pulp and Paper Industry

(b) WRC 489, Damage Mechanisms Affecting Fixed Equipment In the Refining Industry

(c) WRC 490, Damage Mechanisms Affecting Fixed Equipment In the Fossil Electric Power Industry

(d) API 571, Damage Mechanisms Affecting Fixed Equipment in the Refining Industry

(e) ASTM G 15, Standard Terminology Relating to Corrosion and Corrosion Testing

(f) The NACE Corrosion Survey Database

(11) industry-specific failure data. Some industries have societies that track failures and make this information available to the public. Examples are listed below. Other sources should be used as appropriate.

(a) Offshore Reliability Data Handbook

(b) Process Equipment Reliability Database

(c) Generating Availability Data System

(d) Black Liquor Recovery Boiler Advisory Committee Incident List

A limitation of the databases described above is that the damage mechanism may not be recorded. In such cases some assumptions may have to be made about the cause of the failure because the inspection program must look for one or more specific damage mechanisms. Public domain data such as the above can usually be resolved into component parts to obtain failure rates.

[2] In the data collection stage, an analysis of what codes and standards are currently in use and were in use during the equipment design is generally necessary. The codes and standards used by a facility can have a significant impact on RBI results.

(h) Site Conditions

(1) corrosive atmosphere (seawater, downwind of cooling tower, etc.)

(2) seismic

(3) wind

(4) flood

(5) ambient temperature extremes

(6) dust

(7) population density (on-site/off-site personnel)

(8) environmental considerations

(9) off-site data and information (number and proximity of buildings intended for human occupancy, etc.)

(i) Incident Investigation Reports

5.4 Data Quality and Validation

Data quality has a direct relation to the accuracy of the risk analysis and is equally important for all approaches. The integrity of a risk analysis depends upon the use of up-to-date data validated by knowledgeable personnel (see section 13).

Data validation should be done to preclude the introduction of errors (e.g., outdated drawings, inspection errors, clerical errors, measurement equipment inaccuracies, errors in equipment history) into the risk analysis. If baseline thickness was not measured or documented, nominal thickness may have been used for the original thickness, thereby potentially impacting the calculated corrosion rate early in the life of the equipment. The result may be to mask a high corrosion rate or to inflate a low corrosion rate.

A subject matter expert should compare results from the inspections to the expected damage mechanisms and rates, as applicable. These results should be compared to previous measurements on that facility, process unit, system, or component at the site, or similar counterparts at other sites, or with published data and statistics. This review should also factor in the influence of any changes or upsets in the process.

6 DAMAGE MECHANISMS AND FAILURE MODES

6.1 Introduction

This section provides guidance in identifying credible damage mechanisms and failure modes of pressure boundary metallic components that should be included in an RBI analysis. Guidance is provided in Nonmandatory Appendix B.

6.1.1 Damage mechanisms include corrosion, cracking, mechanical, and metallurgical damage (see Nonmandatory Appendix A). Understanding damage mechanisms is important for

(a) the analysis of the probability of failure

(b) the selection of appropriate inspection intervals, locations, and techniques

(c) the ability to make decisions (e.g., modifications to process, materials selection, monitoring) that can eliminate or reduce the probability of a specific damage mechanism

6.1.2 Failure modes identify how the damaged component will fail (e.g., by leakage or by rupture). Understanding failure modes is important for

(a) the analysis of the consequence of failure

(b) the ability to make run-or-repair decisions

(c) the selection of repair techniques

6.2 Identification of Damage Mechanisms

Identification of the credible damage[3] mechanisms and failure modes for equipment included in a risk analysis is essential to the quality and the effectiveness of the risk analysis. The RBI team should consult with a materials or corrosion specialist to define the equipment damage mechanisms, damage modes (optional), and potential failure modes. A sequential approach is as follows.

6.2.1 As indicated in section 5, identify the internal and external operating and environmental conditions, age, design, and operational loading. Data used and assumptions made should be validated and documented. Process conditions as well as anticipated process changes should be considered. Identifying trace constituents (ppm) in addition to the primary constituents in a process can be very important as trace constituents can have a significant affect on the damage mechanisms.

6.2.2 Considering the materials, methods, and details of fabrication, develop a list of the credible damage mechanisms that may have been present in past operation, be presently active, or may become active. Nonmandatory Appendix B may help in development of this list.

6.2.3 Under certain circumstances it may be preferable to list a specific damage mechanism and then list the various damage modes or ways that the damage mechanism may manifest itself. For example, the damage mechanism "corrosion under insulation" may precipitate a damage mode of either generalized corrosion or localized corrosion. Generalized corrosion could result in a rupture or structural failure while localized corrosion might be more likely to result in a pinhole type leak. All credible failure modes for each damage mechanism or damage mode should be considered.

6.2.4 It is often possible to have two or more damage mechanisms at work on the same piece of equipment or piping component at the same time. An example of this could be stress corrosion cracking in combination

[3] *Deterioration* or *degradation* is sometimes used as a synonym for *damage*. However, *damage* is used throughout this document for consistency. The term *aging* mechanism is used in some industries to identify a subset of mechanisms that are dependent upon long-term exposure at specific temperatures or cyclic stress.

with generalized or localized corrosion (thinning or pitting).

6.3 Damage Mechanisms

Understanding equipment operation and the interaction with the process environment (both internal and external) and mechanical environment is key to identifying damage mechanisms. Process specialists can provide useful input (such as the spectrum of process conditions, injection points) to aid materials specialists in the identification of credible damage mechanisms and rates. For example, understanding that localized thinning could be caused by the method of fluid injection and agitation may be as important as knowing the corrosion mechanism. Sources of information on damage and damage mechanisms are provided in section 5.

6.3.1 Table of Damage Mechanism Descriptions. Nonmandatory Appendix A contains a table of damage mechanism descriptions for use in conjunction with Nonmandatory Appendix B in the preparation of a list of credible damage mechanisms for the component under consideration. Table A-1 should not be considered to be all-inclusive but may serve as an aid.

(a) Column 1 contains an alphabetical listing of common damage mechanisms for consideration during a risk-based inspection analysis.

(b) Column 2 provides a brief description or definition of each damage mechanism.

(c) Column 3 provides a description of some common attributes of each damage mechanism.

(d) Column 4 provides a source or reference for additional information regarding each damage mechanism.

6.3.2 Damage Mechanism Screening Table. Nonmandatory Appendix B contains a screening table utilizing the same alphabetical listing of common damage mechanisms noted above to help provide correlations among damage mechanisms and operation, process, and mechanical environments. General categories presented for screening purposes include

(a) manufacturing/fabrication considerations
(b) materials of construction
(c) temperature range
(d) processes
(e) flow
(f) type of loading

Further, each of these major headings is subdivided into columns of specific categories of the major heading. The table lists many of the materials used in construction for pressure equipment and piping, but the listings are not all-inclusive. Furthermore, there are many grades of alloys that in one case may be susceptible to a specific mechanism, but with small changes in chemistry they may not be susceptible (e.g., 316 stainless steel may be susceptible to some corrosion mechanisms, while 316L stainless steel may not be susceptible). The table does not include misapplication of materials, and damage issues rarely experienced or not typical of process environments.

6.3.3 Table of Examination Methods. Nonmandatory Appendix C contains a table of common examination methods utilizing the same alphabetical listing of common damage mechanisms noted above to help provide a correlation between damage mechanisms and potential destructive or nondestructive inspection or testing methods. This table presents commonly accepted examination methods for identifying the damage mechanism of concern, but does not represent the effectiveness of each examination method for each damage mechanism.

6.4 Failure Modes

Once a credible damage mechanism(s) has been identified, the associated failure mode should also be identified. For example, local thinning could lead to a pinhole leak in the pressure boundary. General thinning could lead to a rupture. There may be more than one credible failure mode for each damage mechanism. For example, cracking could lead to a through-wall crack with a leak before break scenario or could lead to a catastrophic rupture. The failure mode will depend on the type of cracking, the geometric orientation of the cracking, the properties of the material of construction, the component thickness, the temperature, and the stress level. Examples of failure modes include

(a) pinhole leak
(b) small to moderate leak
(c) large leak
(d) ductile rupture
(e) catastrophic brittle fracture

6.4.1 Failures Other Than Loss of Containment. The risk analysis may, at the discretion of the owner, also include failures other than loss of containment, such as loss of function. Examples of other failures and failure modes are provided in para. 8.2.

6.5 Accumulated Damage

Damage rates may vary as damage mechanisms progress, i.e., various mechanisms may accelerate or slow or stop completely. In some cases, damage by one mechanism may progress to a point at which a different mechanism takes over and begins to dominate the rate of damage. An evaluation of damage mechanisms and failure modes should include the cumulative effect of each mechanism and/or mode.

6.6 Tabulating Results

The results of a damage mechanisms and failure modes analysis for RBI should indicate

(a) a list of credible damage mechanism(s), e.g., external corrosion.

(b) a list of credible damage mode(s) resulting from the damage mechanisms(s) above. Examples include

(1) localized thinning

(2) general thinning

NOTE: This step is optional. Failure modes may be determined directly without this intermediate step if desired.

(c) a ranking of credible failure mode(s) resulting from the damage mode(s) above. Examples include

(1) localized thinning

(a) failure mode 1: pinhole leak

(b) failure mode 2: small leak

(2) general thinning

(a) failure mode 1: pinhole leak

(b) failure mode 2: small leak

(c) failure mode 3: large leak

(d) failure mode 4: rupture

7 DETERMINING PROBABILITY OF FAILURE

7.1 Introduction to Probability Analysis

The probability analysis phase of a risk analysis process should be performed to estimate the probability of a specific adverse consequence resulting from a loss of containment that occurs due to a damage mechanism. The probability that a specific consequence will occur is the product of the probability of failure and the probability of the consequence scenario under consideration assuming that the failure has occurred. For example, if a tank containing a flammable fluid ruptured, the resulting probability of the consequence (damage) would be a function of the probability of the rupture, the probability of ignition of the released fluid, the probability that a surrounding dike will contain the released fluid, the probability that the installed fire suppression system will work properly, the probability of environmental consequences, etc. Such scenarios should typically be examined using event tree diagrams (see para. 9.2.1).

This section provides guidance only on determining the probability of failure. Guidance on determining the probability of specific consequences is provided in section 9.

The probability of failure analysis should address the damage mechanisms to which the equipment item is susceptible. Further, the analysis should address the situation where equipment is susceptible to multiple damage mechanisms (e.g., thinning and creep). The analysis should be credible, repeatable, and well documented.

It should be noted that damage mechanisms are not the only causes of loss of containment. Other causes of loss of containment could include but are not limited to

(a) seismic activity

(b) weather extremes

(c) overpressure with pressure relief device failure

(d) operator error

(e) fabrication errors

(f) design error

(g) sabotage

These and other causes of loss of containment may have an impact on the probability of failure and may be included in the probability of failure analysis. While these causes are not normally a part of a risk analysis for the purpose of inspection planning, they may be important for an overall risk analysis of an operating facility.

7.2 Determination of Probability of Failure

The probability of failure should be determined based on three main considerations

(a) identification of credible damage mechanisms (internal or external) for the materials of construction (see section 6).

(b) determination of rates of damage.

(c) determination of the effectiveness of inspection programs, particularly the NDE methods employed, for identification and monitoring of flaws and other evidence of damage so that the equipment can be repaired or replaced prior to failure. Inspection effectiveness is determined by many factors including

(1) type of inspection (i.e., the ability of the inspection method to detect and characterize damage mechanisms)

(2) skill and training of inspectors

(3) level of expertise used in selecting inspection locations

More than one inspection technique may be used to detect and characterize a given damage mechanism. Likewise, a given inspection technique may be capable of detecting and characterizing multiple types of damage mechanisms but no single inspection technique is capable of detecting and characterizing all damage mechanisms.

7.2.1 Analyzing the Effect of Inservice Damage. Analyzing the effect of inservice damage and inspection on the probability of failure involves the following steps:

(a) Identify active and credible damage mechanisms and associated failure modes that are reasonably expected to occur during the time period being considered for both normal and upset conditions (see section 6).

(b) Determine the damage susceptibility and rate of the damage accumulation as a function of time. For example, a fatigue crack is driven by cyclic stress; corrosion damage is driven by the temperature, humidity, and/or corrosion current. A damage accumulation rule may be available to mathematically model this process. Rather than a given value of the magnitude of the damage mechanism driving forces, a statistical distribution of these forces may be available (see API RP 579).

(c) Determine the effectiveness of the inspection and maintenance programs as well as other mitigation actions. It is usually necessary to evaluate the probability of failure considering several alternative future mitigation strategies, possibly including a "no inspection" strategy.

(d) Determine the probability that under current conditions, continued damage at the predicted/expected rate will exceed the damage tolerance of the equipment item and result in a failure. The failure mode (e.g., small leak, large leak, equipment rupture) should also be predicated on the damage mechanism. It may be desirable in some cases to determine the probability of more than one failure mode and to combine the resulting risks.

7.2.2 Determine Failure Mode. Probability of failure analysis should be used to evaluate the failure mode (e.g., small hole, crack, catastrophic rupture) and the probability that each failure mode will occur. In a quantitative analysis, failure criteria may also be established. It is important to link the damage mechanism to the resulting failure mode(s). For example

(a) pitting often leads to small hole-sized leaks

(b) stress corrosion cracking may develop into small, through-wall cracks or, in some cases, may result in catastrophic rupture

(c) metallurgical damage and mechanical damage may lead to failure modes that vary from small holes to ruptures

(d) general thinning from corrosion may lead to larger leaks or rupture

Failure mode primarily impacts the magnitude of the consequences. For this and other reasons, the probability and consequence analyses should be worked interactively.

7.2.3 Determine the Damage Susceptibility and Rate. Combinations of process conditions and materials of construction for each equipment item should be evaluated to identify active and credible damage mechanisms (see section 6). Experienced materials or corrosion engineers should be consulted to obtain the best possible analysis. One method of determining these mechanisms and susceptibilities is to group components that have the same material of construction and are exposed to the same internal and external environment (including operating conditions). Inspection results from one item in the group may be related to the other equipment in the group.

For many damage mechanisms, the rate of damage progression is generally understood and can be estimated. Damage rate may be expressed in terms of corrosion rate for thinning or susceptibility for mechanisms where the damage rate is unknown or immeasurable (such as stress corrosion cracking). Susceptibility is often designated as high, medium, or low based on the environmental conditions and material of construction combination. Fabrication variables and repair history should also be considered.

The damage rate in specific equipment items is often not known with certainty. The ability to state the rate of damage precisely is affected by equipment complexity, type of damage mechanism, process and metallurgical variations, inaccessibility for inspection, limitations of inspection and test methods, and the inspector's expertise.

Sources of damage rate information are described in section 5.

Damage rates will often vary as the mechanism progresses. In some cases, the mechanism is self-limiting, i.e., after progressing to a certain point, damage will arrest. In other cases, damage will occur in a slow, stable manner until it reaches a point where failure occurs. In some cases, damage by one mechanism may progress to a point at which a different mechanism takes over to control the rate of further damage.

7.2.3.1 Parameters That May Influence the Damage Rate. The following parameters should be considered in the determination of damage rates:

(a) fluid stream composition, including electrolytes and ions in solution

(b) the temperature, humidity, and corrosiveness of the atmosphere or soil

(c) process temperature

(d) the flow velocity

(e) the amount of dissolved oxygen

(f) the phase of the fluid (liquid, vapor, or gas)

(g) the pH of the solution

(h) the contaminants in the flow stream

(i) the process operating phase (operation, shutdown, wash, etc.)

(j) the mechanical properties of the metal (hardness, cold work, grain size, etc.)

(k) the weld properties [heat treatment, hardness, residual stresses, sensitization, heat-affected zone (HAZ), inclusions, etc.]

(l) the component geometry (crevices, local turbulence, etc.)

(m) the coating and lining condition (no holiday)

(n) the relative size of anodic and cathodic regions

(o) the solubility of corrosion products

(p) the addition of corrosion inhibitors (type, quantity, and distribution)

7.2.3.2 Data and Information for Determining the Damage Rate. The following items may be considered in determining the damage rate:

(a) system-specific operating experience, including past inspections and maintenance records

(b) corrosion coupon results

(c) laboratory testing, standard ASTM or NACE tests, or fluid-specific tests

(d) experience on similar systems within the same facility
(e) company specifications and technical reports
(f) industry experience with the same process
(g) industry publications [see para. 5.3(g)]

7.2.4 Determine Effectiveness of Past Inspection Program. Inspection programs include
(a) NDE methods
(b) frequency of examination
(c) extent of coverage
(d) specific locations to be examined
(e) other inspection activities

7.2.4.1 Limitations of Effectiveness of Inspection Programs. Inspection programs vary in effectiveness for locating and sizing damage and thus for determining damage rates. After damage mechanisms have been identified, the inspection program should be evaluated to determine its effectiveness in finding the flaws that result from the identified damage mechanisms. In addition, the NDE methods should be evaluated to determine their effectiveness in characterizing and sizing flaws.

Limitations in the effectiveness of an inspection program could be due to
(a) lack of coverage of an area subject to damage.
(b) inherent limitations of some NDE methods to detect and quantify certain types of damage.
(c) selection of inappropriate NDE methods and tools.
(d) application of methods and tools by inadequately trained personnel.
(e) inadequate inspection procedures.
(f) human performance factors.
(g) damage rate is so high that failure can occur within a very short time. Even though no damage is found during an inspection, failure could still occur as a result of a change or an upset in conditions. For example, if a very aggressive acid is carried over from a corrosion-resistant part of a system into a downstream vessel that is made of carbon steel, rapid corrosion could result in failure in a few hours or days. Similarly, if an aqueous chloride solution is carried into a sensitized stainless steel vessel, chloride stress corrosion cracking could (depending on the temperature) occur very rapidly.

7.2.4.2 Considerations in Determining the Effectiveness of Inspection Programs. If multiple inspections have been performed, it is important to recognize that the most recent inspection may best reflect current operating conditions. If operating conditions have changed, damage rates based on inspection data from the previous operating conditions may not be valid.

Determination of inspection effectiveness should consider the following:
(a) equipment type and current condition
(b) active and credible damage mechanism(s)
(c) rate of damage or susceptibility
(d) NDE methods, coverage, and frequency
(e) accessibility to expected damage areas
(f) qualification, training, and skill of inspection personnel

The effectiveness of future inspections may be optimized by utilization of inspection methods better suited for the active/credible damage mechanisms, adjusting the inspection coverage, adjusting the inspection frequency, or a combination thereof.

7.2.5 Determine the Probability of Failure by Damage Mechanism. By combining the expected damage mechanisms, rates, or susceptibilities and past inspection data and effectiveness, a probability of failure may be determined for each damage mechanism type and associated failure mode. The probability of failure may be determined for future time periods or conditions as well as the current time frame. The method used should be validated to determine if the probability of failure is in fact thorough and adequate for the specific situation.

7.3 Units of Measure for Probability of Failure Analysis

Probability of failure is typically expressed as a frequency considering a fixed interval (e.g., events per year). For example, if two failures are expected for every 10,000 equipment years of operation, the probability of failure would be expressed as 0.0002 failures per year. The time frame may also be expressed as an occasion (e.g., one run length) and the frequency could be expressed as events per occasion (e.g., 0.03 failures per run). Another expression of probability is cumulative probability of failure as of a specific time. This is the probability of an event occurring up through the specific time. This latter expression is useful when the probability of failure is changing as a function of time.

For a qualitative analysis, the probability of failure may be categorized (e.g., high, medium, and low, or 1 through 6). However, it is appropriate to associate a probability range (frequency range) with each category to provide guidance to the individuals responsible for determining the probability of failure. If this is done, the change from one category to another could be one or more orders of magnitude or other appropriate demarcations that will provide adequate discrimination. See the following examples:

EXAMPLES:
(1) *Three Level*

Possible Qualitative Rank	Annual Failure Probability or Frequency
Low	< 0.0001
Moderate	0.0001–0.01
High	> 0.01

(2) *Six Level*

Possible Qualitative Rank	Annual Failure Probability or Frequency
Remote	< 0.00001
Very Low	0.00001–0.0001
Low	0.0001–0.001
Moderate	0.001–0.01
High	0.01–0.1
Very High	> 0.1

7.4 Types of Probability Analysis

The following paragraphs discuss different approaches to the determination of probability. For purposes of the discussion, these approaches have been categorized as "qualitative" or "quantitative." However, it should be recognized that "qualitative" and "quantitative" are the end points of a continuum rather than distinctive approaches (see Fig. 3.3.1). Most probability analyses use a blend of qualitative and quantitative approaches (sometimes referred to as semiquantitative).

The analysis should be structured such that a sensitivity analysis or other approach may be used to obtain realistic, though conservative, probability values (see para. 9.4).

7.4.1 Qualitative. A qualitative analysis involves identification of the equipment items, internal and external operating environment and conditions, the materials of construction, and damage mechanisms. On the basis of knowledge of the operating history, future inspection and maintenance plans, and possible damage mechanisms, probability of failure may be assessed separately for each grouping or individual equipment item. Engineering judgment should be the basis for this analysis. A probability of failure category may then be assigned for each grouping or individual equipment item. Depending on the methodology employed, the categories may be described with words (such as high, medium, or low) or may have numerical descriptors (such as 0.01 to 0.1 times per year).

7.4.2 Quantitative. There are several methodologies for quantitative probability analysis (see Nonmandatory Appendix D). One example is to take a probabilistic approach where specific failure data and/or expert elicitations are used to calculate probabilities of failure. These failure data may be obtained on the specific equipment item in question or on similar equipment items. The probability may be expressed as a distribution rather than a single deterministic value.

When inaccurate or insufficient failure data exist on the specific equipment item of interest, general industry, company, or manufacturer failure data may be used. However, the applicability of generic data to the specific equipment item being assessed should be validated. As appropriate, the generic failure data should be adjusted and made specific to the equipment being analyzed by increasing or decreasing the predicted failure frequencies based on equipment-specific information. In this way, generic failure data are used to generate an adjusted failure frequency that may be applied to a specific equipment item. Such modifications to generic data may be made for each equipment item to account for the potential damage that may occur in the particular service and the type and effectiveness of inspection and/or monitoring performed. Knowledgeable personnel should make these modifications on a case-by-case basis using expert opinion elicitation as appropriate.

8 DETERMINING CONSEQUENCE OF FAILURE

8.1 Introduction to Consequence Analysis

The consequence of failure analysis should be performed to estimate the consequences that occur due to a failure mode typically resulting from an identified damage mechanism(s) (see section 6). The consequence analysis should result in a simplified, but repeatable and credible estimate of the results of a failure in the equipment item being analyzed. Consequences should generally be categorized as

(*a*) safety and health impacts
(*b*) environmental impacts
(*c*) economic impacts

The consequence analysis should address all failure modes to which the equipment item is susceptible. More or less complex and detailed methods of consequence analysis may be used, depending on the desired application for the analysis. The consequence analysis method chosen should have a demonstrated ability to provide the required level of discrimination between higher and lower consequence equipment items.

8.2 Other Functional Failures

Although RBI is mainly concerned with failures that result in loss of containment, other functional failures could be included in an RBI study if a user desired. Since these other failures are usually covered in reliability-centered maintenance (RCM) or other programs, they are not covered in detail in this Standard. However, the general concepts of RBI are applicable. Examples of other functional failures are

(*a*) functional or mechanical failure of internal components (e.g., column trays, demister mats, coalescer elements, distribution hardware).

(*b*) heat exchanger tube failure. Although tube failures rarely lead to loss of containment for adequately designed heat exchangers, such failures may affect the performance or function of the equipment.

(*c*) pressure relief device failure.

(*d*) rotating equipment failure (e.g., seal leaks, impeller failures, turbine blade failures).

8.3 Types of Consequences and Units of Measure

The types of consequences that should be considered and the common units of measure for each are described in paras. 8.3.1 through 8.3.7. Appropriate units of measure should be selected depending on the analysis approach. Consequence measures should be comparable to the extent practicable for subsequent risk prioritization. Consequences should be expressed in monetary units to the maximum extent practicable as described in the following paragraphs. Consequences that are difficult to monetize, such as safety, health, and environmental, may be placed into consequence categories as described in para. 8.3.5. "Affected area" is sometimes used instead of monetary units or other measures described for each type of consequence. Affected area is a general measure covering all consequence types as described in para. 8.3.8.

