RBI: A Quantitative Solution Made Practical

by Lynne Kaley, P.E. and Phil Henry P.E.

- Lynne Kaley
  - Materials/Corrosion and Risk Management Engineer
  - 30 Years Refining, Petrochemical and Midstream Gas Processing Experience
  - Leader in Risk-Based technology development for plant applications
  - Project Manager of API RBI Joint Industry Project since 1996
  - Member of API committees for development of API 580 and API 581 recommended practices
  - Developer and Official Trainer for API 580/581 Public Training course
  - Vice President and Principal Engineer with Equity Engineering
- Philip A. Henry
  - Principal Engineer, RBI Technology Lead
  - 24 Years Refining consulting experience in heat transfer, fluid flow and pressure relieving systems
  - Chairman of API PRS task force for STD520, "Sizing, Selection and Installation of pressure relieving devices"
  - BME - Cleveland State University

E2G The Equity Engineering Group, Inc.

Purpose

- Purpose of Presentation
  - Highlight differences between the 1st & 2nd edition of API 581
  - Summarize key aspects and upcoming changes in the 2nd Edition of API 580
  - Highlight important areas in API 580 and 581 to the plant inspector
  - Discuss the role of the inspector in RBI
  - Demonstrate the practical application of RBI
- Sources
  - API RBI User Group Joint Industry Project
  - API 580
  - API 581
  - API 510, 570, 653
  - API 571
  - API RBI Software

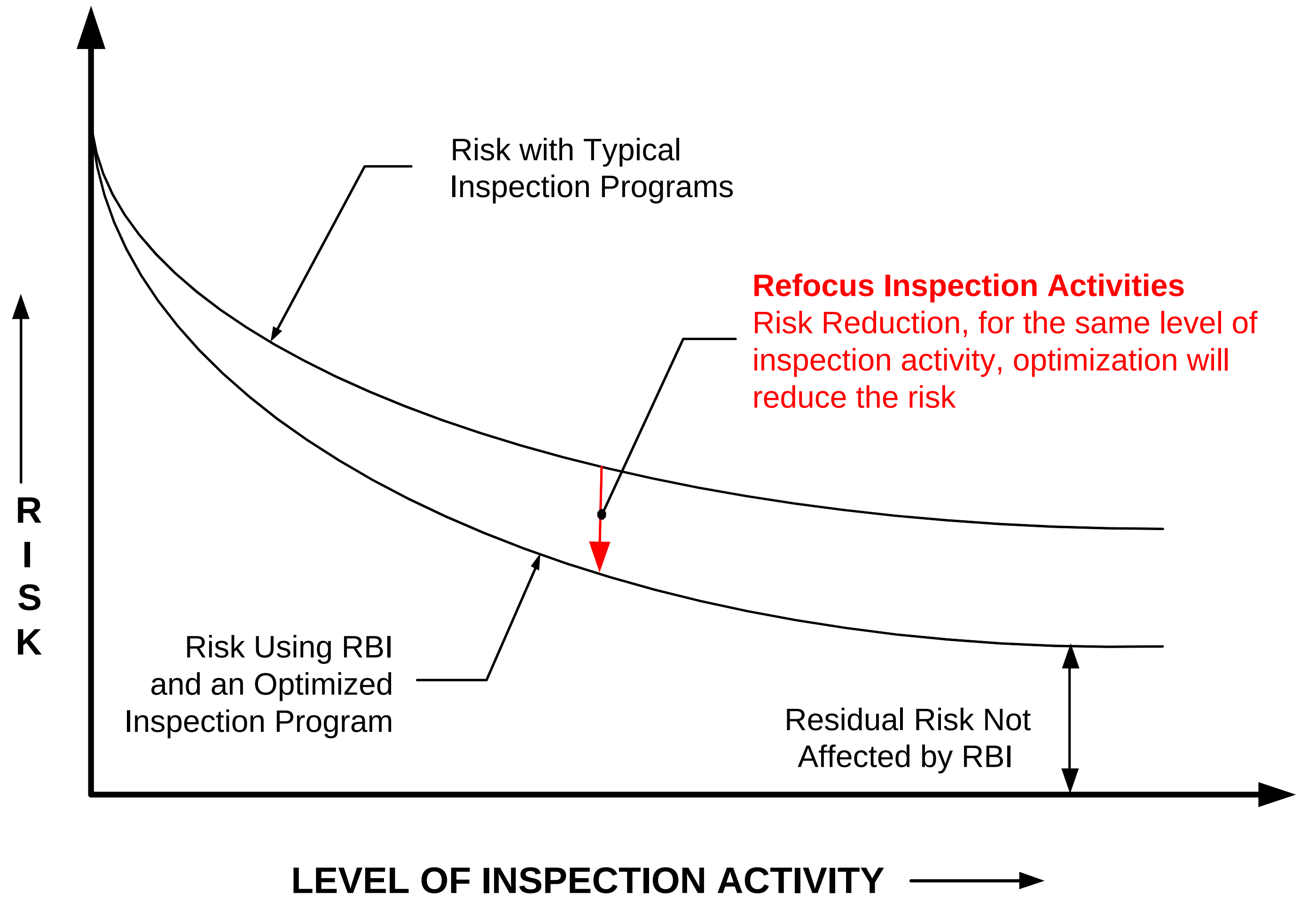
Presentation Overview

- Introduction
- API RBI Document Status
- API 580 Overview
- API 581 Overview
- Risk Analysis
- Probability of Failure
- Consequence of Failure
- Inspection Planning
- Practical Examples of Results
- Summary

Introduction

- The API Risk-Based Inspection (API RBI) methodology may be used to manage the overall risk of a plant by focusing inspection efforts on the equipment with the highest risk
- API RBI provides the basis for making informed decisions on inspection frequency, the extent of inspection, and the most suitable type of Non-Destructive Examination (NDE)
- In most processing plants, a large percent of the total unit risk will be concentrated in a relatively small percent of the equipment items
- These potential high-risk components may require greater attention, perhaps through a revised inspection plan
- The cost of increased inspection effort may sometimes be offset by reducing excessive inspection efforts in the areas identified as having lower risk

Introduction



Introduction

- Calculation of Risk in API RBI
  - Involves determination of Probability Of Failure (POF) and consequence of failure for pressurized equipment
  - Failure in API RBI is defined as loss of containment resulting in leakage to atmosphere or rupture of vessel
  - Accumulation of damage over time results in increased risk
  - At some point in time, the calculated risk exceeds a user specified risk target and an inspection is required
  - RBI is used to focus resources, including identification and elimination of non-value adding activities
- Role of Inspection in API RBI
  - Inspection is used to better understand the true health or damage state of the equipment
  - Reduces uncertainty, reducing likelihood of unexpected failures

API RBI Document Status

- API RBI was initiated as a Joint Industry Project in 1992, two publications produced
  - API 580 Risk-Based Inspection (1st Edition May, 2002)
    - Introduces the principles and presents minimum general guidelines for RBI
    - 2nd Edition targeted for 2009
  - API 581 Base Resource Document – Risk-Based Inspection (1st Edition May, 2000)
    - Provides quantitative RBI methods for inspection planning
- API 581 API RBI Technology (2nd Edition published September, 2008) significantly revised to a new three part document
  - Part 1: Inspection Planning Using API RBI Technology
  - Part 2: Determination of Probability of Failure in an API RBI Assessment
  - Part 3: Consequence Analysis in an API RBI Assessment

