2020

RISK BASED INSPECTION GUIDELINE

GL-0009-E

KR

APPLICATION OF "RISK BASED INSPECTION GUIDELINE"

1. Unless expressly specified otherwise, the requirements in the Guidelines apply to RBI program for which request of the Client is made on or after 1 July 2020.

CONTENTS

CHAPTER 1 GENERAL

Section 1 General

101. Application

These guidelines apply to maintenance and inspection of industrial facilities and offshore facilities which are containing internal pressure.

102. Goal

The goal of these guidelines is to provide information on the procedures and requirements for establishing and maintaining RBI program.

103. Scope

1. The following types of equipment and associated components/internals are covered by these guidelines

(1) Pressure vessels-all pressure-containing components
(2) Process piping-pipe and piping components
(3) Storage tanks-atmospheric and pressurized
(4) Rotating equipment-pressure-containing components
(5) Boilers and heaters-pressurized components
(6) Heat exchangers
(7) Pressure-relief devices.

2. The equipment which is not covered by these guidelines is instrument and control systems, electrical systems, structural systems and machinery components(except pump and compressor casings).

3. The application of RBI program does not cover any statutory survey requirements that may apply to the facility being considered (e.g., MODU code, SOLAS, MARPOL, coastal state regulations, etc.).

Section 2 Definition of Terms

201. Definition of terms

1. Inspection means activities carried out periodically and used to assess the progression of damage in a component Inspection can be by means of technical instruments (NDE) or by a visual examination.

2. Inspection plan means a documented set of actions and/or strategies detailing the scope, extent, methods, and timing of specific inspection activities in order to determine the condition of a specific piece of equipment. For the purposes of this document, the inspection plan is the product of an RBI analysis.

3. Inspection techniques mean a combination of inspection method and the means by which it is to be applied, concerning surface and equipment preparation, execution of inspection with a given method, and area of coverage.

4. Consequence means an outcomes from an event. There may be one or more consequences from an event, and consequences may be expressed qualitatively or quantitatively.

5. Failure means the point at which a component ceases to fulfil its function and the limits placed on it. The failure condition must be clearly defined in its relationship to the component. Failure can be expressed in terms of non-compliance with design codes, or exceeding of a set risk limit, neither of which necessarily implies leakage. In this recommended practice, failure implies loss of containment.

6. COF(consequence of failure) means the outcomes of a failure. This may be expressed, for example, in terms of safety to personnel, economic loss, damage to the environment.

7. **COF ranking** means the qualitative rating of consequence of failure. For example, it is often expressed as high, medium, low or A, B, C.

8. **Failure mode** means the type or mode of failure. In risk-based inspection, the main failure is the loss of containment in the pressure containing equipment, for example cracks, plastic collapse and pinholes.

9. **POF**(probability of failure) means the probability that a component will fail within a given period of time.

10. **POF ranking** means the qualitative rating of probability of failure. A grade that compares the POF of another item against an item, often expressed as high, medium, low, or 1, 2, 3.

11. **Components** means parts that make up a piece of equipment or equipment item. For example a pressure boundary may consist of components (pipe, elbows, nipples, heads, shells, nozzles, stiffening rings, skirts, supports, etc.) that are bolted or welded into assembles to make up equipment items.

12. **MOC**(management of change) means a documented management system for review and approval of changes in process, equipment, or piping systems prior to implementation of the change.

13. **Corrosion group** means a group of components or parts of components that are exposed to the same internal and/or external environment and made of the same material, thus having the same potential degradation mechanisms. Groups should be defined such that inspection results made on one part of the group can be related to all the parts of the same group.

14. **Event** means a series of processes that lead to the occurrence of a specific failure and hence the specific failure. The event can be singular or multiple. The probability of an event occurring within a given period of time can be estimated.

15. **Condition monitoring** means monitoring of plant physical conditions which may indicate the operation of given degradation mechanisms. Examples are visual examination of painting, corrosion monitoring, crack monitoring, wall thickness monitoring.

17. **Damage** means the observed effect on a component of the action of a degradation mechanism. The damage gives rise to the failure mechanism of a component. Examples of damage include cracking, uniform wall thinning and pitting.

16. **Damage mechanism(or deterioration mechanism)** means a process that induces 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, stress corrosion cracking, creep, erosion, fatigue, fracture, and thermal aging.

18. **Deterioration** means the degradation of materials due to various mechanisms (e.g., corrosion, cracking, embrittlement, fatigue) that causes a detrimental effect on the material's physical properties, eventually resulting in the inability of the component to provide its intended function (i.e., failure).

19. **Operator** means the organization responsible for operation of the installation, and having responsibility for safety and environment

20. **Risk** is combination of the probability of an event and its consequence. In some situations, risk is a deviation from the expected. When probability and consequence are expressed numerically, risk is the product.
   (1) **Economic risk** is an expression of the occurrence and outcome of a failure given in financial terms(units of currency per year). This is calculated as the product of the probability of failure and the financial consequences of that failure, and can include (but is not limited to) the value of deferred production, the cost of repairs to equipment and structure, materials and man-time used in repair.
   (2) **Environmental risk** is an expression of the occurrence and outcome of a failure given in terms relevant to environmental damage. This may be expressed in units relevant to the installation, such as volume per year or currency per year.

21. **RBI(risk based inspection)** means a risk assessment and management process that is focused on loss of containment of pressurized equipment in processing facilities, due to material deterioration.

These risks are managed primarily through equipment inspection.

22. **RBI program** means an engineering service that replaces regular inspection with RBI through the set of procedures and activities outlined in this document for a target facility.

23. **Risk analysis** means the process of understanding what undesirable things can happen, how likely they are to happen and how severe the effects may be. More precisely, it is an integrated array of analytical techniques, e.g., reliability, availability and maintainability engineering, statistics, decision theory, systems engineering and human behavior that can successfully integrate diverse aspects of design and operation in order to assess risk. Information can include historical data, theoretical analysis, informed opinions, and concerns of stakeholders.

24. **Risk criteria** means the operator's objective criteria that define acceptable risks. Risk criteria may include associated cost and benefits, legal and statutory requirements, socio-economic and environmental aspects, concerns of stakeholders, priorities, and other inputs to the assessment.

25. **ALARP**(as low as reasonably practicable) means a concept of minimization that postulates that attributes (such as risk) can only be reduced to a certain minimum under current technology and with reasonable cost.

26. **PLL**(potential loss of life) means the number of personnel who may lose their lives as a consequence of failure of a component.

27. **QRA**(quantitative risk analysis) means a risk analysis that uses primarily model-based approaches where numerical values are calculated and more discreet input data used.

28. **IOWs**(integrity operating windows) mean established limits for process variables that can affect the integrity of the equipment if the process operation deviates from the established limits for a predetermined amount of time.

29. **SMEs**(subject matter experts) means persons who have sufficient experience and knowledge involved in the design, construction, installation, operation, and decommissioning of target system.

30. **Turnaround** means a period of downtime to perform inspection, maintenance, or modifications and prepare process equipment for the next operating cycle. ⚓

CHAPTER 2 INTRODUCTION OF RBI

Section 1 Introduction of Risk Assessment

101. Risk

1. Risk is the combination of the probability of some event occurring during a time period of interest and the consequences associated with the event. And risk can be expressed by the following equation.

$$risk = probability \times consequence$$

2. Effective risk assessment should be a rational, logical, structured process that contains at least two key steps:

(1) Determine how significant the risk is, and

(2) Determine whether the risk is acceptable.

3. Once the risk is known and the magnitude of the risk is established, the risk can be managed. Risk management is a process to assess risks, to determine if risk reduction is required, and to develop a plan to maintain risks at an acceptable level. Risk reduction is the act of mitigating a known risk that is deemed to be too high to a lower, more acceptable level of risk with some form of risk reduction activity.

102. Risk assessment

1. Risk is assessed by identifying credible damage mechanisms, estimating the POFs, assessing the COFs, and identifying the risk drivers to enable development of effective risk mitigation strategies.

2. The complexity of a risk analysis is a function of the number of factors that can affect the risk, and the methods range from a strictly relative ranking to rigorous calculation. The methods generally represent a range of precision for the resulting risk analysis.

3. 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 risk represented by the equipment items. Further, analysis results may not be realistic. Therefore, the risk analysis should be validated before decisions are made based on the analysis results.

4. Risk can be assessed by qualitative, quantitative and semi-quantitative approach

(1) Qualitative approach

(A) Qualitative approach requires data inputs based on descriptive information using engineering judgment, subject matter expertise, and experience as the basis for the analysis of probability and COF. Inputs are often given in data ranges instead of discrete values. Results are typically given in qualitative terms such as high, medium, and low, although numerical values may also be associated with these categories. The value of this type of analysis is that it enables completion of a risk assessment in the absence of detailed quantitative data. The accuracy of results from a qualitative analysis is dependent on the background and expertise of the risk analysts and team members.

