

**Risk-Based Inspection (RBI)
based on
API Recommended Practice 580
(First Edition, May 2002)**

TWI Ltd, Training & Examination Services

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1 Introduction

'To look is one thing, to see what you are looking at is something else, to understand what you see is another, to learn from what you understand is another, but to act on what you learn is all that really matter!'

Winston Churchill

Risk-based Inspection (RBI) is fast becoming the oil and gas industry standard mechanism for risk management of equipment integrity issues. API RP 580 is one of the first National / International standards to have been published on this topic, and is intended to provide guidance on developing an RBI programme for fixed equipment and piping in the hydrocarbon and chemical process industries.

RP 580 is intended to supplement API 510 *Pressure Vessel Inspection Code*, API 570 *Piping Inspection Code*, and API 653 *Tank Inspection, Repair, Alteration and Reconstruction*. These API inspection codes and standards allow an owner/user latitude to plan an inspection strategy and to increase or decrease the code designated inspection frequencies based on the results of a RBI assessment. The assessment must systematically evaluate both the probability and the associated consequences of a failure. The probability of failure assessment must be based on all forms of deterioration that could reasonably be expected to affect the piece of equipment in the particular service.

The practices described in RP 580 are not intended to supplant other practices that have proven to be satisfactory, nor are they intended to discourage innovation and originality in the inspection of hydrocarbon and chemical facilities. Users are reminded that no book or manual is a substitute for the judgement of a responsible, qualified inspector or engineer!

The purpose of a RBI programme is to:

- Screen operating units within a plant to identify areas of high risk
- Estimate a risk value associated with the operation of each equipment item, based on consistent methodology
- Prioritise the equipment based on the identified risk
- Design an appropriate inspection programme
- Systematically manage the risk of equipment failures

The expected outcome from the application of the RBI process should be the linkage of risks with appropriate inspection or other risk mitigation activities to manage the risks. The RBI process should generate a ranking by risk of all equipment evaluated, and a detailed description of the inspection plan to be employed for each equipment item, including:

- Inspection method(s) that should be used (eg UT, RT, WFMT)
- Extent of application of the inspection method(s) (eg % of total area examined or specific locations)
- Timing of inspections / examinations
- Risk management achieved through implementation of the inspection plan

The outcome should also include a description of any other risk mitigation activities (such as repairs, replacements or safety equipment upgrades), and the expected risk levels of all equipment after the inspection plan and other risk mitigation activities have been implemented.

Key elements that should exist in any RBI programme are:

- Management systems for maintaining documentation, personnel qualifications, data requirements and analysis updates
- Documented method for probability of failure determination
- Documented method for consequence of failure determination
- Documented methodology for managing risk through inspection and other mitigation activities

The primary outputs from a RBI assessment, are plans that address ways to manage risks on an equipment level. These equipment plans highlight risks from a safety / health / environment perspective, and from an economic perspective. Effective implementation of the plans should provide an overall reduction in risk for the facilities and equipment assessed, and an understanding of the current risk.

The RBI plans also identify equipment that may not require inspection or some other form of mitigation, because of the acceptably low level of risk associated with the current operation. In this way, inspection and maintenance activities can be focussed and more cost effective. This often results in a significant reduction in the amount of inspection activities required, and may result in cost reductions.

Although RBI is based on sound, proven risk assessment and management principles, it will not compensate for:

- Inaccurate or missing information
- Inadequate designs or faulty equipment installation
- Operating outside the acceptable design envelope
- Not effectively executing the plans
- Lack of qualified personnel or teamwork
- Lack of sound engineering or operational judgement

The RBI process is focussed on maintaining the mechanical integrity of the pressure envelope and minimising the risk of loss of containment due to deterioration. Utilisation of RBI provides a vehicle for continuously improving the inspection of facilities and systematically reducing the risk associated with pressure boundary failures. As new data (such as inspection results) becomes available or when changes occur, the RBI programme should be reassessed to provide a refreshed view of the risks, and to adjust the management plan accordingly.

Although the risk management principles and concepts that RBI is built on are universally applicable, API RP 580 is specifically targeted at the application of RBI in the hydrocarbon and chemical process industry. Many types of RBI methods exist and are currently being applied throughout industry. API 580 is not intended to single out any one specific approach as the recommended method for conducting an RBI study, but is intended to clarify the elements required of a thorough RBI analysis.

The types of pressurised equipment and associated components / internals covered by API RP 580 include:

- Pressure vessels – all pressure containing components
- Process piping – pipe and piping components
- Storage tanks – atmospheric and pressurised
- Rotating equipment – pressure containing components
- Boilers and heaters – pressurised components
- Heat exchangers (shells, heads, channels and bundles)
- Pressure relief devices

The following non-pressurized equipment is **not** covered by the document:

- Instrument and control systems
- Electrical systems
- Structural systems
- Machinery components (except pump and compressor casings).

*The primary target audience for RP 580 is inspection and engineering personnel who are responsible for the mechanical integrity and operability of the above equipment. However, RBI is not exclusively an inspection activity, and requires the involvement of various segments of the organisation such as engineering, maintenance and operations departments. **It must be stressed that RBI requires the commitment and co-operation of the total organisation!***

2 Basic Concepts

2.1 What is Risk?

Risk is something that we as individuals live with on a day-to-day basis. Statistics show us that:

- 1 in 1.1M die from gas poisoning / explosion per year
- 1 in 1M deaths from vaccination
- 1 in 25 000 deaths associated with anaesthesia
- 1 in 13 000 deaths associated with pregnancy
- 1 in 10 200 people die in road accidents each year
- 1 in 990 people die in oil and gas accidents each year
- 1 in 750 deep sea fishermen die each year

Knowingly or unknowingly, people are constantly making decisions based on risk. Simple decisions such as driving to work or walking across a busy street involve risk. More important decisions such as buying a house, investing money and getting married all imply an acceptance of risk. Life is not risk-free and even the most cautious, risk-averse individuals inherently take risks.

For example, in driving a car, people accept the probability that they could be killed or seriously injured. The reason this risk is accepted is that people consider the probability of being killed or seriously injured to be sufficiently low as to make the risk acceptable. Influencing the decision are the type of car, the safety features installed, traffic volume and speed, and other factors such as the availability, risks and affordability of other alternatives.

Risk is the combination of the probability of some event occurring during a time period of interest, and the consequences associated with the event. In mathematical terms, risk can be expressed by the equation:

$$\text{Risk} = \text{Probability} \times \text{Consequence}$$

2.2 Risk Management

It may seem that risk management and risk reduction are synonymous, however, risk reduction is only part of risk management. Risk reduction is the act of mitigating a known risk to a lower level of risk. 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. By using risk management, some risks may be identified as acceptable so that no risk reduction (mitigation) is required.

The complexity of risk calculations is a function of the number of factors that can affect the risk. Calculating absolute risk can be very time and cost consuming and often, due to having too many uncertainties, is impossible. RBI is focused on a systematic determination of relative risks. In this way, facilities, units, systems, equipment or components can be ranked based on relative risk. This serves to focus the risk management efforts on the higher ranked risks.

2.3 The Evolution of Inspection Intervals

In process plants, inspection and testing programmes are established to detect and evaluate deterioration due to in-service operation. The effectiveness of inspection programmes varies widely, ranging from reactive programmes, which concentrate on known areas of concern, to broad proactive programmes covering a variety of equipment. One extreme of this would be the 'don't fix it unless it's broken' approach. The other extreme would be complete inspection of all equipment items on a frequent basis.

Setting the intervals between inspections has evolved over time. With the need to periodically verify equipment integrity, organisations initially resorted to time-based or 'calendar-based' intervals. Advances in inspection approaches and better understanding of the type and rate of deterioration, led to inspection intervals becoming more dependent on equipment condition rather than an arbitrary calendar date.

Codes and standards such as API 510, 570 and 653 evolved to an inspection philosophy with elements such as:

- Inspection intervals based on some percentage of equipment life (such as half life)
- On-stream inspection in lieu of internal inspection based on low deterioration rates
- Internal inspection requirements for deterioration mechanisms related to environment induced cracking
- Consequence based inspection intervals

RBI represents the next generation of inspection approaches and interval setting, recognising that the ultimate goal of inspection is the safety and reliability of operating facilities. RBI, as a risk-based approach, focuses attention specifically on the equipment and associated deterioration mechanisms representing the most risk to the facility. In focussing on risks and their mitigation, RBI provides a better linkage between the mechanisms that lead to equipment failure and the inspection approaches that will effectively reduce the associated risks.

2.4 Inspection Optimisation

Figure 1 presents stylised curves showing the reduction in risk that can be expected when the degree and frequency of inspection are increased. The upper curve in Fig. 1 represents a typical inspection programme. Where there is no inspection, there may be a higher level of risk, as indicated on the y-axis. As inspection is increased, risk is significantly reduced, until a point is reached where additional inspection activity begins to show a diminishing return. If excessive inspection is applied, the level of risk may even go up (represented by the dotted line at the end of the upper curve). This is because invasive inspections in certain cases may cause additional deterioration, eg moisture ingress in equipment with polythionic acid; inspection damage to protective linings.

The key to developing an optimised inspection procedure is the ability to assess the risk associated with each item of equipment, and then to determine the most appropriate inspection techniques for that piece of equipment. This is illustrated by the lower curve in Fig. 1, indicating that with the application of an effective RBI programme, lower risks can be achieved with the same level of inspection activity. This is because, through RBI, inspection activities are focussed on higher risk items and away from lower risk items.

