Corrosion and Asset Integrity Management in Oil and Gas Production, Process, Transportation and Storage Facilities

Vittorio Colombo, Cristina Panizza, Bruno Bazzoni
Cescor srl
Milan, Italy

Andy Barnett, Phil Collingwood, Musab Elsamani, Kabir Raheem
Wood Group Kenny UK Ltd
Staines-Upon-Thames, UK

Corrosion is the primary integrity threat in oil & gas pressure containment and process facilities. Managing corrosion is the starting point for integrity management, and defining a corrosion management strategy is key to meeting the requirements of a corrosion management policy. Corrosion is also the main risk driver of Risk Based Inspection (RBI) activities; the primary means by which the inspection strategy, essential for ensuring integrity, is put in place. A number of approaches are considered here to assess and manage integrity of assets - topside facilities, process plant, utilities, marine terminals, tank farms, pipelines, etc. We will evaluate qualitative, semi qualitative and quantitative risk assessment approaches. Risk assessment is one of the main RBI optimisation criteria. We consider how risk assessment approaches influence the resultant risk, and how this impacts integrity management. We will consider the impact of risk assessment on the AIM strategy, and refer to software developed by WGK and how their application can result in safe, cost effective operation/management of oil and gas facilities. RBI has evolved into a sophisticated method for optimising inspection processes and frequency to deliver cost-effective AIM. RBI design incorporates multi-disciplinary knowledge and conditional factors, changes in operating conditions, asset operation and maintenance, asset criticality, data interpretation and condition prediction.

Keywords: Corrosion, Risk Assessment, Risk Based Inspection, Asset Integrity Management

INTRODUCTION

It is well-known that corrosion is the primary threat to asset integrity of oil and gas pressure containment and process facilities, and the management of internal and external corrosion issues is the starting point for any integrity management process. To face all corrosion mechanisms, the available consolidated knowledge shall be applied along the project life at the right time, at the right place and at the lowest costs with the purpose of ensuring the integrity of the asset.

The integrity of an oil and gas asset is the result of a multi-disciplinary approach, that necessitates giving due consideration to the performance of materials in the specific environments, the economics of the oil industry and local operations, the tolerable level of risk and the viable technological resources that may be deployed to reduce integrity-risk to acceptable levels. This requires an appropriate understanding of management, technical, operational and safety issues.

During the lifecycle of an oil and gas asset, activities shall be carried out to ensure integrity be maintained from first evaluation through to decommissioning. For the success of integrity activities, it is necessary that the integrity management system is designed, implemented and continuously revised and optimized during the full service life. Key integrity processes are required from the early design phase and have to be continued with endeavor for each of the stage of the asset lifecycle.

Defining a clear, robust corrosion management strategy is key in accomplishing the targets established by the corrosion management policy of the project. Corrosion is also a main driver in the risk ranking process that is at the base of Risk Based Inspection (RBI) activities; they are the means through which the inspection strategy, an essential part for enduring the integrity of the assets, is put in place.

Corrosion risk assessment is the key activity of corrosion integrity management through a risk-based approach. The task is aimed at identifying, for given assets, the corrosion risk level of each item of the asset. The risk of a corrosion failure is a combination of the probability of the failure occurring with a measure of the consequences of the failure. The main activities of the risk assessment are therefore:

- the assessment of the probability of a corrosion failure based on the identification of the corrosion damage mechanisms, the rate of progression of the damage and the tolerance of the item to damage, and
- the assessment of the consequences in case of failure, including safety, environment and operability aspects.

Different procedures can be adopted using different level of the analysis (qualitative, semi-quantitative and quantitative). In all cases, for each item the probability of corrosion and the entity of the consequences are combined to give a corrosion risk ranking; the corrosion risk matrix represents the most used and effective tool to view this ranking. If the probability/consequence combination (risk) is high enough to be unacceptable, then a mitigation action for preventing the event is required.