8.3.1 Safety and Health Impacts. Safety and health consequences include injuries, illnesses, and fatalities.

8.3.2 Safety and Health Consequence Measures. Safety and health consequences should be characterized by a consequence category associated with the severity of potential injuries and illnesses including fatalities (see para. 8.3.5). For example, safety consequences could be expressed based on the severity of an injury (e.g., fatality, serious injury, medical treatment, first aid) or expressed as a category linked to the injury severity (e.g., a six-category ranking such as A through F). Alternatively, a probability of failure safety limit could be used as described in ASME CRTD-41. A widely accepted approach for assigning monetary values to safety and health consequences is not currently available, however the Federal Aviation Administration has published material on this topic. If it is necessary to convert safety and health consequences into monetary units for subsequent risk ranking or analysis, the analyst should docu

8.3.3 Environmental Impacts. The RBI program typically focuses on acute and immediate environmental consequences. Chronic consequences from low-level emissions should generally be addressed by other programs.

The environmental consequence should typically be derived from the following elements:

(a) volume of fluid released
(b) ability to flash to vapor
(c) leak containment safeguards
(d) environmental resources affected
(e) regulatory consequence (e.g., citations for violations, fines, potential shutdown by authorities)

Liquid releases may result in contamination of soil, groundwater, and/or open water, requiring remediation. Gaseous releases are equally important but more difficult to assess since the consequence typically relates to local regulatory constraints (threshold quantities) and the penalty for exceeding those constraints.

8.3.4 Environmental Consequence Measures. Environmental consequence measures are the least developed among those currently used for risk analysis. A common unit of measure for environmental damage is not available in the current technology, making environmental consequences difficult to assess. Typical parameters used that provide an indirect measure of the degree of environmental damage are

(a) acres of land affected per year
(b) miles of shoreline affected per year
(c) number of biological or human-use resources consumed

However, the portrayal of environmental damage almost invariably leads to the use of cost, in terms of dollars per year, for the loss and restoration of environmental resources. The cost may be calculated as follows:

$$\text{environmental cost} = \text{cost for cleanup} + \text{cost of fines} + \text{other costs}$$

8.3.4.1 Considerations in Determining Environmental Cost. The cleanup cost will vary depending on many factors, including

(a) type of spill (aboveground, belowground, surface water, etc.)
(b) volume of spill
(c) type of liquid (toxic, reactive, flammable, explosive)
(d) method of cleanup
(e) accessibility and terrain at the spill location

The determination of any fines that may be imposed depends on the regulations and laws of the applicable local and federal jurisdictions.

The other component includes costs that may be associated with the spill such as lawsuits by landowners or other parties or cost associated with loss of use. This component is typically specific to the location of the facility.

8.3.5 Safety, Health, and Environmental Consequence Categories. Guidance on placing safety, health, and environmental consequences into categories is provided in Tables 8.3.5-1 and 8.3.5-2. Table 8.3.5-1 shows three levels, while Table 8.3.5-2 shows six levels. In practice, other numbers of levels could be used.

8.3.6 Economic Impacts. Typical economic consequences include

(a) production loss due to rate reduction or downtime as lost opportunity cost
(b) deployment of emergency response equipment and personnel
(c) lost product
(d) degradation of product quality
(e) replacement or repair of damaged equipment
(f) property damage off-site
(g) spill/release cleanup on-site or off-site
(h) loss of market share

Table 8.3.5-1 Three-Level Safety, Health, and Environmental Consequence Categories

Category	Safety Consequence	Health Consequence	Environmental Consequence
High	Fatality or injury with permanent disability	Long-term health effects	Major off-site response and cleanup effort
Moderate	Lost time injury with full recovery expected	Short-term health effect with full recovery expected	Minor off-site, but possible major on-site response
Low	First aid only injury	Minimal health impact	Minor on-site response

Table 8.3.5-2 Six-Level Safety, Health, and Environmental Consequence Categories

Category	Description	Examples
I	Catastrophic	Large number of fatalities, and/or major long-term environmental impact.
II	Major	A few fatalities, and/or major short-term environmental impact.
III	Serious	Serious injuries, and/or significant environmental impact.
IV	Significant	Minor injuries, and/or short-term environmental impact.
V	Minor	First aid injuries only, and/or minimal environmental impact.
VI	Insignificant	No significant consequence.

(*i*) injuries or fatalities
(*j*) land reclamation
(*k*) litigation
(*l*) fines
(*m*) loss of goodwill

8.3.7 Economic Consequence Measures. Economic consequences may be expressed in monetary units. It is possible, although not always practicable, to assign a monetary value to almost any type of consequence. However, in practice some monetary values are neither practicable nor necessary to use in a risk analysis. The cost associated with most of the consequences listed in para. 8.3.6 can be calculated using standard methods, so further discussion is not provided in this Standard. However, guidance on some of the consequences is provided in the following paragraphs.

Information such as product value, capacity, equipment costs, repair costs, personnel resources, and environmental damage may be difficult to derive, and the manpower required to perform a complete financial-based consequence analysis may be limited depending on the complexity of the relationship of failure to lost opportunity cost. However, expressing consequences in monetary units has the advantage of permitting a direct comparison of the various categories of consequences on a common basis. Therefore, it is often better to provide approximations or "best estimates" than to use only verbal descriptions (see para. 8.4.1).

Instead of determining point values or unique ranges of economic loss for each consequence scenario, consequences may be placed into categories that have predefined ranges. Table 8.3.7 provides an example of this. The ranges should be adjusted for the unit or plant to be considered. For example, $10,000,000 may be a catastrophic loss for a small company, but a large company may consider only losses greater than $1,000,000,000 to be catastrophic.

8.3.7.1 Business Interruption Costs. Calculation of business interruption costs can be complex. These costs include lost opportunity cost (production loss), and impact on future business. In many cases, equipment replacement costs may be very low compared to the business loss of a critical unit for an extended period of time. The selection of a specific method of cost analysis depends on

(*a*) the scope and level of detail of the study
(*b*) availability of business interruption data

8.3.7.1.1 Lost Opportunity Cost (Production Loss). Lost opportunity cost is typically associated with production loss. Production losses generally occur with any loss of containment of the process fluid and often with a loss of containment of a utility fluid (water, steam, fuel gas, acid, caustic, etc.). Production losses may be in addition to or independent of flammable events, toxic releases, or other hazardous fluid release. A simple method for estimating the lost opportunity cost is to use the equation

$$\text{lost opportunity cost} = \text{process unit daily value} \times \text{downtime (days)}$$

The unit daily value could be on a revenue or profit basis. The downtime estimate represents the time required to get back into production. The Dow Fire and Explosion Index is a typical method of estimating downtime after a fire or explosion.

8.3.7.1.2 Considerations in Determining Lost Opportunity Costs. Site-specific circumstances should be considered in the business interruption analysis to

Table 8.3.7 Six-Level Table

Category	Description	Economic Loss Range
I	Catastrophic	≥ $100,000,000
II	Major	≥ $10,000,000 but < $100,000,000
III	Serious	≥ $1,000,000 but < $10,000,000
IV	Significant	≥ $100,000 but < $1,000,000
V	Minor	≥ $10,000 but < $100,000
VI	Insignificant	< $10,000

avoid overstating or understating this consequence. Examples of these considerations include

(a) ability to compensate for damaged equipment (e.g., spare equipment, rerouting)

(b) lost production may be compensated at another underutilized or idle facility

(c) loss of profit could be compounded if other facilities use the unit's output as a feedstock or processing fluid

(d) potential for damage to nearby equipment (knock-on damage)

(e) repair of small-damage-cost equipment may take as long as large-damage-cost equipment

(f) extended downtime may result in losing customers or market share, thus extending loss of profit beyond production restart

(g) loss of hard to get or unique equipment items or material may require extra time to obtain replacements

8.3.7.2 Lost Fluid Cost. The cost of the lost fluid may be calculated by

$$\text{lost fluid cost} = \text{volume of fluid lost} \times \text{value of the fluid per unit volume}$$

8.3.7.3 Maintenance and Reconstruction Costs. Maintenance and reconstruction cost represents the cost required to correct the failure and to repair or replace equipment damaged in the subsequent events (e.g., fire, explosion). For some reactive fluids, contact with equipment or piping may result in damage and failure. This damage should be considered. The maintenance and reconstruction cost should be accounted for in the analysis.

8.3.8 Affected Area Approach to Consequence Measurement. Consequences may be expressed in terms of affected area. As its name implies, affected area represents the amount of surface area that experiences an effect (toxic dose, thermal radiation, explosion overpressure, etc.) greater than a pre-defined limiting value. Based on the thresholds chosen, anything — personnel, equipment, environment — within the area will be affected by the consequences of the failure.

In order to rank consequences according to affected area, it should normally be assumed that equipment or personnel are evenly distributed throughout the area under consideration. A more rigorous approach would assign a population density with time or equipment value density to different locations within the area under consideration.

The units of measure for affected area (square feet or square meters) do not readily translate into our everyday experiences because most people think of consequences in terms of costs and personnel impact. Therefore, there is some reluctance to use this measure. It has, however, several features that merit consideration. The affected area approach has the characteristic of being able to compare consequences resulting from different hazards (fire, explosion, toxic release, etc.) by relating the consequence to the physical area impacted by the hazard.

8.3.9 Other Considerations. The following should be considered in addition to the consequences described above:

(a) loss of reputation leading to loss of market share

(b) future insurability

(c) regulatory actions curtailing production or raising costs

It is usually possible to develop a monetary estimate for these considerations.

8.4 Analysis of the Consequence of Failure

The following paragraphs discuss different approaches to the determination of consequences of failure. For the purposes of the discussion, these approaches have been categorized as "qualitative" or "quantitative." However, it should be recognized that "qualitative" and "quantitative" are the end points of a continuum rather than distinctive approaches (see Fig. 3.3.1).

8.4.1 Qualitative. A qualitative analysis (see para. 3.3.1) is based primarily on engineering judgment. Consequence of failure (safety, health, environmental, production, maintenance, reconstruction) should be analyzed for each unit, system, equipment group, or individual equipment item.

For a qualitative method, a consequence category (such as "A" through "F" or "high," "medium," or "low") should be assigned for each unit, system, grouping, or equipment item. It may be appropriate to associate a numerical range, such as economic values (see para. 8.3.7) with each consequence category.

8.4.2 Quantitative. A quantitative analysis (see para. 3.3.2) involves using logic models (e.g., event trees or fault trees) depicting sequences and combinations of events to represent the effects of failure on people, property, business, and the environment. Quantitative models usually contain one or more standard failure scenarios or outcomes and typically calculate consequence of failure based on

(a) type of process fluid in equipment

(b) state of the process fluid inside the equipment (solid, liquid, gas, or mixed)

(c) key properties of process fluid (molecular weight, boiling point, auto-ignition temperature, ignition energy, density, etc.)

(d) process operating variables such as temperature and pressure

(e) mass of inventory available for release in the event of a leak considering the ability and time to isolate the leak

(f) failure mode and resulting leak size

(g) state of fluid after release at ambient conditions (solid, gas, or liquid)

Results of a quantitative analysis should be numeric. Consequence categories may be also used to organize more quantitatively assessed consequences into manageable groups.

8.4.3 Analysis Results. Even though numeric values and processes may be used, the qualitative region of the spectrum tends to have consequences expressed in order of magnitude ranges based on experience and engineering judgment. The quantitative method provides higher levels of resolution with the use of probabilistic distributions.

Comparing or combining analyses from different sources may be problematic. The analyst should review the approaches and criteria used to determine whether the results are comparable.

8.4.4 Predicting Outcome. In a risk analysis, the outcome of a release of hazardous material refers to the physical behavior of the hazardous material. Examples of outcomes are safe dispersion, explosion, jet fire, etc. Outcome should not be confused with consequence. For risk analysis, consequence is the adverse effect on people, the environment, production, and maintenance/reconstruction costs as a result of the outcome.

The actual outcome of a release depends on the nature and properties of the material released. A brief discussion of possible outcomes for various types of events is provided in paras. 8.4.4.1 through 8.4.4.4.

8.4.4.1 Flammable Effects. Six possible outcomes may result from the release of a flammable fluid.

(a) Safe dispersion occurs when flammable fluid is released and then disperses without ignition. The fluid disperses to concentrations below its flammable limits before it encounters a source of ignition. Although no flammable outcome occurs, it is still possible that the release of a flammable material (primarily liquids) could cause adverse environmental effects. Environmental events should be addressed separately.

(b) Jet fires result when a high-momentum gas, liquid, or two-phase release is ignited. Radiation levels are generally high close to the jet. If a released material is not ignited immediately, a flammable plume or cloud may develop. On ignition, this may "flash" or burn back to form a jet fire.

(c) Explosions occur under certain conditions when a flame front travels very quickly. Explosions cause damage by the overpressure wave that is generated by the flame front. They may occur if a release results in a large cloud prior to ignition. For releases of vapor or liquids that vaporize, vapor cloud ignition is a major concern.

(d) Flash fires occur when a cloud of material burns under conditions that do not generate significant overpressure. Consequences from a flash fire are only significant within the perimeter and near the burning cloud. Flash fires do not cause overpressures high enough to damage equipment.

(e) Fireballs occur when a large quantity of fuel ignites after it has undergone only limited mixing with the surrounding air. Thermal effects from the fireball extend well beyond the boundaries of the fireball, but they are usually short-lived.

(f) Pool fires are caused when liquid pools of flammable materials ignite. The effects of thermal radiation are limited to a region surrounding the pool itself.

8.4.4.2 Toxic Effects. Two outcomes are possible when a toxic material is released: safe dispersal or manifestation of toxic effects.

In order for a toxic effect to occur, the following conditions must be met:

(a) The release must reach people in a sufficient concentration.

(b) It must linger long enough for the effects to become harmful.

If either of the conditions is not met, the release of the toxic material results in safe dispersal, indicating that the incident falls below the pass/fail threshold (e.g., API 581).

If both of the above conditions (concentration and duration) are met, and people are present, toxic exposure will occur.

8.4.4.3 Environmental Effects. From an environmental standpoint, safe dispersal occurs if the released material is entirely contained within the containment (dike) area of a facility. If the material soaks into the soil, ground water contamination could result.

8.4.4.4 Business Interruption Effects. Business interruption effects should be considered in the analysis.

These effects should typically be determined by estimating the time that will be needed to repair and return to full service equipment as postulated by the failure scenario.

8.5 Determination of Consequence of Failure

The consequences of releasing a hazardous material should be estimated in six steps (see Fig. 8.5). Each step should be performed using the assumption of a specific scenario. The steps should be repeated for each credible scenario.

(a) Estimate the release rate.

(b) Estimate total volume of fluid that will be released.

(c) Determine if the fluid is dispersed in a rapid manner (instantaneous) or slowly (continuous).

(d) Determine if the fluid disperses in the atmosphere as a liquid or a gas.

(e) Estimate the impacts of any existing mitigation system.

(f) Estimate the consequences.

8.5.1 Factors for Estimating Consequences. Estimate the consequences of a failure from equipment items considering such factors as physical properties of the contained material, its toxicity and flammability, type of release and release duration, weather conditions and dispersion of the released contents, and mitigation actions. Consider the impact on plant personnel and equipment, population in the nearby communities, and the environment. Lost production, loss of raw material, and other losses should also be considered. Several credible consequence scenarios may result from a single failure mode (release) and consequences should be determined by constructing one or more scenarios to describe a credible series of events following the initial failure. For example, a failure may be a small hole resulting from general corrosion. If the contained fluid is flammable, the consequence scenarios could include: small release without ignition, small release with ignition and small release with ignition and subsequent catastrophic failure (rupture) of the equipment item. The following shows how a consequence scenario may be constructed:

(a) Consequence Phase 1: Discharge. Consider the type of discharge (sudden versus slow release of contents) and its duration.

(b) Consequence Phase 2: Dispersion. Consider the dispersion of the released contents due to weather conditions.

(c) Consequence Phase 3: Flammable Events. The consequences should be estimated for the scenario based on the flammability of the released contents (i.e., impact of a resulting fire or explosion on plant personnel and equipment, community, environment) (see para. 8.7.1.1).

(d) Consequence Phase 4: Toxic Releases. The consequences should be estimated for the scenario based on the toxicity of the released contents (i.e., impact due to toxicity on plant personnel, community, and the environment) (see para. 8.7.2.1).

(e) Consequence Phase 5: Releases of Other Hazardous Fluids. The consequences should be estimated for the scenario based on the characteristics of the released contents (i.e., impact due to thermal or chemical burns on plant personnel, community, and the environment) (see para. 8.7.3)

(f) Potential Fatalities and Injuries. The potential number of fatalities and injuries resulting from each scenario should be estimated. Different scenarios, with different associated probabilities, should be developed as appropriate.

8.5.2 Factors for More Rigorous Methods. Each scenario will have an associated overall probability of occurrence that will be lower than the probability of the failure itself so that the probability of failure and consequence of failure should be developed interactively.

After the scenarios have been developed and potential consequences estimated, acceptable ways to list consequences include

(a) classify consequence into three or more categories (e.g., a five-category classification system might be very low, low, moderate, high, very high)

(b) rank consequence on a scale (e.g., a scale might be from one to ten)

(c) measure consequence (e.g., determine the estimated number of fatalities for a scenario and the economic losses in monetary units)

Consequences should be expressed in monetary units (e.g., dollars) to the maximum extent practicable. For example, low, moderate, and high categories could be assigned values of $10,000, $100,000 and $1,000,000 respectively. This will permit adding the different consequences of a single event and facilitate comparisons of risk from one process unit to another. Potential injuries and fatalities may be considered separately, with a maximum acceptable probability of occurrence assigned.

8.6 Volume of Fluid Released

In most consequence analyses, a key element in determining the magnitude of the consequence should be the volume of fluid released. The volume released should typically be derived from a combination of the following:

(a) volume of fluid available for release — volume of fluid in the piece of equipment and connected equipment items. Simplistically, this is the amount of fluid between isolation valves that can be quickly closed.

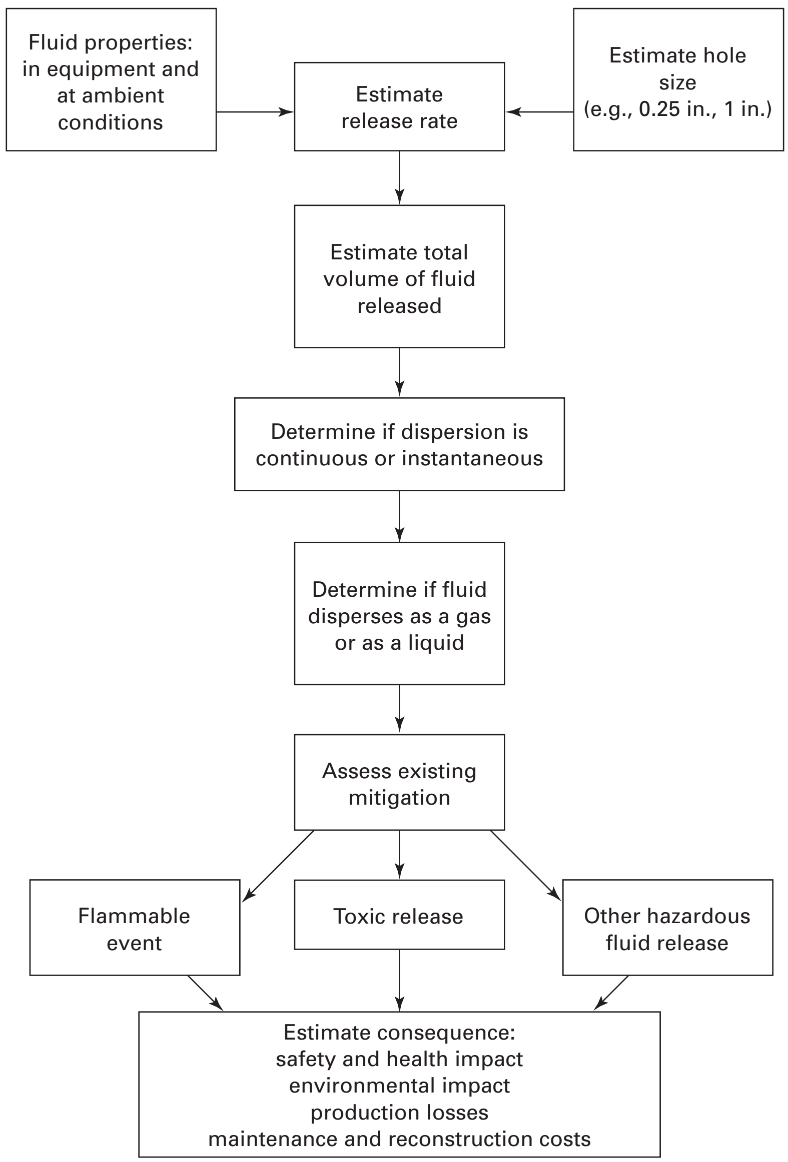
(b) failure mode.

(c) release rate.

(d) detection and isolation time.

In some cases the volume released will be the same as the volume available for release. Usually, there are safeguards and procedures in place so that a loss of

Fig. 8.5 Determination of Consequence of Failure



containment can be isolated and the volume released will be less than the volume available for release.

8.7 Hazard Categories

A loss of containment and subsequent release of fluids may cause adverse consequences (i.e., impact safety, health, and environment, cause production losses, and incur maintenance and reconstruction costs). The risk analyst should consider the nature of the hazards and ensure that appropriate factors are considered for the equipment items being assessed.

Regardless of whether a more qualitative or quantitative analysis is used, factors to consider in assessing the consequences of failure are described below.

8.7.1 Flammable Events (Fire and Explosion). Flammable events occur when both a leak and ignition occurs. The ignition could be through an ignition source or by auto-ignition. Flammable events may cause damage in two ways: thermal radiation and blast overpressure. Most of the damage from thermal effects tends to occur at close range, but blast effects may cause damage over a larger distance from the blast center. Typical categories of fire and explosion events include

(a) vapor cloud explosion
(b) pool fire
(c) jet fire
(d) flash fire
(e) boiling liquid expanding vapor explosion (BLEVE)

8.7.1.1 Consequence of Flammable Events. The consequence of flammable events should typically be derived from a combination of the following elements:

(a) location and type of ignition sources
(b) volume of fluid released
(c) ability to flash to a vapor
(d) possibility of auto-ignition
(e) effects of higher pressure operations
(f) engineered safeguards
(g) personnel, equipment, and infrastructure exposed to damage (on-site and off-site)

8.7.2 Toxic Releases. Toxic releases may cause effects at greater distances than flammable events and, unlike flammable events, toxic releases do not require an additional event (e.g., ignition, as in the case of flammables) to cause personnel injuries. The RBI program typically focuses on acute toxic risks that create an immediate danger. Chronic risks from low-level exposures should typically be addressed by other programs.

8.7.2.1 Consequences of Toxic Releases. Consequence should typically be derived from a combination of the following elements:

(a) volume of fluid released and toxicity
(b) ability to disperse under the expected range of process and environmental conditions
(c) detection and mitigation systems
(d) population in the vicinity of the release

8.7.3 Releases of Other Hazardous Fluids. Other hazardous fluid releases are of most concern in RBI analyses when they affect personnel. These fluids may cause thermal or chemical burns if a person comes in contact with them. Common fluids, including steam, hot water, acids, and caustics may have a safety consequence and should be considered as part of an RBI program. Generally, the consequence of this type of release is significantly lower than for flammable events or toxic releases because the affected area is likely to be much smaller and the magnitude of the hazard is less.

Consequence should typically be derived from a combination of the following elements:

(a) volume of fluid released
(b) personnel density in the area
(c) type of fluid and nature of resulting injury
(d) safety systems (e.g., personnel protective clothing, showers)

9 RISK DETERMINATION, ANALYSIS, AND MANAGEMENT

9.1 Introduction

This section describes the process of determining risk by combining the results of work done as described in sections 7 and 8. It also provides guidelines for prioritizing and assessing the acceptability of risk with respect to risk criteria. This work process leads to creating and implementing a risk management plan.