(B) Although the qualitative approach is less precise than more quantitative approaches, it is effective in screening out units and equipment with low risk; being less precise does not always mean that the qualitative method is less accurate. However, qualitative assessments generally are not as repeatable as quantitative assessments. The qualitative approach may be used for any aspect of inspection plan development. However, the conservatism generally associated with the more qualitative approach should be considered when making final mitigation and inspection plan decisions.

(2) Quantitative approach

(A) Quantitative approaches are model-based approaches where numerical values are calculated and more discreet input data used. The advantages of a quantitative approach are:

(a) calculates, with some precision, when the risk acceptance limit is reached or exceeded;

(b) discrimination between equipment risk allowing prioritization of mitigation;
(c) trending and monitoring risk exposure over time as well as other metrics;
(d) benchmarking of reliability management such as POF trending and comparisons.

(B) Quantitative methods are more systematic, consistent, and documented, and they are easier to update with inspection results than qualitative approaches. A quantitative approach generally uses a software program to calculate risk and develop inspection program recommendations. The models are initially data-intensive, but use of models removes repetitive, detailed work from the traditional inspection planning process.

(C) Quantitative risk assessment outlines a methodology for prioritizing equipment risk in a risk matrix or ISO-risk plot in addition to calculating discrete risk values for prioritization from higher to lower risk. POF and COF are combined to produce an estimate of risk for equipment. Equipment items are ranked based on risk with POF, COF, and risk calculated and reported separately to aid identification of major contributors to risk, or risk drivers.

(3) Semi-quantitative approach

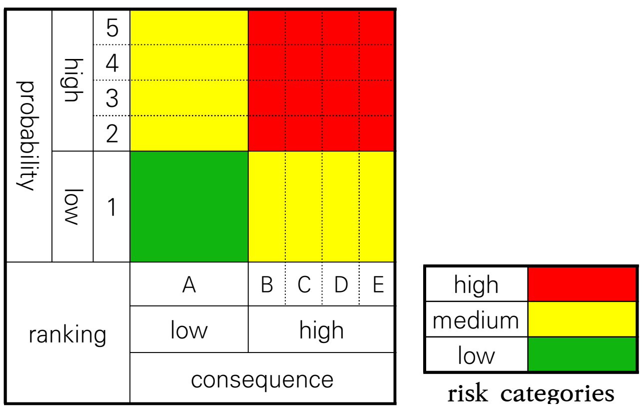
(A) Semi-quantitative is a term that describes any approach that has aspects derived from both the qualitative and quantitative approaches. It is geared to obtain the major benefits of the previous two approaches. Typically, most of the data used in a quantitative approach is needed for this approach, but in less detail. The models may not be as rigorous as those used for the quantitative approach. The results are usually given in consequence and probability categories or as risk numbers, but numerical values may be associated with each category to permit the calculation of risk and the application of appropriate risk acceptance criteria.

5. Risk assessments are divided into screening assessment and detail assessment depending on the purpose.

(1) Screening assessment

(A) The purpose of the screening process is to identify, at a higher level, the elements that are judged to make a significant contribution to the risk levels. This ensures that further data gathering and assessment efforts can be focused on these elements. Given an installation, screening is typically carried out in a qualitative manner that involves identification of risk on a system by system, group by group, or major equipment item basis. On the basis of knowledge of the installation history and future plans and possible components' degradation, the consequence of failure and probability of failure are each assessed separately as seen in **Ch 3, 304. table 1** and **305. table 2**, and expressed as seen in the matrix given in **figure 1**.

(B) Generally, low risk items will require minimal inspection supported by maintenance. Medium and High-risk items will require a more detailed evaluation which is the subject of the second stage of the working process.



Figue 6 Risk matrix for screening assessment(example)

(2) Detail assessment

(A) The elements with medium and high risk from screening assessment are the elements that need to be considered in more detail - i.e. broken down to lower levels and evaluated with either qualitative, quantitative or semi-quantitative methods.

(B) The objectives of this assessment are to identify the relevant degradation mechanisms, estimate the extent of damage, estimate when inspection should be carried out, and propose what inspection technique should be used to ensure ALARP risk levels .

Section 2 Introduction of Risk Based Inspection

201. Inspection

1. Inspection is one of the many dedicated activities within offshore management that contribute to controlling and minimising offshore risks. The role of inspection is to check/confirm whether degradation is occurring, to measure the progress of that degradation, and to help ensure that integrity can be maintained. It provides assurance that asset integrity is maintained in accordance with the design intent.

2. Although inspection does not reduce risk directly, it is a risk management activity (provider of new information) that may lead to risk reduction. Impending failure of pressure equipment is not avoided by inspection activities unless the inspection precipitates risk mitigation activities that change the POF.

3. Some important points to note about inspection are:

(1) Inspection activities provide specific, relevant, accurate and timely information to management on the condition of assets.
(2) Inspection activity is planned and executed with due regard for the policy and the risks to its achievement.
(3) Threats to asset integrity are identified sufficiently early so that they can be remedied cost effectively with no appreciable impact on asset integrity or safety.
(4) The asset register is maintained current with the condition of assets and their inspection history.
(5) Inspection activity is scheduled to provide the necessary level of assurance of the condition of plant and equipment while also minimizing the detrimental impact on production operations.
(6) Equipment is handed over from operations to inspection personnel prior to inspection activity, and from inspection to operations personnel following inspection activity in accordance with a formal procedure which ensures that appropriate information on the condition of the equipment is exchanged.
(7) Inspection activity is subject to appropriate verification of its performance.

202. Risk based inspection(RBI)

1. RBI is a decision making technique for inspection planning based on risk comprising the consequence of failure(COF) and probability of failure(POF). It is a formal approach designed to aid the development of optimized inspection, and recommendations for monitoring and testing plans for production systems. It provides focus for inspection activity, to address explicitly the threats to the integrity of the asset and its capability to generate revenue through production.

2. RBI is carried out for piping and vessels, including heat exchangers, tanks, pressure vessels, and filters. The scope of the RBI encompasses all pressure systems in the plant, whether hydrocarbon-containing or utility.

3. To carry out the RBI analysis for each item, the COF and POF are assessed separately. The two are then combined to obtain risk of failure. This evaluation is carried out separately for safety (addressing personnel death and injury), environmental (addressing damage to the environment) and economic (addressing financial loss).

4. The deliverables of an RBI assessment to the inspection planning are gained as followings.

(1) Prioritization of high risk component(what to inspect)
(2) Determination of inspection intervals(when to inspect)
(3) Expected damage mechanism(where to inspect)
(4) Selection of best inspection method(how to inspect)
(5) Data requirements for continuous improvement(what to report)

5. RBI can be assessed by qualitative, quantitative or semi-quantitative approach as discussed in **102. 5**. Selection of the type of RBI assessment will be dependent on a variety of factors, such as the following.

(1) Is the assessment at a facility, process unit, system, equipment item, or component level?
(2) Objective of the assessment
(3) Availability and quality of data
(4) Resource availability
(5) Perceived or previously evaluated risks
(6) Time constraints

203. Benefits and limitations of RBI

1. The primary work products of the RBI assessment and management approach are plans that address ways to manage risks on an individual equipment level. These equipment plans highlight risk from a safety/health/environment perspective and/or from an economic standpoint. RBI plans should include cost-effective actions along with projected risk mitigation. Implementation of these plans provides one of the following.

   (1) An overall reduction in risk for the facilities and equipment assessed
   (2) An acceptance/understanding of the current risk

2. The RBI plans also identify equipment that does not require inspection or some other form of mitigation because of the acceptable level of risk associated with the equipment's current operation. In this way, inspection and maintenance activities can be focused and more cost-effective. This can result in a significant reduction in the amount of inspection data that is collected. This focus on a smaller set of data should result in more accurate information. In some cases, in addition to risk reductions and process safety improvements, RBI plans may result in cost reductions.

3. RBI is based on sound, proven risk assessment and management principles. Nonetheless, RBI will not compensate for the following.

   (1) Inaccurate or missing information
   (2) Inadequate design or faulty equipment installation
   (3) Operating outside the acceptable IOWs
   (4) Not effectively executing the plans
   (5) Lack of qualified personnel or teamwork
   (6) Lack of sound engineering or operational judgment ⚓

CHAPTER 3 PROCEDURES FOR RBI PROGRAM

Section 1 General

101. General

1. This section will describe a typical methodology used to develop an RBI program, but a variety of methodologies can be applicable, provided that the steps in the development process as described in this section are included. If any of these steps are missing or they are considered in a substantially different way than common industry practice and standards, a suitable technical explanation on the adequacy of the methodology should be needed.

