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The Application of Risk Based Inspection to Pressure Vessels and Aboveground Storage Tanks in Petroleum Fuel Refineries

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Abstract: Plant reliability and profitability are important performance indicators for oil refineries. The amount of inspection and maintenance resources that is devoted to process equipment effects the overall plant performance. Dedicating the same level of resources to inspecting and maintaining each piece of equipment is not cost effective and can lead to oversight of high risk equipment. Although in an operating plant, the number of high risk items usually exists in lower percentages than low risk items, an oversight in the inspection and maintenance of high risk equipment may produce catastrophic results. Risk based inspection (RBI) provides a methodology for prudent assignment of resources to assess and maintain equipment integrity based on their risk levels. The application of RBI to pressure vessels and aboveground storage tanks are demonstrated through two examples related to a crude distillation column and a crude storage tank.

Keywords: Aboveground storage tanks, life assessment, non-destructive testing, plant run length, pressure vessels, refinery fixed equipment, and risk based inspection.

1 Introduction

Inspection intervals prescribed in AS/NZS 3788:2006 *Pressure equipment – In-Service Inspection* [1] are provided to help in assuring safe operation of plant equipment during its defined run length and extended run length intervals. The nominal inspection interval provides a risk level that is as low as reasonably acceptable based on industry experience. Operating equipment beyond this nominal inspection interval (referred to as extended interval in AS/NZS 3788:2006 Table 4.1) requires:

a. completion of at least one nominal interval, as prescribed in Table 4.1
b. if required, completion of first yearly inspection
c. assessment demonstrating it is safe to operate equipment with extended interval
d. justification and documentation of change with correct operating parameters
e. review of change proposal with a competent person
f. formal process of notifying any process conditions change which can affect equipment integrity

Operating equipment on an extended interval with the above requirements fulfilled provides assurance that the equipment can be operated safely at a risk level that is as low as reasonably practicable (ALARP). Inspection practices for both nominal and extended intervals may remain at the same level or vary, depending on the extended interval assessment. If the inspection practice for plant equipment remains the same level during its nominal and extended interval, then it can be said that the equipment is being inspected to a degree well above its required amount ("over inspected") for a risk level that is ALARP during its nominal interval period. If the inspection practice significantly increases between nominal and extended interval, then there may be an oversight of risk applicable to that equipment ("under inspected") and the equipment may benefit from a more stringent inspection approach to proactively reduce this step change in risk level.

To address this risk management gap posed by prescribed inspection intervals, either under inspecting or over inspecting equipment, Risk Based Inspection (RBI) is proposed as a sound methodology for identifying and assessing the risks of operating plant equipment. RBI has developed over the last couple of decades and it helps optimise inspection and maintenance efforts for plant equipment. RBI is now widely used by many upstream and downstream oil & gas, petrochemical companies worldwide to various degrees, with some utilising in-house proprietary RBI software applications and others using commercially available RBI products. The latest revision of AS/NZS 3788:2006 allows the use of RBI to vary inspection intervals different to those prescribed in Table 4.1 of the standard, refer to an extract of Table 4.1 in Figure 1. The intent is to allow large-scale industry to efficiently manage plant integrity since significant resources are needed to assess risks and consider all relevant factors. According to the standard, use of RBI is subject to:

a. owner and inspection body agreement

b. documentation of risk assessment and management with justifications for inspection practice variation
c. multidisciplinary team approach to RBI
d. possible fabrication and construction defects considered in terms of their effects and risks
e. actual service conditions considered in terms of their effects and risks on the equipment design and material of construction