Overview of API 580 Contents

- Foreword
- **Section 1 – Purpose**
- **Section 2 – Scope**
- Section 3 – Normative References
- Section 4 – Definitions and Acronyms
- **Section 5 – Basic Risk Assessment Concepts**
- **Section 6 – Introduction to Risk Based Inspection**
- Section 7 – Planning the RBI Assessment
- Section 8 – Data and Information Collection for RBI Assessment
- Section 9 – Damage Mechanisms and Failure Modes
- Section 10 – Assessing Probability of Failure
- Section 11 - Assessing Consequence of Failure
- Section 12 – Risk Determination, Assessment and Management

Overview of API 580 Contents

- Section 13 – Risk Management with Inspection Activities
- Section 14 – Other Risk Mitigation Activities
- **Section 15 – Reassessment and Updating RBI Assessments**
- Section 16 – Roles, Responsibilities, Training and Qualifications
- Section 17 – RBI Documentation and Record Keeping
- **Section 18 – Summary of Pit RBI Pitfalls**

- Appendix A – Damage Mechanisms Descriptions
- Appendix B – Screening Table for Damage Mechanisms
- Appendix C – Screening Table of Examination Methods
- Bibliography

API RP 580 Foreword

- Intended to provide guidance and includes:
  - What RBI is
  - What are the key elements of RBI
  - How to implement an RBI program
- Not intended to
  - supplant other practices that have proven satisfactory
  - discourage innovation and originality in the inspection of hydrocarbon and chemical facilities
  - substitute for the judgment of a responsible, qualified inspector or engineer
  - substitute for code of rules, regulations, or minimum safe practices

API RP 580 Foreword

- A supplement to API Codes and Standards
  - API 510 Pressure Vessel Inspection Code
  - API 570 Piping Inspection Code
  - API 653 Tank Inspection, Repair, Alteration and Reconstruction
- The Codes and Standards provide the latitude to:
  - Plan an inspection strategy
  - Increase or decrease the code designated inspection frequencies based on the results of a RBI assessment.

Section 5 – Basic Concepts

- Risk is something we live with each day

  Risk = Probability x Consequence

- Risk reduction is only a part of risk management. It is a process to:
  - Assess risks
  - Determine if risk reduction is required
  - Develop a plan to maintain risks at an acceptable level

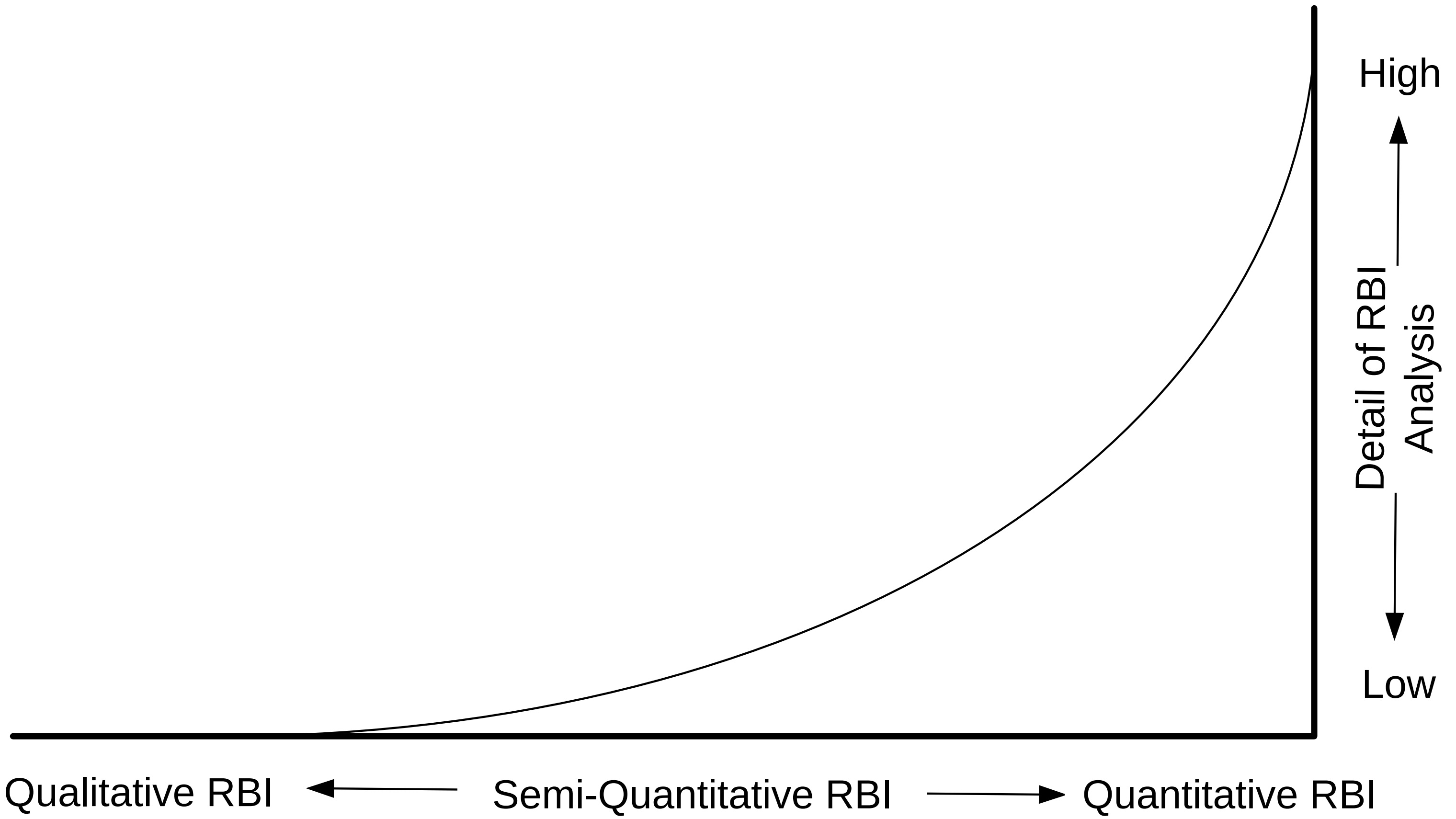
Section 5 – Basic Concepts

- Relative vs. Absolute Risk (5.6)
  - Absolute risk is time consuming and difficult to determine due to uncertainties
  - RBI is focused on the systematic determination of relative risk
  - Serves as a focus of risk management efforts
  - Numeric risk values determined in quantitative assessments use appropriate sensitivity analysis methods