2. General procedures for developing RBI program are as the following.

(1) Planning RBI program
(2) Risk assessment
(3) Risk management
(4) Reassessing and updating RBI assessment

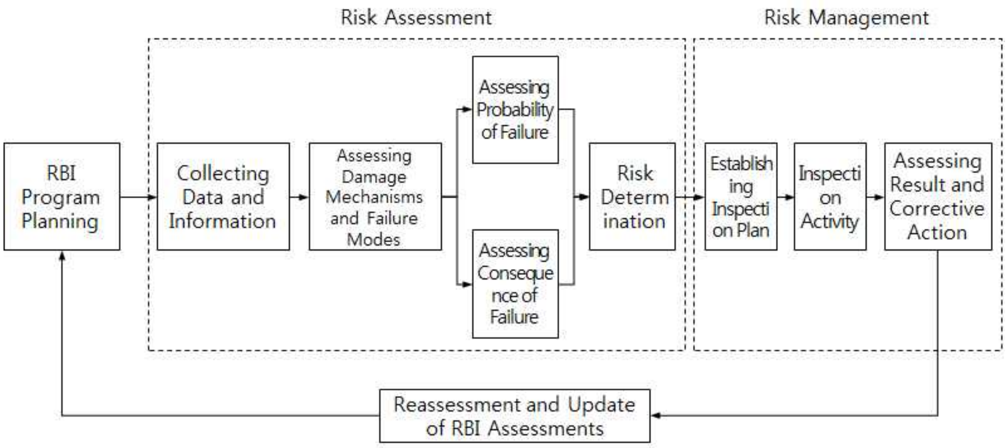


Figure 9 RBI planning process

Section 2 RBI Program Planning

201. General

1. This section helps an owner-user determine the scope and the priorities for an RBI assessment.

2. An RBI assessment is a team-based process that requires proper skills and knowledge from multiple disciplines. At the beginning of the exercise, it is important to answer the following questions.

(1) Why the assessment is being done?
(2) How the RBI assessment will be carried out?
(3) What knowledge and skills are required for the assessment?
(4) Who is on the RBI team?
(5) What are their roles in the RBI process?
(6) Who is responsible and accountable for what actions?
(7) Which facilities, assets, and components will be included?
(8) What data is to be used in the assessment?
(9) What codes and standards are applicable?
(10) When the assessment will be completed?
(11) How long the assessment will remain in effect and when it will be updated?
(12) How the results will be used?

(13) What is the plan period?

3. The following steps must be completed for the planning of the RBI program.

(1) Set up RBI team
(2) Establish the objectives of the risk analysis;
(3) Identify the physical boundaries;
(4) Identify the operating boundaries;
(5) Develop screening questions and criteria consistent with the objectives of the analysis and identified physical and operating boundaries.

202. RBI team setup

1. The development of an effective RBI Plan requires a multidisciplinary team with essential skills, strong technical strengths and a relevant background. A major objective of the team is to ensure that all relevant and adequate information is gathered and organised prior to the RBI Plan development. The RBI team should comprise one or more personnel with expertise in the following disciplines.

(1) Risk assessment and management
(2) Ship/unit structural surveys and Inspection
(3) Structural integrity and reliability analysis
(4) Material and corrosion analysis
(5) Chemistry and process
(6) Operation and maintenance
(7) Health, safety and environment
(8) Financial and business analysis
(9) Naval architecture

2. The specific composition of an RBI team varies depending on the complexity of the facility, scope of the RBI program and any applicable regulatory requirements. Some of the disciplines will be called in as advisors, but a core team is essential for continuity.

3. Each member should provide evidence of their experience and competence in the subject matter using a biography or other acceptable format. The composition of the team may vary depending on the RBI scope and complexity of the vessel. The risk assessment and management personnel should have a thorough understanding of risk analysis through education, training or experience. If the selected personnel lack the necessary skills, they should receive comprehensive training on RBI methodology and the procedures being used for the RBI Plan.

203. Establishing objectives of an RBI program

1. An RBI assessment should be undertaken with clear objectives and goals that are fully understood by all members of the RBI team and by management. Some examples are listed in the following.

(1) Define risk criteria.
(2) Management of risks
(3) Reduce costs.(Reducing inspection costs is usually not the primary objective of an RBI assessment)
(4) Meet safety and environmental management requirements.
(5) Identify mitigation alternatives.
(6) New project risk assessment
(7) Facilities end of life strategies

204. Establishing asset boundary

1. Boundaries for physical assets included in the assessment are established consistent with the overall objectives. The level of data to be reviewed and the resources available to accomplish the objectives directly impact the extent of physical assets that can be assessed. The scope of an RBI assessment may vary between an entire refinery or plant and a single component within single piece of equipment. Typically, RBI is done on multiple pieces of equipment (e.g. an entire process unit) rather than on a single component.

2. Facilities screening

(1) At the facility level, RBI may be applied to all types of plants including but not limited to the following.
  (A) Oil and gas production facilities
  (B) Oil and gas processing and transportation terminals
  (C) Refineries
  (D) Petrochemical and chemical plants
  (E) Ppipelines and pipeline stations
  (F) Liquefied natural gas plants
(2) Screening at the facility level may be done by a simplified qualitative RBI assessment. Screening at the facility level could also be done by the following.
  (A) Asset or product value,
  (B) History of problems/failures at each facility,
  (C) PSM/non-PSM facilities,
  (D) Age of facilities,
  (E) Proximity to the public,
  (F) Proximity to environmentally sensitive areas.
(3) Examples of key questions to answer at the facility level are listed as follows.
  (A) Is the facility located in a regulatory jurisdiction that will accept modifications to statutory inspection intervals based on RBI?
  (B) Is the management of the facility willing to invest in the resources necessary to achieve the benefits of RBI?
  (C) Does the facility have sufficient resources and expertise available to conduct the RBI assessment and sustain the RBI program?

3. Process units screening

(1) If the scope of the RBI assessment is a multi-unit facility, the first step in the application of RBI is screening of entire process units to rank relative risk. The screening points out areas that are higher in priority and suggests which process units to begin with. It also provides insight about the level of assessment that may be required for operating systems and equipment items in the various units.
(2) Priorities may be assigned based on one of the following.
  (A) Relative risk of the process units,
  (B) Relative economic impact of the process units,
  (C) Relative COF of the process units,
  (D) Relative reliability of the process units,
  (E) Turnaround schedule,
  (F) Experience with similar process units.
(3) Examples of key questions to answer at the process unit level are similar to the questions at the facility level.
  (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 process unit operators see that some benefit may be gained through the application of RBI?
  (D) Does the process unit have sufficient resources and expertise available to conduct the RBI assessment?
  (E) What is the failure history in this unit?

4. Systems within process unit screening

(1) It is often advantageous to group equipment within a process unit into systems, loops, or circuits where common environmental operating conditions exist based on process chemistry, pressure and 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. In case the risks of each piece of equipment in the system show a common sensitivity to changes in process conditions, then a screening can establish one single IOW with common variables and ranges for the entire system.
(2) Block flow or process flow diagrams for the unit may be used to identify the systems including information about metallurgy, process conditions, credible damage mechanisms, and historical

problems.

(3) When a process unit is identified for an RBI assessment and overall optimization is the goal, it is usually best to include all systems within the unit. Practical considerations such as resource availability may require that the RBI assessment is limited to one or more systems within the unit. Selection of systems may be based on the following.
   (A) Relative risk of the systems
   (B) Relative COF of systems
   (C) Relative reliability of systems
   (D) Expected benefit from applying RBI to a system
   (E) Sensitivities of risk to changes in process conditions

5. Equipment item screening

(1) In most plants, a large percentage of the total unit risk will be concentrated in a relatively small percentage of the equipment items. These potential high-risk items should receive greater attention in the risk assessment. Screening of equipment items is sometimes conducted to identify the higher risk items to carry forward to more detailed risk assessment.

(2) An RBI assessment may be applied to all pressure-containing equipment such as the following.
   (A) Piping
   (B) Pressure vessels
   (C) Reactors
   (D) Heat exchangers
   (E) Furnaces and boilers
   (F) Tanks
   (G) Pumps (pressure boundary)
   (H) Compressors (pressure boundary)
   (I) Pressure-relief devices
   (J) Control valves (pressure boundary)

(3) Selection of equipment types to be included is based on meeting the objectives discussed in **203.** The following issues may be considered in screening the equipment to be included.
   (A) Will the integrity of safeguard equipment be compromised by damage mechanisms?
   (B) Which types of equipment have had the most reliability problems?
   (C) Which pieces of equipment have the highest COF if there is a pressure boundary failure?
   (D) Which pieces of equipment are subject to the most deterioration that could affect pressure boundary containment?
   (E) Which pieces of equipment have lower design safety margins and/or lower corrosion allowances that may affect pressure boundary containment considerations?