The corrosion risk assessment is an integral part of an RBI strategy. The RBI approach allows management of the overall risk of a plant by focusing inspection efforts on the process equipment with the higher risk. The RBI procedure provides the basis for managing the risk of corrosion and it gives the operator the possibility to make decisions on inspection frequency, level of details of the inspections and type of non-destructive techniques to be used. The cost of inspection can be reduced by concentrating the efforts on the high-risk items and reducing the number and the frequency of the inspections on the low-risk components.

To guarantee its effectiveness, the periodical inspection must be sufficiently frequent in relation to the time between the deterioration becoming detectable and the onset of failure. Inspection techniques must be selected which are capable of detecting the deterioration of concern with sufficient reliability at a sufficient early stage.

This paper discusses a number of examples of oil & gas asset integrity management coming from the long and consolidated industry experience of Cescor and Wood Group Kenny.

Risk Assessment as part of RBI Optimisation Criteria

The risk assessment is structured process of identifying and defining risk. The risk assessment methodologies can be qualitative, semi-quantitative and quantitative. The appropriate methodology is selected based on available design information, inspection data, computing power and most importantly experienced personnel. Regardless of the methodology selected, the process of identifying threats and failure mode is generally similar.

Qualitative RBI relies on subjective assessments and can be more conservative than quantitative methods. In the simplest sense, quantitative studies, whether RBI or other, are based on value inputs (numbers) and precise rule-sets to calculate the final result. This approach is subjective and can lead to incorrect judgments; however, the main advantage of this approach is documenting the experiences and proposed improved mitigations. Qualitative RBI is more heavily dependent on user or expert opinion to drive the analysis.

Semi quantitative risk assessment is a combination of experience and operational and inspection data analysis for the mode of failure. This approach is popular among oil and gas companies because it takes into account the required engineering and scientific assessment and experience simultaneously.

A quantitative approach is more complex and software is increasingly necessary as it encourages standardisation of assessment to improve efficiency. The approach uses engineering and scientific assessment to predict and calculate the mode and consequence of failure. Quantitative RBI requires more data input but should provide greater consistency between users and over time. The main disadvantage of this approach it lacks the experience-based judgement to optimise the resultant risk.

An important consideration in the implementation of an RBI solution is the degree of quantitative assessment to be performed. It is always desirable to have a balance between a qualitative and quantitative approach. Recent development in RBI software offer unprecedented functionality, where the experience is converted into extensive datasets and data is processed and analysed to complement the scientific approach to predict the mode of failure. The model must be able to store as-built design information, inspection data and any changes and modifications, and alert engineers to monitor critical asset locations and flag inspection requirements.

In the following sections, we reference examples of asset integrity management from the oil and gas industry to demonstrate the influence of risk approach on the resultant RBI and ultimately on the asset integrity management.

INTEGRITY ASSESSMENT OF AN OIL STORAGE TANK FARM IN ITALY

In 2013, Cescor was entrusted to perform an exhaustive cathodic protection survey and the corrosion risk assessment of thirty two above ground tanks of a tank farm for crude oil storage prior to export[1]. The tank farm is located in Italy and it is composed of atmospheric storage tanks

having a diameter ranging from 40 to 80 meters and a capacity ranging from 20,000 to 100,000 cubic meters.

This activity was one of the steps and a constituent part of the Integrity Management Philosophy adopted by the Company. The cathodic protection survey was conceived and designed within a Corrosion Risk Assessment (CRA) study for the best result evaluation. In fact, the CRA is intended as the first phase of the Risk Based Inspection implementation process.

The CRA methodology has been applied both internally and externally as the bottom of each tank is exposed to different environments (water / oil and soil) with specific corrosion threats. The CRA has been developed by calculations of the *corrosion factor*, F_C, and of the *overall consequences factor*, F_{OC}. The two factors are then combined in the *corrosion matrix* that represents the CRA output.

