Risk-based Inspection: A Qualitative Risk-Based Methodology for Ranking Fixed Equipment on Probability of Internal Failure

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ABSTRACT

A qualitative, risk-based method for ranking fixed equipment, based on probability of internal failure, is described. The ranking procedure is used to prioritize process equipment inspection programs with limited budgets and personnel resources, and as a tool to meet the mechanical integrity requirements of the OSHA 1910.119 Process Safety Management Standard.

The paper describes current industry activities concerning risk-based inspection, and describes a procedure for ranking equipment using process corrosivity, corrosion rate half life, mean time between failure, environmental cracking, and previous inspection results as independent variables in the ranking process. The results can be combined with a hazard analysis to provide an overall qualitative risk-based equipment ranking. The described procedure incorporates existing industry code and standard inspection requirements.

BACKGROUND INFORMATION

Since promulgation in 1992 of the OSHA 1910.119 Standard, "Process Safety Management of Highly Hazardous Chemicals", the chemical industry has expended enormous
personnel time and money to comply with the standard. The OSHA standard has particularly affected how companies are approaching the mechanical integrity of fixed equipment through inspection. The days of randomly inspecting equipment only when shut down for process reasons and with untrained personnel are rapidly disappearing. Equipment inspection records frequently do not contain adequate documentation of previous inspection results. Often, only process engineers would inspect equipment, primarily with the intent of verifying process operability. Inspection for corrosion or other deterioration was not a primary focus. Therefore, many chemical plants that have been operating for 20 years or more have little or no meaningful information on the condition of their process equipment.

OSHA has changed this approach irreversibly with the 1910.119 standard requirements. Other standards that have also had a major influence on equipment mechanical integrity programs are API 510, “Pressure Vessel Inspection Code”, and API 653, “Tank, Inspection, Repair, Alteration, and Reconstruction”. These two standards contain minimum requirements for equipment inspection, intervals between inspections, and inspection personnel qualifications and training. As such, they are timely complements to the OSHA standard.

The recent changed approach to equipment mechanical integrity has resulted in the need for more inspection personnel and larger inspection budgets. Many plants have so many equipment items that inspecting all items during a single shutdown is not practical. Therefore, decisions on how to allocate limited inspection personnel and budgets is required.

**Risk-based Inspection**

One method for optimizing limited resources and reducing the possibility of equipment failures that has been in use in the nuclear industry for some time now is risk-based inspection. Risk-based inspection is a procedure for ranking or prioritizing equipment for inspection purposes, based upon risk. Risk is the combination of probability and consequence. Probability is the likelihood of an event occurring, in this case an equipment failure. Consequence is a measure, both in lives and property, of the damage that would occur if an equipment item failed.

Risk-based inspection procedures can be based on either qualitative or quantitative methodologies. Qualitative procedures provide a ranking of equipment, based largely on
experience and engineering judgement. Quantitative risk-based methods use several engineering disciplines to set priorities and develop programs for equipment inspection. Some of the engineering disciplines include non-destructive examination, system and component design and analysis, fracture mechanics, probabilistic analysis, failure consequence analysis, and operation of facilities. Quantitative analysis methods are expensive, time consuming, tedious and are outside the scope of this paper. Often, insufficient information is available for conducting a quantitative risk analysis. Two organizations that are currently working on quantitative risk-based analysis procedures for use by the chemical industry are the American Society for Mechanical Engineers and the American Petroleum Institute.

**RISK-BASED INSPECTION PROCEDURE**

**General**

This writer recognized the need for a tool for ranking process equipment for inspection purposes that incorporated the philosophy of qualitative risk-based inspection, and was practical, realistic, and inexpensive to implement. This paper discusses one approach for ranking process equipment, based on internal probability of failure (POF). The procedure is based on an analysis of equipment process and inspection parameters, and ranks equipment on a scale of one to three, with “one” being the highest priority. The procedure requires considerable use of engineering judgement and experience; therefore, the results are dependent on the background and expertise of the analyst. The procedure has been used to rank more than 2,000 equipment items and is both practical, effective, and efficient.

The POF numerical ranking arrived at using the procedure is not meant to be an indicator of an equipment item’s absolute susceptibility to failure. It is intended as a convenient and reproducible means for establishing equipment inspection priorities, based on knowledge. As such, it facilitates the most efficient use of finite inspection monies and personnel where 100% inspection is not practical.