Risk should be determined by combining the probability of failure (results of work done as described in section 7) and the consequence of failure (results of the work done as described in section 8). The general form of the risk equation should be as follows:

$$\text{risk} = \text{probability} \times \text{consequence}$$

9.2 Determination of Risk

9.2.1 Determination of the Probability of a Specific Consequence. The probability of each credible consequence scenario should be determined keeping in mind that the failure of the equipment item (e.g., loss of containment) may be only one event in a series of events that leads to a specific consequence. For example, a specific consequence (economic loss, injury, environmental damage, etc.) may be the result of a series of events along an event tree, such as

(a) local thinning
(b) leak (loss of containment)
(c) initiation or failure of safeguards (isolation, alarms, etc.)
(d) dispersion, dilution, or accumulation of the released fluid
(e) initiation of or failure to initiate preventative action (shutting down nearby ignition sources, neutralizing the fluid, etc.)

The event tree continues until the probability of each final consequence has been determined.

It is important to understand this link between the probability of failure (POF) and the probability of possible resulting events. When a specific consequence is the result of a series of events, the probability of the specific consequence is less than the probability of failure for the equipment item. Further, the probability of a specific consequence is tied to the severity of the consequence and probabilities of events generally decrease with the severity of the incident. For example, the probability of a failure resulting in a fatality will generally be less than the probability that the failure will result in a first aid or medical treatment injury.

The probability of failure of an equipment item is often incorrectly linked with the most severe consequences that can be envisioned. An extreme example would be automatically linking the POF of a damage mechanism where the failure mode is a leak due to a small hole with the consequence of a major fire. This would lead to an overly conservative risk analysis since a small leak does not always result in a major fire. Each type of damage mechanism has its own characteristic failure mode(s). For a specific damage mechanism, the expected mode(s) of failure should be taken into account when considering the probability of incidents in the aftermath of an equipment failure. For example, the consequences expected from a small leak could be very different than the consequences from a brittle fracture.

The example in Fig. 9.2.1 serves to illustrate how the probability of a specific consequence could be determined. The example has been simplified and the numbers used are purely hypothetical.

9.2.2 Calculate Risk. Refer back to the risk equation

$$\text{risk} = \text{probability} \times \text{consequence}$$

It is now possible to calculate the risk for each specific consequence. The risk equation may now be stated as

$$\begin{aligned} &\text{risk of a specific consequence} \\ &= \text{probability of a specific consequence} \\ &\quad \times \text{specific consequence} \end{aligned}$$

The total risk for all consequences is the sum of the individual risks for each specific consequence. Typically, there will be several credible consequences that should be evaluated; however, based on engineering judgment it is often possible to determine a dominant probability/consequence pair, such that it is not necessary to include every credible scenario in the analysis. Engineering judgment and experience should be used to eliminate noncredible cases.

If probability and consequence are not expressed as numerical values, risk should usually be determined by plotting the probability and consequence on a risk matrix (refer to para. 9.5). Probability and consequence pairs for various scenarios may be plotted to determine the risk associated with each scenario. Note that when a risk matrix is used, the probability to be plotted should be the probability of the associated consequence, not the probability of failure.

9.3 Assumptions

Assumptions or estimates of input values are often used when consequence and/or probability of failure data are not available. Even when data are known to exist, conservative estimates may be utilized in an initial analysis pending input of future process or engineering modeling information, such as a sensitivity analysis. Caution is advised in being too conservative because overestimating consequences and/or probability of failure values will unnecessarily inflate the calculated risk values. Presenting overly conservative risk values may mislead inspection planners, management, and insurers, and may create a lack of credibility for the user and the RBI process.

9.4 Sensitivity Analysis

Understanding how each variable influences the risk calculation is important for identifying those input variables that deserve closer scrutiny versus those variables that may be less significant. This is more important when performing risk analyses that are more detailed and quantitative in nature.

Sensitivity analysis typically involves varying some or all input variables to the risk calculation over their credible range to determine the overall influence on the resultant risk value. Once this analysis has been performed, the user can see which input variables significantly influence the risk value and deserve the most focus or attention.

It often is worthwhile to gather additional information on such variables. Typically, the preliminary estimates of probability and consequence may be too conservative or too pessimistic; therefore, the information gathering performed after the sensitivity analysis should be focused on developing more certainty for the key input variables. This process should ultimately lead to a reevaluation of the key input variables increasing the quality and accuracy of the risk analysis.

9.5 Risk Communication

Once risk values have been developed, they may then be presented in a variety of ways to communicate the results of the analysis to decision makers and inspection planners. One goal of the risk analysis should be to communicate the results in a common format that a variety of people can understand. Using a risk matrix or plot is helpful in accomplishing this goal.

9.5.1 Risk Matrix. For risk ranking methodologies that use consequence and probability categories (e.g., for safety, health, and environmental risks), presenting

Fig. 9.2.1 Example of Calculating the Probability of a Specific Consequence

An equipment item containing a flammable fluid is being assessed.

The probability of a specific consequence should be the product of the probability of each event that could result in the specific consequence. In this example, the specific consequence being evaluated is a fire (an example event tree starting with a loss of containment is shown below). The probability of a fire would be

$$\text{probability of fire} = (\text{probability of failure}) \times (\text{probability of ignition})$$

$$\text{probability of fire} = 0.001 \text{ per year} \times 0.01 = 0.00001 \text{ or } 1 \times 10^{-5} \text{ per year}$$

The probability of no fire encompasses two scenarios (loss of containment without ignition and no loss of containment). The probability of no fire would be

$$\text{probability of no fire} = (\text{probability of failure} \times \text{probability of nonignition}) + \text{probability of no failure}$$

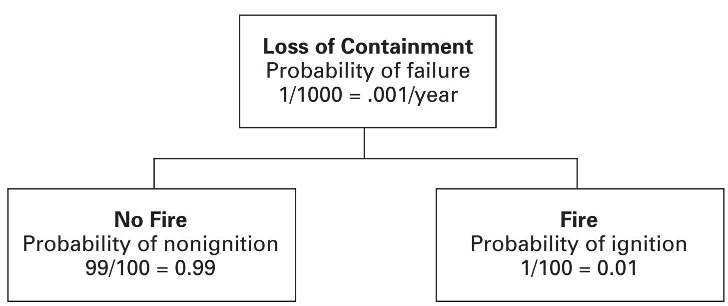
$$\text{probability of no fire} = (0.001 \text{ per year} \times 0.99) + 0.999 \text{ per year} = 0.99999 \text{ per year}$$

Note that the probability of all consequence scenarios should equal 1.0. In the example, the probability of the specific consequence of a fire (1×10^{-5} per year) plus the probability of no fire (0.999999 per year) equals 1.0.

If the consequence of a fire had been assessed at $\$1 \times 10^7$ then the resulting risk would be

$$\text{risk of fire} = (1 \times 10^{-5} \text{ per year}) \times (\$1 \times 10^7) = \$100/\text{year}$$

(a) Sample Assessment



(b) Example Event Tree

the results in a risk matrix is a very effective way of communicating the distribution of risks throughout a plant or process unit without assigning numerical values. An example risk matrix is shown in Fig. 9.5.1. In this figure, the consequence and probability categories are arranged such that the highest risk ranking is toward the upper right-hand corner. It is usually desirable to associate numerical values with the categories to provide guidance to the personnel performing the analysis (e.g., probability category C ranges from 0.001 to 0.01). Different sizes of matrices may be used (e.g., 6 × 6, 5 × 5, 4 × 5, 3 × 3). Regardless of the matrix selected, the consequence and probability categories should provide sufficient discrimination among the items assessed.

Risk categories may be assigned to the boxes on the risk matrix. An example risk categorization (higher, moderate, lower) of the risk matrix is shown in Fig. 9.5.1. In this example, the risk categories are symmetrical. They may also be asymmetrical where, for example, the consequence category may be given higher weighting than the probability category. However, it is important to recognize that a low risk may be associated with either a low probability and high consequence or high probability and low consequence. The risk matrix may be used for either risk ranking or for establishing a threshold of acceptable risk.

9.5.2 Risk Plots. When probability and consequence have been quantified, and/or where showing numeric risk values is more meaningful to the stakeholders, a risk plot (or graph) may be used (see Fig. 2.1). This graph is constructed similarly to the risk matrix in that the highest risk is plotted toward the upper right-hand corner. Often a risk plot is drawn using log-log scales for a better understanding of the relative risks of the items assessed. In the example plot in Fig. 2.1, ten pieces of equipment are shown, as well as an iso-risk line (line of constant risk). If this line is the acceptable threshold of risk in this example, then equipment items 1, 2, and 3 should be mitigated so that their residual (mitigated) risk levels fall below the line.

9.5.3 Numerical Risk Values. Risk may be described in terms of dollars or other numerical values, as described in para. 9.2, even if a qualitative analysis has been performed and the results have been plotted on a risk matrix. Numerical values associated with each of the probability and consequence categories on the risk matrix may be used to calculate the risk. For cost-related risk, a net present value savings (NPVS) versus inspection time plot may be used to time the inspection to avoid the highest risk.

9.5.4 Using a Risk Plot, Matrix, or Numerical Values. Equipment items residing towards the upper right-hand corner of the plot or matrix (in the examples presented) will most likely take priority for mitigation because these items have the highest risk. Similarly, items residing toward the lower left-hand corner of the plot (or matrix) will tend to take lower priority because these items have the lowest risk. Once the plots have been completed, the risk plot (or matrix) may then be used as a screening tool during the prioritization process. When numerical values are used, the highest numerical risk will have the highest priority.

9.6 Establishing Acceptable Risk Thresholds

After the risk analysis has been performed, and risk values plotted, the risk evaluation process begins. Risk plots, matrices, and numerical values may be used to screen and initially identify higher, moderate, and lower risk equipment items. The equipment may also be ranked (prioritized) according to its risk value in tabular form. Thresholds that divide the risk plot, matrix, or table into acceptable and unacceptable regions of risk may be developed. Corporate safety and financial policies and constraints or risk criteria influence the placement of the thresholds. Regulations and laws may also specify or assist in identifying the acceptable risk thresholds.

Reduction of some risks may not be practical due to technology and cost constraints. An "as low as reasonably practical" (ALARP) approach to risk management or other risk management approach may be necessary for these items.

9.7 Risk Management

Based on the ranking of items and the risk threshold, the risk management process begins. For risks that are judged acceptable, no mitigation may be required and no further action is necessary.

For risks considered unacceptable and therefore requiring risk treatment, there are various mitigation categories that should be considered.

(a) *Decommission* — Is the equipment really necessary to support unit operation?

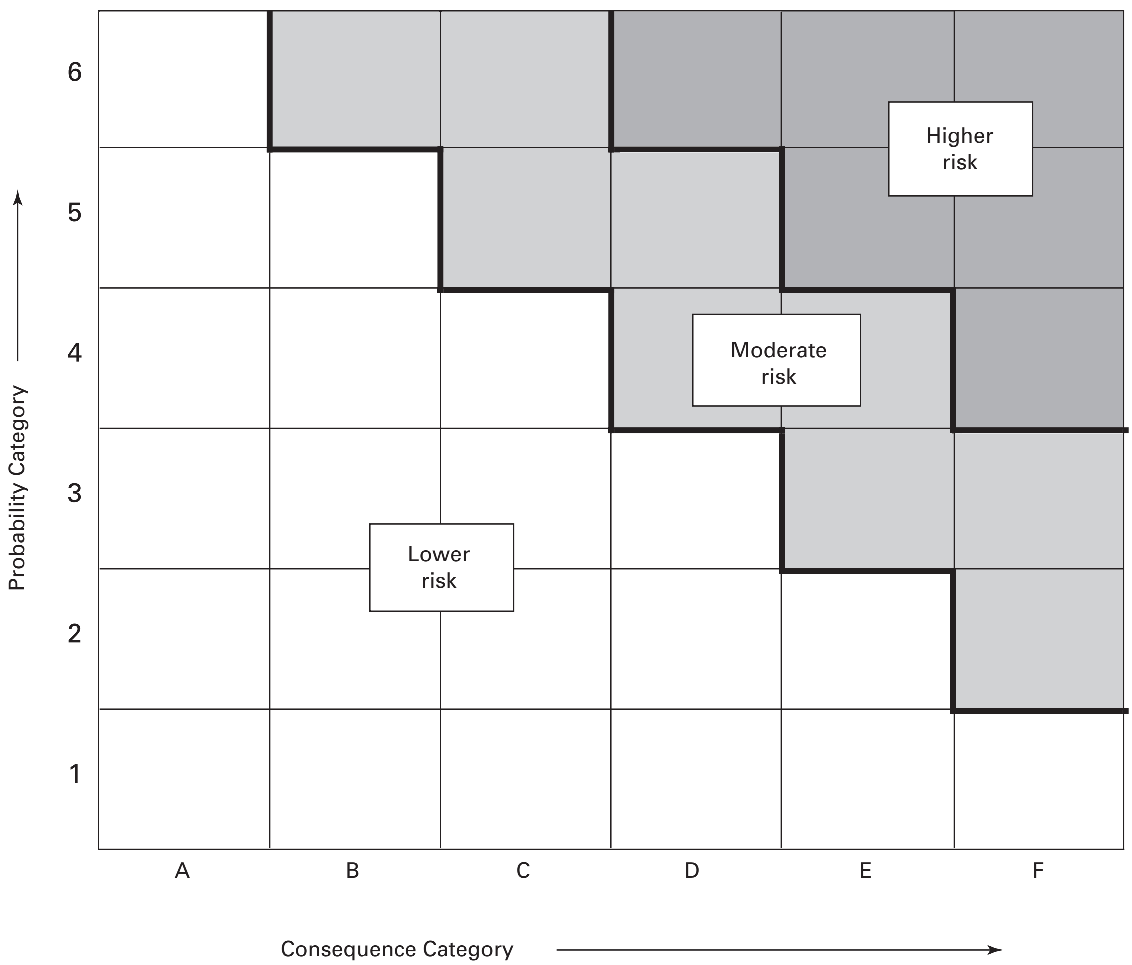
(b) *Inspection/Condition Monitoring* — Can a cost-effective inspection program, with repair as indicated by the inspection results, be implemented that will reduce risks to an acceptable level?

(c) *Consequence Mitigation* — Can actions be taken to lessen the consequences related to an equipment failure?

(d) *Probability Mitigation* — Can actions be taken to lessen the probability of failure such as metallurgy changes or equipment redesign?

9.7.1 Using Decision Analysis and Optimization in Timing of Risk Mitigation. Decision analysis and optimization, as discussed in detail in ASME Risk Analysis Publications, may be used to refine the risk mitigation decision-making process. However, a detailed discussion of these topics is outside of the scope of this Standard.

Fig. 9.5.1 Example Risk Matrix Using Probability and Consequence Categories



10 RISK MANAGEMENT WITH INSPECTION ACTIVITIES

10.1 Managing Risk by Reducing Uncertainty Through Inspection

In previous sections, it has been mentioned that risk may be managed by inspection. Obviously, inspection does not arrest or mitigate damage mechanisms. Inspection serves to identify, monitor, and measure the damage mechanism(s). Also, it is invaluable input in the prediction of when the damage will reach a critical point. Correct application of inspections will improve the user's ability to predict damage mechanisms and rates of damage. The better the predictability, the less uncertainty there will be as to when a failure may occur. Mitigation (repair, replacement, changes, etc.) should then be planned and implemented prior to the predicted failure date. The reduction in uncertainty and increase in predictability through inspection translate directly into a reduction in the probability of a failure and therefore a reduction in the risk.

Risk mitigation achieved through inspection presumes that the organization will act on the results of the inspection in a timely manner. Risk mitigation is not achieved if inspection data that are gathered are not properly analyzed and acted upon where needed. The quality of the inspection data and the analysis or interpretation will greatly affect the level of risk mitigation. Proper inspection methods and data analysis tools are therefore critical.

10.2 Identifying Opportunities for Risk Reduction From RBI and Probability of Failure Results

As discussed in section 9, typically a risk priority list should be developed. RBI will also identify whether consequence or probability of failure or both is driving risk. In the situations where risk is being driven by probability of failure, there is usually potential for risk management through inspection.

Once an RBI analysis has been completed, the items with higher or unacceptable risk should be assessed for potential risk management through inspection. Whether inspection will be effective or not will depend on

(a) equipment type.

(b) active and credible damage mechanism(s).

(c) rate of damage or susceptibility.

(d) inspection methods, coverage, and frequency.

(e) preparation for inspection, such as insulation removal and cleaning.

(f) accessibility to expected damaged areas.

(g) shutdown requirements.

(h) using inspection technology that is sufficient to detect or quantify damage adequately.

(i) amount of achievable reduction in probability of failure (POF) (i.e., a reduction in POF of a low-POF item may be difficult to achieve through inspection). Depending on factors such as the remaining life of the equipment and type of damage mechanism, risk management through inspection may have little or no effect. Examples of such cases are

(1) corrosion rates well-established and equipment nearing end of life.

(2) instantaneous failures, such as brittle fracture, related to conditions outside the design envelope.

(3) too short a time frame from the onset of damage to final failure for periodic inspections to be effective (e.g., high-cycle fatigue cracking).

(4) event-driven failures (circumstances that cannot be predicted).

In cases such as these, an alternative form of mitigation (other than inspection) may be required.

The most practical and cost-effective risk mitigation strategy may then be developed for each item. Usually, inspection provides a major part of the overall risk management strategy.

10.3 Establishing an Inspection Strategy Based on Risk Analysis

The results of an RBI analysis and the resultant risk management analysis may be used as the basis for the development of an overall inspection strategy for the group of items included. The inspection strategy should be designed in conjunction with other mitigation plans so that all equipment items will have resultant risks that are acceptable. Users should consider risk rank, risk drivers, item history, number and results of inspections, type and effectiveness of inspections, equipment in similar service, and remaining life in the development of their inspection strategy.

Inspection is only effective if the inspection technique chosen is sufficient for detecting the damage mechanism and its severity. As an example, spot thickness readings on a piping circuit would be considered to have little or no benefit if the damage mechanism results in unpredictable localized corrosion (e.g., pitting, ammonia bisulfide corrosion, local thin area). In this case, ultrasonic scanning, radiography, etc., will be more effective. The level of risk reduction achieved by inspection will depend on

(a) mode of damage associated with the failure mechanism

(b) time interval between the onset of damage and failure (i.e., speed of damage)

(c) detection capability of inspection technique

(d) scope of inspection

(e) frequency of inspection

Organizations should be deliberate and systematic in determining the level of risk management achieved through inspection and should be cautious not to assume that inspection is the only component of a successful risk management program.

The inspection strategy should be a documented, iterative process to assure that inspection activities are continually focused on items with higher risk and that the risks are effectively reduced by the implemented inspection activity.

10.4 Managing Risk With Inspection Activities

The effectiveness of past inspections should be part of the determination of the present risk. The future risk should now be managed by future inspection activities. RBI may be used as a "what if" tool to determine when, what, and how inspections should be conducted to yield an acceptable future risk level. Key parameters and examples that may affect the future risk are specified in paras. 10.4.1 through 10.4.3.

10.4.1 Inspection Effectiveness. Changing the inspection technique to one that is more effective may mitigate future risk to an acceptable level. Alternative inspection techniques may be evaluated to determine their impact on future risk level. For example, each of the following approaches may have a similar impact on the future risk level:

(a) a 10-year inspection interval using a highly effective inspection technique, which correctly detects/characterizes damage mechanisms almost all of the time

(b) a 5-year inspection interval using a usually effective inspection technique, which correctly detects/characterizes damage mechanisms most of the time

(c) a 30-month inspection interval using a fairly effective inspection technique, which correctly detects/characterizes damage mechanisms half of the time

10.4.2 Frequency of Inspection. Increasing the frequency of inspections may serve to better define, identify, or monitor the damage mechanism(s) and therefore reduce the risk. Conversely, the evaluation may show that inspection frequencies may be reduced provided that the future risk does not exceed the acceptable risk level threshold at the time of the next inspection. Also, inspection frequency may be reduced when evaluation shows essentially no gain in risk reduction due to the increased inspection frequency and the risk level is acceptable. Both routine and turnaround inspection frequencies may be optimized.

10.4.3 Coverage. Different zones or areas of inspection of an item or series of items may be modeled and evaluated to determine the coverage that will produce an acceptable level of risk. See paras. 10.4.3.1 through 10.4.3.5.

10.4.3.1 Extensive Inspection of High-Risk Piping. A high-risk piping system may be a candidate for extensive inspection, using one or more NDE techniques targeted to locating the identified damage mechanisms.

10.4.3.2 Focus on High-Risk Areas. An analysis may reveal the need for focus on parts of a vessel where the highest risk areas may be located and focus on quantifying this risk rather than look at the rest of the vessel where there are perhaps only low-risk damage processes occurring.

10.4.3.3 Tools and Techniques. The selection and usage of the appropriate inspection tools and techniques may be optimized to cost-effectively and safely reduce risk. In the selection of inspection tools and techniques, inspection personnel should take into consideration that more than one technology may achieve risk mitigation. However, the level of mitigation achieved may vary depending on the choice. As an example, radiography may be more effective than ultrasonic for thickness monitoring in cases of localized corrosion.

10.4.3.4 Procedures and Practices. Inspection procedures and the actual inspection practices may impact the ability of inspection activities to identify, measure, and/or monitor damage mechanisms. If the inspection activities are executed effectively by well-trained and qualified inspectors, the expected risk management should be obtained. The user is cautioned not to assume that all inspectors and NDE examiners are well qualified and experienced, but rather to take steps to ensure that they have the appropriate level of experience and qualifications (see section 13).

10.4.3.5 Internal or External Inspection. Risk reductions by both internal and external inspections should be assessed. Often, external inspection with effective onstream inspection techniques will provide useful data for risk analysis. It is worth noting that invasive inspections, in some cases, may cause damage and increase the risk of the item. Examples where this may happen include

(a) moisture ingress to equipment leading to SCC or polythionic acid cracking

(b) internal inspection of glass-lined vessels

(c) removal of passivating films

(d) human errors in start-up (restreaming)

(e) risk associated with shutting down and starting up equipment

The user may adjust these parameters to obtain the optimum inspection plan that manages risk, is cost-effective, and is practical.

10.5 Managing Inspection Costs With RBI

Inspection costs can be more effectively managed through the utilization of RBI. Resources may be applied or shifted to higher risk areas or targeted based on the strategy selected. Consequently, this same strategy allows consideration for reduction of inspection activities in those areas that have a lower risk or where the inspection activity has little or no affect on the associated risks. This results in inspection resources being applied where they are needed most.

Another opportunity for managing inspection costs is by identifying items in the inspection plan that can be inspected nonintrusively onstream. If the nonintrusive inspection provides sufficient risk management, then there is a potential for a net savings based on not having to isolate, open, clean, and internally inspect during downtime. If the item considered is the main driver for bringing an operational unit down, then the nonintrusive inspection may contribute to increased uptime of the unit. The user should recognize that while there is a potential for the reduction of inspection costs through the utilization of RBI, equipment integrity and inspection cost optimization should remain the focus.

10.6 Assessing Inspection Results and Determining Corrective Action

Inspection results such as damage mechanisms, rate of damage, and equipment tolerance to the types of damage should be used as variables in assessing remaining life and future inspection plans. The results may also be used for comparison or validation of the models that may have been used for probability of failure determination.

A documented mitigation action plan should be developed for any equipment item requiring repair or replacement. The action plan should describe the extent of repair (or replacement), recommendations, the proposed repair method(s), appropriate quality assurance/quality control (QA/QC), and the date the plan should be completed.

10.7 Achieving Lowest Life Cycle Costs With RBI

Not only may RBI be used to optimize inspection costs that directly affect life cycle costs, it may assist in lowering overall life cycle costs through various benefit-cost analyses. The following examples provide ideas on how to lower life cycle costs through RBI with benefit-cost analyses.

10.7.1 Enhance Failure Prediction. RBI should enhance the prediction of failures caused by damage mechanisms. This in turn should give the user confidence to continue to operate equipment safely, closer to the predicted failure date. By doing this, the equipment cycle time should increase and life cycle costs decrease.

10.7.2 Assess Effects of Changes. RBI may be used to assess the effects of changing to a more aggressive fluid. A subsequent plan to upgrade construction material or replace specific items may then be developed. The construction material plan would consider the optimized run length safely attainable along with the appropriate inspection plan. This could equate to increased profits and lower life cycle costs through reduced maintenance, optimized inspections, and increased unit/equipment uptime.