TABLE 4.1

INSPECTION INTERVALS

1		2	3	4	5	6
Pressure equipment		Commissioning inspection required? (see Clause 4.2)	First yearly inspection required? (see Clause 4.4.3)	Inspection interval, years		
				External inspection (see Notes 2 and 3 and Clause 4.4.4.1)	Internal inspection	
					Nominal interval (see Clause 4.4.4.1)	Extended interval (see Clause 4.4.4.1)
1	BOILERS (see Note 12)					
1.1	Electric boilers	Y	N	2	4	8
1.2	Coil-type forced circulation boilers	Y	N	2	(see Note 15)	
1.3	All other boilers	Y	Y	1	1	4 (see Note 4)
2	STEAM PRESSURE VESSELS					
2.1	Jacketed vessels					
	$pV \leq 30$ MPa.L	N	N		(See Note 14)	
	$pV > 30$ MPa.L	Y	Y	2	4	8
2.2	Other steam pressure vessels (see Appendix S for deaerators)					
	$pV \leq 30$ MPa.L	N	N	(See Note 14)	(See Note 14)	
	$30 < pV \leq 100$ MPa.L	Y	N	(See Note 14)	(See Note 14)	
	$pV > 100$ MPa.L	Y	Y	2	4	8
3	VESSELS WITH QUICK-ACTUATING CLOSURES					
3.1	Containing gases (including steam)					
	$pV \leq 15$ MPa.L	N	N		(See Note 14)	
	$pV > 15$ MPa.L	Y	Y	2	4	8
3.2	Containing liquids					
	$pV \leq 100$ MPa.L	N	N		(See Note 14)	
	$pV > 100$ MPa.L	Y	Y	2	4	8
4	FIRED HEATERS OR CONVECTION BANKS	Y	Y	2	4	8
5	WATER HEATERS	Y	N	4	12	12
6	COMPRESSED AIR CONTAINING VESSELS					
	$pV \leq 100$ MPa.L	N	N		(See Note 14)	
	$100 < pV \leq 150$ MPa.L	Y	N		(See Note 14)	
	$pV > 150$ MPa.L	Y	N	2	4	12
7	STATIC STORAGE VESSELS (see Notes 5 and 17)					
7.1	Gases (non-corrosive condition) including above-ground LPG storage vessels	Y	N	2	10	12
7.2	Gases (other conditions) including anhydrous ammonia	Y	Y	2	2	4
8	STORAGE TANKS TO API 620 OR EQUIVALENT	(See Appendix T)				

Figure 1: An extract of Table 4.1 from AS/NZS 3788:2006

2 Purpose

Effective application of RBI relies on using a combination of relevant codes and standards, procedures, appropriate RBI methodology, industry knowledge, equipment familiarity and skills in identifying relevant damage mechanisms. The American Petroleum Institute provides RBI guidance documents for the petroleum and petrochemical industries such as API RP 580 Risk-based Inspection [2] and API Publication 581 Risk-based Inspection Base Resource Document [3]. Appendix B of AS/NZS 3788:2006 provides an informative guide on risk management and it refers to AS/NZS 4360 [4] as a generic qualitative Risk Management Standard among other references. This paper facilitates sharing of knowledge on the methodology by providing two examples of RBI application to a crude distillation column and a crude storage tank.

3 Overview of RBI Methodology

RBI methodology uses equipment history and the likely consequences of equipment failure to determine Inspection regimes focused on actual risks, so as to prevent unsafe incidents from occurring. The RBI method adopted by most petroleum oil refineries is based on API 581 base resource document which involved representatives from a number of major oil and petrochemical companies, and a comprehensive statistical analysis of petrochemical facilities over a number of years. Due to the complexity of this RBI method, a computer-based assessment is commonly used.

Each piece of equipment is assigned a risk ranking based on the probability and consequence of failure. Figure 2 shows a typical risk matrix.

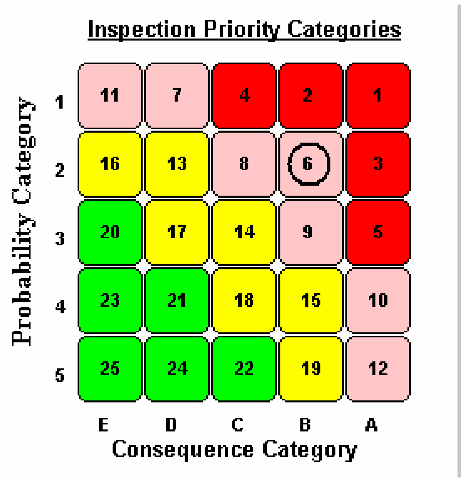

Figure 2 A typical risk matrix (Source: Capstone RBMI software). Red boxes (no. 1 to 5) indicate high risk. Pink boxes (no. 6 to 12) indicate medium-high risk. Yellow boxes (no. 13-19) indicate medium risk. Green boxes (no. 20 to 25) indicate low risk.