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The procedure is based on a set of rules heavily dependent on detailed inspection histories, knowledge of corrosion processes, and knowledge of normal and upset process conditions. As such, the equipment rankings will not stay constant, but will require updating as additional knowledge is gained, process conditions change, and equipment ages. Maximum benefits of the procedure depend on fixed equipment inspection programs that permit the capture, documentation, and retrieval of inspection, maintenance, and corrosion/failure mechanism information.

The POF procedure is one-half of a risk-based inspection procedure. The POF ranking is combined with a consequence ranking to provide a true risk-based ranking. A procedure for ranking equipment based on consequence is also outside the scope of this paper; however, a similar procedure can be developed, using such process attributes as flammability, reactivity, corrosivity, density, toxicity, etc. The three rankings developed from the consequence analysis can be combined with the probability rankings in a three-by-three matrix. Forty-five degree parallel constant-risk lines result in five risk categories. These categories can be used to establish inspection intervals, etc.

The equipment covered by the procedure includes all fixed equipment items designed and constructed to ASME Section VIII, "Rules for Construction of Pressure Equipment", divs. 1 and 2. They are not appropriate for rotating equipment. The fixed equipment to consider in the procedure would normally be based on OSHA’s hazardous chemicals guideline; however, it can be used to rank all equipment, if desired.

As failures can occur from both internal and external causes, a similar procedure is required to rank equipment based on external failures. This internal POF ranking procedure is used for shutdown inspection planning. The external POF ranking procedure is used to plan on-stream inspections.

**Procedure Implementation - General**

An equipment POF rank of one to three is established using independent categories that include inspection and process knowledge. The independent categories are corrosivity of process, corrosion rate half life (CRHL), internal inspection information, mean time between failure
(MTBF), and environmental cracking susceptibility. Each category is assigned a number from one to three, based on the data collected during the review. The final equipment ranking is based on the most critical category. Exhibit 1 describes the rules for assigning ranking numbers to the various categories. Exhibit 2 describes how the individual category rankings are used to arrive at a final POF ranking. The following describes the probability-of-failure categories and the rationale behind them.

**Implementation - Specific**

**Corrosivity of Process**

Process corrosivity is divided into three corrosion-rate intervals, in mils per year (mpy). Section I of Exhibit 1 describes these categories. The corrosion rate information is combined with remaining corrosion allowance (RCA) information to calculate a corrosion rate half life (CRHL) for the equipment item, one category for ranking equipment. Actual corrosion rate data from ultrasonic thickness surveys is used if available. When ultrasonic thickness data is not available corrosion rates can be estimated, based on personal experience or from corrosion literature. Establishing meaningful corrosion rates requires knowledge of the process environment vs. materials-of-construction interactions and is best done by an experienced corrosion engineer. Estimated corrosion rates should be based on both bulk and localized corrosion considerations, as well as stream velocities, turbulence, etc. Where the potential for localized, accelerated corrosion exists, worse case corrosion rates should be used until internal inspections can be conducted to verify actual rates. For equipment items that include one or more alloys or process combinations, worse case corrosion rates should govern based on all alloy/process combinations. Typical examples of this situation include distillation columns with dual metallurgy shell courses, and shell and tube exchangers.

**Corrosion Rate Half Life**

Using actual or estimated corrosion rates, as described above, and remaining corrosion allowance information, a corrosion rate half life for an equipment item is calculated using the following formula.
\[ \text{CRHL} = \left( \frac{t_{\text{actual}} - t_{\text{minimum}}}{2} \right) \div \text{ipy} \] (1)

The calculated CRHL, in years, is used to establish a CRHL ranking from one to three, based on the intervals defined in Section II of Exhibit 1. The CRHL category is designed to incorporate the requirements of API 510, "Pressure Vessel Inspection Code", which states that the period between conducting internal inspections shall be based on one-half of the remaining life of the vessel or ten years, whichever is less. In the procedure, Category 1 is defined as that CRHL between one and five years. This would give a maximum life expectancy of ten years.

Some equipment items require using engineering judgement to arrive at a meaningful CRHL. Tube and shell exchangers are one such example. Corrosion rates should be either known from thickness data or estimated for both the shell and the tubeside of the exchanger. Also, exchanger tubes are not normally designed with a corrosion allowance, so one has to establish some criteria. The procedure can be modified to suit the philosophy of the end user. Some owners may choose to retube exchangers when eddy current or magnetic flux inspections detect O.D. or I.D. tube indications at or above 50% of the tube wall. This retube criteria can be used to establish corrosion rates and CRHL data. Here, \( t_{\text{minimum}} \) would be 50% of the tube thickness. It is this writer's experience that corrosion of exchanger tubes governs the life of exchangers, and therefore, dictates inspection intervals.