As shown in Figure 1, risk cannot be reduced to zero solely by inspection efforts. The residual risk factors for loss of containment include, but are not limited to, the following:

- Human error
- Natural disasters
- External events (eg collisions or falling objects)
- Secondary effects from nearby units
- Consequential effects from associated equipment in the same unit
- Deliberate acts (eg sabotage)
- Fundamental limitations of inspection method
- Design errors
- Unknown mechanisms of deterioration

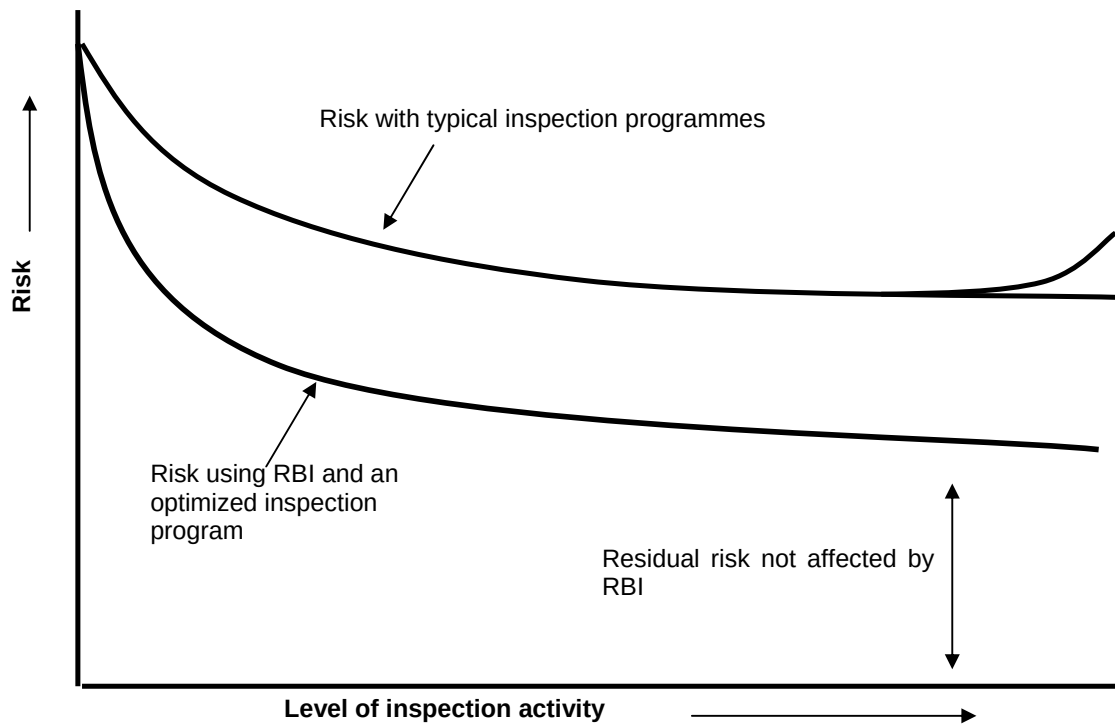


Figure 1 Management of Risk using RBI.

3 Introduction to Risk-Based Inspection

3.1 Consequence and Probability for Risk-Based Inspection

The objective of RBI is to determine what incident could occur (consequence) in the event of an equipment failure, and how likely (probability) is it that the incident could happen. Combining the probability of an event with its consequences will determine the risk to the operation. Some failures may occur relatively frequently without significant adverse safety, environmental or economic impacts. Similarly, some failures have potentially serious consequences, but if the probability of the incident is low, then the risk may not warrant immediate action. However, if the probability and consequence combination (risk) is high enough to be unacceptable, then a mitigation action to predict or prevent the event is recommended.

Some of the possible consequences are:

- Form a vapour cloud that could ignite causing injury and equipment damage
- Release of a toxic chemical that could cause health problems
- Result in a spill and cause environmental deterioration
- Force a unit shutdown and have an adverse economic impact
- Have minimal safety, health, environmental and/or economic impact

Traditionally, organisations have focussed solely on the consequences of failure or on the probability without systematic efforts tying the two together. Only by considering both factors can effective risk-based decision making take place.

3.2 Types of RBI Assessment

Various types of RBI assessment may be conducted at several levels. The RBI procedure can be applied qualitatively, quantitatively or by using aspects of both (ie semi-quantitatively). Use of expert opinion will typically be included in most risk assessments regardless of type or level.

The choice of approach is dependent on multiple variables such as:

- Objective of the study
- Number of facilities and equipment items to study
- Available resources
- Study time frame
- Complexity of facilities and processes
- Nature and quality of available data

3.2.1 Qualitative Approach

This approach requires data inputs based on descriptive information using engineering judgement and experience as the basis for the analysis of probability and consequence of failure. Results are typically given in qualitative terms such as high, medium and low, although numerical values may 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 the results from a qualitative analysis is dependent on the background and expertise of the analysts.

3.2.2 Quantitative Approach

Quantitative risk analysis uses logic models depicting combinations of events that could result in severe accidents, and physical models depicting the progression of accidents and the transport of a hazardous material to the environment. The models are evaluated probabilistically to provide both qualitative and quantitative insights about the level of risk, and to identify the design, site, or operational characteristics that are the most important to risk. Quantitative risk analysis is distinguished from the qualitative approach by the depth of analysis and the integration of detailed assessments. Results using this approach are typically presented as risk numbers (eg cost per year).

3.2.3 Semi-quantitative Approach

Semi-quantitative is a term that describes any approach that has aspects derived from both the qualitative and quantitative approaches. It has the advantage of securing the major benefits of the previous two approaches (eg speed of the qualitative and rigour of the quantitative). Typically, most of the data used in a quantitative approach is needed for this approach but in less detail. The results are usually given in consequence and probability categories rather than 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.

3.2.4 Continuum of Approaches

In practice, a RBI study typically uses aspects qualitative, quantitative and semi-quantitative approaches. These RBI approaches are not considered as competing but rather as complementary. For example, a high level qualitative approach could be used at a unit level to find the unit within a facility that constitutes the highest risk. Systems and equipment within the unit may then be screened using a qualitative approach, with a more quantitative approach used for the higher risk items.

The three approaches are considered to be a continuum with qualitative and quantitative approaches being the extremes of the continuum and everything in between being a semi-quantitative approach, as illustrated in Figure 2.

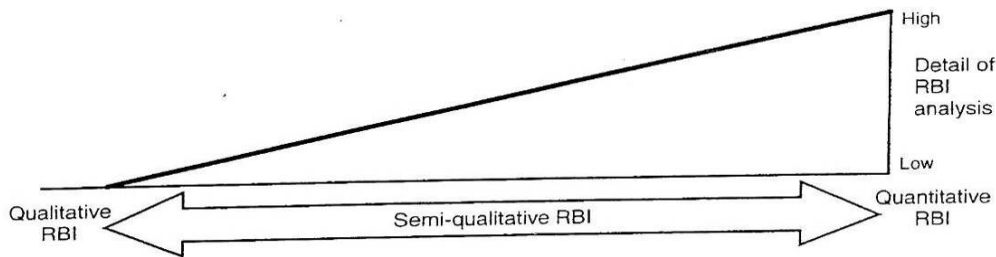


Figure 2 Continuum of RBI approaches

3.2.5 Quantitative Risk Assessment (QRA)

Quantitative Risk Assessment (QRA) is a traditional type of risk analysis that has been applied at many different types of industrial facilities. The QRA is generally comprised of five tasks:

- Systems identification
- Hazards identification
- Probability assessment
- Consequence analysis
- Risk results

A RBI analysis shares many of the techniques and data requirements with a QRA. However, hazard identification in a RBI analysis generally focuses on identifiable failure mechanisms in the equipment (inspectable causes) but does not explicitly deal with other potential failure scenarios resulting from events such as power failures or human errors. A QRA deals with total risk, not just risk associated with equipment deterioration. The QRA typically involves a much more detailed evaluation than a RBI analysis

3.3 Precision vs. Accuracy

It should be noted that when risk is presented as a precise numeric value (as in a quantitative analysis) it implies a greater level of accuracy when compared to a risk matrix, which may not be true in practice. This is because there is an element of uncertainty that is inherent with the assessment of probabilities and consequences. The accuracy of the output is a function of the methodology used as well as the quantity and quality of the data available. The basis for predicted damage and rates, the level of confidence in inspection data and the technique used to perform the inspection are all factors that should be considered. In practice, there are often many extraneous factors that will affect the damage

rate (probability) as well as the magnitude of failure (consequence) that cannot be fully taken into account with a fixed model.

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

3.4 Management of Risks

In performing an RBI assessment, the susceptibility of equipment to deterioration by one or more mechanisms (eg corrosion, fatigue and cracking) is established. The susceptibility of each equipment item should be clearly defined for the current operating conditions including such factors as:

- Process fluid, contaminants and aggressive components
- Unit throughput
- Desired unit run length between scheduled shutdowns
- Operating conditions, including upset conditions: eg pressures, temperatures, flow rates, pressure and/or temperature cycling

The suitability and current condition of the equipment within the current operating envelope will determine the probability of failure (POF) of the equipment from one or more deterioration mechanisms. This probability, when coupled with the associated consequence of failure (COF) will determine the operating risk associated with the equipment item, and therefore the need for mitigation, if any, such as inspection, metallurgy change or change in operating conditions.

Inspection influences the uncertainty of the risk associated with pressure equipment primarily by improving knowledge of the deterioration state and predictability of the probability of failure. Although inspection does not reduce risk directly, it is a risk management activity that may lead to risk reduction.

The primary product from a RBI analysis should be an inspection plan for each item of equipment evaluated. The plan should describe the type, scope and timing of the inspection / examination recommended, while ranking of the equipment by risk level allows the user to assign priorities to the various inspection tasks.

It is recognised that some risks cannot be adequately managed by inspection alone. Examples are:

- Equipment nearing retirement
- Failure mechanisms (such as brittle fracture, fatigue) where avoidance of failure primarily depends on operating within a defined pressure / temperature envelope
- Consequence-dominated risks

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

3.5 Relationship with Jurisdictional Requirements

Codes and legal requirements vary from one jurisdiction to another. In some cases, jurisdictional requirements mandate specific actions such as the type of inspections and intervals between inspections. In jurisdictions that permit the application of the API inspection codes and standards, RBI should be an acceptable method for setting inspection plans.

It is recommended that all users review their jurisdictional code and legal requirements for acceptability of using RBI for inspection and planning purposes.

4 Planning the RBI Assessment

4.1 Getting Started and Establishing Objectives and Goals of a RBI Assessment

It is helpful if boundary limits are identified up front to determine what is vital to include in the assessment. The organising process of aligning priorities, screening risks, and identifying boundaries improves the efficiency and effectiveness of conducting the assessment and its end-results in managing risk.

A RBI assessment is a team-based process. At the beginning of the exercise it is important to define:

- Why the assessment is being done
- How the RBI assessment will be carried out
- What knowledge and skills are required for the assessment
- Who is on the RBI team
- What are their roles in the RBI process
- Who is responsible and accountable for what actions
- Which facilities, assets, and components will be included
- What data is to be used in the assessment
- What codes and standards are applicable
- When the assessment will be completed
- How long the assessment will remain in effect and when it will be updated
- How the results will be used

This should be undertaken with clear objectives and goals that are fully understood by all members of the RBI team and by management.

An objective could be to better understand the risks involved in the operation of a plant or process unit, and to understand the effects that inspection, maintenance and mitigation actions have on the risks. In this way, an inspection programme may be designed that optimises the use of inspection and maintenance resources.