Results of external CRA are the input data for the second performed step: the cathodic protection survey that was designed to identify the corrosion threats and to calculate the corrosion rate of the thirty two above ground storage tank bottoms and it was performed by applying an articulated methodology.

The Cathodic Protection Survey requires, as a main task, the evaluation of the cathodic protection functionality. This is assessed by both inspecting the cathodic protection equipment integrity and by monitoring the protection status of the facilities.

In the present case, the plant is a complex area: buried structures are not electrically insulated from each other (specifically piping and storage tanks); with a common grounding network that impedes any electrically sectioning. The current necessary to achieve the protection conditions is delivered by few groundbeds, which work in parallel.

Protection conditions have been verified using the following techniques:

- On potential measurements;
- instant Off potential measurements;
- current drained by coupons or potential probes, StrayProbe® type;
- long term potential recording to verify the presence of stray currents;
- verification of electrical insulation vs. foreign structures.

When a cathodic protection survey is performed in a Tank Farm that is configured as a complex area, one of the most critical aspects to be considered during the execution of the inspections is the difficulty in assessing the protection status of tank bottoms[3].

The most critical aspect is the difficulty in assessing the protection status of tank bottoms as the presence of an adequate electrolytic contact between bottom and soil is not always guaranteed, but this is one of the necessary conditions for cathodic protection to work and also to correctly measure the potential. It is recognized that, if the electrolytic contact is poor and not uniform, the electric field tend to become concentrated only where the electrolytic contact exists, leaving unprotected spot areas: this is typical for tank bottom laid over an oily-sand pad.

Indicative clues of the adequate electrolytic contact between tank bottom and soil can be obtained in two ways:

- Using Finite Element Modeling (FEM) it is possible to obtain the potential profile when electrolyte is considered homogeneous and the anode is remote. The modeled profile can be used as reference to compare with the trend of a measured potential profile (as measurements through multiple permanent reference electrodes), if available;

- The current balance divergence between the design protection current and the delivered current: when the latter is lower, the poor electrolytic contact between tank bottom and ground could be occurred.

If the poor electrolytic contact between tank bottom and ground is suspected, it is necessary to provide an inspection technique that leaves no doubts on the actual protection status of tank bottoms. The only way forward has been identified as applicable for those tanks that are out of service and therefore accessible. The technique consists in cutting and removing some bottom patches in order to access the area between the bottom plate and the underlying pad. The potential measurement is performed in correspondence of the hole firstly without watering and then by some water addition.

If both measurements indicate that poor electrolytic contact is present with soil, the tank bottom should be considered as unprotected, so that corrosion rate should be estimated to complete the risk assessment tasks.

Finally, it is worth remembering that storage tanks cannot be considered as a static system when assessing the pad properties: it is in fact recognized that the continuous product load/unload operations may progressively alter the pad drainage properties and its electrical conductibility. For this reason, the adopted approach recommended to repeat the assessment procedure every time a tank is out of service and accessible for maintenance operations.

RBI ACTIVITIES FOR AN LNG OFFSHORE RE-GASIFICATION TERMINAL

The corrosion and asset integrity management of an LNG regasification terminal offshore Italy is ensured by applying a Risk Based Inspection (RBI) approach consistently[2].

The RBI general framework and architecture for the offshore terminal was designed step by step between 2013 and 2014 and starting from 2015 the RBI virtuous loop was effectively in place.

The RBI methodology, developed and commonly applied for upstream oil and gas assets, has been adapted for the case of an offshore LNG regasification terminal. Therefore, the facilities peculiarities have been taken into account, such as the cryogenic service (liquefied natural gas is stored and handled at -162°C), the wide variety of involved materials (e.g. carbon and stainless steel, titanium, glass-reinforced plastic, etc.), the big amount of handled fluids as well as the thermal cycles associated with intermittent services.