Section 6 – Introduction to Risk-Based Inspection

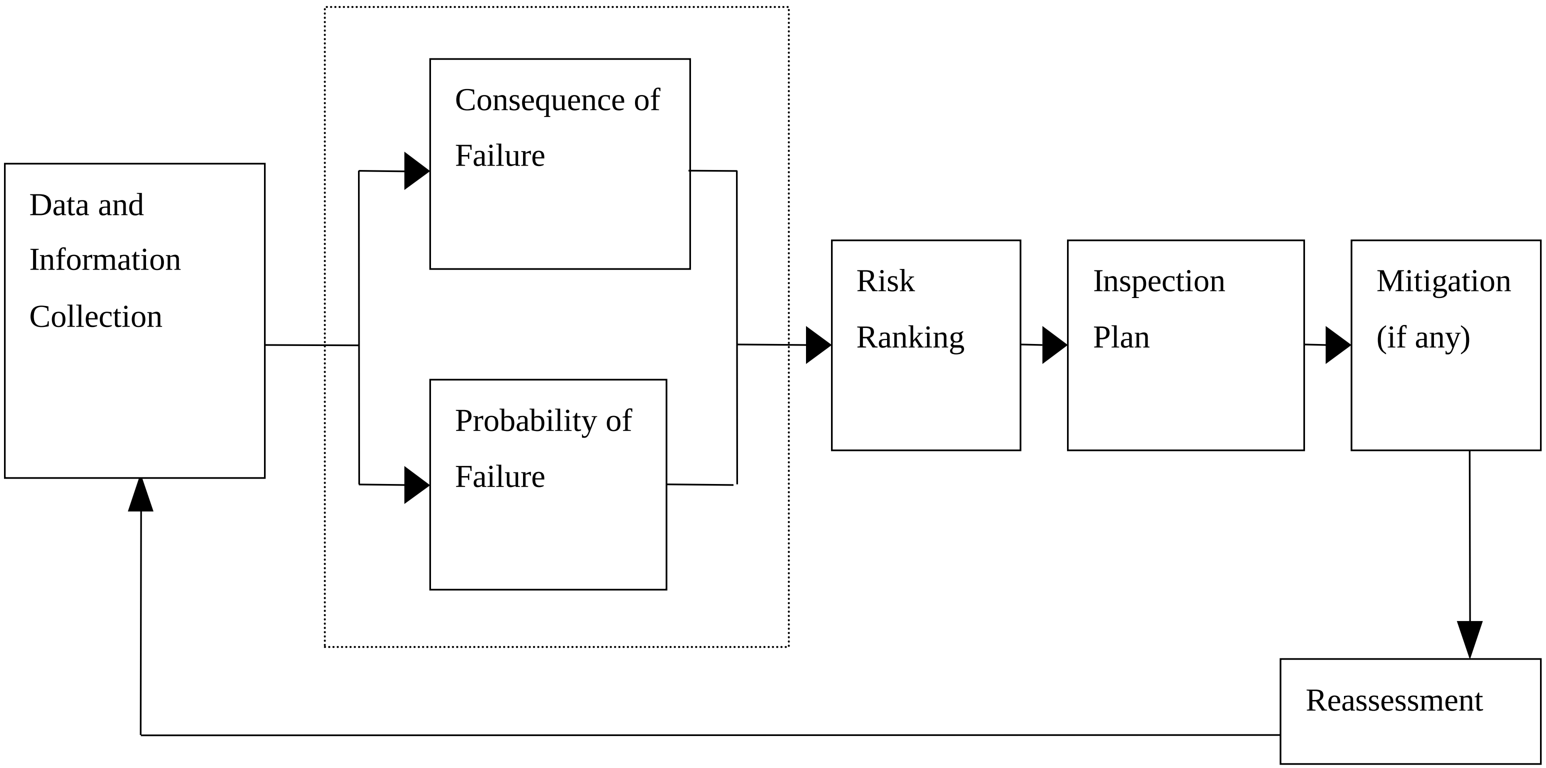
- Types of Assessment (6.2)
  - Qualitative – uses engineering judgment and experience
  - Quantitative – uses logic models and evaluated probabilistically
  - Semi-quantitative
- Continuum of Approaches (6.2.4)

Section 6 – Introduction to Risk-Based Inspection



Section 6 – Introduction to Risk-Based Inspection

Risk Assessment Process



Section 6 – Introduction to Risk-Based Inspection

- Risk associated with equipment is influenced by current operating conditions, such as:
  - Process fluid or contaminants and aggressive components
  - Unit throughput
  - Desired unit run length between scheduled shutdowns
  - Operating conditions, including upset conditions: e.g. pressures, temperatures, flow rates, pressure and/or temperature cycling

Section 6 – Introduction to Risk-Based Inspection

- Risk Management Through Inspection
  - Probability of failure
    - Deterioration type and mechanism
    - Rate of deterioration
    - Probability of identifying and detecting deterioration and predicting future deterioration states with inspection technique(s)
    - Tolerance of the equipment to the type of deterioration

Section 6 – Introduction to Risk-Based Inspection

- Using RBI to Establish Inspection Plans and Priorities
  - Primary output is an inspection plan
  - Risk ranking
  - Mitigation plans

Section 7 – Planning the RBI Assessment

- Clear Objectives and Goals must be defined and understood by the RBI Team and Management.
- The Goals should include:
  - A clear understanding of risk
  - A defined Risk Criteria
  - A plan to manage risk
  - Defined desired results, i.e. safety or environmental and/or cost impact

Section 7 – Planning the RBI Assessment

Considerations for Project Initiation:

- Establish Operating Boundaries
- Consider Start-up, Shut-down, Normal, Upset and Cyclic Operations
- Define Operating Time Period for consideration
- Determine Time and Resources Needed for the Study

Section 7 – Planning the RBI Assessment

- Sort Mitigation Alternatives
  - Examples are; remove unnecessary insulation or upgrade safety systems, change metallurgy
- RBI of New Plant design
- End of Life Strategies
  - Focus inspection to predict actual failure time
  - May incorporate Fitness for Service evaluations for more quantitative analysis per API 579 as part of the strategy

Section 8 – Data and Information Collection for RBI

- General Data Required (8.1)
  - Type of equipment
  - Materials of construction
  - Inspection, repair and replacement records
  - Process fluid compositions
  - Inventory of fluids
  - Operating conditions
  - Safety systems
  - Detection systems
  - Deterioration mechanisms, rates and severity
  - Personnel densities
  - Coating, cladding and insulation data
  - Business interruption cost
  - Equipment replacement costs
  - Environmental remediation costs

Section 8 – Data and Information Collection for RBI

Qualitative Study Needs: (8.1.1)

- Rule Sets
  - Consistency is critical
- Ranges versus Discreet Values
- Higher Skill and Knowledge Levels in RBI Team
  - Must understand data sensitivities

Section 8 – Data and Information Collection for RBI

Quantitative Study Needs (8.1.2)

- More Detailed Information Needed
  - Uses logic models
  - Depicts consequence scenarios
  - Calculates probabilities of events
- Models evaluated probabilistically
  - provide qualitative and quantitative insights
    - Level of risk
    - Identify the design, site, or operational characteristics that are the most important to risk

Section 8 – Data and Information Collection for RBI

- Data Quality (8.2)
  - Good quality data is critical to the relative accuracy of an RBI study
  - Validation step is required to review data for errors
  - Experienced personnel are needed for this step
- The Codes & Standards specify data required to conduct an RBI study (8.3)
- Many other Sources of information exist in an operating facility

Section 9 – Identifying Damage Mechanisms and Failure Modes

- Leads to Loss of Containment
- Critical to Success
  - Role of Corrosion/Materials engineer review
  - Understanding NDE and Damage Mechanisms
  - Impact of operating conditions
    - Normal, upset, start-up, shutdown, etc.
  - Understanding operation vs. Chemical and Mechanical deterioration mechanism identification key to success

Section 10 – Assessing Probability of Failure

- Should consider
  - Deterioration mechanisms
    - Potential, reasonably expected
    - Susceptibility and rate
  - Inspection effectiveness
    - Quantify the effectiveness of the past inspection and maintenance program and a proposed future inspection and maintenance program.
    - Determine the probability that with the current condition, continued deterioration at the predicted/expected rate will exceed the damage tolerance of the equipment and result in a failure.
    - The failure mode (e.g. small leak, large leak, equipment rupture) should also be determined based on the deterioration mechanism.
    - Determine the probability of each of the failure modes and combine the risks.