Reducing inspection costs is usually not the primary objective of a RBI assessment, but it is frequently a side effect of optimisation, leading to the following benefits:

- Ineffective, unnecessary or inappropriate inspection activities may be eliminated
- Inspection of low risk items may be eliminated or reduced
- On-line or non-invasive inspection methods may be substituted for invasive methods that require equipment shutdown
- More effective infrequent inspections may be substituted for less effective frequent inspections

The data within the RBI assessment can be useful in determining the optimum economic strategy to reduce risk. The strategy may be different at different times in a plant's lifecycle. For example, it is usually more economical to modify the process or change metallurgy when a plant is being designed than when it is operating. A RBI assessment made on new equipment or a new project, while in the design stage, may yield important information on potential risks. This may allow the risks to be minimised by design, prior to actual installation.

Facilities approaching the end of their economic or operating service life are a special case where application of RBI can be very useful. The end of life case for plant operation is about gaining the maximum remaining economic benefit from an asset without undue personnel, environmental or financial risk. Inspection efforts are focussed directly on high-risk areas where the inspections will provide a reduction of risk during the remaining life of the plant. End of life inspection RBI strategies may be developed in association with a fitness for service assessment of damaged components using methods described in API RP 579.

4.2 Initial Screening

Boundaries for physical assets included in the assessment are established, which are consistent with the overall objectives. The screening process is important in centring the focus on the most important

physical assets so that time and resources are effectively applied. The scope of a RBI assessment may vary between an entire refinery or plant and a single component within a single piece of equipment. Typically, RBI is done on multiple pieces of equipment (eg an entire process unit) rather than on a single component.

If the scope of the RBI assessment is a multi-unit facility, then 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.

It is often advantageous to group equipment within a process unit into systems 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 most plants, a large percentage of the total unit risk will be concentrated in a relatively small percentage of the equipment items. Statistically, this is known as the 'Pareto' or 80/20 principle, where roughly 20% of the equipment is generally found to constitute 80% of the risk! These potential high-risk items should receive greater attention in the risk assessment.

4.3 Establish Operating Boundaries

The purpose of establishing operational boundaries is to identify key process parameters that may impact on deterioration. The RBI assessment normally includes review of both POF and COF for normal operating conditions. However, start-up and shutdown conditions as well as emergency conditions should also be reviewed for their potential effect on POF and COF. 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. A good example is polythionic acid stress corrosion cracking.

Operating within the boundaries is critical to the validity of the RBI study as well as good operating practice. The following data should be provided:

- Operating temperature and pressure including variation ranges
- Process fluid composition including variation with feed composition ranges
- Flow rates including variation ranges
- Presence of moisture or other contaminant species

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

The essential elements of inspection planning based on risk analysis from the RBI process are depicted in the simplified block diagram shown in Figure 3.

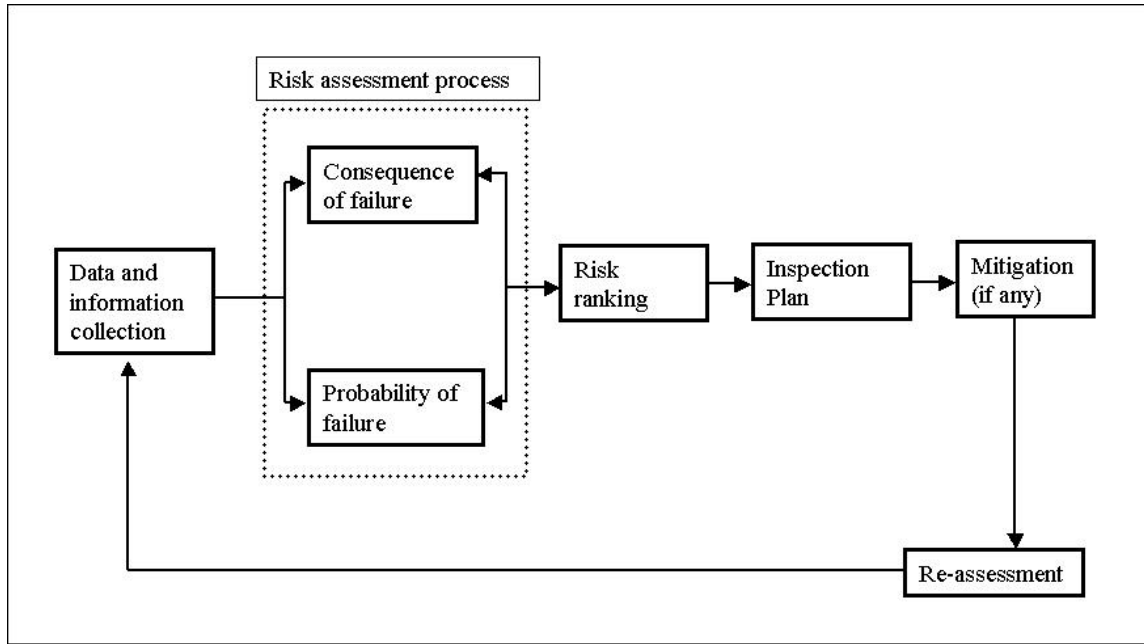


Figure 3 Risk-based inspection planning process.

5 Data and Information Collection for RBI Assessment

5.1 RBI Data Needs

A RBI study may use a qualitative, semi-quantitative and/or quantitative approach, the fundamental difference being the amount and detail of input, calculations and output. For each RBI approach it is important to document all bases for the study and assumptions from the outset, and to apply a consistent rationale. Typical data needed for a RBI analysis may include but is not limited to:

- Type of equipment
- Materials of construction
- Inspection, repair and replacement records
- Process fluid compositions
- Inventory of fluids
- Operating conditions
- Safety systems
- Detection systems
- Deterioration mechanisms, rates and severity
- Personnel densities
- Coating, cladding and insulation data
- Business interruption costs
- Equipment replacement costs
- Environmental remediation costs

For a qualitative approach, it is important to establish a set of rules to assure consistency in categorisation or classification. Generally, a qualitative analysis using broad ranges requires a higher level of judgement, skill and understanding from the user than a quantitative approach. Therefore, despite its simplicity, it is important to have knowledgeable and skilled persons perform the qualitative RBI analysis.

Quantitative risk analysis uses logic models which are evaluated probabilistically to identify the design, site, or operational characteristics that are the most important to risk. Hence, more detailed information and data are needed for quantitative RBI in order to provide input for the models.

The semi-quantitative analysis typically requires the same data as a quantitative analysis but generally not as detailed. For example, the fluid volumes may be estimated. Although the precision of the analysis may be less, the time required for data gathering and analysis will also be less.

5.2 Data Quality

The data quality has a direct relation to the relative accuracy of the RBI analysis. It is beneficial to the integrity of a RBI analysis to assure that the data are up to date and validated by knowledgeable persons. Typical problems encountered during data validation are outdated drawings and documentation, inspector error, clerical error, and measurement equipment accuracy. Another potential source of error in the analysis is assumptions on equipment history. For example, if baseline inspections were not performed or documented, nominal thickness may be used for the original thickness. This assumption can significantly impact the calculated corrosion rate early in the equipment's life, and may either mask a high corrosion rate or inflate a low corrosion rate.

This validation step stresses the need for a knowledgeable individual comparing data from the inspections to the expected deterioration mechanisms and rates.

5.3 Sources of Site Specific Data and Information

Specific potential sources of information include but are not limited to:

Design and Construction Records/Drawings

- P&IDs, PFDs, MFDs, etc.
- Piping isometric drawings
- Engineering specification sheets

- Materials of construction records
- Construction QA/QC records
- Codes & standards used
- Protective instrument systems
- Leak detection and monitoring systems
- Isolation systems
- Inventory records
- Emergency depressurising and relief systems
- Safety systems
- Fire-proofing and fire fighting systems
- Layout

Inspection Records

- Schedules and frequency
- Amount and types of inspection
- Repairs and alterations
- PMI records
- Inspection results

Process Data

- Fluid composition analysis including contaminants or trace components
- Distributed control system data
- Operating procedures
- Start-up and shut-down procedures
- Emergency procedures
- Operating logs and process records

Management of Change (MOC) Records

Failure Data

- Generic failure frequency data – industry or in-house
- Industry specific failure data
- Plant and equipment specific failure data
- Reliability and condition monitoring records
- Leak data

Site Conditions

- Climate/weather records
- Seismic activity records

6 Identifying Deterioration Mechanisms and Failure Modes

Identification of the appropriate deterioration mechanisms, susceptibilities and failure modes for all equipment included in a RBI study is essential to the quality and the effectiveness of the RBI evaluation. The deterioration mechanisms, rates and susceptibilities are the primary inputs into the probability of failure evaluation.

The failure mode is a key input in determining the consequence of failure, where failure is defined as loss of containment caused by deterioration. The term failure mode is defined as the manner of failure, and can range from a small hole to a complete rupture.

6.1 Deterioration Mechanisms

The term deterioration mechanism is defined as the type of deterioration that could lead to a loss of containment. There are four such major mechanisms observed in the hydrocarbon and chemical process industry:

- Thinning (includes internal and external)
- Stress corrosion cracking
- Metallurgical and environmental
- Mechanical

Understanding equipment operation and the interaction with the chemical and mechanical environment is key to performing deterioration mechanism identification.

Appendix A to RP 580 provides tables describing the individual deterioration mechanisms covered by these four categories, the key variables driving deterioration, and typical process industry examples of where they may occur. These tables cover most of the common deterioration mechanisms, but a more comprehensive and detailed coverage is to be found in API RP 571 *Damage Mechanisms Affecting Fixed Equipment in the Refining Industry*.

6.1.1 Thinning

Thinning includes general corrosion, localised corrosion, pitting, and other mechanisms that cause loss of material from internal or external surfaces.

6.1.2 Stress Corrosion Cracking

Stress corrosion cracking (SCC) occurs when equipment is exposed to environments conducive to certain cracking mechanisms such as caustic cracking, amine cracking, sulphide stress cracking (SSC), hydrogen-induced cracking (HIC), stress-oriented hydrogen-induced cracking (SOHIC), carbonate cracking, polythionic acid cracking (PTA), and chloride cracking (CISCC). Literature, expert opinion and experience are often necessary to establish susceptibility of equipment to stress corrosion cracking.

Susceptibility is often designated as high, medium or low, and evaluation should not only consider susceptibility of the equipment / piping to cracking (or probability of initiating a crack), but also the probability of a crack resulting in a leak or rupture.