A second example that illustrates the need for engineering judgement in establishing CRHL data involves stainless steel and other highly alloyed equipment. Normally these items are not designed with a corrosion allowance, the assumption being that they are completely resistant to the environment. This is especially true when stainless or non-ferrous equipment is specified for product contamination reasons. The concept of CRHL is meaningless with equipment that does not include a corrosion allowance. Therefore, if any corrosion occurs, or a baseline ultrasonic thickness measurement reveals an under tolerance component (which occurs frequently with nozzles) this automatically gives the equipment a high CRHL ranking until an engineering assessment can verify that the component is still within code allowable stresses.
Internal Inspection

Internal inspection, performed properly, is an important parameter in ranking equipment based on probability of failure. An internal inspection permits detection of localized areas of corrosion, which are difficult to predict or detect with external thickness measurements. It permits a verification of actual maximum corrosion rates, estimated or determined from on-line external thickness measurements.

A numerical ranking from one to three is assigned to the equipment item, based on the internal inspection parameters in Section III of Exhibit 1. This writer has chosen to supplement the one to three rankings with subcategories, based on the use of arbitrary decimal fractions. The use of subcategories permits capturing more information concerning the reason that the inspection parameter was rated a high-probability of “one”. These subcategories can be added to or modified based on end user preferences. The requirements of API 510 regarding internal inspection frequencies were incorporated into the inspection category rankings, based on its ten-year maximum intervals.

Some minimum requirements were established to define what constitutes an internal inspection. As an example, for distillation columns an internal inspection is not considered to have been conducted unless tray manways or packing are removed for access throughout the column, and the column adequately cleaned to permit a thorough visual inspection. Observing through opened column manways is not considered by this writer as an internal inspection event. For shell and tube exchangers, an internal inspection is not considered to have been conducted unless the exchanger tubes, or a portion thereof, are nondestructively inspected.

Mean Time Between Failure

Mean time between failure (MTBF), if sufficient data is available to apply it statistically, is a most useful tool in establishing probability-of-failure rankings and internal inspection intervals. However, often, insufficient equipment inspection documentation is available to establish meaningful MTBF information. Also, one has to define what is a failure. The procedure rules primarily address corrosion and environmental cracking processes and the results
from previous inspection records. They do not include the influence on failure of mechanical
damage, faulty equipment design, improper maintenance, or process control logic. The
incorporation of these items is best done with a more detailed quantitative approach using Fault
Tree Analysis or Event Analysis.

An MTBF ranking is assigned, if appropriate, based on Section IV of the Exhibit
rules. If previous failures have not occurred, or if an equipment item has recently been installed
or has been upgraded, an MTBF ranking is not assigned. MTBF was included in the rules as it
provided a particularly appropriate way to manage shell and tube exchangers, where the bulk
corrosivity of the cooling water is nominally low (1-2 mpy) and, therefore, would normally be
rated a low-priority three, based on CRHL. However, exchanger tube failures from cooling water
can be frequent, based on localized conditions, low flow or cooling water treatment upsets. The
use of MTBF balances the low probability ranking an exchanger might otherwise receive, based
on the other categories. An MTBF category is less useful when applied to major process
equipment such as columns, reactors, etc. which rarely fail in the sense of a catastrophic rupture.

**Environmental Cracking**

An environmental cracking ranking is established according to the rules in Section
V of Exhibit 1. This category requires a detailed knowledge of process and corrosion
mechanisms. Normally, equipment items are not placed in service where environmental cracking
agents are known to be present. An obvious example of this would be specification of the 300
series stainless steels for hydrochloric acid service, where chloride stress cracking would almost
be certain. However, cracking environments are not always obvious. For example, this writer
would rate an exchanger with 304/316SS tubes with shellside cooling water a high probability
1.02 ranking in the SCC category, as the typically high cycles used in today’s recirculating cooling
water systems can contain up to a thousand ppm chlorides. Admiralty brass tubes, which are
commonly used in compressor lube oil coolers, can suffer from SCC cracking from nitrogen-
containing organics in cooling water, if they are left idle with noncirculating cooling water for
extended periods. This can happen if only one of two spared coolers are used at a time. A less
recognized cracking agent of carbon steel is a CO/CO²/water environment. CO/CO²/water
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cracking of carbon steel is not as well known as the more common cracking agents, as failures from cracking are infrequent, based on the specific environment necessary for cracking to occur, the slow growth rate of the cracks, and the fact that the cracking environment is often not recognized. This is partly due to the fact that CO and/or CO² are not always included in material balance information on process flow sheets.