Section 11 – Assessing Consequences of Failure

- Discriminate items based on the significance of a potential failure
  - Loss of containment
    - Safety and health impact
    - Environmental impact
    - Production losses
    - Maintenance and reconstruction costs
  - Other functional failures can be included
- Units of Measure
  - Safety, cost, affected area, environmental, volume of fluid released, etc.

Section 13 – Risk Management with Inspection Activities

- RBI is reducing uncertainty through inspection (13.1)
- Identifying Risk Management Opportunities from RBI and Probability of Failure Results (13.2)
  - Identify the risk driver
  - Inspection opportunities through POF
- Establishing an Inspection Strategy Based on Risk Assessment (13.3)
  - Mode of failure of the deterioration mechanism
  - Time interval between the onset of deterioration and failure, i.e. speed of deterioration
  - Detection capability of inspection technique
  - Scope of inspection
  - Frequency of inspection

Section 13 – Risk Management with Inspection Activities

- Managing Risk with Inspection Activities
  - Quantify current risk based on inspection results and past effectiveness (eg. Frequency, coverage, tools, internal/external inspections)
  - Use RBI to determine future risk based on various inspection options (What-If)
- Managing Inspection Costs – risk reduction/$ (13.2)
- Assessing Inspection Results and Determining Corrective Action (13.3)
- Achieving Lowest Life Cycle Costs (13.4)

Section 15 – Reassessment and Updating RBI Assessments

- RBI is a dynamic tool that can provide current and projected future risk based on data and knowledge at the time of the assessment
- With time, changes occur that require updating and an RBI assessment
- It is important to maintain and update a RBI program to assure the most recent inspection, process, and maintenance information is included
- The results of inspections, changes in process conditions and implementation of maintenance practices can all have significant effects on risk and can trigger the need for a reassessment

Section 15 – Reassessment and Updating RBI Assessments

- Reasons to Conduct an RBI Reassessment:
  - Deterioration Mechanisms and Inspection Activities
  - Process & Hardware changes
  - RBI Assessment Premise Change
  - Effect of Mitigation Strategies
- When to Conduct an RBI Reassessment
  - After significant changes
  - After a set Time Period
  - After Implementation of Risk Mitigation Strategies
  - Before and After Maintenance Turnarounds

Section 16 – Roles, Responsibilities, Training and Qualifications

- Team Leader
  - Full time, stakeholder
- Equipment Inspector or Inspection Specialist
  - Data gathering
  - Inspection effectiveness translation
  - Implementing the inspection plan
- Materials and Corrosion Specialist
- Process Specialist
- Operations and Maintenance Personnel

Section 16 – Roles, Responsibilities, Training and Qualifications

- Training
  - Leaders
    - Thorough understanding risk analysis and of the methodology via training, experience or education
  - Support staff
    - Basic RBI methodology training
      - Effective implementation
- Document Qualifications and Training
  - Procedure to document qualifications and training of practitioners

Section 17 – Documentation and Record-Keeping

- Fully Document the Assessment
  - Type of assessment
  - Team members performing the assessment
  - Timeframe over which the assessment is applicable
  - The inputs and sources used to determine risk
  - Assumptions made during the assessment
  - The risk assessment results (including information on probability and consequence)
  - Follow-up mitigation strategy, if applicable, to manage risk
  - The mitigated risk levels (i.e. residual risk after mitigation is implemented)
  - References to codes or standards that have jurisdiction over extent or frequency of inspection

Section 17 – Documentation and Record-Keeping

- Sufficient to:
  - Recreate the assessment if needed
  - Update the assessment

By those not involved in the original assessment!

Section 18 – Summary of RBI Pitfalls

- Pitfalls that can lead to less than adequate results (examples):
  - Poor planning – unclear objectives, undefined operating boundaries, inadequate management support or RBI resources, unrealistic expectations
  - Poor Quality Data & Information Collection – poor quality data, failing to collect data needed
  - Damage Mechanisms and Failure Modes – not properly identifying and analyzing appropriate damage mechanisms
  - Assessing Probability of Failure – incorrect assignment of damage mechanisms or damage rates, poor assessment of past inspection
  - Assessing Consequence of Failure – incorrect assessment of potential hazards or outcomes
  - Determination, Assessment and Management – using "black box" technology, inadequate use or documentation of assumptions

Section 18 – Summary of RBI Pitfalls

- Pitfalls that can lead to less than adequate results (examples):
  - Risk Management with Inspection Activities – inadequate inspection planning basis, inadequate planning for inspection resources
  - Other Risk Management Activities – not considering risk management activities other than inspection
  - Reassessment and Updating RBI Assessment – not understanding the dynamic nature of risk over time, not having a good link between RBI and MOC
  - Roles, Responsibilities, Training and Qualifications for RBI Team Members – inadequate skills, training, or experience, or knowledge
  - RBI Documentation and Record-Keeping – Not understanding the need for proper documentation and assumptions

API 510, Ninth Edition

- RBI used to establish appropriate inspection intervals for internal, on-stream and external inspection
  - Allow intervals other than 10 year inspection and ½-life limits for internal and on-stream inspections
  - Allow intervals other than 5 year inspection limits for the external inspections.
- When using an RBI interval for the internal or on-stream, the RBI assessment shall be reviewed and approved by the engineer and inspector at least every 10 years

API 510, Ninth Edition

- RBI assessment review should include review of inspection history and potential for pressure-relieving device(s) fouling
- An RBI assessment can be done to exceed the following inspection intervals for pressure-relieving devices:
  a. Five years for typical process services
  b. Ten years for clean (non-fouling) and noncorrosive services

API 570, Second Edition

- RBI assessment used to develop appropriate inspection intervals for thickness and external inspections (Table 6-1)
- RBI assessment used to develop appropriate inspection intervals for CUI inspection after external visual (Table 6-2)
- When using an RBI interval and inspection coverage, RBI assessments shall reviewed at least at the interval recommended in Table 6.1
- The RBI assessments shall be reviewed and approved by a piping engineer and authorized piping inspector

API 653, Third Edition

- RBI assessment used to establish appropriate tank bottom inspection interval (Table 6.1)
- When using an RBI interval for the internal or on-stream, the RBI assessment shall be reviewed and approved by the engineer and inspector at least every 10 years
- Approval by an authorized inspector and an engineer(s), knowledgeable and experienced in tank design (including tank foundations) and corrosion

API 580 Summary

- Selection process for RBI approach
- Type of process and technology (qualitative vs. quantitative)
- Documented and structured implementations work process
- Documented methodology and risk calculation procedure
- Consistent approach
  - Procedure
  - Facilitator training Consequence analysis
- Probability analysis
- Corrosion/Materials review
- Documented technical basis
- Inspection Planning approach
  - Is there a risk mitigation plan
  - Follow through mechanism
- Re-evaluation process and trigger
- Link to MOC process
- RBI Team Training