10.7.3 Optimize Turnaround and Maintenance Costs. Turnaround and maintenance costs also have an affect on the life cycle costs of an equipment item. By using the results of the RBI inspection plan to identify more accurately where to inspect and what repairs and replacements to expect, turnaround and maintenance work can be preplanned and, in some cases, executed at a lower cost than if unplanned.

11 OTHER RISK MITIGATION ACTIVITIES

11.1 General

As described in the previous section, inspection, followed by appropriate action on the inspection results in a timely manner, is often an effective method of risk mitigation. However, inspection and follow-up actions may not always provide sufficient risk mitigation or may not be the most cost-effective method. The purpose of this section is to describe other risk mitigation methods. This list is not meant to be all-inclusive. These risk mitigation activities fall into one or more of the following categories:

(a) reduce the magnitude of consequence
(b) reduce the probability of failure
(c) enhance the survivability of the facility and people to the consequence
(d) mitigate the primary source of consequence

11.2 Equipment Replacement and Repair

When equipment damage has reached a point that the probability of failure results in unacceptable risk, replacement/repair may be the only way to mitigate the risk.

11.3 Fitness-for-Service Assessment

Inspection may identify flaws in equipment. A fitness-for-service assessment (e.g., API 579-1/ASME FFS-1) may be performed to determine if the equipment may continue to be safely operated, under what conditions, and for what time period. A fitness-for-service analysis may also be performed to determine what size flaws, if found in future inspections, would require repair or equipment replacement.

11.4 Equipment Modification, Redesign, and Rerating

Modification and redesign of equipment may reduce the probability of failure. Examples include

(a) change of metallurgy
(b) addition of protective linings and coatings
(c) removal of dead legs
(d) increased corrosion allowance
(e) physical changes that will help to control/minimize damage
(f) insulation improvements
(g) injection point design changes
(h) resize relief device

Sometimes equipment is underdesigned or overdesigned for the process conditions. Rerating an item may result in a change in the assessed probability of failure for that item.

11.5 Emergency Isolation

Emergency isolation capability can reduce toxic, explosion, or fire consequences in the event of a pressure boundary failure. Proper location of the isolation valves is important for successful risk mitigation. Remote operation is usually required to provide significant risk reduction. The time required to detect the release and actuate the isolation valves and the reliability of the system as a whole under adverse conditions should be considered in determining the level of mitigation of flammable and explosive events. More information concerning the reliability of safety instrumented systems can be found in several standards.

11.6 Emergency Depressurizing/De-inventory

This method reduces the amount and rate of release. Like emergency isolation, the emergency depressurizing and/or de-inventory should be achieved within an appropriate time frame and with acceptable reliability under adverse conditions to affect explosion/fire risk.

11.7 Modify Process

Mitigation of the primary source of consequence may be achieved by changing the process towards less hazardous conditions. Examples include

(a) reduce temperature to below atmospheric pressure boiling point of the process materials to reduce size of cloud

(b) substitute a less hazardous material (e.g., high-flash solvent for a low-flash solvent)

(c) use a continuous process instead of a batch operation

(d) dilute hazardous substances

11.8 Reduce Inventory

This method reduces the magnitude of consequence. Examples include

(a) reduce/eliminate storage of hazardous feedstocks or intermediate products

(b) modify process control to permit a reduction in inventory contained in surge drums, reflux drums, or other in-process inventories

(c) select process operations that require less inventory/holdup

(d) substitute gas phase technology for liquid phase

11.9 Water Spray/Deluge

This method may reduce fire damage and minimize or prevent escalation. A properly designed and operating system may greatly reduce the probability that a vessel exposed to fire will result in a BLEVE. It should be recognized that water sprays can entrain large amounts of air into a cloud.

11.10 Water Curtain

Water curtains mitigate water-soluble vapor clouds by absorption as well as dilution, and insoluble vapors (including most flammables) by air dilution. Early activation is required in order to achieve significant risk reduction. The curtain should preferably be between the release location and ignition sources (e.g., furnaces) or locations where people are likely to be present. Design is critical for flammables, since the water curtain may enhance flame speed under some circumstances.

11.11 Blast-Resistant Construction

Utilizing blast-resistant construction provides mitigation of the damage caused by explosions and may prevent escalation of the incident. When used for buildings (e.g., API RP 752), it may provide personnel protection from the effects of an explosion. This may also be useful for equipment critical to emergency response, critical instrument/control lines, etc.

11.12 Other Mitigation Activities

Other mitigation activities are listed below.

(a) improved training and procedures

(b) spill detectors

(c) steam or air curtains

(d) fireproofing

(e) instrumentation (interlocks, shutdown systems, alarms, etc.)

(f) inerting/gas blanketing

(g) ventilation of buildings and enclosed structures

(h) piping redesign

(i) mechanical flow restriction

(j) ignition source control

(k) improved design, assembly, and installation standards

(l) improvement in process safety management program

(m) emergency evacuation

(n) shelters (safe havens)

(o) toxic scrubbers on building vents

(p) spill containment

(q) facility siting and/or layout

(r) condition monitoring

(s) construction material change

(t) emergency feed stops

(u) improved fire suppression systems

12 REANALYSIS

12.1 Introduction

RBI is a dynamic tool that provides current and projected future risk evaluations based on data and knowledge at the time of the analysis. As time goes by, changes are inevitable and the results from the RBI analysis should be updated. It is important to maintain and update an RBI program to ensure the most recent inspection, process, and maintenance information is included. The results of inspections, changes in process conditions, and implementation of maintenance practices may all have significant effects on risk and may trigger the need to perform a reanalysis. It is important that the facility have an effective management of change process that identifies when a reanalysis is necessary. Paragraphs 12.1.1 through 12.1.4 provide guidance on some key factors that could trigger an RBI reanalysis.

12.1.1 Damage Rates. Many damage mechanisms are time dependent. Typically, the RBI analysis will project damage at a constant rate. For some damage mechanisms or combinations of mechanisms, the damage rate may vary over time. Through inspection activities, the average rates of damage may be better defined. Some damage mechanisms are independent of time (i.e., they occur only when there are specific conditions present). These conditions may not have been predicted in the original analysis but may have subsequently occurred. Inspection activities will increase information on the condition of the equipment. When inspection activities have been performed, the results should be reviewed to determine if an RBI reanalysis is necessary.

12.1.2 Process and Hardware Changes. Changes in process conditions and hardware changes, such as equipment modifications or replacement, can significantly alter the risks and dictate the need for a reanalysis. Process changes in particular have been linked to equipment failure from rapid or unexpected material degradation. Process changes are particularly important for damage mechanisms that depend heavily on process conditions such as chloride stress corrosion cracking of stainless steel. A change in process conditions may dramatically affect the corrosion rate or cracking tendencies. Hardware changes may also have an effect on risk. For example

(a) the probability of failure may be affected by changes in the design of internals in a vessel or size and shape of piping systems that accelerate velocity-related corrosion effects

(b) the consequence of failure may be affected by the relocation of a vessel to an area near an ignition source

12.1.3 RBI Analysis Premise Change. The premises for the RBI analysis could change. This could have a significant impact on the risk results or could trigger a need for reanalysis. Some of the possible changes could be

(a) increase or decrease in population density

(b) change in materials and repair/replacement costs

(c) change in product values

(d) revisions in safety and environmental laws and regulations

(e) revisions in the user's risk management plan (such as changes in risk criteria)

12.1.4 The Effect of Mitigation Strategies. Strategies to mitigate risks such as installation of safety systems, repairs, etc., should be monitored to ensure they have successfully achieved the desired mitigation. Once a mitigation strategy is implemented, a reanalysis of the risk may be performed to update the RBI program.

12.2 When to Conduct RBI Reanalysis

12.2.1 Significant Changes. Qualified personnel should evaluate each significant change to determine the potential for a change in risk. It may be desirable to conduct an RBI reanalysis after significant changes in process conditions, damage mechanisms/rates/severities, or RBI premises.

12.2.2 Set Time Period. Even in the absence of significant changes, over time many small changes may occur and cumulatively cause significant changes in the RBI analysis. Users should set default maximum time intervals for reanalysis. Applicable inspection codes and jurisdictional regulations should be reviewed in this context.

12.2.3 Implementation of Risk Mitigation Strategies. Once a mitigation strategy has been implemented, it is prudent to determine how effective the strategy was in reducing the risk to an acceptable level. This should be reflected in a reanalysis of the risk and appropriate update in the documentation.

12.2.4 Major Maintenance. As part of the planning before major maintenance, it could be useful to perform an RBI reanalysis. This can become a first step in planning the maintenance to focus the work effort on the higher risk equipment items and on issues that might affect the ability to achieve the premised operating run time in a safe, economic, and environmentally sound manner. Since many inspections, repairs, and modifications are performed during a major maintenance activity, it may be useful to update an analysis after completion to reflect the effect of those activities.

13 ROLES, RESPONSIBILITIES, TRAINING, AND QUALIFICATIONS

13.1 Interdisciplinary Approach

Risk-based inspection (RBI) requires input from several disciplines such as risk analysis, financial analysis, materials and corrosion engineering, mechanical engineering, and inspection. It is unlikely that one individual has all the specialized skill sets needed for such an undertaking. Therefore, RBI analyses should be conducted as a project with facility management as stakeholders and a project team composed of facility employees, contractors, and interested parties. Advice on the organizational structure, inputs, and outputs of such a team may be found in project management documents.

13.2 RBI Inspection Team Roles and Responsibilities

The individuals who typically participate in the RBI process are described below. A single individual may fill more than one role. In addition, not all of the personnel described are needed for every analysis

13.2.1 Team Leader. The team leader of the analysis team may be versed in one of the specialized fields required for RBI. He or she may be unfamiliar with the facility to be evaluated, but should be familiar with the concepts of RBI and the types of processes to be assessed. The main function of the team leader should be to integrate the inputs, outputs, organizational structure, reporting facilities, and communications of the analysis team.

The responsibilities of the team leader include the following:

(a) ensure that team members have the necessary skills and knowledge

(b) ensure that assumptions made are logical and incorporated into the final reports

(c) ensure that quality checks are performed on the gathered data

(d) prepare a report and distribute it to the appropriate personnel

13.2.2 Equipment Inspector or Inspection Specialist. The equipment inspector, inspection specialist, or unit inspector should gather data on the condition and history of the equipment in the study. These condition data should include the new/design condition and current condition. Generally, this information will be located in equipment inspection and maintenance files. If condition data are unavailable, the inspector/specialist, in conjunction with the materials and corrosion specialist, should provide predictions of the current condition. The inspector/specialist and materials/corrosion specialist should also be responsible for assessing the effectiveness of past inspections. The equipment inspector/inspection specialist may also be responsible for implementing the recommended inspection plan.

13.2.3 Materials and Corrosion Specialist. The materials and corrosion specialist should be responsible for assessing the types of damage mechanisms and their applicability to the equipment considering the process conditions, environment, metallurgy, and age of the equipment. This specialist should compare this analysis to the current knowledge of the condition of the equipment, determine the reason for differences between predicted and actual condition, and then provide guidance on damage mechanisms, rates, or severity to be used in the RBI analysis. Part of this comparison should include evaluating the appropriateness of the inspections in relation to the damage mechanism. This specialist also should provide recommendations on methods of mitigating the probability of failure.

13.2.4 Process Specialist. The process specialist should be responsible for the provision of process condition information. This information generally will be in the form of process flow sheets. The process specialist should be responsible for documenting variations in the process conditions due to normal occurrences (such as start-ups and shutdowns) and abnormal occurrences. The process specialist should be responsible for describing the composition and variability of all the process fluids/gases as well as their toxicity and flammability. The process specialist should evaluate/recommend methods of risk mitigation through changes in process conditions.

13.2.5 Operations and Maintenance Personnel. Operations personnel should be responsible for verifying that the facility/equipment is being operated within the parameters set out in the process conditions. They should be responsible for providing data on occurrences when the process deviated from the limits of the process condition. Maintenance personnel should be responsible for verifying that equipment repairs/replacements/additions have been included in the equipment condition data supplied by the equipment inspector. Operations and maintenance personnel should be responsible for recommending process or equipment modifications to reduce risk.

13.2.6 Facility Management. Management's role should be to provide sponsorship and resources (personnel and money) for the RBI study. They are responsible for making decisions on risk management or providing the framework/mechanism for others to make these decisions based on the results of the RBI study. Finally, management should be responsible for providing the resources to implement the risk mitigation decisions.

13.2.7 Risk Analyst/Facilitator. The risk analyst/facilitator should be responsible for carrying out the RBI analysis. This person(s) should be responsible for

(a) defining data required from other team members

(b) defining accuracy levels for the data

(c) verifying through quality checks the soundness of data and assumptions

(d) facilitating team discussions

(e) inputting/transferring data into a database (if one is used)

(f) quality control of data input/output

(g) calculating the measures of risk

(h) displaying the results in an understandable way and preparing a report on the RBI analysis

Further, this person(s) should be a resource to the team to conduct benefit-cost analysis if it is deemed necessary.

13.2.8 Environmental and Safety Personnel. Environmental and safety personnel should be responsible for providing data on environmental and safety systems and regulations. He or she should also be responsible for assessing/recommending ways to mitigate the consequence of failures.

13.2.9 Financial/Business Personnel. Financial/business personnel should be responsible for providing data on the cost of the facility/equipment being analyzed and the business interruption impact of having pieces of equipment or the facility shut down. He/she should also recommend methods for mitigating the financial consequence of failure.

13.3 Training and Qualifications

13.3.1 Risk Analysis Personnel. This person(s) needs to have a thorough understanding of risk analysis either by education, training, or experience. He/she should have received detailed training on the RBI methodology and on the program(s) being used.

Contractors that provide risk analysis personnel for conducting RBI analysis should have a program of training and be able to document that their personnel are suitably qualified and experienced. Facility owners that have internal risk analysis personnel conduct RBI analysis should have a procedure to document that their personnel are sufficiently qualified. The qualifications of the risk analysis personnel should be documented.

13.3.2 Other Team Members. It is recommended that the other team members receive basic training on RBI methodology and on the program(s) being used. This training should be geared primarily to an understanding of RBI. This training could be provided by the risk analysis personnel on the RBI team or by another person knowledgeable on RBI methodology and on the program(s) being used.

14 DOCUMENTATION AND RECORD KEEPING

14.1 General

It is important that sufficient information is captured to fully document the RBI analysis. Ideally, sufficient data should be recorded and maintained such that the analysis can be recreated or updated later by others who were not involved in the original analysis. To facilitate this, it is preferable to store the information in a computerized database. A database will enhance the analysis, retrieval, and management capabilities. The usefulness of the database will be particularly important in managing recommendations developed from the RBI analysis, and managing risk over the specified time frame. Documentation should include the following:

(a) RBI methodology
(b) RBI personnel
(c) time frame
(d) basis for assignment of risk
(e) assumptions made to assess risks
(f) risk analysis results, including mitigated risk levels
(g) mitigation and follow-up
(h) applicable codes, standards, and government regulations
(i) source of failure data and adjustments to make plant specific

14.1.1 RBI Methodology. The methodology used to perform RBI analysis should be documented so that it is clear what type of analysis was performed. The basis for both the probability and consequence of failure should be documented. If a specific software program is used to perform the analysis, this also should be documented and maintained. The documentation should be sufficiently complete so that the basis and the logic for the decision-making process can be checked or replicated later.

14.1.2 RBI Personnel. The analysis of risk will depend on the knowledge, experience, and judgment of the personnel or team performing the analysis. Therefore, a record of the team members involved and their qualifications should be captured. This will be helpful in understanding the basis for the risk analysis when the analysis is repeated or updated.

14.1.3 Time Frame. The level of risk is usually a function of time due to either the time dependence of a damage mechanism, or changes in the operation of equipment. Therefore, the time frame over which the RBI analysis is applicable should be captured in the final documentation. This will permit effective tracking and management of risk over time.

14.1.4 Basis for Assignment of Risk. The various inputs used to assess both the probability and consequence of failure should be captured. This should include, but not be limited to, the following information:

(a) basic equipment data and inspection history critical to the analysis (e.g., operating conditions, materials of construction, service exposure, corrosion rates, inspection history)
(b) operative and credible damage mechanisms
(c) criteria used to judge the severity of each damage mechanism
(d) anticipated failure mode(s) (e.g., leak or rupture)
(e) key factors used to judge the severity of each failure mode
(f) criteria used to evaluate the various consequence categories, including safety, health, environmental, and financial
(g) risk criteria used to evaluate the acceptability of the risks

14.1.5 Assumptions Made to Assess Risks. Risk analysis, by its very nature, requires that certain assumptions be made regarding the nature and extent of equipment damage. Moreover, the assignment of failure mode and the severity of the contemplated event will invariably be based on a variety of assumptions, regardless of whether the analysis is quantitative or qualitative. To understand the basis for the overall risk, it is essential that these factors be captured in the final documentation. Clear documentation of the key assumptions made during the analysis of probability and consequence will greatly enhance the capability to either recreate or update the RBI analysis.

14.1.6 Risk Analysis Results. The probability, consequence, and risk results should be captured in the documentation. For items that require risk mitigation, the results after mitigation should be documented as well.

14.1.7 Mitigation and Follow-Up. One of the most important aspects of managing risk through RBI is the development and use of mitigation strategies. Therefore, the specific risk mitigation required to reduce either probability or consequence should be documented in the analysis. The benefit of mitigation assigned to a particular action should be captured along with any time dependence. The methodology, process, and person(s) responsible for implementation of any mitigation should also be documented.

14.1.8 Applicable Codes, Standards, and Government Regulations. Since various codes, standards, and governmental regulations cover the inspection for most pressure equipment, it will be important to reference these documents as part of the RBI analysis. This is particularly important where implementation of RBI is used to reduce either the extent or frequency of inspection. Refer to section 15 for a listing of some relevant codes and standards.

15 DEFINITIONS AND ACRONYMS

15.1 Definitions

components: parts that make up a piece of equipment or equipment item. For example, a pressure boundary may consist of components (elbows, heads, stiffening rings, skirts, supports, etc.) that are bolted or welded into assemblies to make up equipment items (see Fig. 4.3.1).

damage (or deterioration) mechanism: a process that induces deleterious micro and/or macro material changes over time that are harmful to the material condition or mechanical properties. Damage mechanisms are usually incremental, cumulative, and, in some instances, unrecoverable. Common damage mechanisms include corrosion, chemical attack, creep, erosion, fatigue, fracture, and thermal aging.

damage (or deterioration) mode: the physical manifestation of damage (e.g., wall thinning, pitting, cracking, embrittlement, creep).

equipment: an individual item that is part of a system. Examples include pressure vessels, relief devices, piping, boilers and paper machines (see Fig. 4.3.1).

facility: any location containing equipment and/or components to be addressed under the standard (see Fig. 4.3.1).

failure: termination of the ability of a system, structure, or component to perform its required function (i.e., loss of containment).

failure mode: the manner of failure. In this Standard, the principal concern is the loss of containment of pressure equipment items, e.g., small hole, through-wall crack, rupture.

fitness-for-service assessment: a methodology whereby damage or flaws/imperfections contained within a component or equipment item are assessed in order to determine acceptability for continued service.

inspection: activities performed to verify that materials, fabrication, erection, examinations, testing, repairs, etc., conform to applicable code, engineering, and/or owner's written procedure requirements.

mitigation: all activities, including inspection, undertaken to lower the assessed risk of continued operation by reducing the probability of failure, the consequence of failure, or both.

probabilistic remaining life analysis: an engineering probabilistic modeling of the damage mechanism to determine the probability of failure over time.

process unit: a group of systems arranged in a specific fashion to produce a product or service. Examples of processes include power generation, acid production, fuel oil production, and ethylene production (see Fig. 4.3.1).

qualitative analysis: an analysis characterized by having the data inputs expressed descriptively or possibly by numerical estimates (ranges or in some cases single values [see para. 3.3.1]).

quantitative analysis: an analysis characterized by using data inputs expressed as probabilistic distributions (see para. 3.3.2).

reanalysis: the process of integrating inspection data or other changes into the risk analysis.

residual risk: the risk that remains after all of the mitigation actions have been taken.

risk: the combination of the probability and consequence of a failure (event).

risk analysis (or assessment): the process of reviewing process parameters, determining potential damage mechanisms, determining the probability and consequence of failure scenarios, and the resulting risk level.

risk-based inspection (RBI): inspections, including nondestructive examination, metallurgical examinations, onstream monitoring, etc., performed as part of a process implemented to manage the risks identified in a risk analysis.

risk driver: an item affecting either the probability, consequence, or both such that it constitutes a significant portion of the risk.

semiquantitative analysis: a semiquantitative analysis includes aspects of both qualitative and quantitative analyses.

system: a collection of equipment assembled for a specific function within a process unit. Examples of systems include service water system, distillation systems, and separation systems (see Fig. 4.3.1).

turnaround: a period of down time to perform inspection, maintenance, or modifications and prepare process equipment for the next operating cycle.

15.2 Acronyms

ACC	American Chemistry Council
AIChE	American Institute of Chemical Engineers
API	American Petroleum Institute
ASM	ASM International (American Society of Metals)
ASME	American Society of Mechanical Engineers
ASNT	American Society for Nondestructive Testing
ASTM	ASTM International (American Society for Testing and Materials)
AWS	American Welding Society
BLEVE	boiling liquid expanding vapor explosion — a violent release of exploding vapor and boiling liquid that may occur upon failure of pressure equipment containing a liquefied gas.
BLRBAC	Black Liquor Recovery Boiler Advisory Committee
BPV	Boiler and Pressure Vessel
CCPS	Center for Chemical Process Safety (this center is within AIChE)
CGSB	Canadian General Standards Board
CRTD	ASME Center for Research and Technology Development
EPA	United States of America Environmental Protection Agency
EPRI	Electric Power Research Institute
FAA	Federal Aviation Administration
FFS	fitness-for-service
HAZOP	hazard and operability study
HIC	hydrogen-induced cracking
IEC	International Electrotechnical Commission
ISA	The Instrumentation, Systems, and Automation Society
ISO	International Organization for Standardization
NACE	NACE International (National Association of Corrosion Engineers)
NDE	nondestructive examination
NERC	North American Electric Reliability Council
OSHA	Occupational Safety and Health Administration
PHA	process hazards analysis
PSM	process safety management
QA/QC	quality assurance/quality control
RBI	risk-based inspection
RCM	reliability-centered maintenance
SCC	stress corrosion cracking
SOHIC	stress-oriented hydrogen-induced cracking
LTA	local thin area
WRC	Welding Research Council

16 REFERENCES

See Table 16 for a list of standards and specifications referenced in this Standard.