6.1.3 Metallurgical and Environmental Deterioration of Properties

Causes of metallurgical and environmental failure are varied but typically involve some form of mechanical and / or physical property deterioration of the material due to exposure to the process environment. One example of this is high-temperature hydrogen attack (HTHA), which occurs in carbon and low alloy steels exposed to high partial pressures of hydrogen at elevated temperatures. Historically, HTHA resistance or susceptibility has been predicted based on industry experience that has been plotted on a series of curves commonly referred to as the Nelson curves. These are updated periodically in the light of industry experience, and are published in API RP 941 *Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants*.

6.1.4 Mechanical

The most common mechanical deterioration mechanisms are fatigue (mechanical, thermal and corrosion), stress / creep rupture, and tensile overload.

6.2 Other Failures

RBI could be expanded to include failures other than loss of containment, typical examples are:

- Pressure relief device failure – plugging, fouling, non-activation
- Heat exchanger bundle failure – tube leak, plugging
- Pump failure – seal failure, motor failure, rotating parts damage
- Internal linings – hole, disbondment.

7 Assessing Probability of Failure

The probability of failure analysis should address all deterioration mechanisms to which the equipment being studied is susceptible. Further, it should address the situation where equipment is susceptible to multiple deterioration mechanisms (eg thinning and creep). The analysis should be credible, repeatable and well documented.

Probability of failure is typically expressed in terms of frequency, which in turn is expressed as a number of events occurring during a specific time frame. For a qualitative analysis, the probability of failure may be categorised (eg high, medium and low, or 1 through 5). However, even in this case, it is appropriate to associate an event frequency with each probability category to provide guidance to the individuals who are responsible for determining the probability, (eg high = 1 failure per year).

7.1 Qualitative Probability of Failure Analysis

A qualitative method involves identification of the units, systems or equipment, the materials of construction and the corrosive components of the processes. On the basis of knowledge of the operating history, future inspection and maintenance plans and possible materials deterioration, probability of failure can be assessed separately for each unit, system, equipment grouping or individual equipment item. Engineering judgement is the basis for this assessment.

7.2 Quantitative Probability of Failure Analysis

There are several approaches to a quantitative probability analysis. One example is to take a probabilistic approach where specific failure data or expert solicitations are used to calculate a probability of failure.

7.3 Determination of Probability of Failure

Regardless of which type of analysis is used, the probability of failure is determined by two main considerations:

- Deterioration mechanisms and rates of the material of construction, resulting from its operating environment (internal and external).
- Effectiveness of the inspection programme to identify and monitor the deterioration mechanisms so that the equipment can be repaired or replaced prior to the failure.

Analyzing the effect of in-service deterioration and inspection on the probability of failure involves the following steps:

- Identify active and credible deterioration mechanisms that are reasonably expected to occur during the time period being considered (due to normal and upset conditions).
- Determine the deterioration susceptibility and deterioration rate.
- Quantify the effectiveness of the past inspection and maintenance programme and a proposed future inspection and maintenance programme.
- 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 failure mode (eg small leak, large leak, equipment rupture) should also be determined based on the deterioration mechanism.

7.3.1 Determine the Deterioration Susceptibility and Rate

Deterioration rate can be expressed in terms of corrosion rate for thinning or susceptibility for mechanisms where the deterioration rate is unknown or immeasurable (such as stress corrosion cracking). Susceptibility is often designated as high, medium or low based on the environmental conditions and material of construction combination.

The deterioration rate in specific process equipment is often not known with certainty. Sources of deterioration rate information include:

- Published data
- Laboratory testing
- In-situ testing and in-service monitoring
- Experience with similar equipment
- Previous inspection data

The best information will come from operating experiences where the conditions that led to the observed deterioration rate could realistically be expected to occur in the equipment under consideration. Other sources of information could include databases of plant experience or reliance on expert opinion.

7.3.2 Determine Failure Mode

Failure mode primarily affects the magnitude of the consequences. It is important to link the deterioration mechanism to the most likely resulting failure mode. For example:

- Pitting generally leads to small hole-sized leaks
- Stress corrosion cracking can develop into small, through wall cracks, or in some cases, catastrophic rupture
- Metallurgical deterioration and mechanical deterioration can lead to failure modes that vary from small holes to ruptures
- General thinning from corrosion often leads to larger leaks or rupture.

7.3.3 Quantify Effectiveness of Past Inspection Programme

After the likely deterioration mechanisms have been identified, the inspection programme should be evaluated to determine the effectiveness in finding the identified mechanisms. Limitations in the effectiveness of an inspection programme could be due to:

- Lack of coverage of an area subject to deterioration
- Inherent limitations on some inspection methods to detect and quantify certain types of deterioration
- Selection of inappropriate inspection methods and tools
- Application of methods and tools by inadequately trained inspection personnel
- Inadequate inspection procedures.
- Deterioration rate under some extremes of conditions is so high that failure can occur within a very short time.

7.3.4 Calculate the Probability of Failure by Deterioration Type

By combining the expected deterioration mechanism, rate or susceptibility, inspection data and inspection effectiveness, a probability of failure can now be determined for each deterioration type and failure mode.

8 Assessing Consequences of Failure

The consequence analysis in a RBI programme 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 and credible estimate of what might be expected to happen if a failure were to occur in the equipment item being assessed.

The consequence effects for loss of containment can be generally considered to be in the following categories:

- Safety and health impact
- Environmental impact
- Production losses
- Maintenance and reconstruction costs

8.1 Qualitative Consequences Analysis

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, health, environmental or financial impacts) can be estimated, with consequence categories (such as 'A' through 'E' or 'high', 'medium' or 'low') typically being assigned to each unit, system or grouping of equipment items.

8.2 Quantitative Consequence Analysis

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. The calculations are based on:

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

Results of a quantitative analysis are usually numeric.

8.2.1 Cost as a Measure of Consequence

Cost is commonly used as an indicator of potential consequences. It is possible, although not always credible, to assign costs to almost any type of consequence. Typical consequences that can be expressed in 'cost' include:

- Production loss due to rate reduction or downtime
- Deployment of emergency response equipment and personnel
- Lost product from a release
- Degradation of product quality
- Replacement or repair of damaged equipment
- Property damage offsite
- Spill / release cleanup onsite or offsite
- Business interruption costs (lost profits)
- Loss of market share
- Injuries or fatalities
- Land reclamation
- Litigation
- Fines
- Goodwill

8.2.2 Affected Area as a Measure of Consequence

'Affected area' is also used to describe potential consequences in the field of risk assessment. It represents the amount of surface area that experiences an effect (toxic dose, thermal radiation, explosion overpressure, etc.) greater than a pre-defined limiting value. Based on the thresholds chosen, anything (ie personnel, equipment, environment) within the area will be affected by the consequences of the hazard.

8.3 Volume of Fluid Released

In most consequence evaluations, a key element in determining the magnitude of the consequence is the volume of fluid released. This is typically derived from a combination of the following:

- Volume of fluid available for release – Volume of fluid in the piece of equipment and connected equipment items. In theory, this is the amount of fluid between isolation valves that can be quickly closed
- Failure mode
- Leak rate
- Detection and isolation time

8.4 Consequence Effect Categories

The failure of the pressure boundary and subsequent release of fluids may cause safety, health, environmental, facility and business damage. Regardless of whether a more qualitative or quantitative analysis is used, some of the major safety and health factors to consider in evaluating the consequences of failure are as follows:

8.4.1 Flammable Events (Fire and Explosion)

Flammable events occur when both a leak and ignition happen, and can cause damage in two ways: thermal radiation and blast overpressure. Most of the damage from thermal effects tends to occur at close range, but blast effects can cause damage over a larger distance from the blast centre. The following are typical categories of fire and explosion events:

- Vapour cloud explosion
- Pool fire
- Jet fire
- Flash fire
- Boiling liquid expanding vapour explosion (BLEVE)

The flammable event consequence is typically derived from a combination of the following elements:

- Inherent tendency to ignite
- Volume of fluid released
- Ability to flash to vapour
- Possibility of auto-ignition.
- Effects of higher pressure or higher temperature operations
- Engineering safeguards
- Personnel and equipment exposed to damage

8.4.2 Toxic Releases

Toxic releases in RBI are only addressed when they affect personnel (site and public). These releases can cause effects at greater distances than flammable events, eg Bhopal, India. The toxic consequence is typically derived from the following elements:

- Volume of fluid released and toxicity
- Ability to disperse under typical process and environmental conditions
- Detection and mitigation systems
- Population in the vicinity of the release.

8.4.3 Releases of Other Hazardous Fluids

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

8.4.4 Environmental Consequences

Environmental consequences are an important component to any consideration of overall risk in a processing plant. The RBI programme typically focuses on acute and immediate environmental risks, rather than chronic risks from low-level emissions. The environmental consequence is typically derived from:

- Volume of fluid released
- Ability to flash to vapour
- Leak containment safeguards
- Environmental resources affected
- Regulatory consequence (eg citations for violations, fines, potential shutdown by authorities)

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

9 Risk Determination, Assessment and Management

Risk based inspection is a tool to provide an analysis of the risks of loss of containment of equipment. The use of risk assessment in inspection and maintenance planning is unique in that consequential information, which is traditionally operations-based, and probability of failure information, which is typically engineering / maintenance / 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), and the extent of inspection (coverage).

9.1 Sensitivity Analysis

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. Sensitivity analysis typically involves reviewing some or all input variables to the risk calculation to determine the overall influence on the resultant risk value.

Assumptions or estimates of input values are often used when consequence and / or probability of failure data are not available. Caution is advised in being too conservative in these estimates, as overestimating consequences and / or probability of failure 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!

9.2 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. 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 of a risk matrix is shown in Figure 4.

In this figure, the consequence and probability categories are arranged such that the highest risk ranking is towards the upper right-hand corner. Different sizes of matrices may be used (eg 5 x 5, 4 x 4, 3 x 3 etc.). Risk categories may be assigned to the boxes on the risk matrix. An example risk categorisation (higher, medium, lower) 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.

Equipment items residing towards the upper right-hand corner of the matrix (in the example presented) should take priority for inspection planning because these items have the highest risk. Similarly, items residing towards the lower left-hand corner of the matrix will tend to take lower priority because these items have the lowest risk.

Once the plots have been completed, the risk matrix can then be used as a screening tool during the prioritising process. Based on the ranking of items and the risk threshold, the risk management process begins. For risks that are judged acceptable, no mitigation may be required and no further action necessary.