API 581 Document

- Part 1 - Inspection Planning Using API RBI Technology
  - Calculation of Risk as a combination of POF and COF
  - Inspection Planning using time stamping
  - Presentation of results, Risk Matrix (area and financial) – introduce user specified POF and COF category ranges
  - Risk Calculations for Vessels, Piping, Tanks, Bundles and PRDs
- Part 2 - Determination of Probability of Failure in an API RBI Assessment
  - POF calculation
  - Part 2, Annex A - Management Score Audit Tool
  - Part 2, Annex B - Corrosion Rate Determination
- Part 3 - Consequence Modeling in API RBI
  - COF calculation
    - Level 1 modeler with step-by-step procedure
    - Level 2 modeler providing rigorous procedure
    - Tank model consequence calculation
  - Part 3, Annex A - Detailed background of Level 1 and Level 2 consequence modeler
  - Part 3, Annex B – SI and US Unit Conversion Factors

API 581 Document

- Major improvements in API RP 581 2nd Edition
  - Step-by-Step procedures to demonstrate the technology, fully illustrate calculation procedures, and stimulate peer review
  - Improved damage calculations, introduction of t_{min} calculation
  - Multi-level consequence models
  - New algorithm for inspection planning utilizing user specified risk targets
  - Inclusion of RBI models for atmospheric tanks, heat exchanger bundles and pressure relief devices

Risk Analysis

- In general, risk is calculated as a function of time as follows

$$R(t) = POF(t) \cdot C(t)$$

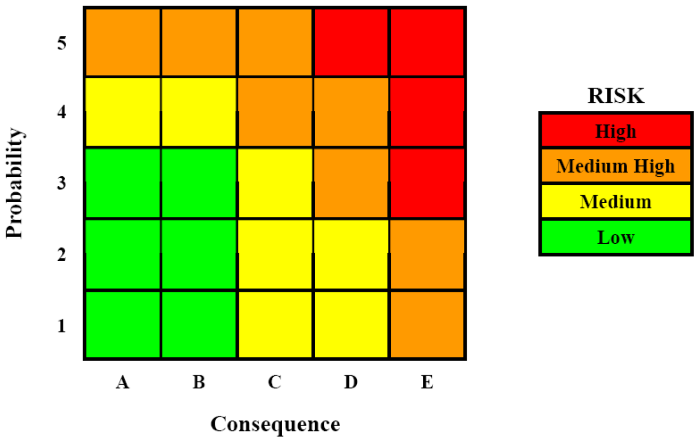
- The probability of failure is a function of time, since damage due to cracking, thinning or other damage mechanisms increases with time
- In API RBI, the consequence of failure is assumed to be independent of time, therefore

$$R(t) = POF(t) \cdot CA \qquad for\ \ Area - Based\ \ Risk$$

$$R(t) = POF(t) \cdot FC \qquad for\ \ Financial - Based\ \ Risk$$

Risk Analysis

- Risk ranking of equipment at a defined point in time may be shown using a Risk Matrix
- Priority for inspection efforts is often given to components in the HIGH or MEDIUM-HIGH risk category



Numerical Values Associated with Consequence and Probability Categories in API RBI

Probability Category (1)		Consequence Category (2)	
Category	Range	Category	Range
1	$D_{f-total} \le 2$	A	$CA \le 100$
2	$2 < D_{f-total} \le 20$	B	$100 < CA \le 1000$
3	$20 < D_{f-total} \le 100$	C	$1000 < CA \le 3000$
4	$100 < D_{f-total} \le 1000$	D	$3000 < CA \le 10000$
5	$D_{f-total} > 1000$	E	$CA > 10000$

Notes:
1. In terms of the total damage factor.
2. In terms of maximum component consequence area.

$$CA = \max\left[CA_{cmd},\ CA_{inj}\right]$$

Probability Of Failure

- The Probability Of Failure used in API RBI is:

$$POF(t) = gff \cdot D_f(t) \cdot F_{MS}$$

$$where:$$

$$\begin{array}{ll} POF(t) & - \ the\ probability\ of\ failure\ as\ a\ function\ of\ time \\ gff & - \ generic\ failure\ frequency \\ D_f(t) & - \ damage\ factor\ as\ a\ function\ of\ time \\ F_{MS} & - \ management\ systems\ factor \end{array}$$

- The time dependency of probability of failure is the basis of using RBI for inspection planning

Probability Of Failure

- Methods for determining damage factors are provided in API 581 covering the following damage mechanisms

$$D_{f-total} = \min\left[D_f^{thin}, D_f^{elin}\right] + D_f^{extd} + D_f^{scc} + D_f^{htha} + D_f^{brit} + D_f^{mfat}$$

$where:$

D_f^{thin} $-damage\ \ factor\ \ for\ thining\ (corrosion/erosion)$

D_f^{elin} $-damage\ \ factor\ \ for\ equipment\ lining$

D_f^{extd} $-damage\ \ factor\ \ for\ external\ damage$

D_f^{scc} $-damage\ \ factor\ \ for\ stress\ corrison\ cracking$

D_f^{htha} $-damage\ \ factor\ \ for\ high\ temperature\ hydrogen\ attack$

D_f^{brit} $-damage\ \ factor\ \ for\ brittle\ \ fracture$

D_f^{mfat} $-damage\ \ factor\ \ for\ mechanical\ \ fatigue$

Probability Of Failure

- Damage Mechanisms - Thinning
  - Modified A_{rt}, base material without clad or overlay is:

$$A_{rt} = \max\left[\left(1 - \frac{t_{rd} - C_{r,bm} \cdot age}{t_{\min} + CA}\right),\ 0.0\right]$$

where:

A_{rt}	– *is the damage factor parameter for thinning damage*
t_{rd}	– *is the thickness reading*
$C_{r,bm}$	– *is the corrosion rate of the base metal*
age	– *is the time since the last thickness reading*
$t_{\min}$	– *is the minimum required wall thickness of the applicable construction code*
CA	– *is the corrosion allowance*

  - Determine thinning Damage Factors based on A_{rt} using Table 5.11
  - Information on corrosion rates is provided in Annex B

Probability Of Failure

Table 5.11 – Thinning Damage Factors

A_{rt}	Inspection Effectiveness												
	E	1 Inspection				2 Inspections				3 Inspections			
		D	C	B	A	D	C	B	A	D	C	B	A
0.02	1	1	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1	1	1
0.10	2	2	1	1	1	1	1	1	1	1	1	1	1
0.12	6	5	3	2	1	4	2	1	1	3	1	1	1
0.14	20	17	10	6	1	13	6	1	1	10	3	1	1
0.16	90	70	50	20	3	50	20	4	1	40	10	1	1
0.18	250	200	130	70	7	170	70	10	1	130	35	3	1
0.20	400	300	210	110	15	290	120	20	1	260	60	5	1
0.25	520	450	290	150	20	350	170	30	2	240	80	6	1
0.30	650	550	400	200	30	400	200	40	4	320	110	9	2
0.35	750	650	550	300	80	600	300	80	10	540	150	20	5
0.40	900	800	700	400	130	700	400	120	30	600	200	50	10
0.45	1050	900	810	500	200	800	500	160	40	700	270	60	20
0.50	1200	1100	970	600	270	1000	600	200	60	900	360	80	40
0.55	1350	1200	1130	700	350	1100	750	300	100	1000	500	130	90
0.60	1500	1400	1250	850	500	1300	900	400	230	1200	620	250	210
0.65	1900	1700	1400	1000	700	1600	1105	670	530	1300	880	550	500