205. Establishing operating boundaries

1. Similar to physical asset boundaries, operating boundaries for the RBI program are established consistent with the program objectives, level of data to be reviewed, and resources. The purpose of establishing operational boundaries is to identify key process parameters that may impact deterioration. The RBI assessment normally includes review of both POF and COF for normal operating conditions. Start-up and shutdown conditions as well as emergency and non routine conditions should also be reviewed for their potential effect on POF and COF. The operating conditions, including any sensitivity analysis, used for the RBI assessment should be recorded as the operating limits for the assessment. Operating within the boundaries is fundamental to the validity of the RBI study as well as good operating practice. It is vital to establish and monitor key process parameters that may affect equipment integrity to determine whether operations are maintained within boundaries(i.e. IOWs).

2. Process conditions during start-up and shutdown can have a significant effect on the risk of a plant especially when they are more severe (likely to cause accelerated deterioration) than normal conditions, and as such should be considered for all equipment covered by the RBI assessment. Start-up lines are often included within the process piping and their service conditions during start-up and subsequent operation should be considered.

3. The normal operating conditions may be most easily provided if there is a process flow model or mass balance . available for the plant or process unit. However, the normal operating conditions found on documentation should be verified by unit operations personnel as it is not uncommon to find discrepancies between design and operating conditions that could impact the RBI results substantially. The following data should be provided.

(1) Operating temperature and pressure including variation ranges
(2) Process fluid composition including variation with feed composition ranges
(3) Flow rates including variation ranges
(4) Presence of moisture or other contaminant species

4. Changes in the process, such as pressure, temperature, or fluid composition, resulting from unit abnormal or upset conditions should be considered in the RBI assessment.

5. The RBI assessment on systems with cyclic operation, such as reactor regeneration systems, should consider the complete cyclic range of conditions. Cyclic or intermittent conditions could impact the POF due to some damage mechanisms such as mechanical fatigue, thermal fatigue, corrosion-fatigue, and corrosion under insulation.

6. The unit run lengths of the selected process units/equipment is an important limit to consider. The RBI assessment 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. An RBI 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 inspection plans that result from the study, such as inspection, repair, replace, operating, and so on. Projected operational changes are also important as part of the basis for the operational time period.

Section 3 Risk Assessment

301. General

1. A logical progression for a risk analysis is as follows.

(1) Collect and validate the necessary data and information.
(2) Identify damage mechanisms and, optionally, determine the damage mode(s) for each mechanism (e.g. general metal loss, local metal loss, pitting).
(3) Determine damage susceptibility and rates.
(4) Determine the POF over a defined timeframe for each damage mechanism.
(5) Determine credible failure mode(s)(e.g. small leak, large leak, rupture).
(6) Identify credible consequence scenarios that will result from the failure mode(s)
(7) Determine the probability of each consequence scenario, considering the POF and the probability that a specific consequence scenario will result from the failure.
(8) Determine the risk, including a sensitivity analysis, and review risk analysis results for consistency/reasonableness.

302. Collecting Data and information

1. Essential data differs fundamentally in the amount and detail of input, calculations, and output, depending on the RBI assessment approach. Typical data needed for an RBI analysis may include but is not limited to the following.

(1) Type of equipment
(2) Materials of construction
(3) Inspection, repair, and replacement records
(4) Process fluid compositions
(5) Inventory of fluids
(6) Operating conditions
(7) Safety systems
(8) Detection systems
(9) Damage mechanisms, rates, and severity
(10) Personnel densities
(11) Coating, cladding, and insulation data
(12) Business interruption cost
(13) Equipment replacement costs
(14) Environmental remediation costs

2. Potential sources of specific information include but are not limited to the following.

(1) Design and construction records/drawings
 (A) P&IDs, process flow diagrams, material selection diagrams (MSDs), etc.
 (B) Piping isometric drawings
 (C) Engineering specification sheets
 (D) Materials of construction records
 (E) Construction quality assurance/quality control (QAIQC) records
 (F) Codes and standards used
 (G) Protective instrument systems
 (H) Leak detection and monitoring systems
 (I) Isolation systems
 (J) Inventory records
 (K) Emergency de-pressurizing and relief systems
 (L) Safety systems
 (M) Fire-proofing and fire-fighting systems
 (N) Layout
(2) Inspection records
 (A) Schedules and frequency
 (B) Amount and types of inspection
 (C) Repairs and alterations
 (D) Positive material identification (PMI) records
 (E) Inspection results.
(3) Process data
 (A) Fluid composition analysis including contaminants or trace components
 (B) Cistributed control system data
 (C) Operating procedures
 (D) Start-up and shutdown procedures
 (E) Emergency procedures
 (F) Operating logs and process records
 (G) PSM/PSI, PHA, RCM, FMEA, and QRA data or reports
(4) MOC records
(5) Off-site data and information-if consequence may affect off-site areas.
(6) Failure data
 (A) Generic failure frequency data-industry or in-house
 (B) Industry-specific failure data
 (C) Plant- and equipment-specific failure data
 (D) Reliability and condition monitoring records
 (E) Leak data
(7) Site conditions
 (A) Climate/weather records
 (C) Seismic activity records
(8) Equipment replacement costs
 (A) Project cost reports
 (B) Industry databases
(9) Hazards data
 (A) PSM studies
 (B) PHA studies
 (C) QRA studies
 (D) Other site-specific risk or hazard studies
(10) Incident investigations.

303. Assessing damage mechanisms and failure modes

1. This section provides guidance in identifying credible damage mechanisms and failure modes of pressure boundary metallic components that are included in an RBI analysis.

2. Damage mechanisms include corrosion, cracking, mechanical, and metallurgical damage. Understanding damage mechanisms is important for the following.

(1) Analysis of the POF

(2) Selection of appropriate inspection intervals/due dates, locations, and techniques
(3) Decision-making ability (e.g. modifications to process, materials selection, monitoring, etc.) that can eliminate or reduce the probability of a specific damage mechanism

3. Failure modes identify how the damaged component will fail(e.g. by leakage or by rupture). Understanding failure modes is important for the following three reasons.

(1) Analysis of the COF
(2) Run-or-repair decision-making
(3) Selection of repair techniques

4. Identification of the credible damage 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 shall consult with a corrosion specialist to define the equipment damage mechanisms and potential failure modes. A sequential approach is as the following.

(1) Equipment design (pressures, temperature, and materials of construction) and current condition shall be considered. Data used and assumptions made shall be validated and documented.
(2) All process conditions, e.g. start-up, shut-down, idle, anticipated abnormal and normal, as well as planned process changes shall 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 effect on the damage mechanisms.
(3) Considering the materials, methods, and details of fabrication, a list of the credible damage mechanisms that may have been present in past operation, be presently active, or may become active shall be developed including the rate of deterioration for primary damage mechanisms and the tolerance of the equipment to the type of damage.
(4) 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 large burst, while localized corrosion might be more likely to result in a pinhole type leak. All credible failure modes for each damage mechanism should be considered.
(5) 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 with generalized or localized corrosion.

5. 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, etc.) to aid corrosion specialists in the identification of credible damage mechanisms and rates. For example, understanding that localized thinning may be caused by the method of fluid injection and agitation may be as important as knowing the corrosion mechanism.

6. 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-containing boundary. 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 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 the following.

(1) Pinhole leak
(2) Small to moderate leak
(3) Large leak
(4) Ductile rupture
(5) Brittle fracture
(6) Fatigue fracture

7. 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.

8. The results of a damage mechanisms and failure modes analysis for RBI should identify the following.

(1) Credible damage mechanism(s) list
   (A) Example: external corrosion.
(2) Credible damage mode(s) list resulting from the damage mechanism(s) in (1)
   (A) Example 1: localized thinning
   (B) Example 2: general thinning
(3) Credible failure mode(s) ranking resulting from the damage mode(s) in (2)
   (A) Example 1: localized thinning:
      - Failure mode 1: pinhole leak
      - Failure mode 2: small leak
   (B) Example 2: general thinning
      - Failure mode 1: pinhole leak
      - Failure mode 2: small leak
      - Failure mode 3: large leak
      - Failure mode 4: rupture

304. Assessing Probability of Failure

1. The probability analysis in an RBI program is performed to estimate the probability of a specific adverse consequence resulting from a loss of containment that occurs due to damage mechanism(s). The probability that a specific consequence will occur is the product of the POF and the probability of the scenario under consideration, assuming that the failure has occurred. This section provides guidance only on determining the POF. Determining the probability of specific consequences is provided in **306.**.