Table 16 References

Referencing Paragraph	Document Details
1.1	ASME BPV Section XI, Rules for Inservice Inspection of Nuclear Power Plant Components; Section XI, Appendix R, Risk-Informed Inspection Requirements for Piping; Section XI Code Case N-663, Alternate Requirements for Class 1 and Class 2 Surface Examinations; Code Case N-716, Alternative Piping Classification Requirements; Code Case N-660, Risk-Informed Safety Classification and Treatment for Repair/Replacement Activities ASME, Three Park Avenue, New York, NY 10016-5990
2.3 (Table 2.3)	The 100 Largest Losses; 1972-2001; Large Property Damage Losses in the Hydrocarbon-Chemical Industries, 20th Edition: February 2003. Marsh's Risk Consulting, Marsh & McLennan Companies, 1166 Avenue of the Americas, New York, NY 10036
3.7	**OSHA Process Safety Management Programs** Compliance Guidelines and Recommendations for Process Safety Management (Nonmandatory). OSHA, 1910.119 App C Occupational Safety and Health Administration (OSHA), 200 Constitution Avenue, NW, Washington, DC 20210
3.7	**EPA Risk Management Programs** Accidental Release Prevention Requirements: Risk Management Program Requirements Under Clean Air Act Section 112(r)(7); Amendments to the Submission Schedule and Data Requirements; Final Rule. 69 FR 18819, April 9, 2004. U.S. Environmental Protection Agency (EPA), Ariel Rios Building, 1200 Pennsylvania Avenue, NW, Washington, DC 20460
3.7	**ACC Responsible Care** Responsible Care, RC14001 Technical Specification American Chemistry Council (ACC), 1300 Wilson Boulevard, Arlington, VA 22209
3.7	**CCPS Risk Analysis Techniques** Guidelines for Chemical Process Quantitative Risk Analysis Second Edition by CCPS Center for Chemical Process Safety (CCPS), Three Park Avenue, 19th Floor, New York, NY 10016
3.7	**Seveso 2 Directive in Europe** Council Directive 82/501/EEC on the major-accident hazards of certain industrial activities (OJ No L 230 of 5 August 1982) Council Directive 96/82/EC of 9 December 1996 on the control of major-accident hazards involving dangerous substances The Council of the European Union (EU), European Commission Joint Research Centre, TP 670, I-21020 Ispra (Va), Italy
3.7.2	OSHA 29 CFR 1910.119, Process safety management of highly hazardous chemicals. Occupational Safety and Health Administration (OSHA), 200 Constitution Avenue, NW, Washington, DC 20210
5.3(g)(10)(a)	WRC 488, Damage Mechanisms Affecting Fixed Equipment in Fossil Electric Power Industry Pressure Vessel Research Council (PVRC), P.O. Box 201547, Shaker Heights, OH 44120
5.3(g)(10)(b)	WRC 489, Damage Mechanisms Affecting Fixed Equipment In the Pulp and Paper Industry Pressure Vessel Research Council (PVRC), P.O. Box 201547, Shaker Heights, OH 44120
5.3(g)(10)(c)	WRC 490, Damage Mechanisms Affecting Fixed Equipment In the Refining Industry Pressure Vessel Research Council (PVRC), P.O. Box 201547, Shaker Heights, OH 44120
5.3(g)(10)(d)	API RP 571, Damage Mechanisms Affecting Fixed Equipment in the Refining Industry American Petroleum Institute (API), 1220 L Street, NW, Washington, DC 20005-4070

Table 16 References (Cont'd)

Referencing Paragraph	Document Details
5.3(g)(10)(e)	ASTM G 15, Standard Terminology Relating to Corrosion and Corrosion Testing ASTM International (ASTM), 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959
5.3(g)(10)(f)	The NACE Corrosion Survey Database NACE International, The Corrosion Society, 1440 South Creek Drive, Houston, TX 77084-4906
5.3(g)(11)(a)	Offshore Reliability Data Handbook OREDA Participants, Distributed by Det Norske Veritas Industri Norge As DNV Technica, Copyright 1992, ISBN 82 515 0188 1
5.3(g)(11)(b)	Process Equipment Reliability Database American Institute of Chemical Engineers, Center for Chemical Process Safety, Three Park Avenue, New York, NY 10016-5991, http://www.aiche.org/ccps/perd/
5.3(g)(11)(c)	Generating Availability Data System North American Electric Reliability Council (NERC), Princeton Forrestal Village, 116-390 Village Boulevard, Princeton, NJ 08540-5731, http://www.nerc.com/~gads/
5.3(g)(11)(d)	BLRBAC Incident List Black Liquor Recovery Boiler Advisory Committee, ESP Subcommittee, http://www.blrbac.org/incidntq.doc Black Liquor Recovery Boiler Advisory Committee (BLRBAC), 1005 59th Street, Lisle, IL 60532, www.blrbac.org
7.2.1(b)	API RP 579, Recommended Practice for Fitness-for-Service, 2000 American Petroleum Institute (API), 1220 L Street NW, Washington, DC 20005-4070
7.2.3.2(c)	ASTM International (ASTM), 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959
7.2.3.2(c)	NACE International, The Corrosion Society, 1440 South Creek Drive, Houston, TX 77084-4906
8.3.2	ASME CRTD-41, Risk-Based Methods for Equipment Life Management: A Step-by-Step Instruction Manual with Simple Applications ASME, Three Park Avenue, New York, NY 10016-5990
8.3.2	*Economic Values for Evaluation of Federal Aviation Administration Investment and Regulatory Programs*, FAA-APO-98-8, June 1998
8.3.7.1.1	Dow's Fire and Explosion Index Hazard Classification Guide, 7th Edition American Institute of Chemical Engineers (AIChE), Three Park Avenue, New York, NY 10016-5991
8.4.4.2	API 581, Base Resource Document — Risk-Based Inspection, 2000 American Petroleum Institute (API), 1220 L Street, NW, Washington, DC 20005-4070
9.7.1	ASME CRTD-41, Risk-Based Methods for Equipment Life Management: A Step-by-Step Instruction Manual with Simple Applications ASME, Three Park Avenue, New York, NY 10016-5990
11.3	API RP 579, Recommended Practice for Fitness-for-Service, 2000 American Petroleum Institute (API), 1220 L Street, NW, Washington, DC 20005-4070
11.5	ANSI/ISA 84.00.01 Part 1 (IEC 61511-1Mod) ANSI/ISA 84.00.01 Part 2 (IEC 61511-2Mod) ANSI/ISA 84.00.01 Part 3 (IEC 61511-3Mod) Functional Safety: Safety Instrumented Systems for the Process Industry Sector The Instrumentation, Systems, and Automation Society (ISA), 67 Alexander Drive, Research Triangle Park, NC 27709

Table 16 References (Cont'd)

Referencing Paragraph	Document Details
11.11	API RP 752 (Blast-Resistant Construction) API RP 752, Management of Hazards Associated with Location of Process Plant Buildings, 2001 American Petroleum Institute (API), 1220 L Street, NW, Washington, DC 20005-4070
13.1	Project Management Texts *A Guide to the Project Management Body of Knowledge*, 2000 Edition, Project Management Institute, Newtown Square, PA 19073.
15.2	American Chemistry Council (ACC), 1300 Wilson Boulevard, Arlington, VA 22209
15.2	American Institute of Chemical Engineers (AIChE), Three Park Avenue, New York, NY 10016-5991
15.2	American Petroleum Institute (API), 1220 L Street, NW, Washington, DC 20005-4070
15.2	ASM International (ASM), 9639 Kinsman Road, Materials Park, OH 44073-0002
15.2	Center for Chemical Process Safety (CCPS), Three Park Avenue, 19th Floor, New York, NY 10016
15.2	American Society for Nondestructive Testing (ASNT), P.O. Box 28518, 1711 Arlingate Lane, Columbus, OH 43228-0518
15.2	ASTM International (ASTM), 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959
15.2	American Welding Society (AWS), 550 NW LeJeune Road, Miami, FL 33126
15.2	Black Liquor Recovery Boiler Advisory Committee (BLRBAC), 1005 59th Street, Lisle, IL 60532, www.blrbac.org
15.2	Canadian General Standards Board (CGSB), Place du Portage III, 6B1, 11 Laurier Street, Gatineau, Quebec, Canada
15.2	United States of America Environmental Protection Agency (EPA), Ariel Rios Building, 1200 Pennsylvania Avenue, NW, Washington, DC 20460
15.2	Electric Power Research Institute (EPRI), 3412 Hillview Avenue, Palo Alto, CA 94304
15.2	Federal Aviation Administration (FAA), National Headquarters, 800 Independence Avenue, SW, Washington, DC 20591
15.2	International Electrotechnical Commission (IEC), IEC Central Office, 3, rue de Varembé, P.O. Box 131, CH-1211 Genèva 20, Switzerland/Swiss
15.2	The Instrumentation, Systems, and Automation Society (ISA), 67 Alexander Drive, Research Triangle Park, NC 27709
15.2	International Organization for Standardization (ISO), 1 rue de Varembé, Case postale 56, CH-1211 Genèva 20, Switzerland/Swiss
15.2	NACE International (NACE), The Corrosion Society, 1440 South Creek Drive, Houston, TX 77084-4906
15.2	North American Electric Reliability Council (NERC), Princeton Forrestal Village, 116-390 Village Boulevard, Princeton, NJ 08540-5731
15.2	Occupational Safety and Health Administration (OSHA), 200 Constitution Avenue, NW, Washington, DC 20210
15.2	Welding Research Council (WRC), P.O. Box 201547, Shaker Heights, OH 44120
General Reference section 2	AIChE/CCPS, Guidelines for Hazard Evaluation Procedures, Center for Chemical Process Safety, American Institute of Chemical Engineers, New York, 1985.
	AIChE/CCPS, Guidelines for Chemical Process Quantitative Risk Analysis, Center for Chemical Process Safety, American Institute of Chemical Engineers, New York, 1989.
	The 100 Largest Losses; 1972-2001; Large Property Damage Losses in the Hydrocarbon-Chemical Industries, 20th Edition: February 2003. Marsh's Risk Consulting, Marsh & McLennan Companies, 1166 Avenue of the Americas, New York, NY 10036

Table 16 References (Cont'd)

Referencing Paragraph	Document Details
General Reference section 6	API RP 571, Damage Mechanisms Affecting Fixed Equipment in the Refining Industry American Petroleum Institute (API), 1220 L Street, NW, Washington, DC 20005-4070
	Welding Research Council Bulletin 490 — Damage Mechanisms Affecting Fixed Equipment in the Fossil Electric Power Industry, Welding Research Council, Inc., New York, NY
	ASM Handbook, Volume 11, Failure Analysis and Prevention ASM International, 9639 Kinsman Road, Materials Park, OH 44073-0002
	ASM Handbook, Volume 13, Corrosion ASM International, 9639 Kinsman Road, Materials Park, OH 44073-0002
	ASM Handbook, Volume 6, Welding, Brazing, and Soldering ASM International, 9639 Kinsman Road, Materials Park, OH 44073-0002
	Report CS-5500-SR, Boiler Tube Failures in Fossil Power Plants Electric Power Research Institute (EPRI), 3412 Hillview Avenue, Palo Alto, CA 94304
General Reference section 7	Short, J. S., Jr., Probabilistic Approaches to Life Assessment, Life Assessment and Improvement of Turbo-Generator Rotors for Fossil Plants, Pergamon Press
	Bloom and Ekval, Eds., Probabilistic Fracture Mechanics and Fatigue Methods, ASTM STP 798, ASTM, 1983.
General Reference section 13	SNT-TC-1A-2001, Guidelines for the Qualification and Certification of Non-Destructive Testing Personnel American Society for Nondestructive Testing (ASNT), P.O. Box 28518, 1711 Arlingate Lane, Columbus, OH 43228-0518
	ANSI/ASNT CP-189-2001, ASNT Standard for Qualification and Certification of Nondestructive Testing Personnel American Society for Nondestructive Testing (ASNT), P.O. Box 28518, 1711 Arlingate Lane, Columbus, OH 43228-0518
	Canadian General Standards Board (CGSB), Place du Portage III, 6B1 11 Laurier Street, Gatineau, Quebec, Canada
	ISO 9712:2005 Non-destructive Testing—Qualification and certification of personnel. Technical Committee TC 135/SC 7 International Organization for Standardization (ISO), 1, rue de Varembé, Case postale 56, CH-1211 Genèva 20, Switzerland/Swiss
Appendix A	API 571, Damage Mechanisms Affecting Fixed Equipment in the Refining Industry American Petroleum Institute (API), 1220 L Street, NW, Washington, DC 20005-4070
Appendix A	ASM Handbook, Volume 11, Failure Analysis and Prevention ASM International, 9639 Kinsman Road, Materials Park, OH 44073-0002
Appendix A	WRC 490, Damage Mechanisms Affecting Fixed Equipment In the Fossil Electric Power Industry Pressure Vessel Research Council (PVRC), P.O. Box 201547, Shaker Heights, OH 44120
Appendix A	ASM Handbook Volume 13, Corrosion ASM International, 9639 Kinsman Road, Materials Park, OH 44073-0002
Appendix A	EPRI CS-5500-SR, Boiler Tube Failures in Fossil Power Plants Electric Power Research Institute (EPRI), 3412 Hillview Avenue, Palo Alto, CA 94304

Table 16 References (Cont'd)

Referencing Paragraph	Document Details
Appendix A	ASM Handbook Volume 6, Welding, Brazing, and Soldering ASM International, 9639 Kinsman Road, Materials Park, OH 44073-0002
Appendix A	NACE RP0472, Methods and Controls to Prevent Inservice Environmental Cracking of Carbon Steel Weldments in Corrosive Petroleum Refining Environments NACE International, 1440 South Creek Drive, Houston, TX 77084-4906
Appendix A	NACE MR0103, Material Resistant to Sulfide Stress Cracking in Corrosive Petroleum Refining Environments NACE International, 1440 South Creek Drive, Houston, TX 77084-4906
Appendix A	NACE MR0175, Metals for Sulfide Stress Cracking and Stress Corrosion Cracking Resistance in Sour Oilfield Environment NACE International, 1440 South Creek Drive, Houston, TX 77084-4906
Appendix D Note (1), D-7.4, D-8.4	Risk-Based Methods for Equipment Life Management: An Application Handbook, ASME Research Report CRTD Vol. 41, ASME, NY, 2003
Appendix D Note (2) D-7.5	Ayyub, B.M, "Guidelines on Expert-Opinion Elicitation of Probabilities and Consequences for Corps Facilities", Tech. Report for Contract DACW72-94-D-0003, June, 1999, U.S. Army Corps of Engineers
Appendix D Note (3) D-8.3	Federal Aviation Administration, 2003, Economic Values for Evaluation of Federal Aviation Administration Investment and Regulatory Decisions, FAA-APO-98-8, http://api.hq.faa.gov/economic/toc.htm.

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NONMANDATORY APPENDIX A
DAMAGE MECHANISM DEFINITIONS

Table starts on next page.

Table A-1 Damage Mechanism Definitions

Damage Mechanism	Definition	Attributes	References From Section 16
885°F embrittlement	885°F (475°C) embrittlement is a loss in toughness due to a metallurgical change that can occur in alloys containing a ferrite phase, as a result of exposure in the temperature range 600°F to 1,000°F (316°C to 540°C).	The embrittlement can be removed by soaking at somewhat higher temperatures for several hours.	API 571
Abrasive wear	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.	. . .	ASM Handbook Vol. 11, Failure Analysis and Prevention
Adhesive wear	The removal or displacement of material from a surface by the welding together and subsequent shearing of minute areas of the two surfaces that slide across each other under pressure (a.k.a., galling).	. . .	ASM Handbook Vol. 11, Failure Analysis and Prevention
Ammonium bisulfide corrosion (alkaline sour water)	Aggressive corrosion occurring in hydroprocessing reactor effluent streams and in units handling alkaline sour water.	Several major failures have occurred in hydroprocessing reactor effluent systems due to localized corrosion.	API 571
Amine corrosion	Amine corrosion refers to the general and/or localized corrosion that occurs principally on carbon steel in amine treating processes. Corrosion is not caused by the amine itself, but results from dissolved acid gases (CO_2 and H_2S), amine degradation products, heat stable amine salts (HSAS), and other contaminants.	Corrosion depends on design and operating practices, the type of amine, amine concentrations, contaminants, temperature, and velocity.	API 571
Amine cracking	Amine cracking is a common term applied to the cracking of steels under the combined action of tensile stress and corrosion in aqueous alkanolamine systems used to remove/absorb H_2S and/or CO_2 and their mixtures from various gas and liquid hydrocarbon streams. Amine cracking is a form of alkaline stress corrosion cracking. It is most often found at or adjacent to non-PWHT'd carbon steel weldments or in highly cold worked parts.	. . .	API 571
Ammonia grooving	Ammonia grooving occurs in copper alloy condenser tubes in the form of a groove adjacent to support plates. Ammonia carries over with the steam and is corrosive to copper alloys.	Ammonia carryover in the steam is necessary for this kind of corrosion. The ammonia may come from either the use of hydrazine or its derivative as an oxygen scavenger or from ammonia used as a pH-control chemical.	WRC 490
Ammonia stress corrosion cracking	Aqueous streams containing ammonia may cause stress corrosion cracking (SCC) in some copper alloys. Carbon steel is susceptible to SCC anhydrous ammonia.	Anhydrous ammonia with $< 0.2\%$ water will cause cracking in carbon steels. Stresses required for cracking can be from residual stresses.	API 571
Brittle fracture	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.	Material toughness, crack size, and tensile stress are generally the three factors that control the susceptibility to brittle fracture.	API 571
Carbonate stress corrosion cracking	Carbonate stress corrosion cracking (often referred to as carbonate cracking) is the term applied to surface breaking or cracks that occur adjacent to carbon steel welds under the combined action of tensile stress and corrosion in carbonate-containing systems. It is a form of alkaline stress corrosion cracking (ASCC)	. . .	API 571

Table A-1 Damage Mechanism Definitions (Cont'd)

Damage Mechanism	Definition	Attributes	References From Section 16
Carburization	Carbon is absorbed into a material at elevated temperature while in contact with a carbonaceous material or carburizing environment.	A material dependent process, carbon can react in the metal to form carbides which tend to embrittle the material or, in low alloy steels, act as a potential hardening agent if the materials undergo an appropriate thermal cycle.	API 571
Casting porosity/voids	Voids that are created in a casting during solidification. The voids are typically in the last part of the casting to solidify	. . .	ASM Handbook Vol. 11, Failure Analysis and Prevention
Metal dusting (catastrophic carburization)	Metal dusting is a form of carburization resulting in accelerated localized pitting which occurs in carburizing gases and/or process streams containing carbon and hydrogen. Pits usually form on the surface and may contain soot or graphite dust.	. . .	API 571
Cavitation	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.	Mechanical honeycomb or no corrosion product visible. Significant pressure and extremely high local forces at work.	API 571
Cold cracking	Cracking in a weld that occurs typically during cooldown of the weld at temperatures below 600°F (316°C). The cracks can form hours or days after welding.	. . .	ASM Handbook Vol. 11, Failure Analysis and Prevention
Pitting corrosion	Extreme localized corrosion caused by a concentration-cell that generally produces sharply defined holes; occurs when an area of a metal surface becomes anodic with respect to the rest of the surface	Pitting can cause failure by perforation while producing only a small weight loss on the metal.	ASM Handbook Vol. 11, Failure Analysis and Prevention
Acid dew point corrosion	Corrosion that occurs when gas is cooled below the saturation temperature of condensable acidic species contained by the gas.	Can be similar to atmospheric attack.	ASM Handbook Vol. 11, Failure Analysis and Prevention
Caustic stress corrosion cracking (caustic embrittlement)	A form of stress corrosion cracking characterized by surface-initiated cracks that occur in piping and equipment exposed to caustic, primarily adjacent to non-PWHT'd welds.	Caustic cracking is often adjacent to nonpost weld heat-treated welds.	API 571
Caustic corrosion (caustic gouging)	Localized corrosion due to the concentration of caustic or alkaline salts that usually occurs under evaporative or high heat transfer conditions. However, general corrosion can also occur depending on alkali or caustic solution strength.	Generally, very localized attack. High pH values >9.5–10.	API 571
Chelant corrosion	Corrosive attack caused by excessive chelants.	Dosing by chelants in excess of requirements, e.g., EDTA, general and localized attack often linked to flow irregularities.	ASM Handbook Vol. 11, Failure Analysis and Prevention
Chloride stress corrosion cracking	Surface initiated cracks caused by environmental cracking of 300 Series SS and some nickel-based alloys under the combined action of tensile stress, temperature, and an aqueous chloride environment. The presence of dissolved oxygen increases propensity for cracking.	All 300 Series SS are highly susceptible: duplex stainless steels are more resistant, nickel-based alloys are highly resistant.	API 571

Table A-1 Damage Mechanism Definitions (Cont'd)

Damage Mechanism	Definition	Attributes	References From 16.1
CO_2 corrosion	Carbon dioxide (CO_2) corrosion results when CO_2 dissolves in water to form carbonic acid (H_2CO_3). The acid may lower the pH and sufficient quantities may promote general corrosion and/or pitting corrosion of carbon steel.	Partial pressures of CO_2 are a critical factor and increasing partial pressures results in lower pH condensate and higher rates of corrosion.	API 571
Corrosion under insulation (CUI) and corrosion under fireproofing (CUF)	Corrosion of piping, pressure vessels, and structural components resulting from water trapped under insulation or fireproofing.	Damage can be aggravated by contaminants that may be leached out of the insulation, such as chlorides.	API 571
Crevice corrosion	A type of electrolytic concentration-cell corrosion at a joint between two metallic surfaces or between a metallic and a nonmetallic surface or beneath a particle of solid matter on a metallic surface	Any layer of solid matter on the surface of a metal that offers the opportunity for exclusion of oxygen from the surface or for the accumulation of metal ions beneath the deposit because of restricted diffusion is a probable site for crevice corrosion. Mechanism and appearance similar to pitting attack.	ASM Handbook Vol. 13, Corrosion
Dissolved O_2 attack corrosion	Corrosion that occurs as a result of exposure of a metal to dissolved oxygen.	Differential oxygen concentration cells. Localized attack patches.	ASM Handbook Vol. 13, Corrosion
Filiform corrosion	Corrosion that occurs under some coatings in the form of randomly distributed threadlike filaments.	Pattern — network surfaces effect often interacting series of criscross lines. Thinned surfaces, cosmetic problem.	ASM Handbook Vol. 13, Corrosion
Galvanic corrosion	A form of corrosion that can occur at the junction of dissimilar metals when they are joined together in a suitable electrolyte, such as a moist or aqueous environment, or soils containing moisture.	The corrosion is more severe near the junction of the two metals than elsewhere. Galvanic corrosion is usually the result of poor design and selection of materials. Two different metals in contact with an electrolyte. Interfacial junction attack usually within 3–5 diameters of a junction.	API 571
Intergranular corrosion	Preferential dissolution of the grain-boundary phases or the zones immediately adjacent to them, usually with slight or negligible attack on the main body of the grains.	Susceptibility to intergranular corrosion is usually related to thermal processing, such as welding or stress relieving, and can be corrected by a solution heat treatment or alloy trace additives. Microscopic examination reveals attack at grain boundaries.	ASM Handbook Vol. 13, Corrosion
Liquid slag attack corrosion	A process in which slag forms on the surface of a component causing fluxing of the normally protective oxide scales on the alloys and results in accelerated oxidation and metal loss	Molten slag usually, but not always, involves a sulfur or sodium bearing compound.	EPRI CS-5500-SR, Boiler Tube Failures in Fossil Power Plants
Microbiological induced corrosion (MIC)	A form of corrosion caused by living organisms such as bacteria, algae, or fungi. It is often associated with the presence of tubercles or slimy organic substances.	Most common attack is due to sulphite reducing bacteria. Very deep pitting, high concentration rates	API 571

Table A-1 Damage Mechanism Definitions (Cont'd)

Damage Mechanism	Definition	Attributes	References From 16.1
Oxidation corrosion	Oxygen reacts with carbon steel and other alloys at high temperature converting the metal to oxide scale. It is most often present as oxygen is in the surrounding air (approximately 20%) used for combustion in fired heaters and boilers.	Usually referred to as dry or high temperature attack.	API 571
Phosphate attack corrosion	A continuous addition of phosphate to keep boiler water in specification could cause a boiler to operate in a zone that may result in acidic phosphate corrosion causing failures.	Linked to sodium phosphate water treatment in boilers. Also known as phosphate hideout	EPRI CS-5500-SR, Boiler Tube Failures in Fossil Power Plants
Selective leaching (dealloying) corrosion	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.	Generally leaves one of the phases of the metal with the same geometry as the uncorroded metal. Results in a significant loss of strength without a visually apparent corresponding loss in metal thickness. Matrix of component often seems unaffected.	API 571
Under deposit corrosion	A special version of crevice corrosion	Solution chemistry under the deposit is different than the bulk solution. Often occurs under deposits. Particulates may be transported corrosions products.	ASM Handbook Vol. 13, Corrosion
Uniform corrosion	The deterioration of metal caused by chemical or electrochemical reaction of a metal with its environment over a uniform area	Gross topographic features are general metal loss over a large area, not localized like pitting. Can be attended to by corrosion allowance.	ASM Handbook Vol. 13, Corrosion
Corrosion-fatigue	The combined action of repeated or fluctuating stress and a corrosive environment to produce cracking. Cyclic loading plus a corrosive environment.	An observed dependence of fatigue strength or fatigue life on frequency often is considered definitive in establishing corrosion fatigue as the mechanism of failure. Beach marks and corrosion products. Similar to mechanical fatigue but cycles to failure often lessened. Usually transgranular.	ASM Handbook Vol. 11, Failure Analysis and Prevention
Creep/stress rupture	At high temperatures, metal components can slowly and continuously deform under load below the yield stress. This time dependent deformation of stressed components is known as creep. Deformation leads to damage that may eventually lead to a rupture.	A change in dimensions that can result in failure. Long term elongation of component. Can progress to stress rupture resulting in internal cracking. Material will elongate until intergranular tears initiate which can then join together to form a stress. Temperatures greater than 0.4 times the melting point "softens" alloys.	API 571
Decarburization	A condition where steel loses strength due the removal of carbon and carbides leaving only an iron matrix. Decarburization occurs during exposure to high temperatures, during heat treatment, from exposure to fires, or from high temperature service in a gas environment.	Loss of carbon from the surface of steel can occur during heat treatment if the furnace atmosphere is oxidizing. The surface will be soft and low in strength.	API 571
Electrical discharge	A pitting mechanism caused by passing electrical currents between two surfaces. If current is high enough, very localized melting can occur.	Typically found in bearings and shafts associated with electrical equipment such as motors or generators	ASM Handbook Vol. 11, Failure Analysis and Prevention