Probability Of Failure

- Component – t_{min} Calculation
  - Calculation of t_{min} is based on the applicable construction code calculations specific to component geometry type, i.e. cylindrical shell, formed head, etc.
  - Use ASTM material specification to determine all material properties including allowable stress
  - Furnished thickness is actual supplied component thickness, including the original specified corrosion allowance
  - Nominal thickness is a specified design thickness, used if the furnished thickness is not provided, only used for piping components
  - The value of t_{min} used in the calculations is

$$t_{\min} = \max\left[t_{\min,\,pressure},\;\; t_{\min,\,structural}\right]$$

Probability Of Failure

- t_{min} Calculation
  - Calculated t_{min} is based on the original construction code calculations specific to geometry type
  - For a Cylinder:

$$t_{min}^{C} = \frac{PR_c}{SE - 0.6P}$$

$$where:$$

$$t_{min}^{c} - Required\ thickness,\ circumferential\ stress$$

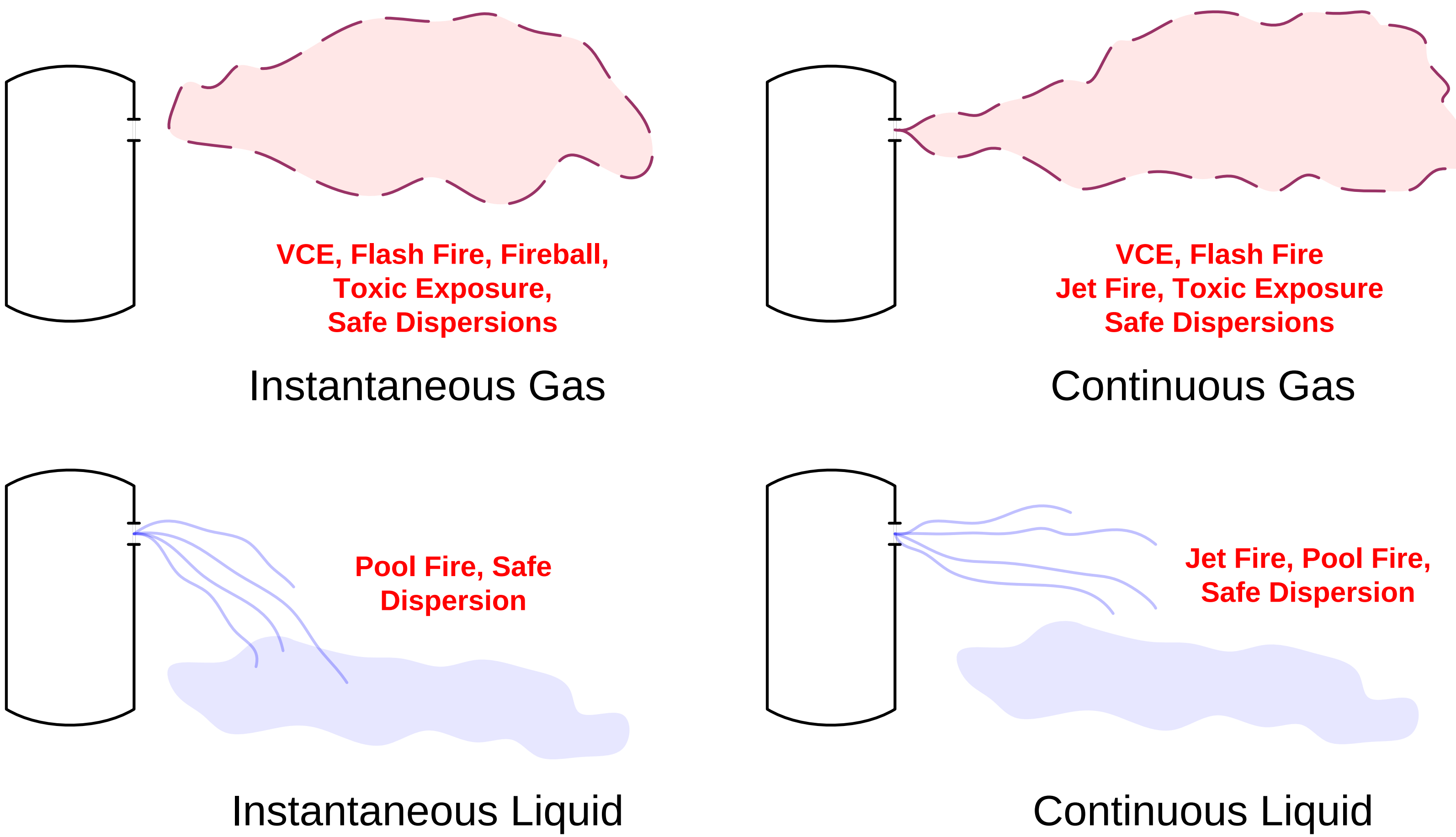
$$P - Design\ pressure$$

$$R_c - Radius\ in\ the\ corroded\ condition$$

$$S - Allowable\ design\ stress$$

$$E - Weld\ joint\ efficiency$$

Consequence of Failure



Consequence of Failure

- The consequence of failure or loss of containment for a pressurized component is expressed as an impact area (ft^2) or in financial terms ($)
- Event outcomes include Vapor Cloud Explosions (VCE), pool fires, jet fires, flash fires, fireballs, physical explosions, BLEVEs and toxic releases
- Use of cloud dispersion analysis is needed for several of the flammable event outcomes and for toxic releases
- Impact areas are calculated based on well-established limits for thermal radiation and overpressure on personnel and equipment
- Impact areas for toxic releases are based on published dosage (concentration and duration) limits such as IDLH (Immediately Dangerous to Life and Health), ERPG (Emergency Response Planning Guideline), Probit Equations and AEGL (Acute Exposure Guideline Levels)

Consequence of Failure

- Final consequence areas are determined as a probability-weighted area of each of the individual event outcome areas

$$CA_{flam} = \left(p \cdot CA\right)_{pool} + \left(p \cdot CA\right)_{jet} + \left(p \cdot CA\right)_{VCE} + \text{..........}$$

$$CA_{flam} = \sum_{i=1}^{n} \left(p \cdot CA\right)_{i}$$

- Financial consequences are calculated including the costs associated with:
  - Equipment repair
  - Downtime and associated production losses
  - Serious injury to personnel
  - Environmental impact
- API RBI provides two levels of consequence modeling

Inspection Planning

- Risk increases with time as component damage increases
- If multiple damage mechanisms occur at the same time, then the principal of superposition is used to derive total risk
- At some point in time, risk reaches the user's specified risk target