2. The POF analysis shall address all credible damage mechanisms to which the equipment being reviewed is or can be susceptible. Further, it shall address the situation where equipment is or can be susceptible to multiple damage mechanisms(e.g. thinning and creep). The analysis should be credible, repeatable, and documented.

3. It should be noted that damage mechanisms are not the only causes of loss of containment(e.g. seismic activity, weather extremes, etc.). These and other causes of loss of containment may have an impact on the POF and may be (but typically are not) included in the POF analysis for RBI.

4. POF is typically expressed in terms of frequency. Frequency is expressed as a number of events occurring during a specific timeframe. POF can be analyzed in qualitative or quantitative approach, and the results can be assigned to each unit, system, group or equipment item in the categories shown in **Table 1**.

(1) A qualitative method involves identification of the units, systems, or equipment, the materials of construction, and the corrosive components of the processes. Based on knowledge of the operating history, future inspection and maintenance plans, and possible materials deterioration, POF can be assessed separately for each unit, system, equipment grouping, or individual equipment item. Engineering judgment is the basis for this assessment. Refer to the API 581 2008 edition for an example of qualitative POF analysis.
(2) There are several approaches to a quantitative probability analysis. Refer to the latest edition API 581 for the detailed procedure of quantitative POF analysis.
   (A) One example is to take a probabilistic approach where specific failure data or expert solicitations are used to calculate a POF. These failure data may be obtained on the specific equipment item in question or on similar equipment items. This probability may be expressed as a distribution rather than a single deterministic value.
   (B) Another approach is used when inaccurate or insufficient failure data exists on the specific item of interest. In this case, general industry, company, or manufacturer failure data is used. A methodology should be applied to assess the applicability of these general data. As appropriate, this 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, general failure data is used to generate an adjusted failure frequency that is applied to equipment for a specific application. Such modifications to general values may be made for each equipment item to account for the potential deterioration that may occur in the particular service and the type and effectiveness of inspection and/or monitoring performed. Qualified persons should make these modifications on a case-by-case basis.

Table 1 Categories for POF ranking(for example)

Ranking	Annual POF		Description
	Quantitative	Qualitative	
1	〈 10^{-5}	Improbable	Unlikely to occur in many system similar to the target system (e.g., no experience in the related companies or industries.)
2	10^{-5} to 10^{-4}	Rare	Unlikely but possible to occur in many system similar to the target system (e.g., it has occurred in the related companies or industries.)
3	10^{-4} to 10^{-3}	Occasional	Likely to occur over the lifetime operation of the target system (e.g., likely to occur once per decades, etc.)
4	10^{-3} to 10^{-2}	Probable	Likely to occur during long-time operation of the target system (e.g., likely to occure one per year, etc.)
5	〉 10^{-2}	Frequent	Likely to occur during short-time operation of the target system (e.g., likely to occure one per year, etc.)

5. Regardless of whether a more qualitative or a quantitative analysis is used, the POF is determined by two main considerations, as follows.

(1) Damage mechanisms and rates of the equipment item's material of construction, resulting from its operating environment (internal and external)

(2) Effectiveness of the inspection program to identify and monitor the damage mechanisms so that the equipment can be repaired or replaced prior to failure

6. Analyzing the effect of in-service deterioration and inspection on the POF involves the following steps.

(1) Identify active and credible damage mechanisms that are reasonably expected to occur during the time period being considered (considering normal and upset conditions).

(2) Determine the deterioration susceptibility and rate. For example, a fatigue crack is driven by cyclic stress; corrosion damage is driven by the temperature, concentration of corrosive, corrosion current, etc. 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 579-1/ASME FFS-1).

(3) Using a consistent approach, evaluate the effectiveness of the past inspection, maintenance, and process monitoring program and a proposed future inspection, maintenance, and process monitoring program. It is usually necessary to evaluate the POF considering several alternative future inspection and maintenance strategies, possibly including a "no inspection or maintenance" strategy.

(4) Determine the probability that with the current condition, continued deterioration at the predicted/expected rate will exceed the damage tolerance of the equipment and result in a failure. The fai lure mode (e.g. small leak, large leak, equipment rupture) should be determined based on the damage mechanism. It may be desirable in some cases to determine the probability of more than one failure mode and combine the risks.

7. By combining the expected damage mechanism, rate or susceptibility, process monitoring, inspection data, and effectiveness of inspections, POF can now be determined for each deterioration type and failure mode. The POF may be determined for future time periods or conditions as well as current operating conditions. It is important for users to validate that the method used to calculate the POF is in fact thorough and adequate for the owner-users' needs.

305. Assessing Consequence of Failure(COF)

1. The consequence analysis in an RBI program is performed to provide discrimination between equipment items on the basis of the significance of a potential failure. The consequence analysis should be a repeatable, simplified, credible estimate of what might be expected to happen if a failure were to occur in the equipment item being assessed. The COF analysis shall be performed to estimate the consequences that are likely to occur due to a failure mode typically resulting from an identified damage mechanism(s). Consequence should typically be categorized as the following.

(1) Safety and health impacts
(2) Environmental impacts
(3) Economic impacts

2. Representative approaches for determining COF include the following qualitative or quantitative methods. Depending on the data provided for the analysis, a combination of these two methods can be performed The results of the COF analysis can be expressed in the categories shown in **Table 2**.

(1) A qualitative method involves identification of the units, systems, or equipment, and the hazards present as a result of operating conditions and process fluids. On the basis of expert knowledge and experience, the consequences of failure (safety and health, environmental, and economic impacts) can be estimated separately for each unit, system, equipment group, or individual equipment item. For a qualitative method, a consequences category is typically assigned for each unit, system, grouping, or equipment item. It may be appropriate to associate a numerical value with each consequence category.

(2) A quantitative method involves using a logic model depicting combinations of events to represent the effects of failure on people, property, the business, and the environment. Quantitative models usually contain one or more standard failure scenarios or outcomes and calculate COF based on the following.

(A) Type of process fluid in equipment
(B) State of the process fluid inside the equipment (solid, liquid, or gas)
(C) Key properties of process fluid (molecular weight, boiling point, autoignition temperature, ignition energy, density, flammability, toxicity, etc.)
(D) Process operating variables such as temperature and pressure
(E) Mass of inventory available for release in the event of a leak
(F) Failure mode and resulting leak size
(G) State of fluid after release in ambient conditions (solid, gas, or liquid)

Table 2 Categories for COF ranking(for example)

Ranking	COF	Description		
		Safety and health	Environmental	Economic
A	Slight	Slight injury (first-aid needed)	Slight pollution (immediate restoration available)	Slight damage/failure (no downtime or asset damage)
B	Minor	Minor injury Absence〈2days	Minor local effect (short-term restoration need	〈 ₩10,000,000 damage or 〈 1 shift downtime
C	Major	Major injury Absence〉2days	Significant local effect (more than 1 man week restoration needed)	〈 ₩100,000,000 damage or 〈 4 shifts downtime
D	Critical	Single fatality or multiple major injuries	Significant effect upon surrounding ecosystem (long-term restoration needed)	〈 ₩1,000,000,000 damage or 〈 1 month downtime
E	Catastrophic	Multiple fatalities	Massive and irreparable damage to ecosystem.	〈₩10,000,000,000 damage or 〈 1 year downtime

3. The failure of the pressure boundary and subsequent release of fluids may cause safety, health, environmental, facility, and business damage. The RBI analyst should consider the nature of the hazards and assure that appropriate factors are considered for the equipment, system, unit, or plant being assessed.

4. Regardless of whether a more qualitative or quantitative analysis is used, the major factors to consider in evaluating the consequences of failure shall include the following.

(1) Flammable events (fire and explosion)
(2) Toxic releases
(3) Release of other hazardous fluids

5. Additionally, other impacts that may be considered include the following.

(1) Environmental consequences
(2) Production consequences (business interruption)
(3) Maintenance and reconstruction impact

6. The consequences of releasing a hazardous material can be estimated in six steps (see Figure 5), with each step performed using the assumption of a specific scenario, and the steps should be repeated for each credible scenario. The steps are as follows.

(1) Estimate the release rate.
(2) Estimate total volume of fluid that will be released.
(3) Determine if the fluid is dispersed in a rapid manner (instantaneous) or slowly (continuous).
(4) Determine if the fluid disperses in the atmosphere as a liquid or a gas.
(5) Estimate the impacts of any existing mitigation system.
(6) Estimate the consequences.

7. Estimate the consequence 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, escalation effects, 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 failure (rupture) of the equipment item. The following shows how a consequence scenario may be constructed.