Table A-1 Damage Mechanism Definitions (Cont'd)

Damage Mechanism	Definition	Attributes	References From 16.1
Erosion	Destruction of materials by the abrasive action of moving fluids.	Horseshoe-shaped indentations, particularly for copper alloys. Other alloys may have a scalloping effect. Special case turbulent flow accelerated corrosion (FAC).	ASM Handbook Vol. 11, Failure Analysis and Prevention
Erosion—droplets	Erosion accelerated by two-phase flow.	Flow-oriented patterning	ASM Handbook Vol. 11, Failure Analysis and Prevention
Erosion—solids	A form of erosion in which the suspended particles are solid.	Often a polished surface.	ASM Handbook Vol. 11, Failure Analysis and Prevention
Erosion/corrosion	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. Erosion-corrosion is a description for the damage that occurs when corrosion contributes 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.	Generally a roughened surface with flow patterning lines visible.	API 571
Fatigue, contact	Cracking and subsequent spalling of metal subjected to alternating Hertzian (contact) stresses	. . .	ASM Handbook Vol. 11, Failure Analysis and Prevention
Fatigue, mechanical	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. These stresses can arise from either mechanical loading or thermal cycling and are typically well below the yield strength of the material.	Characterized by incremental propagation of cracks until the cross section has been reduced so that it can no longer support the maximum applied load; often mistakenly called "crystallization." Progress of crack usually indicated by appearance of "beach marks." The majority of fatigue cracks in welded members initiate at a weld toe or at a termination near a stiffener or other attachments such as gusset plates. Circular striations noted emanating from the origin or point of the stress concentration.	API 571
Fatigue, thermal	The progressive localized permanent structural change that occurs in a material subjected to repeated or fluctuating thermal stresses. Cyclic loading caused by thermal cycles. The cracking is often enhanced by oxidation.	Caused by a temperature change acting against an external or internal restraint. Low cycle thermal fatigue failures may be characterized by multiple initiation sites, transverse fractures, an oxide wedge filling the crack, or transgranular fracture. Also, may involve differential alloy expansion/contraction rates	ASM Handbook Vol. 11, Failure Analysis and Prevention
Fatigue, vibration	A form of mechanical fatigue in which cracks are produced as the result of dynamic loading due to vibration, water hammer, or unstable fluid flow.	Typically start from areas of stress concentration such as notches, sharp edges, grooves, etc.	API 571

Table A-1 Damage Mechanism Definitions (Cont'd)

Damage Mechanism	Definition	Attributes	References From 16.1
Flow accelerated corrosion (FAC)	Thinning corrosion usually associated with high purity, low oxygen steam condensate caused by the relative movement of a corrosive fluid against the metal surface. It does not involve or require the formation of bubbles due to cavitation. Metal loss results from the dissolution of the protective oxide film by localized turbulence.	Loss in thickness at bends and regions of localized turbulence.	WRC 490
Flue gas dew point corrosion	Sulfur and chlorine species in fuel will form sulfur dioxide, sulfur trioxide and hydrogen chloride within the combustion products. At low enough temperatures, these gases and the water vapor in the flue gas will condense to form sulfurous acid, sulfuric acid and hydrochloric acid which can lead to severe corrosion.	. . .	API 571
Fretting	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.	Very clean surfaces, often noted in localized zones. Can also occur in aqueous environments, e.g., heat exchanger tube bundle rubbing.	ASM Handbook Vol. 11, Failure Analysis and Prevention
Fuel ash corrosion	Fuel ash corrosion is accelerated high temperature wastage of materials that occurs when contaminants in the fuel form deposits and melt on the metal surfaces of fired heaters, boilers, and gas turbines. Corrosion typically occurs with fuel oil or coal that is contaminated with a combination of sulfur, sodium, potassium, and/or vanadium. The resulting molten salts (slags) dissolve the surface oxide and enhance the transport of oxygen to the surface to reform the iron oxide at the expense of the tube wall or component.	. . .	API 571
Graphitization	Graphitization is a change in the microstructure of certain carbon steels and 0.5Mo steels after long-term operation in the 800°F to 1,100°F (427°C to 593°C) range that may cause a loss in strength, ductility, and/or creep resistance. At elevated temperatures, the carbide phases in these steels are unstable and may decompose into graphite nodules. This decomposition is known as graphitization.	Reduced ductility primarily in weld heat affected zones due to presence of flake graphite.	API 571
High temp H_2/H_2S corrosion	The presence of hydrogen in H_2S streams increases the severity of high temperature sulfide corrosion at temperatures above about 500°F (260°C). This form of sulfidation usually results in a uniform loss in thickness associated with hot circuits in hydroprocessing units.	. . .	API 571
Hot cracking	Intergranular cracking in a weld that occurs during solidification of the weld. It typically occurs at weld metal temperatures above 1,200°F (650°C).	. . .	ASM Handbook Vol. 11, Failure Analysis and Prevention
Hot tensile	Occurs when the stress in a component exceeds the at-temperature tensile strength of the metal.	Discoloration and distortion. Materials have permanent and detrimental change in properties. A mechanical phenomenon.	ASM Handbook Vol. 11, Failure Analysis and Prevention

Table A-1 Damage Mechanism Definitions (Cont'd)

Damage Mechanism	Definition	Attributes	References From 16.1
Hydrochloric acid corrosion	Hydrochloric acid (aqueous HCl) causes both general and localized corrosion and is very aggressive to most common materials of construction across a wide range of concentrations. Damage in refineries is most often associated with dew point corrosion in which vapors containing water and hydrogen chloride condense from the overhead stream of a distillation, fractionation, or stripping tower. The first water droplets that condense can be highly acidic (low pH) and promote high corrosion rates.	. . .	API 571
Hydrofluoric (HF) acid corrosion	Corrosion by HF acid can result in high rates of general or localized corrosion and may be accompanied by hydrogen cracking, blistering, and/or HIC/SOHIC.	. . .	API 571
Hydrogen damage	Hydrogen damage occurs in high pressure boilers, usually under heavy scale deposits, on the waterside of the boiler tube. The damage develops first in the highest heat-release zones of the furnace, often just downstream of welded joints. Regardless of whether the conditions are acidic or basic, hydrogen atoms are produced by the corrosion reaction. The hydrogen is trapped between the scale and the steel, and some hydrogen penetrates into the steel. Since hydrogen is a small atom, it can easily diffuse into the steel where it reacts with iron carbide to form methane and iron. Methane is a large molecule and cannot easily diffuse and therefore collects at the grain boundaries within the steel. When sufficient methane collects, a series of intergranular cracks that weaken the steel are formed.	. . .	WRC 490
Hydrogen embrittlement	A loss in ductility of high strength steels due to the penetration of atomic hydrogen can lead to brittle cracking. Hydrogen embrittlement (HE) can occur during manufacturing, welding, or from services that can charge hydrogen into the steel in an aqueous, corrosive, or a gaseous environment.	The degree of hydrogen embrittlement is highly dependent on the strength level of steel. Primarily intergranular low ductility fracture, generally without corrosion products. Nacent hydrogen evolved at cathodic surfaces diffuses into matrix of alloy and forms molecular hydrogen leading to overpressure.	API 571
Hydrogen-induced crack (HIC)	Hydrogen blisters can form at many different depths from the surface of the steel, in the middle of the plate, or near a weld. In some cases, neighboring or adjacent blisters that are at slightly different depths (planes) may develop cracks that link them together. Interconnecting cracks between the blisters often have a stair step appearance, and so HIC is sometimes referred to as "stepwise cracking."	Nacent molecular hydrogen transmutes after diffusion in alloy matrix.	API 571
Knife-line attack	Intergranular corrosion of an alloy, usually stabilized stainless steel, along a line adjoining or in contact with a weld after heating into the sensitization temperature range.	See "sensitization." Very well-defined line, attack.	ASM Handbook Vol. 11, Failure Analysis and Prevention
Lack-of-fusion	Weld fusion that is less than complete, also known as incomplete fusion.	. . .	ASM Handbook Vol. 6, Welding, Brazing, and Soldering

Table A-1 Damage Mechanism Definitions (Cont'd)

Damage Mechanism	Definition	Attributes	References From Section 16
Lack-of-penetration	Joint penetration which is less than that specified.	. . .	ASM Handbook Vol. 6, Welding, Brazing, and Soldering
Liquid metal cracking (LMC)	A form of cracking that results when certain molten metals come in contact with specific alloys. Cracking can be very sudden and brittle in nature.	Usually involves the softer alloys such as Pb, Hg, Cd, Cu, Zn, Al, etc., as the liquid metal. Formerly called liquid metal embrittlement (LME).	API 571
Naphthenic acid corrosion (NAC)	A form of high temperature corrosion that occurs primarily in crude and vacuum units, and downstream units that process certain fractions or cuts that contain naphthenic acids.	The various acids which comprise the naphthenic acid family can have distinctly different corrosivity.	API 571
Phenol (carbolic acid) corrosion	Corrosion of carbon steel can occur in plants using phenol as a solvent to remove aromatic compounds from lubricating oil feedstocks.	. . .	API 571
Phosphoric acid corrosion	Phosphoric acid is most often used as a catalyst in polymerization units. It can cause both pitting corrosion and localized corrosion of carbon steels depending on water content.	Corrosion rates increase with increasing temperatures. Corrosion can penetrate a $^1/_4$-in. thick steel tube in 8 hr.	API 571
Polythionic acid cracking	A form of stress corrosion cracking normally occurring during shutdowns, start-ups, or during operation when air and moisture are present. Cracking is due to sulfur acids forming from sulfide scale, air, and moisture acting on sensitized austenitic stainless steels. Usually adjacent to welds or high stress areas. Cracking may propagate rapidly through the wall thickness of piping and components in a matter of minutes or hours.	. . .	API 571
Porosity	Cavity-type discontinuities formed by gas entrapment during solidification.	. . .	ASM Handbook Vol. 6, Welding, Brazing, and Soldering
Sensitization	In austenitic stainless steels, the precipitation of chromium carbides, usually at grain boundaries, on exposure to temperatures in the range of 1,000°F to 1,550°F (550°C to 850°C). Leaving the grain boundaries depleted of chromium and, therefore, susceptible to attack.	. . .	ASM Handbook Vol. 11, Failure Analysis and Prevention
Sigma phase embrittlement	Formation of a metallurgical phase known as sigma phase can result in a loss of fracture toughness in some stainless steels as a result of high temperature exposure.	Sigma phase is an iron-chromium compound of approximately equal atomic proportions of iron and chromium. It is extremely brittle and hard. Noted and identified after metallurgical examination under a microscope.	API 571
Sigma and chi phase	Detrimental phase formation in austenitic alloys as a result of long-term exposures in the 1,200°F to 1,600°F (650°C to 870°C) range. Susceptibility is greater in higher chrome containing alloys.	Components in heaters and furnaces exposed to the appropriate temperature range for extended periods. Noted and identified after metallurgical examination under a microscope.	ASM Handbook Vol. 11, Failure Analysis and Prevention
Softening (over aging)	Caused by exposure to elevated temperatures, generally less than 1,300°F (705°C), which lowers the tensile strength and hardness of the metal as well as increasing the ductility and reduction of area.	. . .	ASM Handbook Vol. 11, Failure Analysis and Prevention

Table A-1 Damage Mechanism Definitions (Cont'd)

Damage Mechanism	Definition	Attributes	References From Section 16
Sour water corrosion (acidic)	Corrosion of steel due to acidic sour water containing H_2S at a pH between 4.5 and 7.0. Carbon dioxide (CO_2) may also be present. Sour waters containing significant amounts of ammonia, chlorides, or cyanides may significantly affect pH but are outside the scope of this section.	. . .	API 571
Spheroidization	Spheroidization is a change in the microstructure of steels after exposure in the 850°F to 1,400°F (440°C to 760°C) range, where the carbide phases in carbon steels are unstable and may agglomerate from their normal plate-like form to a spheroidal form, or from small, finely dispersed carbides in low alloy steels like 1Cr–0.5Mo to large agglomerated carbides. Spheroidization may cause a loss in strength and/or creep resistance.	The change from the laminar pearlitic structure to the spheroidized carbides generally produces a slight reduction in tensile and yield strength and a corresponding slight increase in elongation.	API 571
Strain aging	Strain aging is a form of damage found mostly in older vintage steels and C–0.5Mo low alloy steels under the combined effects of deformation and aging at an intermediate temperature. This results in an increase in hardness and strength with a reduction in ductility and toughness.	Strain aging can produce an increase in strength but generally produces problems in deep drawing the rimmed or capped steels.	API 571
Stray current corrosion	Corrosion typically caused when two pipes are in close proximity of each other and one pipe is cathodically protected. The other pipe can act as the anode and will corrode	. . .	ASM Handbook Vol. 13, Corrosion
Sulfidation	Corrosion of carbon steel and other alloys resulting from their reaction with sulfur compounds in high-temperature environments. The presence of hydrogen accelerates corrosion.	. . .	API 571
Sulfide-stress cracking (SSC)	Cracking under the combined action of tensile stress and corrosion in the presence of water and hydrogen sulfide.	. . .	ASM Handbook Vol. 11, Failure Analysis and Prevention; NACE RP 0472, MR0103, MR0175
Sulfuric acid corrosion	Sulfuric acid promotes general and localized corrosion of carbon steel and other alloys. Carbon steel heat-affected zones may experience severe corrosion.	. . .	API 571
Temper embrittlement	Temper embrittlement is the reduction in toughness due to a metallurgical change that can occur in some low alloy steels as a result of long term exposure in the temperature range of about 650°F to 1,100°F (343°C to 593°C) . This change causes an upward shift in the ductile-to-brittle transition temperature as 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-up and shutdown.	Temper embrittlement causes an increase in the ductile to brittle transition temperature but the condition can be reversed by retempering at a temperature above the critical range followed by rapid cooling.	API 571
Weld decay	A band of intergranular corrosion next to a weld in the base metal of a nonstabilized stainless steel (e.g.,304 stainless steel).	Similar to intergranular type attack, but localized close to weldments because temperature from welding puts local region in sensitizing range.	ASM Handbook Vol. 11, Failure Analysis and Prevention
Weld metal crater cracking	A crack in the crater of a weld bead. The crater, in arc welding, is a depression at the termination of a weld bead or in the molten weld bead.	. . .	ASM Handbook Vol. 6, Welding, Brazing, and Soldering

Table A-1 Damage Mechanism Definitions (Cont'd)

Damage Mechanism	Definition	Attributes	References From Section 16
Weld metal fusion line cracking	A crack at the interface between the weld metal and the area of base metal melted (fusion line) from welding.	. . .	ASM Handbook Vol. 6, Welding, Brazing, and Soldering
Weld metal longitudinal cracking	Cracking parallel to or along a weld.	. . .	ASM Handbook Vol. 6, Welding, Brazing, and Soldering
Weld metal root cracking	A crack in the root of a weld. The root is defined as the points, as shown in cross section, at which the back of the weld intersects the base metal surfaces.	. . .	ASM Handbook Vol. 6, Welding, Brazing, and Soldering
Weld metal toe cracking	A crack in the base metal occurring at the toe of a weld, which is the junction between the face of a weld and the base metal.	. . .	ASM Handbook Vol. 6, Welding, Brazing, and Soldering
Weld metal transverse cracking	Cracking across (perpendicular to) a weld.	. . .	ASM Handbook Vol. 6, Welding, Brazing, and Soldering
Weld metal underbead cracking	Cold cracks that are most frequently encountered when welding a hardenable base metal. Excessive joint restraint and the presence of hydrogen are contributing causes.	. . .	ASM Handbook Vol. 6, Welding, Brazing, and Soldering

NONMANDATORY APPENDIX B
DAMAGE MECHANISM AND DEFECTS SCREENING TABLE

Table starts on next page.

Table B-1 Damage Mechanism and Defects Screening Table

	Damage/ Defect	Materials of Construction in Which Mechanism Typically Occurs													Operating Environment: Temperature (*T*) Range in Which Mech. May Occur					Operating Environment: Processes in Which Mechanism May Be Suspected. Process Contains:															Operating Environment: Flow Req.		Operating Environment: Type of Loading			
Mechanism	Mode [Note (1)]	Damage Mechanism	Manufacturing Defect	Carbon Steel	Low Alloy Steel	300 Series Stainless Steel	400 Series Stainless Steel	Duplex Stainless Steel	Fe-Ni Alloys (0.6–1.3 Fe:Ni Ratios)	Ni-Based Alloys (>50% Ni)	Cu Alloys	Ti	Al Alloys	Cast Iron	$T>1{,}000°F$	$800<T<1{,}000°F$	$250<T<800°F$	$32<T<250°F$	$T<32°F$	Water, Steam, Air	Hydrogen	Carbon	Sodium	Carbonate	Sulfur	Amines	Ammonia	Chloride	HF	Phenol	Crude Oil	Phosphoric Acid	Particulates	Other	Motionless—Static	Hydrodynamic	Static Stress [Note (2)]	Impact	Thermal Gradients or Shock	Cyclic Stress (e.g., Vibratory)
885°F embrittlement	Metallurgical damage	X					X	X								X	X																							
Abrasive wear	Metal loss	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X														X			X				
Acid dew point corrosion	Metal loss	X		X	X	X	X	X	X					X			X	X		X								X	X			X		X	X					
Adhesive wear	Metal loss	X		X	X	X	X	X	X	X	X	X	X	X			X	X																						X
Amine corrosion	Metal loss	X		X	X						X						X	X								X														
Amine cracking	Cracking	X		X							X						X	X								X														
Ammonia grooving	Metal loss	X									X						X	X		X						X	X									X				
Ammonia stress corrosion cracking	Cracking	X		X							X						X	X									X										X			
Ammonium bisulfide corrosion (alkaline sour water)	Metallurgical damage	X		X	X						X		X	X				X		X					X		X									X				
Brittle fracture	Cracking	X	X	X	X		X							X			X	X	X																		X	X	X	X
Carbonate stress corrosion cracking	Cracking	X		X	X												X	X						X													X			
Carburization	Metallurgical damage	X		X	X	X	X	X	X	X					X	X						X																		
Metal dusting (catastrophic carburization)	Metal loss	X			X	X				X					X							X																		
Caustic stress corrosion cracking	Cracking	X		X	X	X	X	X									X	X		X			X											X			X			
Caustic corrosion (caustic gouging)	Metal loss	X		X	X						X		X				X	X		X			X											X		X				
Cavitation	Metal loss	X		X	X	X	X	X	X	X	X	X	X	X			X	X		X														X		X				

Table B-1 Damage Mechanism and Defects Screening Table (Cont'd)

	Damage/ Defect	Materials of Construction in Which Mechanism Typically Occurs													Operating Environment																									
															Temperature (*T*) Range in Which Mech. May Occur					Processes in Which Mechanism May Be Suspected. Process Contains:															Flow Req.		Type of Loading			
Mechanism	Mode [Note (1)]	Damage Mechanism	Manufacturing Defect	Carbon Steel	Low Alloy Steel	300 Series Stainless Steel	400 Series Stainless Steel	Duplex Stainless Steel	Fe-Ni Alloys (0.6–1.3 Fe:Ni Ratios)	Ni-Based Alloys (>50% Ni)	Cu Alloys	Ti	Al Alloys	Cast Iron	$T>1{,}000°F$	$800<T<1{,}000°F$	$250<T<800°F$	$32<T<250°F$	$T<32°F$	Water, Steam, Air	Hydrogen	Carbon	Sodium	Carbonate	Sulfur	Amines	Ammonia	Chloride	HF	Phenol	Crude Oil	Phosphoric Acid	Particulates	Other	Motionless–Static	Hydrodynamic	Static Stress [Note (2)]	Impact	Thermal Gradients or Shock	Cyclic Stress (e.g., Vibratory)
Chelant corrosion	Metal loss	X		X	X												X			X																X				
Chloride stress corrosion cracking	Cracking	X				X		X	X								X	X		X								X						X			X			X
CO_2 corrosion	Metal loss	X		X	X												X	X				X																		
Cold cracking	Weld defects		X	X	X	X	X	X	X	X	X		X																											
Corrosion under insulation (CUI)	Metal loss	X		X	X	X	X	X			X	X	X	X				X	X	X															X					
Corrosion–fatigue	Cracking	X		X	X	X	X	X	X	X	X	X	X	X			X	X	X	X				X	X	X	X	X	X	X	X	X		X						X
Creep	Cracking	X		X	X	X	X	X	X	X	X	X	X	X	X	X																					X			
Creep fatigue	Cracking			X	X	X	X	X	X	X	X	X	X	X	X	X																					X			
Crevice corrosion	Metal loss	X		X	X	X	X	X	X	X	X	X	X	X			X	X		X															X					
Decarburization	Metallurgical damage	X		X	X										X					X	X				X									X						
Dissimilar metal weld cracking (DMW)	Cracking	X		X	X	X	X	X	X	X	X				X	X																								
Dissolved O_2 attack	Metal loss	X		X	X													X		X														X						
Electrical discharge	Metal loss	X		X	X	X	X	X	X	X	X	X	X	X			X	X																						
Erosion	Metal loss	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X				
Erosion–droplets	Metal loss	X		X	X	X	X	X	X	X	X	X	X	X			X	X		X	X	X	X	X	X	X	X	X	X	X	X	X		X		X				
Erosion–solids	Metal loss	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X													X			X				
Erosion/corrosion	Metal loss	X		X	X	X	X	X	X	X	X	X	X	X			X	X		X	X	X	X	X	X	X	X	X	X	X	X	X		X		X				
Fatigue	Cracking	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X																					X
Fatigue, contact	Cracking	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X																					X

Table B-1 Damage Mechanism and Defects Screening Table (Cont'd)

	Damage/ Defect	Materials of Construction in Which Mechanism Typically Occurs													Operating Environment: Temperature (T) Range in Which Mech. May Occur					Operating Environment: Processes in Which Mechanism May Be Suspected. Process Contains:															Operating Environment: Flow Req.		Operating Environment: Type of Loading			
Mechanism	Mode [Note (1)]	Damage Mechanism	Manufacturing Defect	Carbon Steel	Low Alloy Steel	300 Series Stainless Steel	400 Series Stainless Steel	Duplex Stainless Steel	Fe-Ni Alloys (0.6–1.3 Fe:Ni Ratios)	Ni-Based Alloys (>50% Ni)	Cu Alloys	Ti	Al Alloys	Cast Iron	$T>1{,}000°F$	$800<T<1{,}000°F$	$250<T<800°F$	$32<T<250°F$	$T<32°F$	Water, Steam, Air	Hydrogen	Carbon	Sodium	Carbonate	Sulfur	Amines	Ammonia	Chloride	HF	Phenol	Crude Oil	Phosphoric Acid	Particulates	Other	Motionless—Static	Hydrodynamic	Static Stress [Note (2)]	Impact	Thermal Gradients or Shock	Cyclic Stress (e.g., Vibratory)
Fatigue, thermal	Cracking	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X																						X	
Fatigue, vibration	Cracking	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X																					X
Filiform corrosion	Metal loss	X																X		X														X	X					
Flow-accelerated corrosion (FAC)	Metal loss	X		X													X	X																		X				
Flue gas dew point corrosion	Metal loss	X		X	X	X	X	X	X	X								X		X								X	X							X				
Fretting	Metal loss	X		X	X	X	X	X	X	X	X		X	X	X	X	X	X	X																					X
Fuel ash corrosion	Metal loss	X		X	X	X	X	X	X	X	X		X	X	X	X							X		X															
Galvanic corrosion	Metal loss	X		X	X	X	X	X	X	X	X	X	X	X			X	X		X														X						
Graphitization	Metallurgical damage	X		X	X										X	X																								
High temp H_2/H_2S corrosion	Metal loss	X		X	X	X	X				X		X				X				X				X															
Hot cracking	Weld defects		X	X	X	X	X	X	X	X	X		X																											
Hot tensile	Metallurgical damage	X		X	X	X	X	X	X	X	X	X	X	X	X	X																					X			
Hydrochloric acid corrosion	Metal loss	X		X	X	X	X			X	X	X	X	X				X										X												
Hydrofluoric acid corrosion	Metal loss	X		X	X	X	X				X	X	X					X											X											
Hydrogen damage (HTHA)	Cracking	X		X	X										X	X					X													X						
Hydrogen embrittlement	Metallurgical damage	X	X	X	X		X					X						X							X									X						
Hydrogen-induced crack (HIC)	Cracking	X		X	X							X						X							X															

