Corrosion is a major environmental deterioration phenomenon in chemical process industries affecting the life of process equipment and pipelines resulting in leakage, product loss, environmental pollution and loss of life. The overall risk associated with corrosion cracking in terms of its likely possibilities and its consequences to the plant and environment need to be addressed while designing the plant and before commencing regular operation. Corrosion risk analysis results should be used to formulate risk based inspection (RBI) procedures that should be a part of the plant operation. RBI concentrates inspection resources more on ‘High Risk’ and ‘Medium Risk’ assets and less on ‘Low Risk’ equipment. This paper gives two case studies dealing with oil and gas pipelines, preceded by a summary of the basic principles and procedures of corrosion risk assessment and RBI applicable to the Process Industries.

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1. Introduction

Corrosion is a major deterioration phenomenon in the chemical process industries (CPI) affecting process equipment, pipelines and structures. During the design stage, materials of construction (MOC) for the above are chosen carefully, keeping corrosion resistance as a major decision factor; the others being mechanical and physical properties, cost, availability, economics etc. In spite of such a selection, corrosion is likely to occur during operation, perhaps as ‘general’ or ‘uniform’ corrosion at an unexpectedly high rate, or possibly as some form of localized attack. This is mainly because of unexpected process condition transients, process stream impurities, a requirement to increase production rates, etc.
To monitor both expected and unexpected corrosion, inspection programs, typically based initially on visual and non-destructive testing (NDT), are planned as a part of normal plant activities. These inspection activities, either off-line during shut-down (SD) periods or on-line during operation, are time-consuming, expensive and lead to consequential losses. Hence, the inspection activities should be properly planned to achieve optimal plant safety, reliability, productivity and profitability.

In achieving these objectives, the corrosion risk analysis is very important in classifying the relative severity of corrosion risk in the ‘low risk’, ‘medium risk’ and ‘high risk’ categories. Accordingly, inspection resources can be planned allocate greater attention on those areas identified to be in the ‘high risk’ and ‘medium risk’ categories. The present talk attempts to summarize the basic principles of the Risk Based Inspection (RBI) approach and the Criticality Assessment. This is followed by presentation of two case studies, one dealing with RBI/CA and the other dealing with monitoring, as related to oil and gas pipelines.

2. Principles Of Risk Assessment

“Risk” is a mathematical expression that combines the probability and consequence of an incident. It is usually expressed as follows:

\[
\text{Risk} = \text{Likelihood (Probability)} \times \text{Consequence (Severity)}
\]

is the results are shown on a 3-by-3 X-Y risk matrix as columns entitled ‘Low risk’, ‘Medium risk’ and ‘High risk’.

Though there may be a strong probability of a particular form of corrosion taking place in a process vessel, the risk may be low if the consequence of failure is not serious (for example, the vessel contains cold water). On the other hand, the risk may be high if the above mentioned consequence is high (for example, if the vessel contains hot combustible gas). Some such examples are illustrated in Table 1 below.

| Likelihood                              | Consequence                                              | Risk Ranking |
|-----------------------------------------|----------------------------------------------------------|--------------|
| Small Pinhole Corrosion Pit in a water pipeline | Leakage of water                                        | Low          |
| Small Pinhole Corrosion Pit in an acid pipeline | Leakage of acid with possible damage to personnel nearby | Low to Medium|
| Small Pinhole Corrosion Pit in a High Pressure Gas Pipeline | Leakage of gas with damage to many persons in the area | High         |
| Small crack by SCC in a small Reactor Wall | Leakage of the process medium with damage to the operating person | Low to Medium|
| Small crack by SCC in a large Pressure Vessel or Column | Leakage of large quantity of process fluid under pressure with huge loss of the product and damage to environment and many persons in the area | High         |

It should be noted that for the same likelihood (probability) of a certain type of corrosion occurring, the risk can vary depending upon the extent of the consequence of a failure. The latter depends upon the process medium handled, size of the vessel, hold-up volume, thickness of the vessel, pressure of the medium, etc. Correspondingly, the Risk Rating also varies from ‘low’ to ‘high’. Relatively more attention, in terms of inspection and protective measures, then can be directed towards the higher risk component, thereby improving the knowledge and understanding of plant condition at these locations. In process plant applications, there is generally little that can be done to affect the ‘consequence’ factor because the service environment/pressure/temperature parameters are defined by process requirements. However, increasing the knowledge of the condition of the plant (by carrying out appropriate inspection) reduces the probability of failure, thereby reducing the risk that a failure will take place, making the plant safer and more reliable.
In Chemical Process Industry, probability of leakage due to corrosion and consequential damages in terms of materials loss, production loss, release of toxic gases, fire, injury to operating personnel nearby and damage to the surrounding environment is much higher from equipment under positive pressure than those under atmospheric or low pressure. Pipelines transferring oil and gas under pressure are such equipments.