Based on this risk ranking, one can decide whether to:

- remove equipment from service and conduct inspection (if equipment is showing high risk and there are no suitable on-line inspection methods available that can help reduce the risk level)
- apply appropriate on-line inspection methods for equipment to help reduce the risk level
- add to equipment inspection scope during turnaround to aid future risk assessments
- leave equipment on-line inspection and/or turnaround inspection scope at current level
- reduce equipment on-line inspection and/or turnaround inspection scope from current level

A clear understanding of expected and possible damage mechanisms for equipment is required to conduct the risk assessment and apply suitable inspection methods to mitigate risk posed by them. In 2002, a RBI industry application study by HSE in the UK [4] found that there is considerable variation in the selection of damage mechanism for assessment and assignment of their importance. A consistent approach is required for the reporting and assessment of damage mechanism. API RP 571 [6] provides valuable guidance in identifying and understanding relevant damage mechanisms in process equipment.

4 Application of RBI to Crude Distillation Column

Conducting RBI on a crude distillation column requires three basic processes:

1. Data collection and condition review
2. Criticality assessment and stakeholders input
3. Inspection planning and implementation

4.1 Data Collection and Review

The RBI process begins by collecting accurate data on the equipment with regards to its process conditions, operating parameters, design, construction & installation considerations, drawings, maintenance activities, reliability, inspection history, modifications to the equipment/process, safety incidents, etc. The data collected is usually entered into a RBI software application that facilitates the RBI process for ease of computation, data management, inspection coordination and consistency between risk assessments.

Identifying the relevant damage mechanisms and their susceptible locations are particularly important for managing the risk of equipment failure. For a physically large piece of equipment such as a crude distillation column containing various process fluids, consideration is given to dividing the equipment into sub-components for this exercise. The column is divided into three sections: (i) Top section - consisting of the top head and top section of the distillation column with light fractions; (ii) Middle section – representing a large portion of the distillation column's cylindrical body containing medium fractions; (iii) Bottom section – including the bottom head and bottom section of the distillation column with heavy fractions. Refer to Table 1 for damage mechanisms identified at these three sections.

Table 1 - Damage mechanisms in a crude distillation column, measures for their prevention/mitigation and inspection/monitoring. (*Compiled from damaged mechanisms covered in Ref. [6]*)