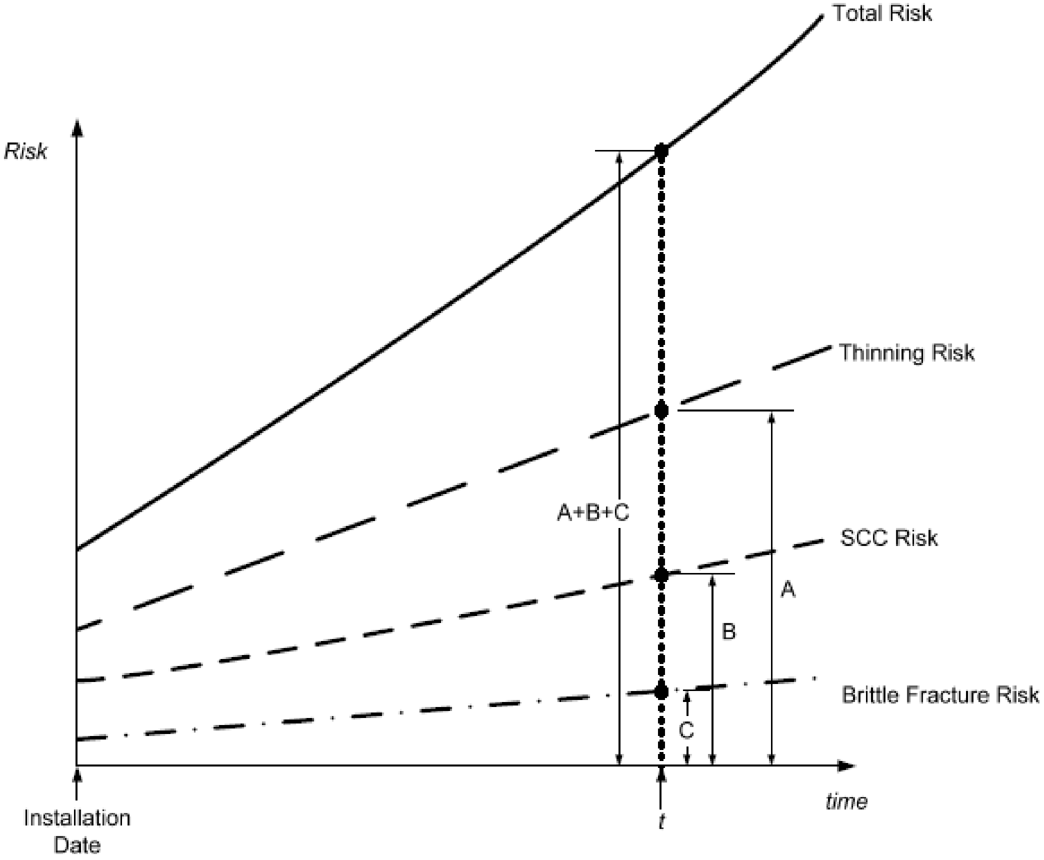


Figure 5 – Superposition Principle for the Calculation of Risk in API RBI

Inspection Planning

- Inspection planning involves recommending the number and level of inspections required to reduce risk to acceptable value at the plan date
- Inspection effectiveness is graded A through E, with A providing the greatest certainty of finding damage mechanisms that are active and E representing no inspection
- Consider the following three cases…..

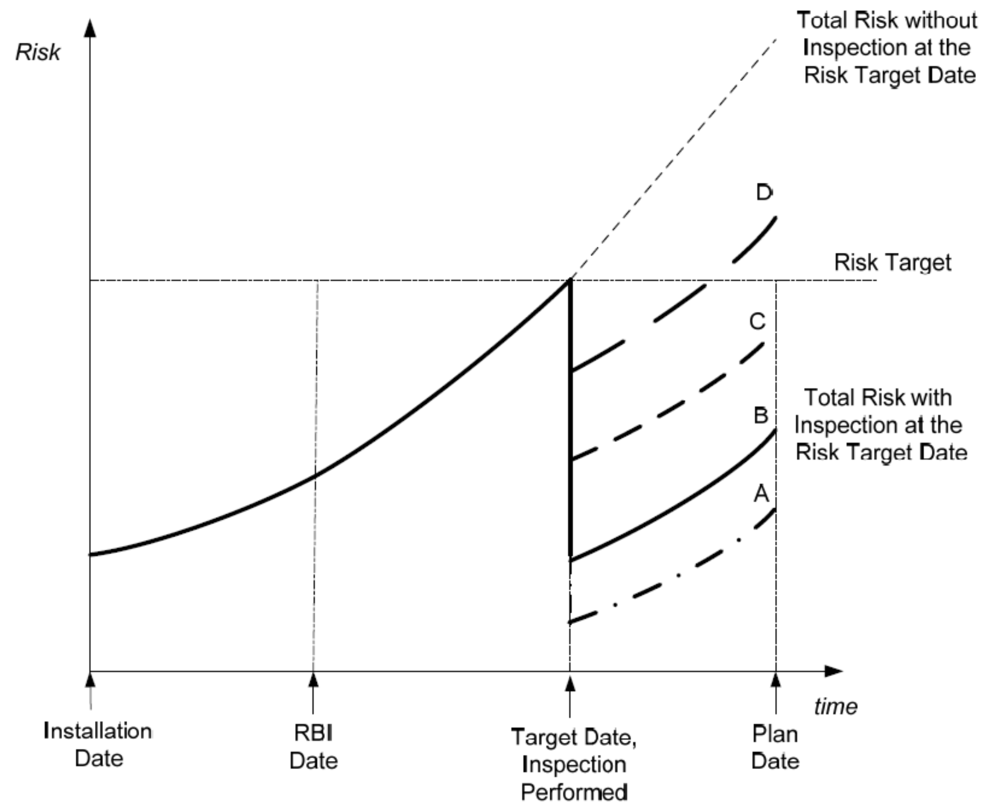


Figure 7 – Case 1: Inspection Planning When the Risk Target is Exceeded Between the RBI Date and the Plan Date

Inspection Planning

- For many applications, the user's risk target has already been exceeded at the time the RBI analysis is performed
- Inspection is recommended immediately

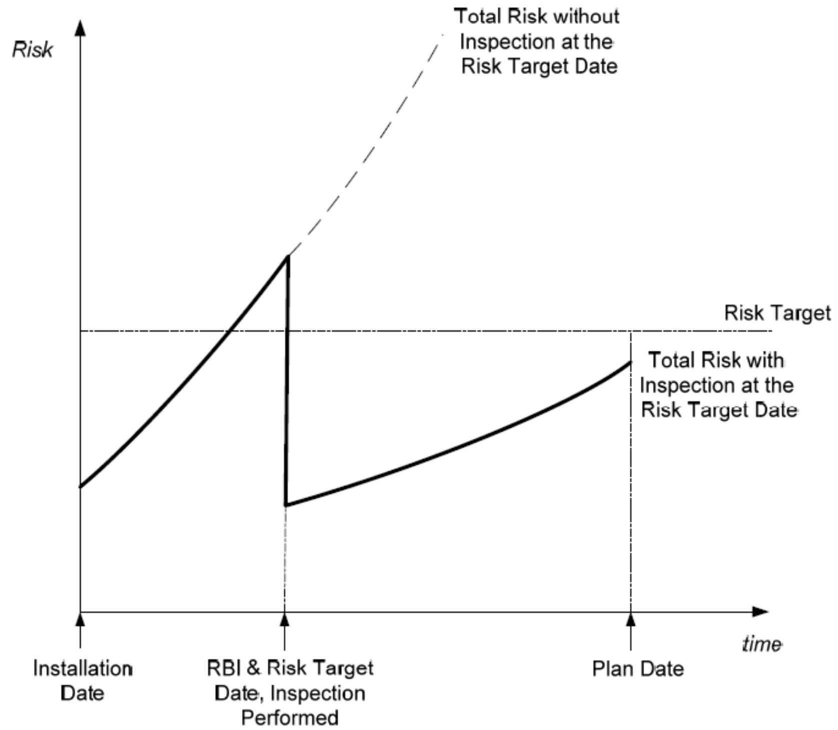


Figure 8 – Case 2: Inspection Planning When the Risk Target has been Exceeded Prior to the RBI Date