(1) Consequence Phase 1-Discharge: Consider the type of discharge (sudden vs slow release of contents) and its duration.
(2) Consequence Phase 2-Dispersion: Consider the dispersion of the released contents due to weather conditions.
(3) 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).
(4) 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).
(5) 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).
(6) Consequence Phase 6-The potential number of fatalities and injuries(safety and health, environmental and/or economic impacts) resulting from each scenario should be estimated. Different scenarios, with different associated probabilities, should be developed as appropriate.

306. Determination of Risk

1. This section describes the process of determining risk by combining the results of work done as described in the previous two sections. It also provides guidelines for prioritizing and assessing the acceptability of risk with respect to risk criteria.

2. The general form of the risk equation shall be as follows:

$$risk\ of\ a\ specific\ consequence = probability\ of\ a\ specific\ consequence \times specific\ consequence$$

3. Once the POF and failure mode(s) have been determined for the relevant damage mechanisms, the probability of each credible consequence scenario should be determined. In other words, the loss of containment failure may only be the first event in a series of events that lead to a specific consequence. The probability of credible events leading up to the specific consequence should be factored into the probability of the specific consequence occurring. For example, after a loss of containment, a series of events may be as follows.

(1) First, initiation or failure of safeguards (isolation, alarms, etc.)
(2) Second, dispersion, dilution, or accumulation of the fluid
(3) Third, initiation of or failure to initiate preventative action (shutting down nearby ignition sources, neutralizing the fluid, etc.)
(4) Additional events until the specific consequence event (fire, toxic release, injury, environmental release, etc.) occurs

4. It is important to understand this linkage between the POF and the probability of possible resulting incidents(or probability of specific consequence). The probability of a specific consequence is tied to the severity of the consequence and may differ considerably from the probability of the equipment failure itself. Probabilities of incidents generally decrease with the severity of the incident. For example, the probability of an event resulting in a fatality will generally be less than the probability that the event will result in a first aid or medical treatment injury.

5. Each type of damage mechanism has its own characteristic failure mode(s). For a specific damage mechanism, the expected mode of failure should be considered when determining the probability of specific consequence in the aftermath of an equipment failure.

6. Typically, there will be other credible consequences that should be evaluated. However, 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 trivial cases.

7. Calculating the probability of a specific consequence and risk

(1) 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 in **Figure 3**.

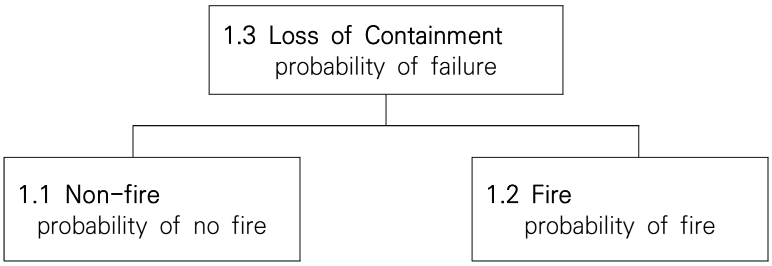


Figure 10 Calculating probability of specific consequence(example)

(A) The probability of a fire would be as follows.
probability of fire = probability of failure x probability of ignition
probability of fire= 0.001 per year x 0.01
probability of fire= 0.00001 per year

(B) 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 as follows.
probability of no fire = (probability of failure x probability of non-ignition) + probability of no failure
probability of no fire = (0.001 per year x 0.99) + 0.999 per year
probability of no fire = 0.99999 per year

(C) The probability of all consequence scenarios should equal 1.0. In the example, the probability of the specific consequence of a fire (0.00001 per year) plus the probability of no fire (0.99999 per year) equals 1.0.

(D) If the consequence of a fire had been assessed at ₩10,000,000,000 then the resulting risk would be as follows.
risk of fire =0.00001 per year x ₩10,000,000,000 = ₩100,000 per year

(2) If probability and consequence are not expressed as numerical values, risk is usually determined by plotting the probability and consequence on a risk matrix (see Figure 4.). Probability and consequence pairs for various scenarios may be plotted to determine risk of 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 POF

8. Sensitivity analysis

(1) Understanding the value of each variable and how it influences the risk calculation is key to identifying which input variables deserve closer scrutiny versus other variables which may not have significant effects. This is more important when performing risk analyses that are more detailed and quantitative in nature.

(2) Sensitivity analysis typically involves reviewing some or all input variables to the risk calculation 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. Those key input variables deserve the most attention.

(3) 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. As such, the quality and accuracy of the risk analysis should improve. This is an important part of the data validation phase of risk assessment.

9. Assumptions

(1) Assumptions or estimates of input values are often used when consequence and/or POF data are not available. Even when data are known to exist, conservative estimates may be used 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, as overestimating consequences and/or POF values will unnecessarily inflate the calculated risk values. Presenting over inflated risk values may mislead inspection planners, management, and insurers and can create a lack of credibility for the user and the RBI process. Appropriate members of the RBI team should agree on the assumptions made for RBI analysis and the potential impacts on the risk results.

307. Evaluation of Risk

1. Risk criteria

(1) RBI is a tool to provide an analysis of the risk of loss of containment of equipment. Many companies have corporate risk criteria defining acceptable and prudent levels of safety, environmental, and financial risks. These risk criteria should be used when making RBI decisions. Because each company may be different in terms of acceptable risk levels, risk management decisions can vary among companies.

(2) Cost-benefit analysis is a powerful tool that is being used by many companies, governments, and regulatory authorities as one method in determining risk acceptance. Risk acceptance may vary for different risks. For example, risk tolerance for an environmental risk may be higher than for a safety/health risk.

(3) The use of risk assessment in inspection and maintenance planning is unique in that consequence information, which is traditionally operations based, and POF information, which is typically engineering, maintenance, or inspection based, is combined to assist in the planning process. Part of this planning process is the determination of what to inspect, how to inspect (technique), where to inspect (location), how much to inspect (coverage), and when to inspect. Determining the risk of process units, or individual process equipment items, facilitates this, as the inspections are now prioritized based on the risk value. The second part of this process is determining when to inspect the equipment. Understanding how risk varies with time facilitates this part of the process.

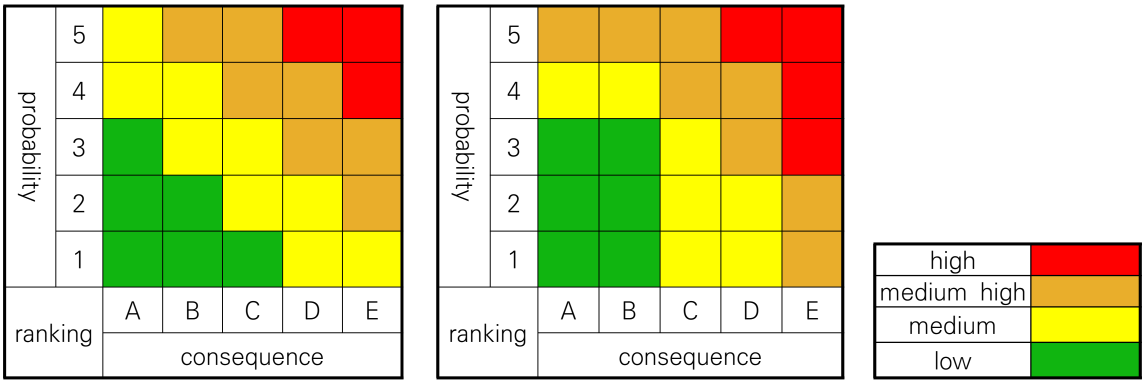
2. Risk presentation

Once risk values are developed, they can 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 is 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.

(1) Risk matrix

(A) For risk ranking methodologies that use consequence and probability categories, presenting the results in a risk matrix is a very effective way of communicating the distribution of risks throughout a plant or process unit without numerical values. An example risk matrix is shown in **Figure 4**. 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 assessment (e.g. probability category C ranges from 0.001 to 0.01). The commonly used 5 x 5 matrix is available, and the consequence and probability categories should provide sufficient discrimination between the items assessed.

(B) Risk categories may be assigned to the boxes on the risk matrix. An example risk categorization (high, medium high, medium, and low) of the risk matrix is shown in **Figure 4**. In this example, the risk categories are symmetrical. They may also be asymmetrical where for instance the consequence category may be given higher weighting than the probability category. A risk matrix depicts results at a particular point in time.



(a) balanced risk matrix **(b) unbalanced risk matrix** **risk categories**

Figure 11 Risk matrix(exmaple)

(2) Risk plot

When more quantitative consequence and probability data are being used, and where showing numeric risk values is more meaningful to the stakeholders, a risk plot (or graph) is used (see **Figure 5**). 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 **Figure 5**, 10 pieces of equipment are shown, as well as an ISO-risk line. 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 resultant risk levels fall below the line.