The object of the RBI scope of work comprises more than 2100 lines and 180 vessels; for managing such a huge number of items, grouping of items into homogeneous circuits has been applied systematically.

Complex piping systems were divided into homogeneous circuits to better identify degradation mechanisms and the related risk levels (resulting from the risk assessment sessions) and to better focus the requirements for the inspections. Item grouping was carried out considering technical aspects such as handled fluid, purpose of the pipe, construction material, pipe diameter, operating and design parameters and national regulatory requirements.

The pressure equipment and atmospheric storage tanks have been mainly grouped individually as single vessel or, in case working in parallel, as groups of vessels. In addition, groups of pressure equipment have been proposed in utility systems when the criteria of the same handled fluid and the same purpose are met (e.g. all wet air handling vessels have been grouped).

At the end of the grouping process about 30 homogeneous piping circuits and 30 groups of vessels were defined.

The risk assessment of each homogeneous circuit was assessed in a number of workshop sessions with technical round table discussions.

Since many interdisciplinary competences were required to define actual risk and consequences of a failure, the following qualified and experienced personnel were involved in the workshop sessions:

- equipment strategies facilitators with a specific expertise in the facilities integrity management;
- pressure equipment integrity program owner;
- material and corrosion experts with a specialized competence in materials, degradation mechanisms, corrosion mitigations and inspections, and regulatory requirements;
- plant operations and maintenance personnel with a deep knowledge of the process functioning and troubleshooting;
- Company personnel with expertise in SHE (Safety, Health & Environment) as well as in the evaluation of the potential financial losses caused by the investigated failure scenario.

The output from the risk assessment workshops was the issue of an equipment strategy for each homogeneous piping / vessel circuit that provided the inspection / monitoring / surveillance / regulatory tasks and the associated inspection frequencies.

Inspections are planned over a medium term period taking into account the prioritization of the activities: items which resulted to be more critical for SHE / business considerations, operational reasons, etc. are scheduled to be inspected first and more thoroughly. Moreover, the equipment strategy assigns at each inspection task a specific inspection frequency.

Each year a number of inspection tasks taken from the relevant equipment strategies are reviewed and considered in a dedicated inspection plan. The inspection plan provides details of inspection activities such as:

- Identification of the items to be inspected and the type of Non Destructive Testing (NDT) to be used;
- Definition of the precise location for the inspections to be carried out and the amount of records to be gathered;
- Definition of the need for specific support for the inspections, i.e. scaffolding, need of remove the external thermal insulation, need of specific technical competence to accomplish a specific task, etc.;
- Estimation of the expected overall time of the inspection campaign which is a useful information for inspection planning;
- Definition of the inspection reporting requirements.

During the phase of inspection planning, the possibility to postpone some scheduled inspection tasks or to waive them in view of sound technical considerations can be discussed and agreed with the operator of the terminal.

Finally, to complete the RBI loop and make it effective, the results of the yearly inspection campaign are reviewed and analysed in a dedicated study with the purpose to identify possible criticalities and actions to be undertaken.

Critical items are highlighted and scheduled to be re-inspected in the next year campaign. These items will be added to the list of items scheduled to be inspected for the year to come. The new inspection plan will consider these items and specific considerations will be done regarding new inspection activities.

QUANTITATIVE RISK BASED INSPECTION IN GAS PROCESSING FACILITIES

WGK has worked with a major Oil & Gas client to undertake Integrity Management of its Fractionation Towers, Gas transport and Processing equipment since 2012. This client has been in the process of implementing an extensive update to its static pressure equipment inspection and integrity management programmes, following formal API RP 581[5] RBI principles.

This significant multi-year project involved a full financial RBI approach to manage all Static Pressure Equipment, including vessels, tanks, piping and PSVs, requiring substantial resource commitment. A full financial quantitative risk assessment approach allows informed inspection and integrity management decisions to be taken, considering all of the potential risk impacts (safety, environmental and production and equipment costs).