Column Location	Damage mechanisms	Prevention/Mitigation	Inspection/Monitoring
Top	Ammonium Chloride Corrosion	Use Ni and Ti based alloys, but some may suffer pitting corrosion Limit chlorides in tower feed through desalting and/or caustic addition to desalted crude Flush salt deposits on overhead line with water wash Control corrosion with filming amine inhibitors	Look for localised accumulation of ammonium chloride salts Monitor thickness loss - RT, UT Monitor ammonia and chlorides in feed streams Look for drop in thermal performance and pressure drop of downstream heat exchangers Use corrosion probes or coupons but deposits must be on them to work
	HCl Corrosion	Reduce chloride in feed by optimising crude oil tank water separation & withdrawal, and crude desalting operation Upgrade carbon steel to Ni or Ti based alloys Water wash to quench overhead stream and help dilute condensing HCl concentration Inject caustic downstream of desalter to reduce amount of HCl going overhead. Use proper design and operating methods to avoid caustic SCC and fouling in feed preheat train. Inject various combinations of ammonia, neutralising amines and filming amines in overhead line before water dew point.	Monitor general thinning on carbon steel, look for highly localised thinning where a water phase is condensing Look for signs of serious corrosion at mix points where dry chloride containing streams mix with streams containing free water or where water saturated streams are cooled below the dew point Use UT scanning or profile RT to identify locally thinned areas Use an effective process & corrosion monitoring program Regularly check the water pH in the boot of overhead accumulator, also check chloride and iron content. Use strategically placed corrosion probes/coupons
Middle	Sulfidation	Upgrade to higher chromium alloy Use solid or clad 300 Series SS or 400 Series SS Use aluminium diffusion treatment of low alloy steel components	Monitor process conditions for increasing temperatures and/or changing sulphur levels Use thermocouples and/or IR thermography to monitor temperature Check for thickness loss with UT and RT Verify alloy used with PMI, prevent alloy mix-ups
	Naphthenic Acid Corrosion (NAC)	Change or blend crudes, upgrade metallurgy, utilise chemical inhibitors. Use alloys with higher molybdenum content, 317L SS Use high temperature NAC inhibitors	Use RT as primary detection method for localised erosion, followed by UT Monitor Total Acid Number (TAN) and sulphur content of crude change and side streams Use corrosion probes/coupons, H_2 probes Monitor streams for Fe and Ni content
	Erosion/ Erosion-Corrosion (E/EC)	Improve design on shape, geometry and materials selection Increasing substrate hardness using harder alloys or surface-hardening treatments Use corrosion-resistant alloys , alter process environment	Visual inspection, UT or RT – look for troublesome areas and detect thickness loss Specialised corrosion coupons, on-line corrosion monitoring electrical resistance probes On-line IR scans
	Chloride Stress Corrosion Cracking (Cl SCC)	Use resistant materials, properly apply coatings under insulation and design out stagnant regions to avoid chloride accumulation. High temperature stress relief 300 Series SS after fabrication considering the effects of sensitisation. Hydrotest with low chloride content water, rinse & dry out thoroughly and quickly.	Visual inspection, PT, UT, phase analysis EC techniques For PT, may need polishing or high-pressure water blast RT may not be sufficiently sensitive to detect cracks except in advanced stages (network of cracks)

Column Location	Damage mechanisms	Prevention/Mitigation	Inspection/Monitoring
Bottom	Sulfidation	Refer to "Sulfidation" above	Refer to "Sulfidation" above
	NAC	Refer to "NAC" above	Refer to "NAC" above
	E/EC	Refer to "E/EC" above	Refer to "E/EC" above
	Cl SCC	Refer to "Cl SCC" above	Refer to "Cl SCC" above
	885°F (475°C) embrittlement	Use low ferrite or non-ferritic alloys or avoid material exposure to embrittling range Reverse embrittlement by heat treating to 1100°F (593°C) followed by rapid cooling(1)	Impact or bend test sample removed from service Look for cracking formed during turnarounds, startup or shutdown when material is below ~200°F (93°C) Check for increase in hardness

Note: (1) If the de-embrittled component is exposed to the same service conditions it will re-embrittle faster than it did initially.

Reviewing the data collected before using them for the criticality assessment underpins an accurate outcome, after all, there is a saying of "garbage in, garbage out". The RBI analyst should review the equipment inspection history being mindful of the relevant damage mechanisms, their effects on the equipment and effectiveness of inspections done in the past. Communication with stakeholders such as production, engineering, maintenance and inspection personnel is necessary to form a complete picture about the equipment and gain insight about it that is not often readily documented.

Equipment data and information relevant to the risk assessment are entered into the RBI software application before criticality assessment. A simple calculation of corrosion rates (e.g. external and internal) is often required and their entry into the RBI application should be accompanied by a clear explanation of their basis.

4.2 Criticality Assessment and Stakeholders Input

Criticality can be assessed for each three sections of the crude distillation column using section-specific information to determine the consequence and probability of failure. The consequence of failure usually considers flammability, toxicity and production loss, while the probability of failure usually considers the effects of internal & external corrosion, environmental cracking and other damage mechanisms. Other considerations for consequence and probability may be included depending on the configuration of RBI software application and user requirements. For the criticality analysis on each column section, a risk level can be evaluated for the section's current state and risk levels can be evaluated for the section's future states, depending on the number of equipment run length intervals being considered, or the level of conservatism used in the criticality analysis (e.g. Comparing risk using a more severe corrosion rate versus a less severe corrosion rate to reflect various repair or operating strategies). Figure 3 shows a typical criticality assessment for the top head of a crude distillation column.