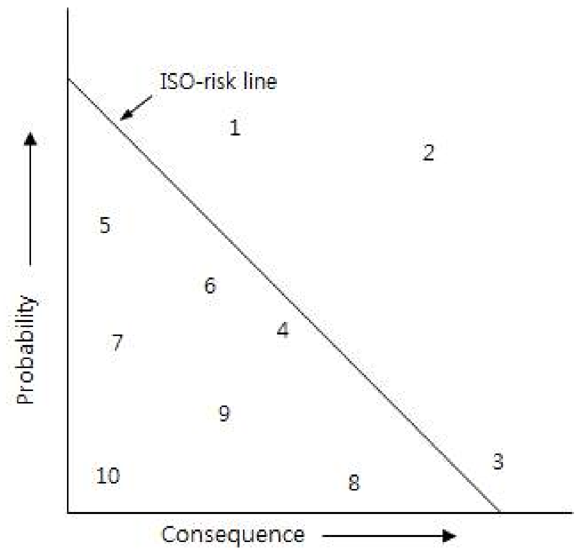


Figure 12 Risk plot when using quantitative risk values (example)

(3) Using a risk plot or matrix

(A) Equipment items residing toward the upper right-hand corner of the plot or matrix will most likely take priority for inspection planning because these items have the highest risk. Similarly, items residing toward the lower left-hand comer 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) can then be used as a screening tool during the prioritization process.

(B) Risk may be described in terms of dollars or other numerical values as described in **304. 3** 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 vs inspection time plot may be used to time the inspection activities.

3. Establishing acceptable risk thresholds

(1) After the risk analysis has been performed, and risk values plotted, the risk evaluation process begins. Risk plots and matrices can be used to screen and initially identify higher, intermediate, and lower risk equipment items. The equipment can also be ranked according to its risk value in tabular form. Thresholds that divide the risk plot, matrix, or table into acceptable and unacceptable regions of risk can 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.

(2) Reduction of some risks to a lower level 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.

Section 4 Risk Management

401. General

1. Inspection itself does not arrest or mitigate damage mechanisms or reduce risk, but the information gained though effective inspection can better quantify the actual risk. Impending failure of pressure equipment is not avoided by inspection activities unless the inspection precipitates risk mitigation activities that change the POF. Inspection serves to identify, monitor, and measure the damage mechanism(s). 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 the damage mechanisms and rates of deterioration. The better the predictability, the less uncertainty there will be as to when a failure may occur. Mitigation (repair, replacement, changes, etc.) can then be planned and implemented prior to the predicted failure date. The reduction in uncertainty and increase in predictability through inspection translates directly to a better estimate of the probability of a failure and therefore a reduction in the calculated risk. However, users should be diligent to assure that temporary inspection alternatives, in lieu of more permanent risk reductions, are actually effective.

2. The foregoing **1** does not imply that RBI plans and activities are always the answer to monitoring degradation and reducing risks associated with pressure equipment. Some damage mechanisms are very difficult or impossible to monitor with just inspection activities (e.g. metallurgical deterioration that may result in brittle fracture, many forms of stress corrosion cracking, and even fatigue). Other damage mechanisms precipitated by short-term, event-driven operating changes can happen too fast to be monitored with normal inspection plans, be they risk based, condition based, or time based, hence the need for establishing and implementing a comprehensive program for IOWs, along with adequate communications to inspection personnel when deviations occur and a rigorous MOC program for changes from the established parameters.

3. Risk mitigation(by the reduction in uncertainty) 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 is gathered is 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.

4. For risks that are judged acceptable, no mitigation may be required and no further action necessary. For risks considered unacceptable and therefore requiring risk mitigation, there are various mitigation categories that should be considered.

(1) Decommission – Is the equipment really necessary to support unit operation?
(2) Inspection and Repairs – Can a cost-effective inspection program, with repair as indicated by the inspection results, be implemented that will reduce risks to an acceptable level?
(3) Consequence Mitigation – Can actions be taken to lessen the COF related to an equipment failure such as operational changes or design changes(e.g. isolation, detection system) that can reduce the COF?
(4) Probability Mitigation – Can actions be taken to lessen the POF such as material of construction changes, operational changes, or equipment redesign?

402. Managing risks from RBI results

1. Typically a risk priority list is developed as a result of the RBI process. RBI will also identify whether consequence or POF or both is driving risk. In the situations where risk is being driven by POF, there is usually potential for risk management through inspection.

2. Once an RBI assessment has been completed, the items with unacceptable risk to the owner-user shall be assessed for potential risk management through inspection plans or other risk management strategies. Higher risk items should also be assessed for potential risk management actions. Whether inspections will be effective or not will depend on the following.

(1) Equipment type
(2) Active and credible damage mechanism(s);
(3) Rate of deterioration or susceptibility;
(4) Inspection methods, coverage, and frequency;
(5) Accessibility to expected damage areas;
(6) Shutdown requirements;
(7) Amount of achievable reduction in POF(i.e. a reduction in POF of a low POF item is usually difficult to achieve through inspection).

3. 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 as follows.

(1) Corrosion rates well-established with equipment nearing end of life
(2) Instantaneous failures related to operating conditions such as brittle fracture
(3) Inspection technology that is not sufficient to detect or quantify deterioration adequately
(4) Too short a timeframe from the onset of deterioration to final failure for periodic inspections to be effective(e.g. high-cycle fatigue cracking)
(5) Event-driven failures(circumstances that cannot be predicted)

4. When alternative measures in **3** are taken, the most practical and cost-effective risk mitigation strategy can then be developed for each item. Usually, inspection provides a major part of the overall risk management strategy, but not always.

403. Establishing an inspection plan

1. The results of an RBI assessment are normally 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. For the development of their inspection plan, users should consider the following.

(1) Risk criteria and ranking
(2) Risk drivers
(3) Equipment history
(4) Number and results of inspections
(5) Type and effectiveness of inspections
(6) Equipment in similar service and remaining life

2. Inspection is only effective if the examination 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, etc.). In this case, ultrasonic scanning, radiography, and/or other approaches would be more effective. The level of risk reduction achieved by inspection will depend on the following.

(1) Mode of failure of the damage mechanism
(2) Time interval between the onset of deterioration and failure (i.e. speed of deterioration)
(3) Detection capability of examination technique
(4) Scope and extent of inspection
(5) Frequency of inspection

3. Organizations should be deliberate and systematic in assigning the level of risk management achieved through inspection and should be cautious not to assume that there is an unending capacity for risk management through inspection.

4. The inspection strategy shall be a documented, iterative process to assure that inspection activities are continually focused on items with higher risk.

404. Managing risk with inspection activities

1. The effectiveness of past inspections is part of the determination of the present risk. The future risk can now be influenced by future inspection activities. Key parameters and examples that can affect the future risk are as follows.

(1) Frequency of inspection - Increasing the frequency of inspections may serve to better define, identify, or monitor the damage mechanism(s) and therefore better quantify the risk. Both routine and turnaround inspection frequencies can be optimized.

(2) Coverage - Different zones or areas of inspection of an item or series of items can be modeled and evaluated to determine the coverage that will produce an acceptable level of risk.

(A) A higher risk piping system may be a candidate for more extensive inspection, using one or more NDE techniques targeted to locating the identified damage mechanisms.

(B) An assessment may reveal the need for focus on parts of a vessel where the highest risk may be located and focus on quantifying this risk rather than focusing on the rest of the vessel where there are perhaps only low risk deterioration processes occurring.

(3) Tools and techniques - The selection and usage of the appropriate inspection tools and techniques can be optimized to cost-effectively and safely quantify the POF. 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 can vary depending on the choice. As an example, profile radiography would typically be more effective than digital ultrasonics for thickness monitoring in cases of localized corrosion.

(4) Procedures and practices - Inspection procedures and the actual inspection practices can 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 benefits should be obtained. The user is cautioned not to assume that all inspectors and NDE examiners are well qualified, but rather to take steps to assure that they have the appropriate level of qualifications.

(5) Internal, on-stream, or external inspection - Risk quantification by internal, on-stream, and external inspections should be assessed. Often external inspection with effective on-stream inspection techniques can provide useful data for risk assessment. It is worth noting that invasive inspections, in some cases, may cause deterioration and increase the risk of the item. Examples where this may happen include the following.

(A) Moisture ingress to equipment leading to stress corrosion cracking or PASCC(polythionic acid stress corrosion cracking)
(B) Internal inspection of glass lined vessels
(C) Removal of passivating films
(D) Human errors in start-up(re-streaming)
(E) Increased risks associated with shutting down and starting up equipment

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

405. Assessing inspection result and determining corrective action

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

2. 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 QA/QC, and the date the plan should be completed.