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

- Decommission.
- Inspection / condition monitoring.
- Consequence mitigation.
- Probability mitigation.

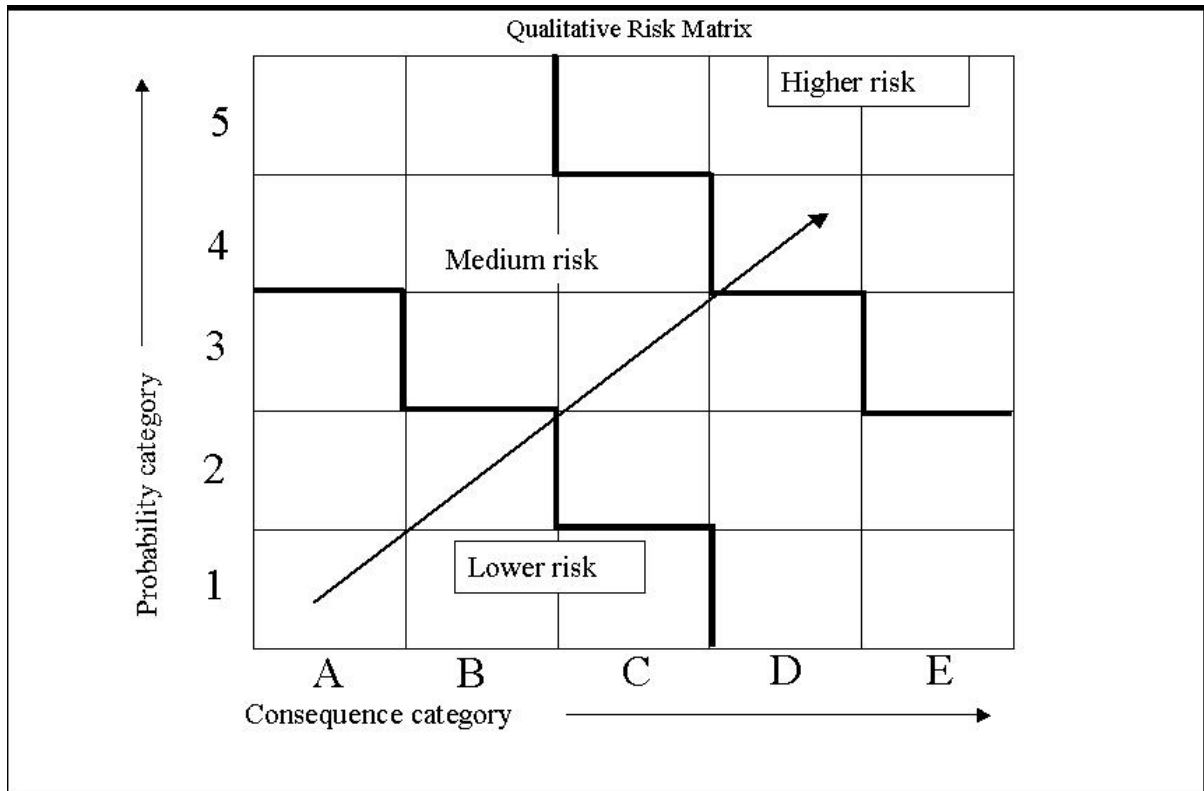


Figure 4 Example risk matrix using probability and consequence categories to display risk rankings

10 Risk Management with Inspection Activities

Inspection does not arrest or mitigate deterioration mechanisms, but serves to identify, monitor and measure them. Correct application of inspections will improve the user's ability to predict the deterioration mechanisms and rates of deterioration. The better the predictability, the less uncertainty there will be as to when a failure may occur, and this translates directly into a reduction in the probability of a failure and therefore a reduction in the risk. It should be noted, however, that risk mitigation is not achieved if inspection data that are gathered are not properly analysed and acted upon where needed!

10.1 Establishing an Inspection Strategy Based on Risk Assessment

In the situations where risk is being driven by probability of failure, there is usually potential for risk management through inspection. Inspection is only effective as a risk management strategy if the inspection technique chosen is sufficient for detecting the deterioration 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 deterioration mechanism results in unpredictable localised corrosion (eg pitting, ammonia bisulphide corrosion, local thin area, etc). In this case, ultrasonic scanning, radiography, etc. will be more effective.

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

10.2 Managing Risk with Inspection Activities

The effectiveness of past inspections is part of the determination of the present risk. The future risk can now be impacted by future inspection activities. RBI can be used as a 'what if' tool to determine when, what and how inspections should be conducted to yield an acceptable future risk level. Key parameters and examples that can affect the future risk are:

- Frequency of inspection – Increasing the frequency of inspections may serve to better define, identify or monitor the deterioration mechanism(s) and therefore reduce the risk. Both routine and turnaround inspection frequencies can be optimised.
- Coverage – Different zones or areas of inspection of an item or series of items can be modelled and evaluated to determine the coverage that will produce an acceptable level of risk. For example:
 1. A high risk piping system may be a candidate for extensive inspection, using one or more NDE techniques targeted to locate the identified deterioration mechanisms.
 2. 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 look at the rest of the vessel where there are perhaps only low risk deterioration processes occurring.
- Tools and techniques – The selection and usage of the appropriate inspection tools and techniques can be optimised to cost effectively and safely reduce risk. As an example, radiography may be more effective than ultrasonic for thickness monitoring in cases of localised corrosion.
- Procedures and practices – Inspection procedures and the actual inspection practices can impact the ability of inspection activities to identify, measure, and / or monitor deterioration mechanisms. If the inspection activities are executed effectively by well-trained and qualified inspectors, the expected risk management should be obtained. The user is cautioned not to assume that all inspectors and NDE examiners are well qualified and experienced, but rather to take steps to assure that they have the appropriate level of experience and qualifications.
- Internal or external inspection – Risk reductions by both internal 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:
 1. Moisture ingress to equipment leading to SCC or polythionic acid cracking.
 2. Internal inspection of glass lined vessels.
 3. Removal of passivating films.
 4. Human errors in re-streaming.
 5. Risk associated with shutting down and starting up equipment.

10.3 Managing Inspection Costs with RBI

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

Another opportunity for managing inspection costs is by identifying items in the inspection plan that can be inspected non-intrusively on-stream. If the non-intrusive inspection provides sufficient risk management, then there is a potential for a net savings based on not having to blind, open, clean, and internally inspect during downtime.

It should be noted that while there is a potential for reduction of inspection costs through the utilization of RBI, the focus should remain clearly on equipment integrity management and inspection cost optimization.

11 Other Risk Mitigation Activities

Although inspection is often an effective method of risk management, it may not always provide sufficient risk mitigation or may not be the most cost-effective method. Typical situations where risk management through inspection may have little or no effect are:

- Corrosion rates well established and equipment nearing end of life
- Instantaneous failures related to operating conditions such as brittle fracture
- Inspection technology that is not sufficient to detect or quantify deterioration adequately
- Too short a time frame from the onset of deterioration to final failure for periodic inspections to be effective (eg high-cycle fatigue cracking)
- Event-driven failures (circumstances that cannot be predicted)

Alternative risk mitigation activities fall into one or more of the following categories:

- Reduce the magnitude of consequence
- Reduce the probability of failure
- Enhance the survivability of the facility and people to the consequence
- Mitigate the primary source of consequence

Some of the considerations for alternative risk mitigation strategies are outlined below.

11.1 Evaluating Flaws for Fitness-For-Service

When inspection has identified flaws in equipment, a fitness-for-service assessment (eg API RP 579) 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. FFS analysis can also be used to determine the sensitivity of the inspection technique required to confidently identify a specific deterioration mechanism in a specific item of equipment.

11.2 Equipment Modification, Redesign and Re-Rating

When equipment deterioration has reached a point that the risk of failure cannot be managed to an acceptable level, then replacement / repair is often the only way to mitigate the risk. Modification and redesign of equipment can provide mitigation of probability of failure. Examples include:

- Change of metallurgy
- Addition of protective linings and coatings
- Removal of deadlegs
- Increased corrosion allowance
- Physical changes that will help to control / minimise deterioration
- Insulation improvements
- Injection point design changes

11.3 Modify Process

Mitigation of the primary source of consequence may sometimes be possible by changing the process towards less hazardous conditions. Typical examples could be:

- Reduce temperature to below atmospheric pressure boiling point to reduce size of cloud
- Substitute a less hazardous material (eg high flash solvent for a low flash solvent)
- Use a continuous process instead of a batch operation
- Dilute hazardous substances.

11.4 Other Risk Mitigation Actions

Emergency isolation capability can reduce toxic, explosion or fire consequences in the event of a release. Remote operation of isolation valves is usually required to provide significant risk reduction. Emergency depressurizing / de-inventory can reduce the amount and rate of release. Water spray / deluge can reduce fire damage and minimize or prevent escalation.

Water curtains mitigate water soluble vapour clouds by absorption as well as dilution, and insoluble vapours (including most flammables) by air dilution.

Utilizing blast-resistant construction provides mitigation of the damage caused by explosions, and may prevent escalation of the incident.

Other factors include spill detectors, fireproofing, instrumentation (interlocks, shut-down systems, alarms, etc.), piping redesign, mechanical flow restriction, ignition source control.

11.5 Reduce Inventory

Reducing the inventory can reduce the magnitude of consequence. Some examples are:

- Reduce / eliminate storage of hazardous feed-stocks or intermediate products
- Modify process control to permit a reduction in inventory contained in surge drums, reflux drums or other in-process inventories
- Select process operations that require less inventory / hold-up
- Substitute gas phase technology for liquid phase.

12 Reassessment and Updating RBI Assessments

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 should be updated.

It is important to maintain and update a RBI programme to assure 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 can trigger the need to perform a reassessment.

12.1 Why Conduct a RBI Reassessment?

There are several events that will change risks and make it prudent to conduct a RBI reassessment. It is important, therefore, that the facility have an effective management of change process that identifies when a reassessment is necessary.

12.1.1 Deterioration Mechanisms and Inspection Activities

Many deterioration mechanisms are time dependent. Typically, the RBI assessment will project deterioration at a continuous rate. In reality, the deterioration rate may vary over time. Through inspection activities, the average rates of deterioration may be better defined.

Some deterioration mechanisms are independent of time (ie they occur only when there are specific conditions present). These conditions may not have been predicted in the original assessment but may have subsequently occurred.

Inspection activities will increase information on the condition of the equipment, and when they have been performed, the results should be reviewed to determine if a RBI reassessment is necessary.

12.1.2 Process and Hardware Changes

Changes in process conditions and hardware changes, 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.