Table B-1 Damage Mechanism and Defects Screening Table (Cont'd)

	Damage/ Defect	Materials of Construction in Which Mechanism Typically Occurs													Operating Environment: Temperature (T) Range in Which Mech. May Occur					Operating Environment: Processes in Which Mechanism May Be Suspected. Process Contains:															Operating Environment: Flow Req.		Operating Environment: Type of Loading			
Mechanism	Mode [Note (1)]	Damage Mechanism	Manufacturing Defect	Carbon Steel	Low Alloy Steel	300 Series Stainless Steel	400 Series Stainless Steel	Duplex Stainless Steel	Fe-Ni Alloys (0.6–1.3 Fe:Ni Ratios)	Ni-Based Alloys (>50% Ni)	Cu Alloys	Ti	Al Alloys	Cast Iron	$T > 1{,}000°F$	$800 < T < 1{,}000°F$	$250 < T < 800°F$	$32 < T < 250°F$	$T < 32°F$	Water, Steam, Air	Hydrogen	Carbon	Sodium	Carbonate	Sulfur	Amines	Ammonia	Chloride	HF	Phenol	Crude Oil	Phosphoric Acid	Particulates	Other	Motionless—Static	Hydrodynamic	Static Stress [Note (2)]	Impact	Thermal Gradients or Shock	Cyclic Stress (e.g., Vibratory)
Intergranular corrosion	Metal loss/ cracking	X				X		X	X	X							X	X		X					X									X						
Knife-line attack	Cracking		X			X												X		X														X						
Lack-of-fusion	Weld defects		X	X	X	X	X	X	X	X	X	X	X	X																										
Lack-of-penetration	Weld defects		X	X	X	X	X	X	X	X	X	X	X																											
Liquid (molten) slag attack	Metal loss	X		X	X	X				X					X																			X	X					
Liquid metal embrittlement	Cracking	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X																							
Microbiological induced corrosion (MIC)	Metal loss	X		X	X	X	X			X	X							X	X	X														X	X					
Napthenic acid corrosion	Metal loss	X		X	X	X	X			X							X	X													X									
Oxidation corrosion	Metal loss	X		X	X	X	X	X	X	X					X					X														X						
Phenol (carbolic acid)	Metal loss	X		X	X												X													X					X					
Phosphate attack	Metal loss	X		X	X												X	X		X																X				
Phosphoric acid corrosion	Metal loss	X		X	X							X	X				X	X		X												X								
Pitting corrosion	Metal loss	X		X	X	X	X	X	X	X	X	X	X				X	X		X					X									X						
Polythlonic acid cracking	Cracking	X				X			X									X		X					X												X			
Porosity	Weld defects		X	X	X	X	X	X	X	X	X	X	X	X																										

Table B-1 Damage Mechanism and Defects Screening Table (Cont'd)

	Damage/ Defect	Materials of Construction in Which Mechanism Typically Occurs													Operating Environment: Temperature (T) Range in Which Mech. May Occur					Operating Environment: Processes in Which Mechanism May Be Suspected. Process Contains:															Operating Environment: Flow Req.		Operating Environment: Type of Loading			
Mechanism	Mode [Note (1)]	Damage Mechanism	Manufacturing Defect	Carbon Steel	Low Alloy Steel	300 Series Stainless Steel	400 Series Stainless Steel	Duplex Stainless Steel	Fe-Ni Alloys (0.6–1.3 Fe:Ni Ratios)	Ni-Based Alloys (>50% Ni)	Cu Alloys	Ti	Al Alloys	Cast Iron	$T>1{,}000°F$	$800<T<1{,}000°F$	$250<T<800°F$	$32<T<250°F$	$T<32°F$	Water, Steam, Air	Hydrogen	Carbon	Sodium	Carbonate	Sulfur	Amines	Ammonia	Chloride	HF	Phenol	Crude Oil	Phosphoric Acid	Particulates	Other	Motionless—Static	Hydrodynamic	Static Stress [Note (2)]	Impact	Thermal Gradients or Shock	Cyclic Stress (e.g., Vibratory)
Selective leaching (dealloying)	Metal loss	X									X			X			X	X		X				X										X						
Sensitization	Metallurgical damage	X	X			X			X						X	X																								
Sigma phase	Metallurgical damage	X				X	X								X																									
Sigma and chi phase	Metallurgical damage	X				X	X								X																									
Sliding wear	Metal loss	X		X	X	X	X	X	X	X	X	X	X	X			X	X																						X
Softening (over aging)	Metallurgical damage	X		X	X	X	X	X	X	X	X	X	X	X	X	X																								
Sour water corrosion (acidic)	Metal loss	X		X	X								X				X	X		X	X				X															
Spheroidization	Metallurgical damage	X		X	X										X	X																								
Strain aging	Metallurgical damage	X		X														X																						
Stray current corrosion	Metal loss	X		X	X	X	X	X	X	X	X	X	X	X			X	X																						
Sulfidization	Metal loss	X		X	X		X		X	X	X				X	X									X															
Sulfide-stress cracking (SSC)	Cracking	X		X	X		X										X	X																			X			X
Sulfuric acid corrosion	Metal loss	X		X	X	X	X	X	X	X	X	X	X	X			X	X		X																X				
Temper embrittlement	Metallurgical damage	X	X		X										X	X	X																							

Table B-1 Damage Mechanism and Defects Screening Table (Cont'd)

Mechanism	Damage/Defect	Materials of Construction in Which Mechanism Typically Occurs												
	Mode [Note (1)]	Damage Mechanism	Manufacturing Defect	Carbon Steel	Low Alloy Steel	300 Series Stainless Steel	400 Series Stainless Steel	Duplex Stainless Steel	Fe-Ni Alloys (0.6–1.3 Fe:Ni Ratios)	Ni-Based Alloys (>50% Ni)	Cu Alloys	Ti	Al Alloys	Cast Iron
Under deposit corrosion	Metal loss	X		X	X	X	X	X	X	X	X	X	X	X
Uniform corrosion	Metal loss	X		X	X	X	X	X	X	X	X	X	X	X
Weld decay	Metal loss	X				X								
Weld metal crater cracking	Weld defects		X	X	X	X	X	X	X	X	X		X	
Weld metal fusion line cracking	Weld defects		X	X	X	X	X	X	X	X	X		X	
Weld metal longitudinal cracking	Weld defects		X	X	X	X	X	X	X	X	X		X	
Weld metal root cracking	Weld defects		X	X	X	X	X	X	X	X	X		X	
Weld metal toe cracking	Weld defects		X	X	X	X	X	X	X	X	X		X	
Weld metal transverse cracking	Weld defects		X	X	X	X	X	X	X	X	X		X	
Weld metal underbead cracking	Weld defects		X	X	X	X	X	X	X	X	X		X	

Mechanism	Operating Environment: Temperature (*T*) Range in Which Mech. May Occur					Processes in Which Mechanism May Be Suspected. Process Contains:															Flow Req.		Type of Loading			
	$T>1{,}000°F$	$800<T<1{,}000°F$	$250<T<800°F$	$32<T<250°F$	$T<32°F$	Water, Steam, Air	Hydrogen	Carbon	Sodium	Carbonate	Sulfur	Amines	Ammonia	Chloride	HF	Phenol	Crude Oil	Phosphoric Acid	Particulates	Other	Motionless—Static	Hydrodynamic	Static Stress [Note (2)]	Impact	Thermal Gradients or Shock	Cyclic Stress (e.g., Vibratory)
Under deposit corrosion			X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X							
Uniform corrosion			X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X						
Weld decay			X	X		X														X						
Weld metal crater cracking																										
Weld metal fusion line cracking																										
Weld metal longitudinal cracking																										
Weld metal root cracking																										
Weld metal toe cracking																										
Weld metal transverse cracking																										
Weld metal underbead cracking																										

GENERAL NOTE: This table does not include misapplication of materials, and damage issues rarely experienced or not typical of process environments.

NOTES:

(1) Manufacturing, weld, and casting defects can become a factor and also can lead to other damage mechanisms.

(2) Static stress can include residual tensile stress.

NONMANDATORY APPENDIX C
TABLE OF INSPECTION/MONITORING METHODS

Table starts on next page.

Table C-1 Inspection/Monitoring Methods

	Damage/Defect			Common Examination Methods Used to Identify [Note (1)]															
				Surface					Subsurface					Other Methods					
Mechanism	Mode [Note (2)]	Damage Mechanism	Manufacturing Defect	Visual (Including Borescope)—VT [Note (3)]	Liquid Penetrant—PT [Note (3)]	Fluorescent Liquid Penetrant—FPT [Note (3)]	Magnetic Particle—MT [Note (4)]	Wet Fluorescent Magnetic Particle—WFMT [Note (4)]	Ultrasonics for Thickness—UTT	Ultrasonics—Straight Beam—UTS	Ultrasonics—Shear Wave—UTSW	Ultrasonics—Shear Wave Adv. Techniques—UTSWA	Radiography—RT	Eddy-Current—ET	Acoustic Emission—AE	Dimensional Measurements	Hardness Tests	In-Place Metallography (Replication)	Boat/Plug Sample
885°F embrittlement	Metallurgical damage	X																	X
Abrasive wear	Metal loss	X		X					X							X			
Acid dew point corrosion	Metal loss	X		X					X	X									X
Adhesive wear	Metal loss	X		X	X				X							X			
Amine corrosion	Metal loss	X		X					X										
Amine cracking	Cracking	X		X			X	X			X	X			X				
Ammonia grooving	Metal loss	X		X					X										
Ammonia stress corrosion cracking	Cracking	X		X			X	X			X	X		X					
Carbonate stress corrosion cracking	Cracking	X		X				X			X	X							
Carburization	Metallurgical damage	X															X		X
Casting porosity/voids	Casting defects		X	X	X	X				X	X	X	X						X
Catastrophic carburization (metal dusting)	Metal loss	X		X					X	X	X	X							X
Caustic cracking (caustic embrittlement)	Cracking	X		X		X		X			X	X	X	X					
Caustic corrosion (caustic gouging)	Metal loss	X		X						X			X	X					X
Cavitation	Metal loss	X		X															
Chelant corrosion	Metal loss	X		X					X					X					X
CO_2 corrosion	Metal loss	X																	
Cold cracking	Weld defects		X	X	X	X	X	X		X	X	X	X						X
Corrosion under insulation (CUI)	Metal loss	X		X					X	X									
Corrosion—fatigue	Cracking	X		X	X	X	X	X		X	X	X		X	X				X
Creep	Cracking	X								X	X	X			X	X		X	X
Crevice corrosion	Metal loss	X		X															X
Decarburization	Metallurgical damage	X															X		X

Table C-1 Inspection/Monitoring Methods (Cont'd)

	Damage/Defect			Common Examination Methods Used to Identify [Note (1)]															
				Surface					Subsurface					Other Methods					
Mechanism	Mode [Note (2)]	Damage Mechanism	Manufacturing Defect	Visual (Including Borescope)—VT [Note (3)]	Liquid Penetrant—PT [Note (3)]	Fluorescent Liquid Penetrant—FPT [Note (3)]	Magnetic Particle—MT [Note (4)]	Wet Fluorescent Magnetic Particle—WFMT [Note (4)]	Ultrasonics for Thickness—UTT	Ultrasonics—Straight Beam—UTS	Ultrasonics—Shear Wave—UTSW	Ultrasonics—Shear Wave Adv. Techniques—UTSWA	Radiography—RT	Eddy-Current—ET	Acoustic Emission—AE	Dimensional Measurements	Hardness Tests	In-Place Metallography (Replication)	Boat/Plug Sample
Dissimiliar metal weld cracking (DMW)	Cracking	X		X	X	X	X	X			X	X							
Dissolved O_2 Attack	Metal loss	X		X										X					X
Electrical discharge	Metal loss	X		X															
Erosion	Metal loss	X		X					X	X	X	X				X			
Erosion—droplets	Metal loss	X		X					X	X	X	X				X			
Erosion—solids	Metal loss	X		X					X	X	X	X				X			
Erosion/corrosion	Metal loss	X		X					X	X	X	X				X			
Fatigue	Cracking	X		X	X	X	X	X		X	X	X		X	X				X
Fatigue, contact	Cracking	X		X	X	X		X							X				
Fatigue, thermal	Cracking	X		X	X	X	X	X		X	X	X		X	X				X
Fatigue, vibration	Cracking	X		X	X	X	X	X		X	X	X		X	X				X
Filiform, corrosion	Metal loss	X		X															X
Flow-accelerated corrosion (FAC)	Metal loss	X		X					X					X					
Flue gas dew point corrosion	Metal loss	X		X					X										
Fretting	Metal loss	X		X	X	X													X
Fuel ash corrosion	Metal loss	X																	
Galvanic corrosion	Metal loss	X		X															X
Graphitization	Metallurgical damage	X															X	X	X
High temp H_2/H_2S corrosion	Metal loss	X		X					X				X						
Hot cracking	Weld Defects		X	X	X	X	X	X					X		X				X
Hot tensile	Metallurgical damage	X		X												X		X	X
Hydrochloric acid corrosion	Metal loss	X		X					X										
Hydrofluoric acid corrosion	Metal loss	X		X					X				X						

Table C-1 Inspection/Monitoring Methods (Cont'd)

	Damage/Defect			Common Examination Methods Used to Identify [Note (1)]															
				Surface					Subsurface					Other Methods					
Mechanism	Mode [Note (2)]	Damage Mechanism	Manufacturing Defect	Visual (Including Borescope)—VT [Note (3)]	Liquid Penetrant—PT [Note (3)]	Fluorescent Liquid Penetrant—FPT [Note (3)]	Magnetic Particle—MT [Note (4)]	Wet Fluorescent Magnetic Particle—WFMT [Note (4)]	Ultrasonics for Thickness—UTT	Ultrasonics—Straight Beam—UTS	Ultrasonics—Shear Wave—UTSW	Ultrasonics—Shear Wave Adv. Techniques—UTSWA	Radiography—RT	Eddy-Current—ET	Acoustic Emission—AE	Dimensional Measurements	Hardness Tests	In-Place Metallography (Replication)	Boat/Plug Sample
Hydrogen damage (HTHA)	Cracking	X								X	X	X			X				X
Hydrogen embrittlement	Metallurgical damage	X	X																X
Hydrogen-induced crack (HIC)	Cracking	X				X		X		X	X	X		X	X			X	X
Intergranular corrosion	Metal loss	X																X	X
Knife-line attack	Cracking		X	X						X	X	X			X				
Lack-of-fusion	Weld defects		X							X	X	X	X						X
Lack-of-penetration	Weld defects		X	X	X		X			X	X	X	X						X
Liquid (molten) slag attack	Metal loss	X		X					X	X									X
Liquid metal embrittlement	Cracking	X	X		X	X	X	X		X	X	X			X			X	X
Microbiological induced corrosion (MIC)	Metal loss	X		X					X	X									X
Napthenic acid corrosion	Metal loss	X		X					X				X						
Oxidation corrosion	Metal loss	X		X					X	X									X
Phenol (carbolic acid)	Metal loss	X		X					X				X						
Phosphate attack	Metal loss	X							X										X
Phosphoric acid corrosion	Metal loss	X		X					X				X						
Pitting corrosion	Metal loss	X		X	X					X				X					X
Polythionic acid cracking	Cracking	X			X	X				X	X	X							
Porosity	Weld defects		X							X	X	X	X						X
Selective leaching (dealloying)	Metal loss	X																X	X
Sensitization	Metallurgical damage	X																X	X
Sigma Phase	Metallurgical damage	X																X	X
Sigma and chi phase	Metallurgical damage	X																X	X

Table C-1 Inspection/Monitoring Methods (Cont'd)

	Damage/Defect			Common Examination Methods Used to Identify [Note (1)]															
				Surface					Subsurface					Other Methods					
Mechanism	Mode [Note (2)]	Damage Mechanism	Manufacturing Defect	Visual (Including Borescope)—VT [Note (3)]	Liquid Penetrant—PT [Note (3)]	Fluorescent Liquid Penetrant—FPT [Note (3)]	Magnetic Particle—MT [Note (4)]	Wet Fluorescent Magnetic Particle—WFMT [Note (4)]	Ultrasonics for Thickness—UTT	Ultrasonics—Straight Beam—UTS	Ultrasonics—Shear Wave—UTSW	Ultrasonics—Shear Wave Adv. Techniques—UTSWA	Radiography—RT	Eddy-Current—ET	Acoustic Emission—AE	Dimensional Measurements	Hardness Tests	In-Place Metallography (Replication)	Boat/Plug Sample
Sliding wear	Metal loss	X		X					X							X			
Softening (over aging)	Metallurgical damage	X															X		X
Sour water corrosion (acidic)	Metal loss	X		X					X				X						
Spheroidization	Metallurgical damage	X															X	X	X
Strain aging	Metallurgical damage	X															X		X
Stray current corrosion	Metal loss	X		X					X	X	X	X							
Sulfidation	Metal loss	X																X	X
Sulfide-stress cracking (SSC)	Cracking	X			X	X	X	X		X	X	X		X	X			X	X
Sulfuric acid corrosion	Metal loss	X		X					X				X						
Temper embrittlement	Metallurgical damage	X	X																X
Under deposit corrosion	Metal loss	X							X	X									X
Uniform corrosion	Metal loss	X		X					X	X	X	X				X			
Weld decay	Metal loss	X		X						X	X	X							X
Weld metal crater cracking	Weld defects		X	X	X	X	X	X		X	X	X			X				X
Weld metal fusion line cracking	Weld defects		X	X	X	X	X	X		X	X	X	X		X				X
Weld metal longitudinal cracking	Weld defects		X	X	X	X	X	X		X	X	X	X		X				X
Weld metal root cracking	Weld defects		X							X	X	X	X		X				X
Weld metal toe cracking	Weld defects		X	X	X	X	X	X		X	X	X	X		X				X
Weld metal transverse cracking	Weld defects		X	X	X	X	X	X		X	X	X	X		X				X
Weld metal underbead cracking	Weld defects		X							X	X	X	X		X				X

Table C-1 Inspection/Monitoring Methods (Cont'd)

NOTES:

(1) Many of these examination methods depend upon proper access and surface preparation and thus will not be appropriate for all situations. Many factors influence the detectability of imperfections, including using qualified personnel to perform the inspection.

(2) Manufacturing, weld, and casting defects can become a factor and also can lead to other damage mechanisms.

(3) These methods are capable of detecting imperfections that are open to the surface only.

(4) These methods are capable of detecting imperfections that are open to the surface or slightly subsurface.

NONMANDATORY APPENDIX D QUANTITATIVE METHODS INCLUDING EXPERT OPINION ELICITATION

D-1 INTRODUCTION

Quantitative analysis by definition performs analyses using numbers for inputs. The inputs can be single value estimates or a range or distribution of numbers that not only represent the most likely single value estimate but represent the spread or uncertainty in the value including the uncertainty over time. In risk analysis this can occur in either the probability or consequence analysis or both. Quantitative probability analysis is discussed first, followed by a discussion of consequence analysis.

D-2 QUANTITATIVE PROBABILITY ANALYSIS

D-2.1 Definition

Quantitative probability analysis of plant components provides the measure of the chance (probability) of failure between 0 and 1.0. Because of the time-dependent behavior of some damage mechanisms, this analysis usually provides the probability of failure over a period of time as opposed to a single number for ranking as discussed in para. 3.3.1. This probability can be calculated by one of several methods. This Appendix will discuss the inputs, characteristics, outputs, etc., of these methods.

D-2.2 Approaches to Quantitative Probability Analysis

There are two types of approaches to developing a probability of a failure using quantitative methods. See paras. D-2.2.1 and D-2.2.2.

D-2.2.1 Objective Approach. The objective or frequency approach uses a proportion based on repeated trials (e.g., number of heads on flips of a coin or number of times seven will appear on the roll of the dice). This approach is useful for events that occur frequently enough that a statistically significant database can be developed.

D-2.2.2 Subjective Approach. The subjective approach reflects personal belief (e.g., a subject matter expert says, based on his review of all of the information on a component and past experience, there is a 10% chance of a through-wall crack within the next 3 years). Subjective probability is useful for estimating probability of future failures of equipment over time or for rare events.

D-2.3 Rules of Probability

No matter which approach is used, the failure probabilities should follow the rules of the mathematical theory of probability.

D-3 FAULT TREE/EVENT TREE/DECISION TREE

D-3.1 Tree Structures

It is often useful to use structured probabilistic tools such as tree structures (event trees, fault trees, or decision trees) that contain a set of events or scenarios that describe the probabilistic relationship of the individual supporting events to the failure event of concern. In more straightforward systems, such as boilers, where failure is defined as loss of pressure containment capability, it may not be necessary to use this structured approach.

D-3.1.1 Event Tree. In an event tree, the path flows from the initiating event as the cause to the end failure event of concern. In addition, the event tree will typically continue to include each of the credible consequences of the failure. It is looking for what states are possible, positive or negative, subsequent to an initiating event. The probability of the failure event is calculated by combining the probabilistic estimates of the initiating and subsequent events along the event tree that would lead to the end failure event. If the initiating event and/or subsequent events are time-dependent, such as with some damage mechanisms, this analysis can provide the probability of failure over time of the end failure event. In addition, the probability of each of the credible consequences can be determined.

D-3.1.2 Fault Tree. In a fault tree, the path flows from the end failure event back to the initiating event and circumstances that result in an end failure event. This approach is frequently used in investigative work. When this approach is used, the consequences can be considered using either an event tree or a fault tree.

D-3.1.3 Decision Tree. Decision trees, which are similar to event trees, are used in decision analysis, where the focus is on the result of making a decision rather than the results of an initiating event.

D-3.2 Event Trees Versus Fault Trees

Fault trees qualitatively model the relationships among fault events and system states. Event trees qualitatively model sequences. Each can be quantitatively evaluated using the axioms of probability to determine probability versus time of the fault state or event of interest.

D-3.3 Fault/Event Tree Construction

Event or fault tree construction requires knowledge of the system, its subsystems (if any), its components and environment, and its relations with other systems. Event or fault trees should meet the following criteria:

(a) system boundaries should be clearly defined

(b) trees are generally constructed using standard symbols

(c) trees should be kept as simple as possible

(d) there should be a logical, uniform, and consistent format from one tier or time step to the next

(e) once a tree has been constructed, it should be validated by a person knowledgeable in the process, who should review the tree for completeness and accuracy

(f) if the tree is quantified and evaluated, the calculations should be reviewed again for completeness and to ensure that the event or state probabilities are combined appropriately and that the results are realistic

D-3.3.1 Components of Event and Fault Trees.

(a) Event trees involve the following components:

initiating event: the beginning event of a failure sequence.

intermediate events: failure events or states that result from or follow the initiating event. Each intermediate event will have more than one outcome, for example, a safety device may succeed or fail. Intermediate events may be followed by other intermediate events or by final events. In practice, intermediate events are often similar to events in fault trees.

final failure events: the end state failure events or states that result from the initiating event combined with the intermediate events.

consequence scenario events: the consequences that result from the failure.