**Probability of Failure (POF)**

Using the numerical rankings established in Sections II through V of Exhibit 1, an overall POF ranking for the equipment item is established using Exhibit 2, based on a boolean logic use of the Exhibit 1 Rules. The final POF ranking is a nonweighted approach that assigns the highest rated category as the ranking number for the equipment item. The procedure is well suited for set-up and maintenance using a spreadsheet program.

**CONCLUSIONS**

A qualitative method for ranking equipment, based on probability of internal failure, has been presented. The procedure was developed to provide a practical, yet simple methodology to help owners in meeting the mechanical integrity section of the OSHA 1910.119 Standard. The procedure is particularly useful when combined with a hazard, or consequence equipment ranking, for establishing equipment inspection intervals, and in prioritizing shutdown strategies when capital budgets and/or inspection personnel are constrained.
Fixed Equipment- Rules For Establishing Probability of Internal Failure Numerical Rankings

Probability of Failure Input Parameters

I. Corrosivity of Process

A. Bulk process is essentially non-corrosive to equipment materials-of-construction with documented corrosion rates of 0-10 mils per year (MPY) and with no localized, unpredictable corrosion anticipated.

B. Bulk process can exhibit moderate corrosion rates of 10-20 MPY at areas of velocity, turbulence, etc. in locations not predictable or accessible to external inspection.

C. Potential exists for corrosion rates as high as 20-50 MPY in locations not predictable or accessible to an external inspection.

II. Corrosion Rate Half-Life

1.00 \[0.5 \times (\text{RCA})^{1}] = \text{mpy} = 1 - 5 \text{ years}

2.00 \[0.5 \times (\text{RCA})^{1}] = \text{mpy} = 6 - 10 \text{ years}

3.00 \[0.5 \times (\text{RCA})^{1}] = \text{mpy} = 11 - 20 \text{ years}

III. Internal Inspection

1.00 Equipment older than ten years, no internal inspection within last ten years.

1.04 Equipment with less than five years of service and in process corrosivity categories IB or IC with no inspection.

1.05 Unresolved defect, deficiency, or observation, documented during a previous inspection, resulting in a repair recommendation to a pressure boundary

\[1 \text{ RCA} = \text{Remaining corrosion Allowance}\]

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Fixed Equipment - Rules For Establishing Probability of Internal Failure
Numerical Rankings

2.01 Equipment less than 10 years old in corrosivity category IA with no inspection.

2.02 One internal inspection within ten years with no reportable findings.

3.00 Two or more internal inspections with no reportable findings, the last inspection within ten years.

IV. Mean Time Before Failure (MTBF)

1.00 0 - 10 years.
2.00 11 - 15 years.
3.00 16 - 20 years.

V. Environmental cracking (process only).

1.02 Stress corrosion cracking (SCC) potential during normal operation.
1.03 SCC potential following a documented process upset.
3.00 No SCC potential.
Fixed Equipment- Rules For Establishing Probability of Internal Failure Numerical Rankings

Probability of Failure Ranking

A. **Probability of Failure = 1**

1.00 Corrosion-rate half-life equals 0 - 5 years.
   
   or

1.00 MTBF equals 0 - 10 years.
   
   or

1.01 Equipment in service more than ten years, with no internal inspection performed within the last ten years.
   
   or

1.02 SCC potential during normal operation.
   
   or

1.03 Documented process upset with SCC potential since last internal inspection.
   
   or

1.04 Newly installed equipment with less than 5 years of service and in process corrosivity categories IB or IC.
   
   or

1.05 Unresolved deficiency, or observation, documented during a previous inspection, resulting in a repair recommendation to a pressure boundary component, or a recommendation to monitor or replace a component during the next scheduled shutdown.
   
   or

1.06 Exchangers only- No magnetic flux exclusion or eddy current inspection.

B. **Probability of Failure = 2**

2.00 Corrosion-rate half-life equals 6 - 10 years.

   and

2.00 MTBF equals 11 - 15 years.

   or

2.01 Equipment less than 10 years old in process corrosivity IA service with no inspection.
Fixed Equipment- Rules For Establishing Probability of Internal Failure
Numerical Rankings

or

2.02 One internal inspection within last ten years with no reportable findings.

C. Probability of Failure = 3.

3.00 No SCC potential.

and

3.00 Corrosion-rate half-life equals 11+ years.

and

3.00 MTBF equals 16-20 years.

and

3.00 Two or more documented internal inspections with no reportable findings.