Hardware changes can also have an effect on risk, for example:

- The probability of failure 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.
- The consequence of failure can be affected by the relocation of a vessel to an area near an ignition source.

12.2 When to Conduct a RBI Reassessment

12.2.1 After Significant Changes

As discussed in 12.1 above, significant changes in risk can occur for a variety of reasons, and qualified personnel should therefore evaluate each significant change to determine the potential for a change in risk.

12.2.2 After a Set Time Period

Although significant major changes may not have occurred, over time, many small changes may occur and cumulatively cause significant changes in the RBI assessment. Users should therefore set default maximum time periods for reassessments. The governing inspection codes (such as API 510, 570 and 653) and jurisdictional regulations should be reviewed in this context.

12.2.3 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.

12.2.4 Before and After Maintenance Turnarounds

As part of the planning before a maintenance turnaround, it could be useful to perform a RBI reassessment to ensure the work effort is focussed on the higher risk equipment items. Since a large amount of inspection, repairs and modifications are performed during a maintenance turnaround; it may be useful to update an assessment after the turnaround to reflect the new risk levels.

13 Roles, Responsibilities, Training and Qualifications

13.1 RBI Team

RBI requires data gathering from many sources, specialised analysis, and then risk management decision-making. Generally, one individual does not have the background or skills to single-handedly conduct the entire study. Usually, a team of people, with the requisite skills and background, is needed to conduct an effective RBI assessment.

A typical RBI team would comprise the following team members on either a full-time or part-time basis:

- **Team Leader:** The team leader should be a full-time team member, and should ideally be a stakeholder in the facility / equipment being analysed. The leader is typically responsible for formation of the team and verifying that the team members have the necessary skills and knowledge; assuring that the study is conducted properly; and following up to ensure that the appropriate risk mitigation actions have been implemented.
- **Equipment Inspector or Inspection Specialist:** The inspector is generally responsible for gathering data on the condition and history of equipment in the study. This condition data should include the new / design condition and the current condition.
- **Materials and Corrosion Specialist:** The materials and corrosion specialist is responsible for assessing the types of deterioration mechanisms and their applicability and severity to the equipment, considering the process conditions, environment, metallurgy, age, etc, of the equipment.
- **Process Specialist:** The process specialist is responsible for the provision of process condition information. This information generally will be in the form of process flow sheets. The process specialist is responsible for documenting variations in the process conditions due to normal occurrences (such as start-ups and shutdowns) and abnormal occurrence.
- **Operations and Maintenance Personnel:** Operations and Maintenance personnel are responsible for verifying that the facility / equipment is being operated within the parameters set out in the process operating envelope. They are responsible for providing data on occurrences when the process deviated from the limits of the process operating envelope.
- **Management:** Management's role is to provide sponsorship and resources (personnel and funding) for the RBI study. They are responsible for making decisions on risk management or providing the framework / mechanism for others to make these decisions based on the results of the RBI study.
- **Risk Assessment Personnel:** This person(s) should be a resource to the team, and is responsible for assembling all of the data and carrying out the RBI analysis. These activities are typically:
 1. Defining data needed from other team members.
 2. Defining accuracy levels for the data.
 3. Verifying through quality checks the soundness of data and assumptions.
 4. Inputting / transferring data into the computer programme and running the programme (if one is used).
 5. Quality control of data input / output.
 6. Manually calculating the parameters of risk (if a computer programme is not used).
 7. Displaying the results in an understandable way and preparing appropriate reports on the RBI analysis.

13.2 Training and Qualifications for RBI Application

13.2.1 Risk Assessment Personnel

This person should have a thorough understanding of risk analysis either by education, training, or experience. He / she should have received detailed training on the RBI methodology and on the procedures being used for the RBI study so that he / she understands how the programme operates and the vital issues that affect the final results.

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

13.2.2 Other Team Members

The other team members should receive basic training on RBI methodology and on the programme(s) being used. This training should be geared primarily to an understanding and effective application of RBI. The training could be provided by the risk assessment personnel on the RBI Team or by another person knowledgeable on RBI methodology and on the programmes being used.

14 RBI Documentation and Record-keeping

It is important that sufficient information is captured to fully document the RBI assessment. Ideally, sufficient data should 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 computerised 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 time frame.

14.1 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 consequences of failure should be documented. If a specific software programme is used to perform the assessment, this also should be documented and maintained. The documentation should be sufficiently complete so that the basis and the logic for the decision making process can be checked or replicated at a later time.

14.2 RBI Personnel

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

14.3 Time Frame

The level of risk is usually a function of time. Therefore, the time frame over which the RBI analysis is applicable should be defined and captured in the final documentation.

14.4 Assignment of Risk

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

- Basic equipment data and inspection history critical to the assessment, eg operating conditions, materials of construction, service exposure, corrosion rate, inspection history, etc.
- Operative and credible deterioration mechanisms
- Criteria used to judge the severity of each deterioration mechanism
- Anticipated failure mode(s) (eg leak or rupture)
- Key factors used to judge the severity of each failure mode
- Criteria used to evaluate the various consequence categories, including safety, health, environmental and financial
- Risk criteria used to evaluate the acceptability of the risks

14.5 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 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.

14.6 Risk Assessment Results

The probability, consequence and risk results should be captured in the documentation.

14.7 Mitigation and Follow-up

One of the most important aspects of managing risk through RBI is the development and use of mitigation strategies. Therefore, the specific risk mitigation required to reduce either probability or

consequence should be documented in the 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.

14.8 Codes, Standards and Government Regulations

Since various codes, standards and governmental regulations cover the inspection of 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.

Appendix A

Deterioration Mechanisms

Table 1—Thinning

Deterioration Mechanism	Description	Behavior	Key Variables	Examples
Hydrochloric Acid Corrosion	Typically causes localized corrosion in carbon and low alloy steel, particularly at initial condensation points (< 400°F). Austenitic stainless steels experience pitting and crevice corrosion. Nickel alloys can corrode under oxidizing conditions.	Localized	Acid %, pH, materials of construction, temperature	Crude unit atmospheric column overhead, Hydrotreating effluent trains, Catalytic reforming effluent and regeneration systems.
Galvanic Corrosion	Occurs when two metals are joined and exposed to an electrolyte.	Localized	Joined materials of construction, distance in galvanic series	Seawater and some cooling water services.
Ammonia Bisulfide Corrosion	Highly localized metal loss due to erosion corrosion in carbon steel and admiralty brass.	Localized	NH ₄ HS % in water (Kp), velocity, pH	Formed by thermal or catalytic cracking in hydrotreating, hydrocracking, coking, catalytic cracking, amine treating and sour water effluent and gas separation systems.
Carbon Dioxide (Carbonic Acid) Corrosion	Carbon dioxide is a weakly acidic gas which is corrosive when dissolved in water becoming carbonic acid (H ₂ CO ₃). CO ₂ is commonly found in upstream sections before treatment. Aqueous CO ₂ corrosion of carbon and low alloy steels is an electrochemical process involving the anodic dissolution of iron and the cathodic evolution of hydrogen. The reactions are often accompanied by the formation of films of FeCO ₃ (and/or Fe ₃ O ₄) that can be protective or non-protective depending on the conditions.	Localized	Carbon dioxide concentration, process conditions.	Refinery steam condensate system, hydrogen plant and the vapor recovery section of catalytic cracking unit.
Sulfuric Acid Corrosion	Very strong acid that causes metal loss in various materials and depends on many factors.	Localized	Acid %, pH, material of construction, temperature, velocity, oxidants	Sulfuric acid alkylation units, demineralized water.
Hydrofluoric Acid Corrosion	Very strong acid that causes metal loss in various materials.	Localized	Acid %, pH, material of construction, temperature, velocity, oxidants	Hydrofluoric acid alkylation units, demineralized water.
Phosphoric Acid Corrosion	Weak acid that causes metal loss. Generally added for biological corrosion inhibition in water treatment.	Localized	Acid %, pH, material of construction, temperature	Water treatment plants.
Phenol (carbolic acid) Corrosion	Weak organic acid causing corrosion and metal loss in various alloys.	Localized	Acid %, pH, material of construction, temperature	Heavy oil and dewaxing plants.
Amine Corrosion	Used in gas treatment to remove dissolved CO ₂ and H ₂ S acid gases. Corrosion generally caused by desorbed acid gases or amine deterioration products.	General at low velocities, localized at high velocities	Amine type and concentration, material of construction, temperature, acid gas loading, velocity	Amine gas treating units.
Atmospheric Corrosion	The general corrosion process occurring under atmospheric conditions where carbon steel (Fe) is converted to iron oxide Fe ₂ O ₃ .	General uniform corrosion	Presence of oxygen, temperature range and the availability of water/moisture	This process is readily apparent in high temperature processes where carbon steels have been used without protective coatings (steam piping for example).
Corrosion Under Insulation	CUI is a specific case of atmospheric corrosion where the temperatures and the concentrations of water/moisture can be higher. Often residual/trace corrosive elements can also be leached out of the insulation material itself creating a more corrosive environment.	General to highly localized	Presence of oxygen, temperature range and the availability of water/moisture and corrosive constituents within the insulation.	Insulated piping/vessels.

Table 1—Thinning

Deterioration Mechanism	Description	Behavior	Key Variables	Examples
Soil Corrosion	Metallic structures in contact with soil will corrode.	General to localized	Material of construction, soil characteristics, type of coating.	Tank bottoms, underground piping.
High Temperature Sulfidic Corrosion without H ₂	A corrosive process similar to atmospheric corrosion in the presence of oxygen. In this case the carbon steel (Fe) is converted in the presence of sulfur to iron sulfide (FeS). Conversion rate (and therefore corrosion rate) is dependent on temperature of operation and sulfur concentration.	General uniform corrosion	Sulfur concentration and temperature.	All locations where there is sufficient temperature (450°F minimum) and sulfur is present in quantities greater than 0.2%. Common locations are crude, coker, FCC, and hydroprocessing units.
High Temperature Sulfidic Corrosion with H ₂	With the presence of hydrogen, a significantly more aggressive case of sulfidation (sulfidic corrosion) can exist.	General uniform corrosion	Sulfur and hydrogen concentration and temperature.	All locations where there is sufficient temperature (450°F minimum) and sulfur is present in quantities greater than 0.2%. Areas of hydroprocessing units- reactor feed downstream of the hydrogen mix point, the reactor, the reactor effluent and the recycle hydrogen gas including the exchangers, heaters, separators, piping, etc.
Naphthenic Acid Corrosion	Naphthenic acid corrosion is attack of steel alloys by organic acids that condense in the range of 350°F to 750°F. The presence of potentially harmful amounts of naphthenic acids in crude may be signified by higher neutralization numbers.	Localized corrosion	Naphthenic/organic acid concentration and temperature.	Middle section of a vacuum column in a crude unit (primarily in the MVGO cut), can also occur in atmospheric distillation units, furnaces and transfer lines.
Oxidation	A high temperature corrosion reaction where metal is converted to a metal oxide above specific temperatures.	General uniform corrosion	Temperature, presence of air, material of construction.	Outside of furnace tubes, furnace tube hangers, and other internal furnace components exposed to combustion gases containing excess air.