RBI of ageing equipment places a high demand on the integrity of the underlying data; including collating, interpretation and analysis of results. Supported by Wood Group Kenny the company successfully implemented a fully quantitative RBI programme across multiple sites, efficiently and with confidence, resulting in substantial reductions in risk and opex cost. In the course of this project over 60,000 separate files were sourced and reviewed.

The RBI process is only one element of an integrity management approach used by many leading operators. Through the RBI process, it is possible to add significant value and enhance Integrity Management Plans (IMPs), accurately define Integrity Operating Windows (IOWs), update Business Processes and the associated Guidelines and Procedures including Training and Support for personnel involved in the RBI process.

The RBI approach is well established used extensively in the oil & gas, refining, petrochemical and chemical industries. The essential elements of a "quality" risk based inspection analysis have been documented by the American Petroleum Institute (API) in API RP 580 (2009)[6]. API RP 581 (2008)[5] describes a specific RBI methodology with full details: data tables, algorithms, equations, models. Implementation of the RBI methodologies has been facilitated by a number of commercially available software tools, including Wood Group's NEXUS Integrity Centre© version 6. Benefits of RBI are well documented, as outlined in API RP 580[6] with the intent of a fully quantitative RBI implementation being to:

- Understand risks better (prevent unknowns);
- Reduce known risks further (less conservative, targeted inspections);
- Manage risks at a reducing cost base;
- And deliver higher equipment availability.

Risk based inspection is an important part of a broader asset integrity management system (AIMS) to meet the requirements of ISO 55001 Asset Management[14]. There are three fundamental building blocks for integrity excellence that delivers confidence in asset management for optimal cost.

Integrity Operating Windows (IOW's)[15].

- Clearly define the boundaries within which equipment can be safely operated
- Response plans and criticality of limits clearly articulated to operators
- Required governance processes to review IOW compliance

Integrity Management Plans (IMP's)

- Define credible damage mechanisms, controls and activities that prevent or mitigate them
- Describes the management of non-age-related damage mechanisms that would not be covered in RBI (e.g. vibration induced fatigue)
- Management of non-RBI components such as structural components (e.g. tower skirt Corrosion Under Fireproofing)
- Include corrosion and materials diagrams (C&MD's) and corrosion loop drawings

Risk Based Inspection (RBI)

- Integrated with an inspection data management system (IDMS)
- Contains estimates or measurements of the degree of degradation of pressure containing equipment and the risk levels associated with that knowledge
- Includes full coverage of vessels, tanks, pressure relief devices and piping (corrosion loops)
- Maximises the use of "non-intrusive inspection" (Nii) [15] scopes (thereby minimising downtime)

Holistic Asset Integrity Management

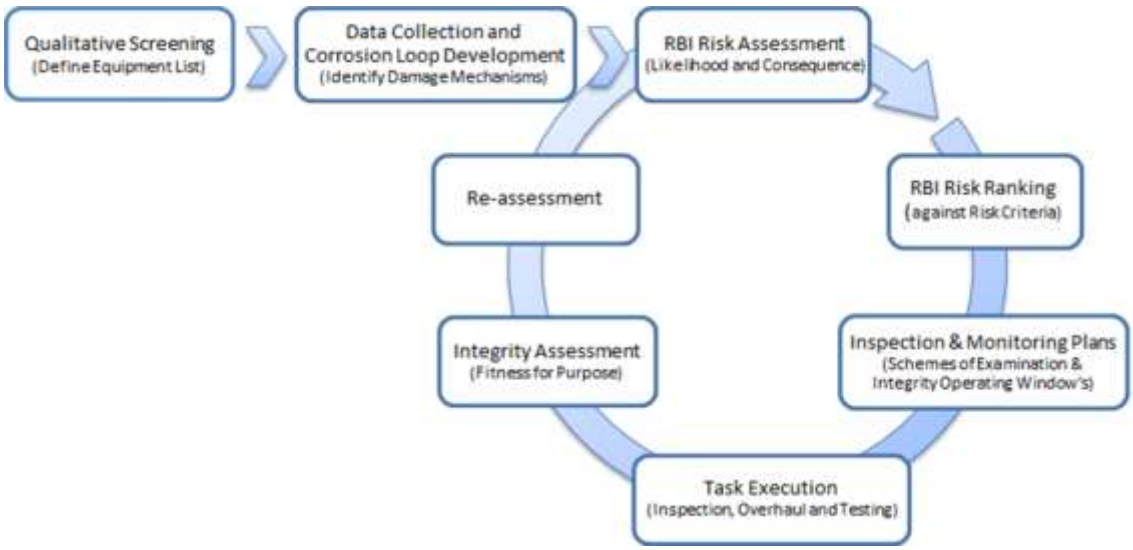
Deterioration and damage mechanisms (API RP 571[7]) in gas processing facilities need to be managed to prevent corrosion, cracking or other physical damage. Integrity management is not solely a matter of inspection activity to verify current and future status and so determine how advanced the conditions are, and then responding to this knowledge.