Stakeholders input from operations, engineering, environmental, safety and maintenance departments may be required to accurately reflect the consequence of failure. The RBI analyst must carefully interpret inspection records and seek input from experienced inspectors when addressing the probability of failure. A range of personnel are involved in equipment integrity assurance and reliability maintenance, effectively using the input from various stakeholders will help produce accurate criticality outputs for the equipment's current and future states.

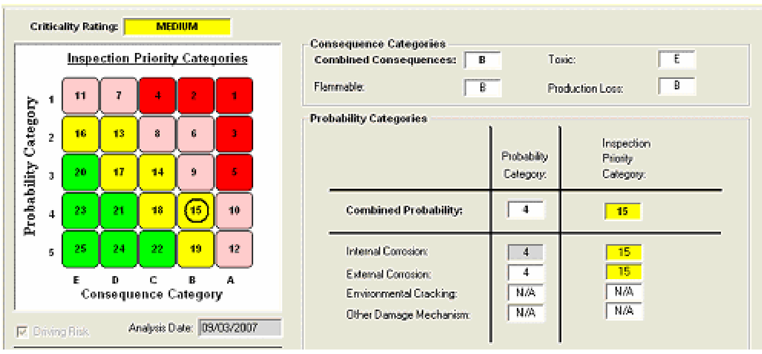

Figure 3 A typical criticality assessment for the top head of a crude distillation column using Capstone RBMI, an RBI software application (© Lloyd's Register Capstone, Inc.)

4.3 Inspection Planning and Implementation

An inspection plan is developed based on the criticality evaluated in the current state and future states of the crude distillation column for its three sections, and the acceptable level of risk. For example, following equipment turnaround with an effective inspection scope (and repairs if required), one would not expect the equipment to still show high criticality. If a high criticality is evaluated for its future state depending on its run length, design, inspection history, relevant damage mechanisms, environment, operating & process conditions, and consequence parameters, then one or a combination of these must be addressed in order to reduce the criticality to a more acceptable level (e.g. medium or low).

For a crude distillation column, the inspection and monitoring measures presented in Table 1 should be included in the inspection plan along with regular on-line visual external inspection. The inspection scrutiny for each type of damage mechanism should be matched with the equipment history, as well as process and operating conditions.

5 Application of RBI to Crude Storage Tank

Application of RBI to a crude storage tank follows a similar process to the crude distillation column with the following exceptions.

5.1 Data Collection and Review

The tank is divided into three sections: (i) Bottom - consisting of the annular plates and floor island plates. Sometimes, these are divided into two sub-sections for analysis. (ii) Shell –the tank shell strakes; (iii) Roof – the roof plates. Relevant damage mechanisms are:

- HCl Corrosion – related to crude heating
- Mechanical fatigue – at shell corner joint with regular tank filling and emptying
- Atmospheric corrosion – tank external components
- Corrosion under insulation – for insulated crude tanks with heavy crude
- Microbiologically induced corrosion – crude with hydrocarbon contaminants and water present
- Soil corrosion – underside of tank bottom

5.2 Criticality Assessment and Stakeholders Input

Criticalities are assessed for the tank bottom, shell and roof representing the equipment's current state and future states.

5.3 Inspection Planning and Implementation

An inspection plan is developed based on the criticalities evaluated in the current state and future states of the tank for its three sections, and the acceptable level of risk. Implementing this plan and re-assessing this plan is crucial to keeping the risk ALARP.

6 Conclusions

With RBI, the equipment risk is managed by:

- Understanding the failure mechanism, susceptible locations, analysing the risk of sub-components, identify and address the highest risk, planning inspection and addressing the risk with stakeholders to prevent all undesired failures.
- Monitoring process variables and recognising changes in the process such as upset conditions, change in process composition and operating limits. A management of change system is required.
- Knowing the level of inspection confidence (data representative of equipment's true condition and location) and inspection quality. Inspection confidence reflects how accurately inspection data represents the true condition of equipment, it relates to the damage type identified, inspection method used for its detection and location inspected. Inspection quality reflects the repeatability of the inspection process in terms of equipment access, instruments, operator, environment and process.

When applied and implemented properly, value is obtained from RBI by reducing equipment risk and cost.

References

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