Table 2—Stress Corrosion Cracking

Deterioration Mechanism	Description	Behavior	Key Variables	Examples
Chloride Cracking	Cracking that can initiate from the ID or OD of austenitic stainless steel equipment, primarily due to fabrication or residual stresses. Some applied stresses can also cause cracking.	Transgranular cracking.	Acid (chloride) concentration, pH, material of construction, temperature, fabrication, stresses approaching yield.	Externally present in equipment with poor insulation and weatherproofing, downwind of cooling water spray and equipment exposed to fire water. Internally wherever chlorides can be present with water such as atmospheric column overheads of crude units and reactor effluent condensing streams.
Caustic Cracking	Cracking primarily initiated from the ID of carbon steel equipment, primarily due to fabrication or residual stresses.	Typically, intergranular, also can be transgranular cracking.	Caustic concentration, pH, material of construction, temperature, stress.	Caustic treating sections, caustic service, mercaptan treatment, crude unit feed preheat desalting, sour water treatment, steam systems.
Polythionic Acid Cracking	Cracking of austenitic stainless steels in the sensitized condition (due to high temperature exposure or welding) in the presence of polythionic acid in wet, ambient conditions. Polythionic acid is formed by a conversion of FeS in the presence of water and oxygen.	Intergranular cracking.	Material of construction, sensitized microstructure, presence of water, polythionic acid.	Generally occurs in austenitic stainless steel materials in catalytic cracking unit reactor and flue gas systems, desulfurizer furnaces and hydroprocessing units.
Amine Cracking	Amine is used in gas treatment to remove dissolved CO ₂ and H ₂ S acid gases. Cracking generally caused by desorbed acid gases or amine deterioration products.	Intergranular cracking.	Amine type and concentration, material of construction, temperature, stress.	Amine treating units.
Ammonia Cracking	Cracking of carbon steel and admiralty brass.	Intergranular cracking in carbon steel, transgranular in copper zinc alloys.	Material of construction, temperature, stress.	Generally present in ammonia production and handling such as overhead condensation where ammonia is a neutralizer.
Hydrogen Induced Cracking / Stress Oriented Hydrogen Induced Cracking	Occurs in carbon and low alloy steel materials in the presence of water and H ₂ S. Deterioration of the material properties is caused when atomic hydrogen, generated through corrosion, diffuses into the material and reacts with other atomic hydrogen to form molecular hydrogen gas in inclusions of the steel. Deterioration can take the form of blisters and step-wise cracking in stress relieved equipment and non-stress relieved equipment.	Planar cracks (blisters), Transgranular cracks as blisters progress toward welds.	H ₂ S concentration, water, temperature, pH, material of construction.	Anywhere that H ₂ S is present with water such as crude units, catalytic cracking compression and gas recovery, hydroprocessing, sour water and coker units.
Sulfide Stress Cracking	Occurs in carbon and low alloy steel materials in the presence of water and H ₂ S. Deterioration takes the form of cracking in non or improperly stress relieved equipment.	Transgranular cracking, normally associated with fabrication, attachment and repair welds.	H ₂ S concentration, water, temperature, pH, material of construction, post weld heat treatment condition, hardness	Anywhere that H ₂ S is present with water such as crude units, catalytic cracking compression and gas recovery, hydroprocessing, sour water and coker units.
Deterioration Mechanism	Description	Behavior	Key Variables	Examples
Hydrogen Blistering	Occurs in carbon and low alloy steel materials in the presence of water and H ₂ S. Deterioration of the material properties is caused by atomic hydrogen generated through corrosion diffuses into the material and reacts with other atomic hydrogen to form molecular hydrogen gas in inclusions of the steel. Deterioration takes the form of planar blisters and can occur in stress relieved and non-stress relieved equipment.	Planar cracks (blisters).	H ₂ S concentration, water, temperature, pH, material of construction.	Anywhere that H ₂ S is present with water such as crude units, catalytic cracking compression and gas recovery, hydroprocessing, sour water and coker units.
Hydrogen Cyanide Cracking	Presence if hydrogen cyanide can promote hydrogen deterioration (SOHIC, SCC, and blistering) by destabilizing the iron sulfide protective surface scale.	Planar cracks (blisters) and transgranular cracking.	Presence of HCN, H ₂ S concentration, water, temperature, pH, material of construction.	Anywhere that H ₂ S is present with water such as crude units, catalytic cracking compression and gas recovery, hydroprocessing, sour water and coker units.

Table 3—Metallurgical and Environmental Failures

Deterioration Mechanism	Description	Behavior	Key Variables	Examples
High-Temperature Hydrogen Attack	Occurs in carbon and low alloy steel materials in the presence of high temperature and hydrogen, usually as a part of the hydrocarbon stream. At elevated temperatures ($> 500^{\circ}\text{F}$), deterioration of the material properties is caused by methane gas forming fissures along the grain boundaries. Atomic hydrogen diffuses into the material and reacts with carbon from the steel, forming methane gas and depleting the steel of carbon.	Intergranular fissure cracking, decarburization.	Material of construction, hydrogen partial pressure, temperature, time in service.	Typically occurs in reaction sections of hydrocarbon processing units such as hydrodesulfurizers, hydrocrackers, hydroforming and hydrogen production units.
Grain Growth	Occurs when steels are heated above a certain temperature, beginning about 1100°F for CS and most pronounced at 1350°F . Austenitic stainless steels and high nickel-chromium alloys do not become subject to grain growth until heated to above 1650°F .	Localized	Maximum temperature reached, time at maximum temperature, material of construction.	Furnace tubes failures, fire damaged equipment, equipment susceptible to run-away reactions.
Graphitization	Occurs when the normal pearlite grains in steels decompose into soft weak ferrite grains and graphite nodules usually due to long term exposure in the 825°F – 1400°F range.	Localized	Material of construction, temperature and time of exposure.	FCC reactor.
Sigma Phase Embrittlement	Occurs when austenitic and other stainless steels with more than 17% chromium are held in the range of 1000°F – 1500°F for extended time periods.	Generalized	Material of construction, temperature and time of exposure.	Cast furnace tubes and components, regenerator cyclones in FCC unit.
885°F Embrittlement	Occurs after aging of ferrite containing stainless steels at 650°F – 1000°F and produces a loss of ambient temperature ductility.	Generalized	Material of construction, temperature.	Cracking of wrought and cast steels during shutdowns.
Temper Embrittlement	Occurs when low alloy steels are held for long periods of time in temperature range of 700°F – 1050°F . There is a loss of toughness that is not evident at operating temperature but rather shows up at ambient temperature and can result in brittle fracture.	Generalized	Material of construction, temperature and time of exposure.	During shutdown and start-up conditions the problem may appear for equipment in older refinery units that have operated long enough for this condition to develop. Hydrotreating and hydrocracking units are of interest because they are used at elevated temperatures.
Liquid Metal Embrittlement	Form of catastrophic brittle failure of a normally ductile metal caused when it is in, or has been in, contact with a liquid metal and is stressed in tension. Examples include stainless steel and zinc combination and copper based alloys and mercury combination.	Localized	Material of construction, tension stress, presence of liquid metal.	Mercury is found in some crude oils and subsequent refinery distillation can condense and concentrate it at low spots in equipment such as condenser shells. Failure of process instruments that utilize mercury has been known to introduce the liquid metal into refinery streams.

Table 3—Metallurgical and Environmental Failures

Deterioration Mechanism	Description	Behavior	Key Variables	Examples
Carburization	Caused by carbon diffusion into the steel at elevated temperatures. The increased carbon content results in an increase in the hardenability of ferritic steels and some stainless steels. When carburized steel is cooled a brittle structure can result.	Localized	Material of construction, temperature and time of exposure.	Furnace tubes having coke deposits are a good candidate for carburization (ID).
Decarburization	Loss of carbon from the surface of a ferrous alloy as a result of heating in a medium that reacts with carbon.	Localized	Material of construction, temperature environment.	Carbon steel furnace tubes (OD). Result of excessive over-heating (fire).
Metal Dusting	Highly localized carburization and subsequent wastage of steels exposed to mixtures of hydrogen, methane, CO, CO ₂ , and light hydrocarbons in the temperature range of 900°F–1500°F.	Localized	Temperature, process stream composition.	Dehydrogenation units, fired heaters, coker heaters, cracking units and gas turbines.
Selective Leaching	Preferential loss of one alloy phase in a multiphase alloy.	Localized	Process stream flow conditions, material of construction.	Admiralty tubes used in cooling water systems.