The steps involved in undertaking criticality appraisal and the associated risk based inspection planning procedure are typically the following:

- Classify qualitatively all of the operating units, equipment, systems, pipelines, etc. within the particular plant as high, medium and low risk items.
- Carry out detailed corrosion assessment for items categorized as being high and/or medium risk items and estimate the overall risk rating in association with process parameters, their variations and results/consequences due to the corrosion leakage.
- Prioritize the items according to their risk rating based on the results of criticality appraisal.
- Design an appropriate Risk Based Inspection Program (RBI) to monitor corrosion more actively in high and medium risk units.
- Systematically monitor the inspection activities and performance of the concerned equipments/systems.
- Modify the database based on the inspection findings and repeat the process as necessary to reduce progressively the overall risk of failure.

3. **Corrosion Risk Analysis Procedure**

3.1 **Procedure in Brief**

The procedure starts with a process flow diagram. A meeting is then convened with representative stakeholders with interest in the plant under consideration. The condition of plant equipment is then considered with respect to the likelihood of possible corrosion phenomena, and the consequence of any failure of that piece of equipment. The likelihood probabilities are given the ratings 1, 2, 3…etc, 1 being the lowest probability with other numbers indicating increasingly higher probabilities. Similarly the consequence probabilities are given the ratings A, B, C,…etc, A being the lowest probability with other letters indicating increasingly higher probabilities. These probabilities are plotted in an X-Y Risk Matrix as shown in Figure 1 below.

![Figure 1: Qualitative risk matrix](image)

From this risk matrix, the final overall risk ranking is given in terms of 1-A, 1-B, 3-C etc, indicated by the corresponding square in the matrix and given the ranking as ‘low’, ‘medium’ or ‘high’ for a given asset or plant component.
3.2 Plant Input data

Corrosion Risk Analysis requires the collection of various plant input data. The essential data required are listed below:

- System Identification number and/or description
- Type of Equipment/Piping
- Materials of Construction (MOC)
- Coating, Cladding, Insulation data
- Process parameters: Fluid nature, its composition, velocities and hold up volumes
- Operating Conditions: Temperature and Pressure, both Design and operating range
- Inspection history, if any, for existing systems and proposed inspection schedules for new systems
- Replacements and repair records, along with their purpose
- Detection and safety systems incorporated
- Personnel densities in and around the system
- Replacement/repair cost
- Production downtime cost
- Cost of hold up product inventories in the system
- Environmental damage and its remedy cost

The above list is only indicative. Based on similar plant experience elsewhere, as much input information as possible should be obtained.

3.3 Corrosion Damage Mechanism Determination

Once all the plant input information is obtained, the possible corrosion damage mechanism(s) should be identified from the input data. The corrosion damage mechanisms are the ones which could lead to the leakage of the process fluid to the environment (leakage of containment). Typical corrosion damage mechanisms are given below in Table 2.

| Damage type                | Description                                                                 |
|----------------------------|-----------------------------------------------------------------------------|
| Thinning, General and Localized | Loss of metal from surface throughout (general uniform corrosion, erosion corrosion) or from localized places (pitting, crevice, galvanic corrosion) either from inside or from outside. |
| Surface connected cracking | Stress Corrosion Cracking by chloride, caustic, sulfide, amines etc          |
|                            | Corrosion Fatigue                                                           |
|                            | Liquid Metal Embrittlement                                                  |
| Sub-surface Cracking       | Hydrogen Induced Cracking and its variations such as blistering, hydrogen embrittlement etc. |

3.4 Likelihood Category (Probability determination)

Once the damage mechanisms are identified, for general or ‘uniform’ corrosion, its rate (mm/year) for the particular MOC in the given environment under the operating conditions is obtained either from plant records, or open literature or from opinion of corrosion experts. The probability of leakage due to such general uniform corrosion is determined from system parameters like thickness of the wall of the equipment/piping, flow velocity, corrosion allowance, etc.

If localized corrosion phenomena, such as stress corrosion cracking and/or subsurface cracking, are the likely mechanisms, their probabilities are determined and modified with respect to operating conditions, MOC, stresses present, metallurgical treatment of the MOC, design for the absence of stress concentrators
etc. The above probability (either general corrosion or localized corrosion) is given a rating 1 to 5, 1 for the lowest probability and 5 for the highest probability.