API RP 584[15] is a relatively recent standard for Integrity Operating Windows (IOWs) that are critical process parameters that control damage mechanisms (corrosion, cracking, etc.). IOW's can also define the boundary conditions used in an RBI inspection programme. The premise is that asset integrity is assured when the equipment meets its design life criteria for lowest lifecycle cost and ALARP risk under defined operating conditions. IOWs ensure deterioration rates are kept within RBI analysis boundaries. Management of Change (MoC) systems should also include and consider changes to critical process parameters, and/or other factors that might change the basis of the RBI analysis and otherwise keep the RBI analysis relevant and appropriate.

Certain damage mechanisms are not modelled in the API Recommended Practices (e.g. non age-related damage/defects), and therefore need to be handled outside of RBI. IMPs define vibration monitoring regimes and proactive corrosion monitoring e.g. cathodic protection, corrosion probes, IOWs for temperature/pressure/composition.

Overview of the Quantitative RBI Process

Process mapping was conducted to ensure that the end-to-end inspection process was documented and understood by all stakeholders. This helped in understanding key focus areas, and ensured that all aspects of the process were covered. The integration points and responsibilities were documented. The typical RBI process includes: Data Collection, Analysis, Risk Assessment, Validation Activities/Workshops, Inspection Planning/Scoping, Execution and Periodic Re-assessment.

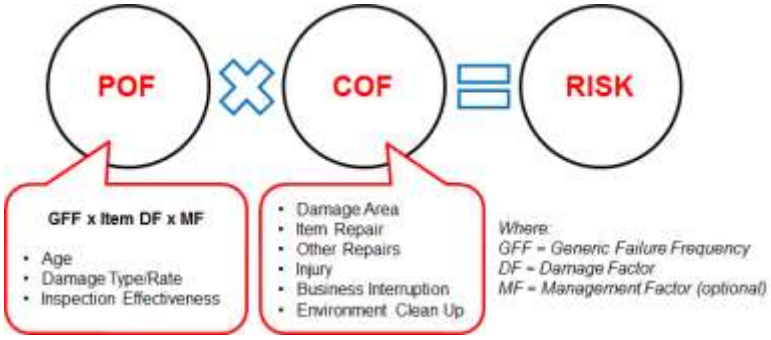


Key process steps of implementing RBI

An RBI manual was developed standardising the input process, clarifying data input and analysis options, and was recognised as a critical success factor for consistent application of the API RP 581 methodology by different users over time. The RBI manual documented comprehensive data and results checking. Quantitative RBI involves extensive data collection, and methods are required to deal with missing information (e.g. conservative default values). A validation plan was required for input and outputs. The output review included 'sense-checking' of results and Pareto analysis of outliers and 'deep dives' for a sample of results.