Table 4—Mechanical Failures

Deterioration Mechanism	Description	Behavior	Key Variables	Examples
Mechanical Fatigue	Failure of a component by cracking after the continued application of cyclic stress which exceeds the material's endurance limit.	Localized	Cyclic stress level, material of construction.	Reciprocating parts in pumps and compressors and the shafts of rotating machinery and associated piping, cyclic equipment such as pressure swing absorbers.
Corrosion Fatigue	Form of fatigue where a corrosion process, typically pitting corrosion adds or promotes the mechanical fatigue process.	Localized	Cyclic stress, material of construction, pitting potential of the process stream.	Steam drum headers, boiler tubes.
Cavitation	Caused by the rapid formation and collapse of vapor bubbles in liquid at a metal surface as a result of pressure variations.	Localized	Pressure head value along the flow of process stream.	Backside of pump impellers, elbows.
Mechanical Deterioration	Typical examples are the misuse of tools and equipment, wind deterioration, careless handling when equipment is moved or erected.	N/A	Equipment design, operating procedures.	Flange faces and other machined seating surfaces may be damaged when not protected with covers or when not handled with care.
Overloading	Occurs when loads in excess of the maximum permitted by design are applied to equipment.	N/A	Equipment design, operating procedures.	Hydrostatic testing can overload supporting structures due to excess weight applied. Thermal expansion and contraction can cause overloading problems.
Over-pressuring	Application of pressure in excess of the maximum allowable working pressure of the equipment under consideration.	N/A	Equipment design, operating procedures.	Excess heat as a result of upset process condition can result in over-pressuring; blocking off equipment which is not designed to handle full process pressure.
Brittle Fracture	Loss of ductility wherein the steel is referred to as having low notch toughness or poor impact strength.	Localized	Material of construction, temperature.	During equipment pressurization in absence of precautionary measures.
Creep	High temperature mechanism wherein continuous plastic deformation of a metal takes place while under stresses below the normal yield strength.	Localized	Material of construction, temperature, applied stress.	Furnace tubes and supports.
Stress Rupture	Time to failure for a metal at elevated temperatures under applied stress below its normal yield strength.	Localized	Material of construction, temperature, applied stress, time of exposure.	Furnace tubes.
Thermal Shock	Occurs when large and non-uniform thermal stresses develop over a relatively short time in a piece of equipment due to differential expansion or contraction. If movement of the equipment is restrained this can produce stresses above the yield strength of the material.	Localized	Equipment design, operating procedures.	Associated with occasional, brief flow interruptions or during a fire.
Thermal Fatigue	Thermal fatigue is a process of cyclic changes in stress in a material due to cyclic change in temperature.	Localized	Equipment design, operating procedures.	Coke drums are subject to thermal cycling and associated thermal fatigue cracking. Bypass valves and piping with heavy weld reinforcement on reactors in cyclic temperature service are also prone to thermal fatigue.

Appendix B

Definitions and Acronyms

Definitions

For purposes of this recommended practice, the following definitions shall apply.

3.1.1 absolute risk: An ideal and accurate description and quantification of risk.

3.1.2 ALARP (As Low As Reasonably Practical): 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.

3.1.3 consequence: Outcome from an event. There may be one or more consequences from an event. Consequences may range from positive to negative. However, consequences are always negative for safety aspects. Consequences may be expressed qualitatively or quantitatively.

3.1.4 damage tolerance: The amount of deterioration that a component can withstand without failing.

3.1.5 deterioration: The reduction in the ability of a component to provide its intended purpose of containment of fluids. This can be caused by various deterioration mechanisms (e.g., thinning, cracking, mechanical). Damage or degradation may be used in place of deterioration.

3.1.6 event: Occurrence of a particular set of circumstances. The event may be certain or uncertain. The event can be singular or multiple. The probability associated with the event can be estimated for a given period of time.

3.1.7 event tree: An analytical tool that organizes and characterizes potential accidents in a logical and graphical manner. The event tree begins with the identification of potential initiating events. Subsequent possible events (including activation of safety functions) resulting from the initiating events are then displayed as the second level of the event tree. This process is continued to develop pathways or scenarios from the initiating events to potential outcomes.

3.1.8 external event: Events resulting from forces of nature, acts of God or sabotage, or such events as neighboring fires or explosions, neighboring hazardous material releases, electrical power failures, tornadoes, earthquakes, and intrusions of external transportation vehicles, such as aircraft, ships, trains, trucks, or automobiles. External events are usually beyond the direct or indirect control of persons employed at or by the facility.

3.1.9 failure: Termination of the ability of a system, structure, or component to perform its required function of containment of fluid (i.e., loss of containment). Failures may be unannounced and undetected until the next inspection (unannounced failure), or they may be announced and detected by any number of methods at the instance of occurrence (announced failure).

3.1.10 failure mode: The manner of failure. For risk-based inspection, the failure of concern is loss of containment of pressurized equipment items. Examples of failure modes are small hole, crack, and rupture.

3.1.11 hazard: A physical condition or a release of a hazardous material that could result from component failure and result in human injury or death, loss or damage, or environmental degradation. Hazard is the source of harm. Components that are used to transport, store, or process a hazardous material can be a source of hazard. Human error and external events may also create a hazard.

3.1.12 Hazard and Operability (HAZOP) Study: A HAZOP study is a form of failure modes and effects analysis. HAZOP studies, which were originally developed for the process industry, use systematic techniques to identify hazards and operability issues throughout an entire facility. It is particularly useful in identifying unforeseen hazards designed into facilities due to lack of information, or introduced into existing facilities due to changes in process conditions or operating procedures. The basic objectives of the techniques are:

- To produce a full description of the facility or process, including the intended design conditions.
- To systematically review every part of the facility or process to discover how deviations from the intention of the design can occur.
- To decide whether these deviations can lead to hazards or operability issues.
- To assess effectiveness of safeguards.

3.1.13 likelihood: Probability.

3.1.14 mitigation: Limitation of any negative consequence or reduction in probability of a particular event.

3.1.15 probability: Extent to which an event is likely to occur within the time frame under consideration. The mathematical definition of probability is "a real number in the scale 0 to 1 attached to a random event". Probability can be related

to a long-run relative frequency of occurrence or to a degree of belief that an event will occur. For a high degree of belief, the probability is near one. Frequency rather than probability may be used in describing risk. Degrees of belief about probability can be chosen as classes or ranks like "Rare/unlikely/moderate/likely/almost certain" or "incredible/improbable/remote/occasional/probable/frequent".

3.1.16 Qualitative Risk Analysis (Assessment):

Methods that use engineering judgment and experience as the bases for the analysis of probabilities and consequences of failure. The results of qualitative risk analyses are dependent on the background and expertise of the analysts and the objectives of the analysis. Failure Modes, Effects, and Criticality Analysis (FMECA) and HAZOPs are examples of qualitative risk analysis techniques that become quantitative risk analysis methods when consequence and failure probability values are estimated along with the respective descriptive input.

3.1.17 Quantitative Risk Analysis (Assessment):

An analysis that:

- Identifies and delineates the combinations of events that, if they occur, will lead to a severe accident (e.g., major explosion) or any other undesired event.
- Estimates the frequency of occurrence for each combination.
- Estimates the consequences.

Quantitative risk analysis integrates into a uniform methodology the relevant information about facility design, operating practices, operating history, component reliability, human actions, the physical progression of accidents, and potential environmental and health effects, usually in as realistic a manner as possible.

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

Quantitative risk analysis logic models generally consist of event trees and fault trees. Event trees delineate initiating events and combinations of system successes and failures, while fault trees depict ways in which the system failures represented in the event trees can occur. These models are analyzed to estimate the frequency of each accident sequence.

3.1.18 relative risk: The comparative risk of a facility, process unit, system, equipment item or component to other facilities, process units, systems, equipment items or components, respectively.

3.1.19 residual risk: The risk remaining after risk mitigation.

3.1.20 risk: 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.

3.1.21 risk acceptance: A decision to accept a risk. Risk acceptance depends on risk criteria.

3.1.22 risk analysis: Systematic use of information to identify sources and to estimate the risk. Risk analysis provides a basis for risk evaluation, risk mitigation and risk acceptance. Information can include historical data, theoretical analysis, informed opinions and concerns of stakeholders.

3.1.23 risk assessment: Overall process of risk analysis and risk evaluation.

3.1.24 risk avoidance: Decision not to become involved in, or action to withdraw from a risk situation. The decision may be taken based on the result of risk evaluation.

3.1.25 risk-based inspection: 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.

3.1.26 risk communication: Exchange or sharing of information about risk between the decision maker and other stakeholders. The information may relate to the existence, nature, form, probability, severity, acceptability, mitigation or other aspects of risk.

3.1.27 risk control: Actions implementing risk management decisions. Risk control may involve monitoring, re-evaluation, acceptance and compliance with decisions.

3.1.28 risk criteria: Terms of reference by which the significance of risk is assessed. 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.

3.1.29 risk estimation: Process used to assign values to the probability and consequence of a risk. Risk estimation may consider cost, benefits, stakeholder concerns and other variables, as appropriate for risk evaluation.

3.1.30 risk evaluation: Process used to compare the estimated risk against given risk criteria to determine the significance of the risk. Risk evaluation may be used to assist in the acceptance or mitigation decision.

3.1.31 risk identification: Process to find, list, and characterize elements of risk. Elements may include; source, event, consequence, probability. Risk identification may also identify stakeholder concerns.

3.1.32 risk management: Coordinated activities to direct and control an organization with regard to risk. Risk management typically includes risk assessment, risk mitigation, risk acceptance and risk communication.

3.1.33 risk mitigation: Process of selection and implementation of measures to modify risk. The term risk mitigation is sometimes used for measures themselves.

3.1.34 risk reduction: Actions taken to lessen the probability, negative consequences, or both associated with a particular risk.

3.1.35 source: Thing or activity with a potential for consequence. Source in a safety context is a hazard.

3.1.36 source identification: Process to find, list, and characterize sources. In the safety area, source identification is called hazard identification.

3.1.37 stakeholder: Any individual, group or organization that may affect, be affected by, or perceive itself to be affected by the risk.

3.1.38 toxic chemical: Any chemical that presents a physical or health hazard or an environmental hazard according to the appropriate Material Safety Data Sheet. These chemicals (when ingested, inhaled or absorbed through the skin) can cause damage to living tissue, impairment of the central nervous system, severe illness, or in extreme cases, death. These chemicals may also result in adverse effects to the environment (measured as ecotoxicity and related to persistence and bioaccumulation potential).

3.1.39 unmitigated risk: The risk prior to mitigation activities.

Acronyms

ACC	American Chemistry Council
AIChE	American Institute of Chemical Engineers
ALARP	As Low As Reasonably Practical
ANSI	American National Standards Institute
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ASNT	American Society of Nondestructive Testing
ASTM	American Society of Testing and Materials
BLEVE	Boiling Liquid Expanding Vapor Explosion
CCPS	Center for Chemical Process Safety
COF	Consequence of Failure
EPA	Environmental Protection Agency
FAR	Fatality Accident Rate
FMEA	Failure Modes and Effects Analysis
HAZOP	Hazard and Operability Assessment
ISO	International Organization for Standardization
MOC	Management of Change
NACE	National Association of Corrosion Engineers
NDE	Non destructive examination
NFPA	National Fire Protection Association
OSHA	Occupational Safety and Health Administration
PHA	Process Hazards Analysis
PMI	Positive Material Identification
POF	Probability of Failure
PSM	Process Safety Management
PVRC	Pressure Vessel Research Council
QA/QC	Quality Assurance/Quality Control
QRA	Quantitative Risk Assessment
RBI	Risk-Based Inspection
RCM	Reliability Centered Maintenance
RMP	Risk Management Plan
TEMA	Tubular Exchangers Manufacturers Association
TNO	The Netherlands Organization for Applied Scientific Research

Appendix C

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