3.5 Consequence Category (Severity determination)

The identified damage mechanism, if occurred under the service conditions as per the likelihood probability, would lead to certain consequences through leakage of the process fluid. These consequences are basically loss of containment, quantity based on hold up volumes, and hazardous nature of the process fluid (fire hazard and health hazard due to acidity of liquids and toxicity of vapors). The consequence factor for any particular event is arrived at giving weightage to the following aspects:

- The type of process fluid contained in the vessel
- The quantity of process fluid leaked
- Dispersion and/or accumulation of the fluid and its results
- Installation of safe guards if any and Failure of such safe guards if installed
- Failure to initiate preventive action
- Environmental hazard
- Fatalities if likely

The consequence factor is estimated on the basis of the process fluid concerned and assuming a certain leaking hole/crack size followed by the release rate. This factor is increased or decreased according to the above mentioned aspects. The resultant factor is given a rating, ranging from A to E, A being the lowest probability and E, the highest.

3.6 Risk Ranking

The final Risk Ranking (the result of the Criticality Analysis) is obtained by considering the Likelihood rating (1 to 5) on the Y-axis and the consequence rating (A to E) on the X axis of the Risk Matrix. An example risk rating is shown below in Figure 2.

![Figure 2: Typical Risk Ranking (MEDIUM) as a result of Corrosion Risk Analysis Study](image-url)
The particular risk ranking of 3-B (MEDIUM) shown in the above Figure means the following: The likelihood of a certain corrosion damage occurring has a moderate probability (i.e. not a high) giving the probability rating as 3. On the other hand, the consequence category is quite low (i.e. not ‘low’) giving the probability rating as B. The latter may be the result of small size of equipment, good safety devices under operation, less population density in the area of leakage etc. Putting the above two probabilities in the Risk Matrix gives the ‘MEDIUM’ Risk.

As far as Risk Based Inspection (RBI) is concerned for this illustrative example, no unusual, specialized or high frequency inspection would be required.

4. Qualifications required to Conduct a Criticality Assessment

The criticality assessment is a team activity and should not be a job to be carried out by an individual. It requires data gathering from many sources, specialized analysis from different disciplines and risk decisions and inspection guidelines from management. It requires input by a corrosion engineering specialist, an inspection specialist, a chemical engineer or process specialist, representatives from the Operations and Maintenance Departments, the involvement of Environment/Safety personnel, representatives from management and the Finance Department and finally co-ordination by the Project Leader, and a Risk Analyst. The latter should co-ordinate with all of the specialists, acquire the relevant required information, carry out the study and prepare and submit the findings to management.

5. Risk Based Inspection (RBI)

As outlined in the above paragraphs, combining the probability of a corrosion event with that of its consequences determines the risk. If this risk rating is unacceptably high, then the inspection plan should be revised to improve knowledge of the condition of the plant. When properly implemented, risk-based inspection is highly effective in improving plant safety, compared to conventional code-based inspection programs. RBI can reduce risk considerably, even before any corrosion mitigation methods are put into practice. This is illustrated schematically in Fig. 3 below.

![Figure 3: Comparison of Risk arrived at through RBI with that of Normal Inspection](image-url)
Such a reduction in Risk Rating due to RBI stems from the recognition of the following facts:

- Risk Based Inspection uses a formalized procedure that allows areas of the plant which are operating in a high-risk condition to be reliably identified, thereby enabling inspection resources to be directed at them in order to improve knowledge of plant condition and thereby avoid the possibility of unexpected failure.
- The volume of conventional code-based inspection requirements is now so high that it is not possible or necessary for all aspects of such inspections to be carried out in many operating plants.
- Properly-implemented risk-based inspection ensures that inspection resources are correctly targeted at areas that are likely to sustain unexpected failures while ensuring also that appropriate attention is available for lower-risk assets.

The RBI process, shown below in a simplified block diagram (Fig. 4) depicts the essential elements of inspection planning based on Corrosion Risk Analysis.

![RBI planning based on CRAS](image)

It is clear from this Figure that RBI process requires Corrosion Risk Analysis. The risk analysis gives risk rating for the particular unit, section, equipment, piping, etc., and based on the inspection plan is developed and executed. The RBI procedure includes inspection planning and implementation, inspection data collection, updating and continuous improvement. As it is likely that processes and systems may change with time, updating is necessary to maintain the integrity of the database and to ensure continued safe operation of the plant. When RBI identifies potential equipment flaws, the equipment must be evaluated using appropriate engineering analysis to evaluate its suitability for continued operation (fitness for service) and decisions taken on repair, replacement, maintenance or for continued operation.