API RP 581 RBI Methodology

The quantitative API RP 581 methodology assesses the risk level and optimises inspection intervals of pressure equipment by firstly calculating the probability of failure by comparing the current knowledge of the equipment condition (Damage Factor - DF) to a generic "undamaged" industry failure rate (Generic Failure Frequency - GFF) and combines this with the consequence of failure (injury, economic, environmental, asset damage, etc.) to produce a risk value (see below). The risk value can either be presented as a financial (€/yr) or area based (m2/yr) value. The area based risk method, however, does not strictly consider environment and economic impacts; rather, this is inferred by assuming a correlation between damage, injury and the specific area.



Key Concepts of the API RP 581 Risk Based Inspection Technology

Risk value is modelled over time to assess the point it exceeds the risk criteria set by the business, triggering corrective action to reduce the risk. Typically this action would include further inspection to collect additional information, reduce uncertainty and conservatism in the remaining life estimate (Probability of Failure); the result being an assessment that more accurately represents the "true damage condition" of the equipment. Actions may also include 'consequence reduction' measures (mitigation) where the probability of failure is not the primary risk-driver. As equipment is assessed in an RBI program, there will be situations where the risk of failure for some equipment cannot easily be reduced through inspection efforts, because the consequence of a failure is the driving component of risk. Inspection can only lower the probability element of the equation. If the risk is still unacceptable, it may then be necessary to make hardware or procedural changes to reduce the consequence by mitigating the impact of a release, or refining the inputs and assumptions in the risk assessment. The addition of water sprays, shutdown systems, and block valves to reduce the size of inventory groups, or the creation of new operating procedures, are examples of measures that can lessen the consequence of a failure. Consequence

of failure isn't impacted by inspection since the loss of containment will have the same consequences regardless of inspection activity.

Risk Criteria

The business must define the quantitative risk criteria "boundary conditions" and triggers for the RBI assessment. Risk criteria typically include:

- Maximum Allowable Financial Risk (€/yr)
- Minimum Allowable Thickness (mm)
- Maximum Allowable Inspection Interval (years)

Other criteria can be configured including:

- Maximum Allowable Damage Factor - based on Individual Risk (No. fatalities per year) and cracking susceptibility, rather than selecting a fixed value (e.g. 100)
- Minimum Allowable Inspection Interval (years)
- Maximum Allowable Area Risk (m2/yr.)