(b) Fault trees involve the following components:

top event: the event or state of interest.

basic events: events whose probabilities are known or can be estimated.

logical gates: generally "AND" and "OR" gates, though other types may be defined. Gates describe the logical connection among the basic events, any intermediate states, and the top event.

D-3.4 Decision Trees

A decision tree begins with the decision and is structured with the events and circumstances that bear on the results of that decision. It ends with one or more outcomes that flow from the combination of the decision and the subsequent events and circumstances. The outcome is usually measured in financial terms, but it may also consider safety, health, and environmental consequences that may or may not be assigned a financial value.

Sometimes, acceptance criteria are used with fault trees or event trees to determine whether an action is necessary to mitigate an event. This is not generally necessary when using decision trees with decision analysis. Decision analysis using decision trees typically combines probability of failure and consequence of failure to provide a quantitative risk analysis.

D-4 MONTE CARLO SIMULATION METHOD

D-4.1 Definition

Monte Carlo simulation is a mathematical method used to estimate the future probability of failure of a plant component. In a more complex system, the Monte Carlo simulation is used to estimate the probability of failures versus time using the relationships established in the event tree/fault tree describing the failure process.

D-4.2 Methodology

In the Monte Carlo method, values are randomly selected from probability distributions of events along an event tree or fault tree. These probability distributions are all possible values of a parameter weighted as to the probability of their presence. Monte Carlo simulation then combines them to estimate if the resulting value will exceed the failure criteria at any moment in time. This sampling or simulation process is mathematically repeated for different times in the future to estimate the probability or chance of failure at that time.

D-4.3 Components

The primary components of a Monte Carlo simulation include the following:

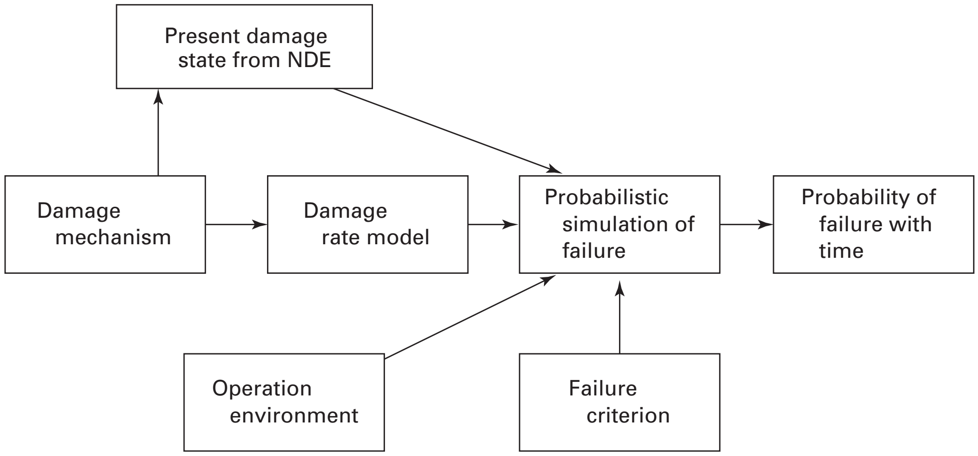
probability distribution functions (PDFs): a graphical description of the distribution uncertainty of a variable or parameter that has an effect on component life.

random number generator: a mathematical computer code that randomly generates numbers from zero to one.

sampling rule: the translator used to interpret the numbers generated from the random number generator so that the results follow the weighted variation shown in the PDF.

damage model: the mathematical equation or other method of characterizing the damage that is used to combine all of the PDFs with time according to their effect on component failure.

Fig. D-4.3 Process of Performing a Monte Carlo Simulation



failure criterion: the value from the mathematical damage model that is exceeded when failure is estimated to occur.

probability of failure: the portion of trials of the mathematical damage model that exceed the failure criterion at a specific time.

Figure D-4.3 shows the process of performing a Monte Carlo simulation.

D-4.4 Inputs

In order to perform this analysis for inspection planning, the following information should be acquired:

(a) the damage mechanism(s) acting on the material and the damage model used to represent it/them

(b) the PDFs for the random variables in the damage model (e.g., operating temperature, chemical environment, material properties)

(c) the PDF of the present state of damage in the equipment item (e.g., crack depth, wall thickness, pit depth)

(d) the PDF of the failure criterion (e.g., leakage, component rupture)

D-4.5 Requirements

D-4.5.1 Probability of Failure With Time. The output of the Monte Carlo simulation method is probability of failure versus future time. The shape of this curve depends on the probability distribution of the parameters used in the analysis and the form of the damage model.

D-4.5.2 Probabilistic Simulation of Failure. The mathematical simulation of the failure process is the Monte Carlo simulation process. It compares the randomly sampled probability inputs processed through the damage model to the random sample from the failure criterion to produce a failure versus no failure result at each future time increment. The resulting number of failures over the number of simulations run provides the probability of failure at each future time increment.

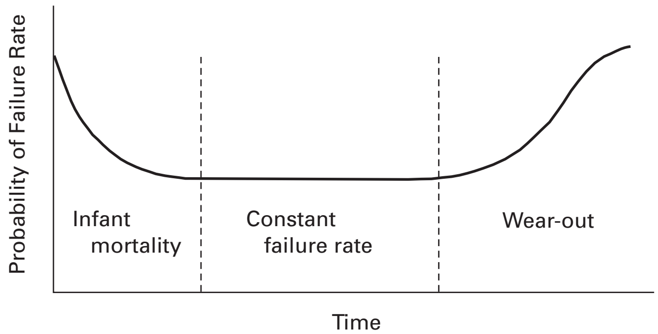
D-4.5.3 Failure Criterion. Failure is defined as the state when the damage from the damage mechanism exceeds a predefined failure definition, such as formation of an unstable crack or through-wall penetration. Once the failure criteria are known, their distributions can be determined from the literature or laboratory tests. The scatter in failure test data is typically used to represent the scatter in the failure criterion.

D-4.5.4 Present Damage State From NDE. The present state of damage is indicated by an inspection that quantifies the extent of damage that is relatable to the failure criterion. This could be the amount of corrosion, the crack depth, the wall thickness, etc. Of course, the damage mechanism should be known to insure that the appropriate NDE technique is being used. A distribution for these measurements is determined by the evaluation of the inspection system, the individual, and the inspection situation. The PDF used to represent this and its source should be documented.

D-4.5.5 Operating Environment. The operating environment and its variations are used as input to the model of the damage mechanism to estimate the progression of the damage over time. Note that some damage mechanisms do not result in a steady progression of damage over time, but rather a sudden increase in the extent of the damage under a specific combination of operating conditions. For example, chloride carryover can cause rapid cracking of austenitic stainless steel. The specific inputs used to describe the operating environment distribution are dependent on what affects the damage mechanism and the failure criterion.

D-4.5.6 Damage Rate Model. This is the model that represents the rate of damage accumulation as a function of time and operating environment. As noted above,

Fig. D-5.1 Probability of Failure Rate vs. Time



some damage mechanisms do not result in a steady progression of damage over time. Also, the user is cautioned that the damage rate is often nonlinear and, in some cases, it is possible to experience a sudden increase in the rate of damage accumulation even if the operating conditions do not change significantly. For example, creep damage may progress very slowly for many years, then progress at a rapid rate in the final stages. Damage models can be developed from tests performed in a controlled environment. Rates for some damage mechanisms are available in the literature, from laboratory testing, etc. The source of the damage rate should be documented. A compendium of damage rate models is available in API 571 and API 579-1/ASME FFS-1.

D-4.5.7 Damage Mechanism. The damage mechanism(s) acting on the component is typically determined through expert elicitation based on previous metallurgical failure analyses. A model of the damage mechanism is required to predict the damage with time. The presence of the damage mechanism, the specific damage model, and its applicability should be documented.

D-5 LIFETIME RELIABILITY MODELS

D-5.1 Population Lifetime

The lifetime of a population of some products, including pressure vessels that are subject to some time-dependent damage mechanisms such as general corrosion, can generically be represented graphically by the well-known "bathtub curve," probability of failure rate versus time (see Fig. D-5.1). The bathtub curve consists of three periods: an infant mortality period with a decreasing failure rate followed by a normal life period (also known as "useful life") with a low, relatively constant failure rate and concluding with a wear-out period that exhibits an increasing failure rate.

D-5.2 Periods of the Bathtub Curve

D-5.2.1 Infant Mortality. The infant mortality period is that period in a component's life when start-up problems are being worked out. They are usually operation and fabrication problems.

D-5.2.2 Constant Failure Rate. The majority of a population's lifetime is spent in the useful life period with a constant failure rate. Therefore, in this period of the bathtub curve one can speak of a failure rate per unit time. Some call this a failure probability per unit time (see para. 7.3).

D-5.2.3 Wear-Out Period. The wear-out period usually does not reveal itself until damage is well advanced. In some components like electronics and active components like motors and valves this period is never seen because the component is replaced before this period for other reasons. In other situations, an operational upset may occur before the wear-out period is achieved resulting in a pre-wear-out period replacement. In still other cases (e.g., where damage mechanisms are not time-dependent), there may be no wear-out period at all.

For example, some forms of stress corrosion cracking can result in failure over a short period of time if a process upset occurs. Considering only this damage mechanism, there may still be an infant mortality portion of the curve, but after that the probability of failure is constant with time, with no wear-out period.

D-5.3 Weibull Distribution

In the infant mortality period and wear-out period, the failure rate and probability of failure are not constant and must be represented by more elaborate mathematical models. One such model is the Weibull distribution, often used in the field of reliability.

$$F\,(x,\,\alpha,\,\beta) = 1 - e^{-(x/\beta)^{\alpha}}$$

where
F = probability of failure
x = time
α = shape parameter
β = scale parameter

The infant mortality period of the Weibull curve has a shape parameter less than one and the constant failure rate period has a shape parameter of one. The wear-out period (if applicable) has a shape parameter greater than one. The age of the component and the damage mechanism should be noted in the analysis since this determines what model is appropriate for the component under investigation.

Estimating the failure probability in this manner assumes that the future operation of the component will be similar to past operation. This should be confirmed.

D-6 GENERIC FAILURE CURVES

D-6.1 Generic Databases

A database of generic failure frequencies is based on a compilation of available equipment failure histories from a specific or multiple industries. From these data, generic probabilities of failure can be developed for each type of equipment.

D-6.2 Generic Versus Specific Databases

One approach to probability analysis begins with a database of generic failure frequencies for the specific equipment types and operating environments of concern. However, such databases are available for only a limited number of equipment types and environments. These generic frequencies are then modified based on local plant experience. It is of course more desirable to use the specific component failure frequency when available.

D-6.2.1 Specific Databases. With specific failure data for the component of concern, probability of failure versus time curves can be generated directly as described in ASME CRTD Volume 41, Risk-Based Methods for Equipment Life Management.

D-6.3 Updating Specific and Generic Data

D-6.3.1 Combining Data. Rather than relying on specific plant, component, or facility information alone, it may be useful to combine local plant personnel expert opinion with generic failure data modified to account for the operating conditions at the specific facility. The source of the generic and local plant personnel opinion should be noted.

D-6.3.2 Bayes' Theorem. One method of combining local plant personnel opinion and generic data is by use of Bayes' Theorem. For more detail on use of Bayesian methods in this situation see ASME CRTD Volume 41, Risk-Based Methods for Equipment Life Management.

D-7 EXPERT ELICITATION AND INTUITIVE OPINION

D-7.1 Description of Process

When expert opinion is the only source of information available to establish a probability of failure distributed over time, probabilistic expert opinion elicitation can be used. The expert opinion elicitation process is defined as a formal, heuristic process of obtaining information or answers to specific questions about quantities such as expected service life. Expert opinion elicitation should not be used in lieu of rigorous probabilistic analysis methods if the data necessary for these rigorous methods are available. The elicitation should be performed using a specific interview process to insure as unbiased results as possible.

D-7.2 Characteristics of the Expert Elicitation Process

D-7.2.1 Availability. Availability refers to the ease or extent with which experts have experience with events similar to the one at issue.

D-7.2.2 Unanchoring. Unanchoring is a process in which experts start with an initial estimate and a window of uncertainty is opened by the process for the expert.

D-7.3 Methods of Elicitation

There are at least three methods of elicitation. Subjectively assessed probabilities should be examined for signs of errors. Such signs include data spread, data dependence, reproducibility, and calibration.

D-7.3.1 Indirect (Intuitive). In the indirect or intuitive method, a graphical weighting (e.g., histogram of objects such as coins) is used to allow the expert to express his intuition within the window of uncertainty

D-7.3.2 Direct. In the direct method, belief from an expert on some issue is elicited from the expert's cognitive opinion as opposed to the intuitive. For the fully-quantitative approach, the indirect methods described in this Appendix are more applicable.

D-7.3.3 Parametric Estimation. The parametric estimation method is used to assess the confidence interval on a parameter of interest such as a mean value and will not be addressed here as it is not often used in this context.

D-7.4 Indirect or Intuitive Opinion Interview Techniques[1]

D-7.4.1 Plant Personnel Intuition. People who deal with a plant component on a daily basis, year after year, develop an intuitive "feel" for the state of a component and for the changes that have been taking place in that component and its state over time. Their intuition has been subconsciously integrating information on the component over time. This "feel" is a ready and knowledgeable information source that can be tapped to estimate the expected future state of the component. The objective is to use a proven methodology that will obtain this information in the best way.

[1] Risk-Based Methods for Equipment Life Management: An Application Handbook, ASME Research Report CRTD Vol. 41, ASME, NY, 2003

Over the last 20 years, cognitive psychologists who are associated with decision analysis have developed a method that is comprised of a series of questions that are used to tap the integrated information found in the intuition. Sometimes, it is difficult for engineers to accept the value of intuition because of their training and inclination. However, the intuitive information that people have accumulated as a result of being associated with equipment for many years is valuable (e.g., equipment operation, inspection, design, maintenance).

The process that follows should be strictly followed to obtain the best results. All of the steps are important. Brief reasons for each step are given.

D-7.4.2 Interview Steps. The following list briefly discusses each step and the background behind it. The interview subject is referred to as the "individual" and "he," with the understanding that the person could be a mechanic, engineering technician, supervisor, shift engineer, or any other position and/or could be female.

D-7.4.3 Team Approach. If possible, though it is not necessary, try to simultaneously interview two or more people who have the information that you need. This team approach will probably give more accurate information because of the multiple viewpoints that are available. Use a consensus process. Do not allow voting, because this tends to become adversarial and will inhibit consensus formation. Note that "consensus" means that all interviewees have input and that all interviewees eventually agree. You should referee to ensure that no topic or individual dominates the decisions. Also, be aware before you begin that consensus building can take a long time, as much as an hour per component, and should not be rushed. You want to seek consensus instead of voting so that you maximize the input from all individuals involved.

D-7.4.4 Interview Process. The interview process proceeds as follows:

(a) Ask the individual (e.g., operator, inspector, maintenance technician) to tell you "his story" about his experience with the component. Listening to the individual tell his story about what has gone on with the component and about his relationship with it helps him get comfortable with you on this subject and also gets him to focus on the component and its history.

(b) Ask what the individual's personal exposure would be if component life estimates proved to be in error. Knowing what the individual thinks his exposure would be if the life estimate proved wrong provides a basis upon which you may decide whether the individual feels free to express himself. If the interview results later appear to be biased, the individual's perceived exposure may suggest why. For example, an individual who fears death, injury or job loss might bias low; an individual who fears negligence accusations might bias high. The individual's perceived exposure could even help you to decide whether to use him or seek another subject.

(c) Ask the individual how soon the component could possibly fail. Asking about the earliest possible failure date begins to expand his mind.

(d) Ask the individual how long the component could possibly last, if it is a single-element component, or when it will no longer be worth fixing, if it is a multiple-element component. This "no longer worth fixing" is meant to be an intuitive feel. It is not from analytics nor does it represent monetary worth, but the individual's feel of whether continuing to do damage repairs on this component is "worthless." Asking about the latest possible failure date further expands his mind and gets him thinking in the other direction.

(e) These questions will unanchor the individual from any previous life-estimates in which he may have been involved. To further unanchor him, use questions that will prompt him to tell stories about why the component might fail on the earliest date. Getting him to theorize about the component will help him to forget numbers that he might have previously heard or been given about the expected failure date. Asking for stories about the latest failure date also helps unanchoring. During this step, ask for a couple of stories about each end of the failure date range. Ask him for more stories if he does not appear to be relaxing.

D-7.4.5 Time Estimate to Failure. Get the individual to agree upon some reasonable time increments with which to position the interval between the shortest and longest time to failure. This agreement is important. If the time increment is too large, the next step will not have fine enough resolution to effectively reveal the time uncertainty. If the increment is too small, the failure probability consideration at each increment requires too much detailed thinking. Usually, four or five time increments between the earliest and latest failure dates are about right.

D-7.4.6 Determine Relative Probability of Failure. Using the previously agreed-upon time increment, prepare a time line that runs from the individual's earliest stated failure date up to his latest failure date. Determine the relative probability of failure that the individual assigns to each time increment using a visual technique. One way to do this is to provide the individual with 50 identical coins or washers and ask him to stack them at the points on the time line at which he thinks the component will most likely fail. Ask him to stack the coins based on his feeling about when the component will fail, if it is a single-element component, or when it is not worth fixing anymore, if it is a multiple-element component. Tell him that he must place at least one coin on each year interval; otherwise, he can place the coins any way he wishes.

Verify that the individual feels comfortable with the stacks, or failure probability distribution, that he has just provided. Don't be concerned if the individual is not comfortable with the process; this is not unusual. The important thing is that he is comfortable with the stacks along the time line.

Record the result for each time interval for future spreadsheet entry.

D-7.4.7 Probability of Failure by Time Increment. To calculate the probability of failure by time increment, follow the following process:

Time increment (year in this example)	Relative probability (number of coins stacked on it)	Doubled	Divided by 100
2010	1	2	0.02
2015	5	10	0.1
2020	10	20	0.2
2025	25	50	0.5
2030	9	18	0.18

D-7.4.8 Summary of Steps The abbreviated steps in the process are

Expert Opinion Elicitation Steps

1. Listen to the subject's story about the component.
2. Ask about the subject's exposure in case of an erroneous component life estimate.
3. Ask how soon the component could fail.
4. Ask how long the component could possibly last (single-element component) or when it will not be worth fixing (multiple-element component).
5. Unanchor the subject from any existing life estimates by asking for stories that illustrate #3 and #4.
6. Get agreement on a reasonable measuring increment.
7. Have the subject estimate the failure likelihood on a time line (e.g., by stacking coins).
8. Verify comfort with the resulting probability curve.
9. Record the probability.

D-7.5 Direct or Cognitive Expert Elicitation Interview Techniques[2]

D-7.5.1 Delphi Method. This method is usually found in the literature under "expert elicitation." A method of this type is called the Delphi method. It is usually used with teams of engineers or people that have more of a thinking or cognitive opinion on the component in question as opposed to a firsthand initiative feel.

The process is conducted by gathering a group of experts on the subject in a room. A group of questions is used to facilitate the process of the experts expressing themselves quantitatively. These questions are usually distributed ahead of time.

D-7.5.2 Questions. The questions should have the following characteristics:

(a) clearly communicate the issue

(b) keep ambiguity as low as possible in the statement of the question

(c) keep ambiguity as low as possible in the response expected

(d) insure that the design of the questions gathers all the information necessary to calculate the uncertainties on the issue

The overall questionnaire should include

(a) a description of the issue

(b) aspects of the issue that should be considered

(c) aspects of the issue that should not be considered

(d) response expected in content, units, and presentation

D-7.5.3 Combination of Probabilities. The response to these questions is usually a single number probability (chance) of occurrence or a 10%, 50%, 90% probability of occurrence. This latter form of question assumes a normal distribution for the response. The probabilities are then combined using the addition and multiplication laws of probability to determine the probability of occurrence of the issue. The method by which the probabilities are combined should be clearly documented.

D-8 ASPECTS OF FULLY QUANTITATIVE CONSEQUENCE ANALYSIS

D-8.1 Definition

To determine the quantitative consequence of failure one should understand the component operational function and how the overall system depends on the component operation. The loss of production due to component failure as well as component repair and other costs should be included where applicable. The total expected failure consequence is

$$C_f = C_p + C_r + C_o$$

$$C_p = nt\,pc$$

where

C_f = failure consequence
C_o = other costs associated with the failure
C_p = loss of production cost
C_r = repair cost
c = lost net revenue per unit of production loss
n = number of elements
p = production lost per hour with the failure of an element
t = lost production time per failure, hr

$$C_r = F_c + nR_c$$

where

C_r = repair cost

[2] Ayyub, B. M., "Guidelines on Expert-Opinion Solicitation of Probabilities and Consequences for Corps Facilities," Tech. Report for Contract DACW72-94-D-0003, June 1999, US Army Corps of Engineers

F_c = overall fixed cost for component repair from failure
n = number of elements
R_c = per failed element repair cost

D-8.2 Consequence When Few Components

If the number of elements is small or one, then the consequence is the consequence of the monolithic or near-monolithic component failing. This usually has to be estimated because of the lack of failure experience with these components. In this case, the consequence is usually the estimated number of production shutdown hours that component failure would cause plus the repair and other costs from the failure.

D-8.3 Safety, Health, and Environmental Consequence

If the consequence is a safety concern, the probability in time of a person being within the safety concern zone should be determined. This should be multiplied by the change in probability of failure or rate to determine the safety concern risk. An alternate method is to assign a value to the life or injury of a person in the safety concern zone[3] then multiply the probability of a person being there to get the safety consequence. This should be multiplied by the probability of failure or rate to determine the monetary value of the safety concern risk. A similar approach should be taken to address health and environmental consequences.

D-8.4 Probability Distributions

As in quantification of probability of failure, consequence distributions can be determined using Monte Carlo simulation to incorporate uncertainty distributions of lost production time, lost production amount, and cost per unit of lost production as well as cost of component repair and other costs. In the area of safety concerns, the distribution of probability in time of a person being within the safety concern zone can be used with a Monte Carlo simulation analysis to estimate the consequence distribution.

As described initially in this Appendix, the combining of these distributions from the quantitative probability of failure analysis and consequence analysis are typically performed using a decision analysis and optimization techniques to determine inspection need and timing[1].

[3] Federal Aviation Administration, 2003, Economic Values for Evaluation of Federal Aviation Administration Investment and Regulatory Decisions, FAA-APO-98-8, http://api.hq.faa.gov/economic/toc.htm.

NONMANDATORY APPENDIX E EXAMPLES OF RISK-BASED INSPECTION PROGRAM AUDIT QUESTIONS

E-1 INTRODUCTION

The questions listed below are examples of questions an auditor might ask when auditing a risk-based inspection (RBI) program that has been developed and implemented using this Standard. They are intended for guidance only and are not intended to be all-inclusive. Auditors should develop their own audit plan based on the scope of the audit.

E-2 RBI PROGRAM REVIEW

(a) Are company documents such as policies or procedures in place to define the RBI program?

(b) Is the program scope defined?

(c) Does the program document the applicable regulatory requirements?

(d) Have required resources (budget, expertise, people, tools, etc.) been identified?

(e) Does the inspection plan include information such as

(1) location?

(2) type of inspection?

(3) frequency?

(4) extent of examinations?

(f) Are the data requirements for conducting the RBI analysis defined?

(g) Have necessary data been collected?

(h) Are the applicable damage mechanisms identified for the items to be inspected?

(i) Is there a process in place to review and update the inspection plan?

(j) Is there a process in place to determine the effectiveness of the inspection program?

(k) Is incident history available for specific equipment?

(l) Are inspection plans filed and retrievable?

(m) Are completed inspection results reviewed and analyzed by the RBI team to identify concerns raised by the results and recommend appropriate follow-up activity?

(n) Is component history maintained in a database or in an easily retrievable file?

(o) Are inspection results maintained in a database or in an easily retrievable file?

(p) Does the database or file contain the most recent inspection results?

(q) Does the program include provisions for performing RBI reanalysis?

E-3 INSPECTION PROGRAM TEAM STAFFING

(a) Have team member selection criteria been established and are they being used?

(b) Do the criteria include the required expertise?

(c) Have the team members been identified?

(d) Are training requirements identified?

(e) Has training of team members been conducted? See section 13.

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