In choosing the particular inspection method/technique as a part of the RBI program, it should be noted that each and every available inspection technique (NDT method) is not highly effective by itself for detecting all corrosion damage flaws. Table 3 below gives the effectiveness of various inspection techniques for detecting different corrosion damage types.
Table 3: Effectiveness of Inspection Techniques for Various Corrosion Types

| Inspection Technique                  | Thinning | Surface Connected Cracking | Sub-Surface Cracking |
|--------------------------------------|----------|---------------------------|---------------------|
| Visual Examination                   | 1—3      | 2—3                       | X                   |
| Ultrasonic Straight Beam             | 1—3      | 3—X                       | 3—X                 |
| Ultrasonic Shear Wave                | X        | 1—2                       | 1—2                 |
| Fluorescent Magnetic Particle        | X        | 1—2                       | 3—X                 |
| Dye Penetrant                        | X        | 1—3                       | X                   |
| Eddy Current                         | 1—2      | 1—2                       | X                   |
| Radiography                          | 1—3      | 3—X                       | 3—X                 |
| Dimensional Measurement              | 1—3      | X                         | X                   |
| Metallography                        | X        | 2—3                       | 2—3                 |

1= Highly effective  
2= Moderately effective  
3= Possibly effective  
X= Not normally used

It can be seen that for almost all corrosion mechanisms, more than one inspection technique can be used, each enhancing the effectiveness of the other. For example, UT measurements are much more effective at locating internal corrosion if they are combined with internal inspection, where possible.

6. RBI Case Study on a Hydrocarbon Condensate Pipeline

A corrosion risk analysis was conducted for a proposed new hydrocarbon condensate line a few kilometers in length. The MOC was a plain carbon steel and the line was seamless pipe. Along with hydrocarbon liquids, the condensate contained small quantities of condensed moisture and dissolved CO₂ and H₂S. Corrosion Risk Analysis was required to formulate guidelines for a risk based inspection plan.

Hydrocarbons themselves are not corrosive. The CO₂ content was relatively low and should not cause any appreciable corrosion. However, the H₂S content, along with its partial pressure, were such that the fluid should be classified as “sour”, meaning that sulfide induced corrosion, including sulfide stress corrosion cracking, could occur. The most likely corrosion deterioration mechanism under the operating conditions was sulfide stress corrosion cracking (SSCC), due to the presence of H₂S. Assuming usually effective inspection techniques and a yearly inspection frequency, the ‘likelihood of failure’ category was assessed to be “2”.

The consequence category was assessed to be “C”, a somewhat high consequence, due to the possibility of leakage of hydrocarbons through the cracks produced by SSCC and the associated risk if fire and/or explosion. This is because the pipeline is quite long and the containment fluid is a flammable hydrocarbon liquid. Putting the above probabilities 2-C in the Risk Matrix, the overall ranking classification was assessed to be ‘medium risk’, as shown below in Fig. 5.
Figure 5: Risk Matrix corresponding to the Case Study

On the basis of the above appraisal, an inspection plan based on the above results was formulated, with inspections to be carried out at least once in a year, to concentrate specifically on the detection of occurrence of SSCC in stressed areas such as bends and elbows. Routine inspection of the general pipeline, using techniques such as thickness measurements, coupon exposures, dye penetrant tests of weld joints, etc., was reduced as they would not provide useful information on the condition of the line. This strategy could offer significant savings on inspection costs but would also reduce substantially the risk of unexpected failure.

These are the major advantages of RBI.

7. Summary and Conclusions

The paper has dealt with the principles of Corrosion Risk Analysis and Risk Based Inspection (RBI) as applicable to pressure parts of the oil and gas production, refining, petrochemical and chemical process industries. This was followed by a case study of an application of RBI for internal corrosion of an on-shore condensate pipeline. The importance of the criticality analysis within the RBI procedure, and the example of the specific case study were highlighted. It is concluded that RBI is a very effective method to assess risk and target inspection resources on critical items. When correctly implemented, the RBI approach is a powerful means of increasing the safety and reducing the inspection and maintenance costs of process plant equipment.

8. References

1. American Petroleum Institute Specification API 580 (May 2002). Recommended Practice for Risk-Based Inspection.
2. American Petroleum Institute Specification API 581 (May 2000) Risk-Based Inspection, Base Research Document.