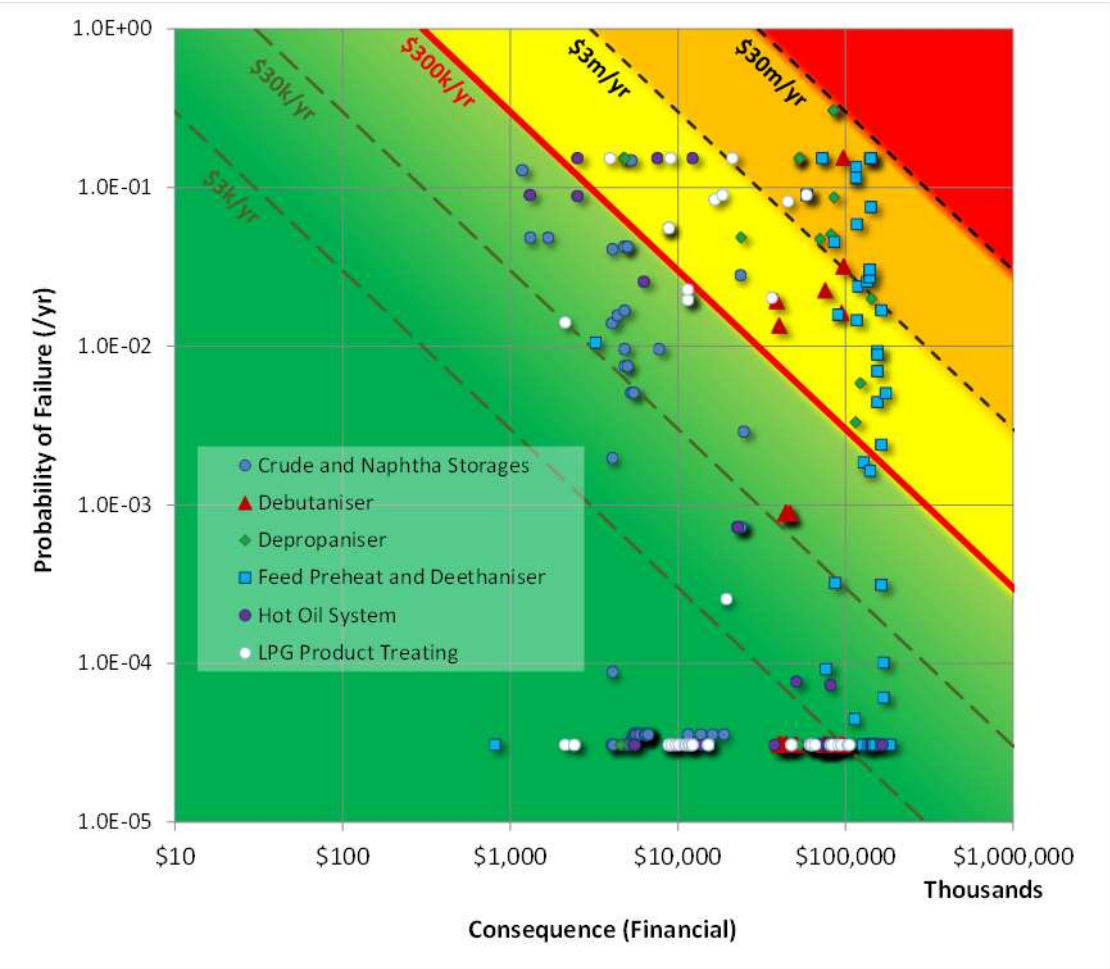
Risk criteria should mirror Corporate risk criteria; however where these are presented in qualitative terms (e.g. Risk Matrix) then interpretation is required. The client in this example delineated a new standard for risk criteria and its application for use with quantitative RBI. This helped define the parameters, how to calculate them consistently, and where/when to apply them. The methods for quantifying ALARP are also important and must also be covered. Typically this would include cost benefit analysis methods, disproportion or hurdle-rate criteria, etc. Risk criteria and ALARP determination is also important for Local Authorities, Regulators and insurance bodies.

Experience indicates inconsistency within the industry of normative values or standards regarding the consistent application of risk criteria, despite these criteria having a significant impact on RBI output results, and despite their risk/cost/benefit influence.

Consistency and standardisation of risk criteria would ensure that minimum requirements for societal and individual safety levels are maintained across companies and industry. The Centre for Chemical Process Safety (CCPS) has documented procedures on how to best determine quantitative risk criteria[19], and these were used for this project to guide the risk criteria.

CONCLUSIONS

One of the key benefits of a fully quantitative risk assessment method is the visibility and granularity of risk rankings available to support decision making and optimising asset integrity management activity. The main benefits of a quantitative RBI implementation is the ability to visualise risk levels, quantify risk reduction for inspection or mitigation effort and target inspection efforts where they are most needed.



The figure above shows an example iso-risk plot of the quantitative financial risk rankings of pressure equipment components of a Gas Processing facility. The figure shows components in a unit have similar consequence for the same isolatable inventory, which helps to visualise the benefit of any consequence mitigation project (which reduces the consequence of these components – moving points left on the chart), whilst inspection would reduce likelihood (Probability of Failure for each component - moving points downward on the chart). There are multiple components with no damage (DF=1) grouped at the base of the plot where the probability of failure is determined by the generic failure frequency (GFF) of the component.

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