406. Other risk mitigation activities

1. Inspection is often an effective method of risk management. However, inspection may not always provide sufficient risk mitigation or may not be the most cost-effective method. These risk mitigation activities fall into one or more of the following.

(1) Reduce the magnitude of consequence.
(2) Reduce the POF.
(3) Enhance the survivability of the facility and people to the consequence.
(4) Mitigate the primary source of consequence.

2. When equipment deterioration has reached a point that the risk of failure cannot be managed to an acceptable level, replacement/repair is often the only way to mitigate the risk.

3. 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 can also be performed to determine what size flaws, if found in future inspections, would require repair or equipment replacement.

4. Modification and redesign of equipment, utilizing a rigorous MOC process, can provide mitigation of POF. Examples include the following.

(1) Change of metallurgy
(2) Addition of protective linings and coatings
(3) Removal of deadlegs
(4) Increased corrosion allowance
(5) Physical changes that will help to control/minimize deterioration
(6) Insulation improvements
(7) Injection point design changes
(8) Resizing of the relief device

Section 5 Reassessment and Update of RBI Assessment

501. General

1. RBI is a dynamic tool that can provide current and projected future risk evaluations. However, these evaluations are based on data and knowledge at the time of the assessment. As time goes by, changes are inevitable and the results from the RBI assessment shall be updated.

2. It is important to maintain and update an RBI program to ensure that the most recent inspection, process, and maintenance information is included. The results of inspections, changes in process conditions, and implementation of maintenance practices can all have significant effects on risk, and therefore the inspection plan, and can trigger the need to perform a reassessment.

502. Why to conduct an RBI reassessment

1. There are several events that will change risk and make it prudent to conduct an RBI reassessment. It is important that the facility have an effective work process that identifies when a reassessment is necessary. The following **2** through **5** provide guidance on some key factors that could trigger an RBI reassessment.

2. Damage mechanisms and inspection activities

(1) Many damage mechanisms are time dependent. Typically, the RBI assessment will project deterioration at a constant rate. In reality, the deterioration rate may vary over time. Through

inspection activities, the rate of deterioration (both short-term and long-term) may be better defined.

(2) Some damage mechanisms are independent of time (i.e. they occur only when there are specific conditions present). When those intermittent conditions occur, an RBI reassessment may be appropriate. As part of the reassessment, it is important to review the operating histories over the past run, including IOW exceedances and trends, to better predict if non-time-dependent damage mechanisms could have occurred.

(3) Inspection activities will increase information on the condition of the equipment. When inspection activities have been performed, the results shall be reviewed to determine if an RBI reassessment is necessary.

3. Process and hardware changes

Changes in process conditions and hardware, such as equipment modifications or replacement, frequently can significantly alter the risks and dictate the need for a reassessment. Process changes, in particular, have been linked to equipment failure from rapid or unexpected corrosion or cracking. This is particularly important for damage mechanisms that depend heavily on process conditions. Typical examples include chloride stress corrosion cracking of stainless steel, wet H2S cracking of carbon steel, and accelerated corrosion at points of salt deposition or at dew points and sour water corrosion. In each case, a change in process conditions can dramatically affect the corrosion rate or cracking tendencies. Hardware changes can also have an effect on risk.

(A) POF can 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) COF can be affected by the relocation of a vessel to an area near an ignition source.

(C) Process conditions can be changed by hardware modifications, additions, deletions, or bypassing.

4. RBI assessment premise change

The premises for the RBI assessment could change and have a significant impact on the risk results. Some of the possible changes could be as follows.

(A) Increase or decrease in population density in the process unit
(B) Change in construction material and repair/replacement costs
(C) Change in product values
(D) Revisions in safety and environmental laws and regulations
(E) Revisions in the users RMP(such as changes in risk criteria)
(F) Change in feed amount or composition
(G) Changes in operating conditions
(H) Change in unit operating lengths between maintenance turnarounds
(I) Changes in inspection codes/standards

5. The effect of mitigation strategies

Strategies to mitigate risk such as installation of safety systems, repairs, and other approaches when utilized should be monitored to ensure that they have successfully achieved the desired mitigation. Once a mitigation strategy is implemented, a reassessment of the risk may be performed to update the RBI program with the new current risks.

503. When to conduct an RBI reassessment

1. After significant changes

As discussed in **502.**, significant changes in risk can occur for a variety of reasons. Qualified personnel should evaluate each significant change to determine the potential for a change in risk. It may be desirable to conduct an RBI reassessment after significant changes in process conditions, damage mechanisms/rates/severities, or RBI premises.

2. After a set time period

Although significant changes may not have occurred, over time many small changes may occur and cumulatively cause significant changes in the RBI assessment. Users should set default maximum time periods for reassessments. The governing inspection codes and jurisdictional regulations, if any, shall be reviewed in this context.

3. After implementation of risk mitigation strategies

Once a mitigation strategy is 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 reassessment of the risk and appropriate update in the documentation.

4. Before and after maintenance turnarounds

(1) As part of the planning for a maintenance turnaround, it is usually useful to perform an RBI reassessment. This can become a first step in planning the turnaround to ensure that the work effort is focused 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.

(2) Since a large number of inspection, repairs, and modifications are performed during a typical maintenance turnaround, it may be useful to update an assessment soon after the turnaround to reflect the new risk levels.

Section 6 RBI Documentation and Recordkeeping

601. General

1. A documented management system to implement and sustain RBI program shall be developed and typically would include the following elements.

(1) Procedures covering implementation, maintenance, and reassessment
(2) Roles/responsibilities, experience/training requirements
(3) Documented assumptions
(4) Timeframe for RBI analysis applicability
(5) Data requirements
(6) Risk targets
(7) Program audit requirements
(8) Scope and boundary limits
(9) Triggers for reassessment(e.g. process changes, equipment damage, failures, IOW exceedances, etc.)
(10) Timeframe for reassessment

2. It is important that sufficient information is captured to fully document the RBI assessment. Typically, this documentation should include the following data and information.

(1) Type of assessment, objectives, and boundaries
(2) Procedure for how the selected RBI methodology will be applied at the site(e.g. how to deal with all the options provided by the methodology)
(3) Team members performing the assessment and their skill set relative to RBI
(4) Timeframe over which the assessment is applicable
(5) Inputs and sources used to determine risk
(6) Assumptions made during the assessment
(7) Risk assessment results(including information on probability and consequence)
(8) Follow-up mitigation strategy, if applicable, to manage risk
(9) Mitigated risk levels(i.e. residual risk after mitigation is implemented)
(10) References to in-service codes or standards being applied

3. Sufficient data shall be captured and maintained such that the assessment can be recreated or updated at a later time by others who were not involved in the original assessment. To facilitate this, it is preferable to store the information in a computerized database. This will enhance the analysis, retrieval, and stewardship capabilities. The usefulness of the database will be particularly important in stewarding recommendations developed from the RBI assessment and managing overall risk over the specified timeframe.

602. RBI methodology

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

603. Personnel

The assessment 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 should be captured, as well as the skill set that they bring to the team for RBI purposes. This will be helpful in understanding the basis for the risk assessment when the analysis is repeated or updated.

604. Timeframe

The level of risk is usually a function of time. This is either a result of the time dependence of a damage mechanism or simply the potential for changes in the operation of equipment. Therefore, the timeframe over which the RBI analysis is applicable should be defined and captured in the final documentation. This will permit tracking and management of risk effectively over time.

605. Basis for the assignment of risk

The various inputs used to assess both the probability and COF shall be captured. This should include, but not necessarily be limited to, the following information.

(1) Basic equipment data and inspection history critical to the assessment (e.g. operating conditions, materials of construction, service exposure, corrosion rate, inspection history);
(2) Operative and credible damage mechanisms;
(3) Criteria used to judge the severity of each damage mechanism;
(4) Anticipated failure mode(s) (e.g. leak, crack, or rupture);
(5) Key factors used to judge the severity of each failure mode;
(6) Criteria used to evaluate the various consequence categories, including safety, health, environmental, and financial;
(7) Risk criteria used to evaluate the acceptability of the risk.

606. Assumptions made to assess risk

Risk analysis, by its very nature, requires that certain assumptions be made regarding the nature and extent of equipment deterioration. 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. Clearly documenting the key assumptions made during the analysis of probability and consequence will greatly enhance the capability to either recreate or update the RBI assessment.

607. Risk assessment results

The probability, consequence, and risk results shall be captured in the documentation. For items that require risk mitigation, the recommendations for and results after mitigation should be documented as well.

608. 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 assessment. The mitigation "credit" 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.

608. 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 assessment. This is particularly important where implementation of RBI is used to reduce either the extent or frequency of inspection. ⚓

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