Inspection Planning

- When the risk is determined to be acceptable at the plan date, inspection is not required

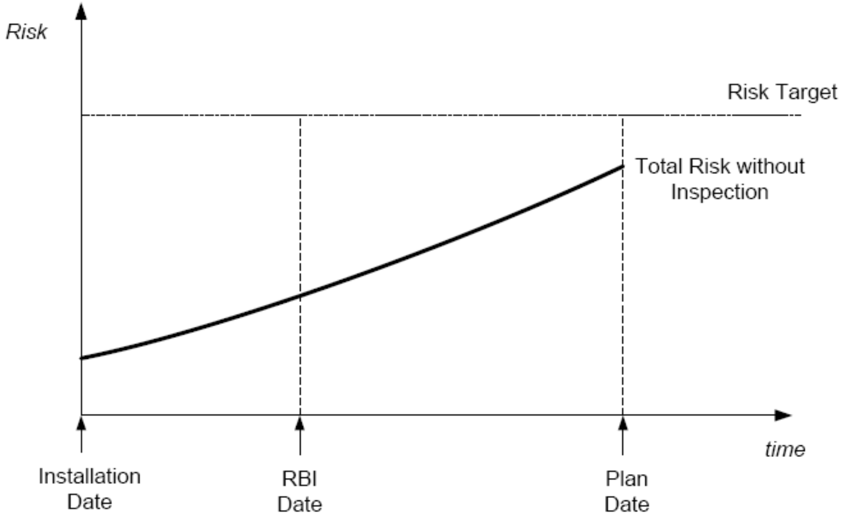


Figure 9 – Case 3: Inspection Planning When Risk Target is Not Exceeded Prior to the Plan Date

Inspection Planning

- Based on the previous three cases, an inspection plan is developed on a component basis
- Equipment is modeled as an assemblage of components in API RBI
- Therefore, the final inspection plan for the equipment is based on the results derived for the components
- The inspection plan includes:
  - The date and timing of the required inspection,
  - The type of NDE (e.g., visual, UT, Radiography, WFMT) based on the active damage mechanisms
  - The extent of the inspection (e.g., percent of total area examined or specific locations)
  - Location of inspection (external or internal)

API RBI Activity

- API RBI was originally developed in a Joint Industry Project (JIP) sponsored by API, the JIP includes 47 companies many with worldwide processing plant facilities
- Stewardship of documented API RBI technology (API 581) has been moved to a consensus Standards Committee within the API Committee on Refinery Equipment
- Consensus committee process ensures industry development, documentation and acceptance of RBI technology
- Data requirements minimal compared with output value
- API RP 581 Second edition released September 2008
- API RP 580 Second edition at final draft/ballot stage

Case Study – Pressure Vessels & Piping

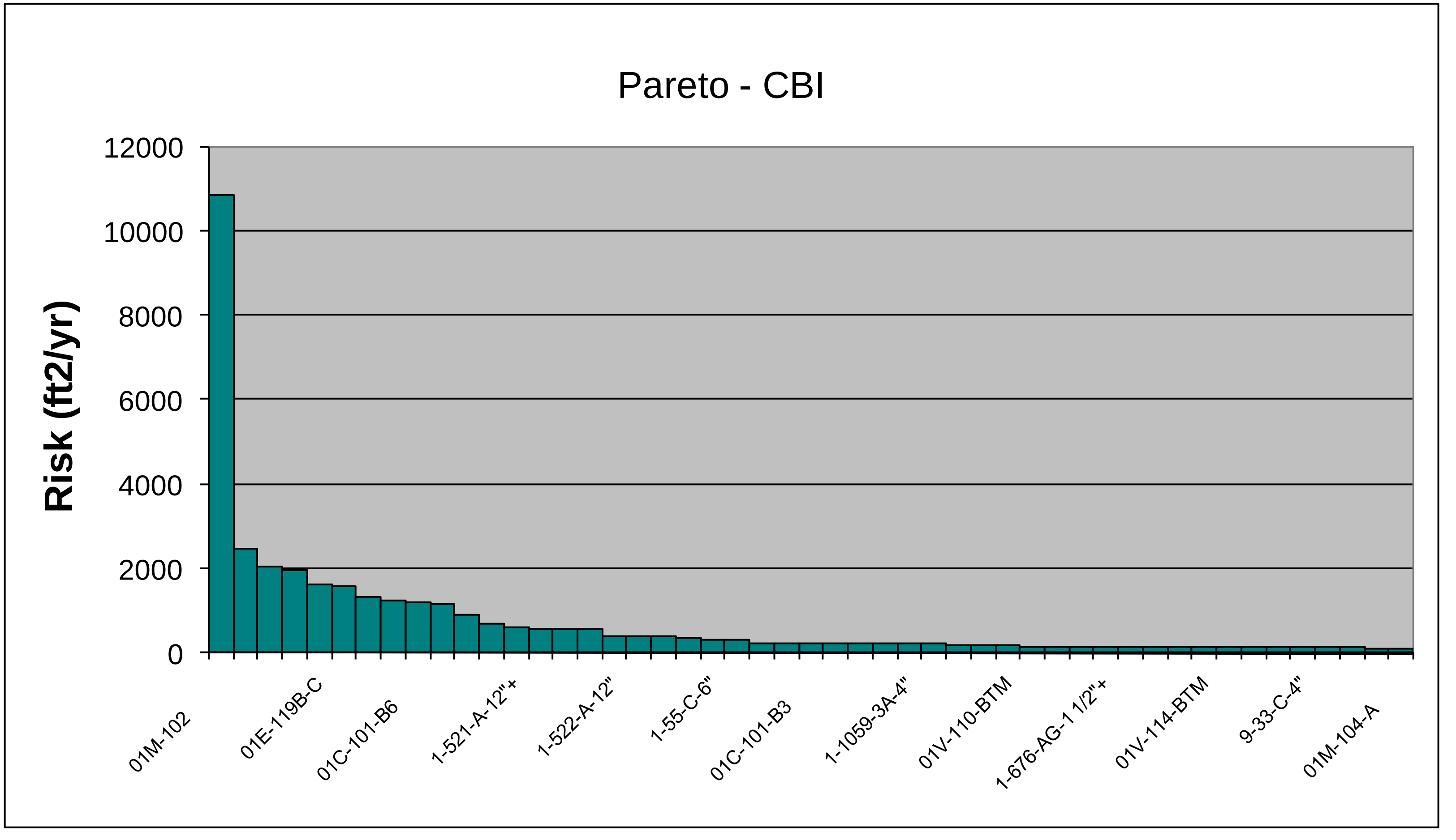
Background:

- Light Ends Recovery Unit (LERU) in a Refinery
- Processing a combination of Light Ends & high levels of H_2S
- 365 total components
  - 188 pressure vessels
  - 177 Piping components
- Production Value on Unit – $200,000/day
- Risk Driven primarily by susceptibility to Wet H_2S damage and toxic releases
- Prior history of cracking and blistering damage in this Unit

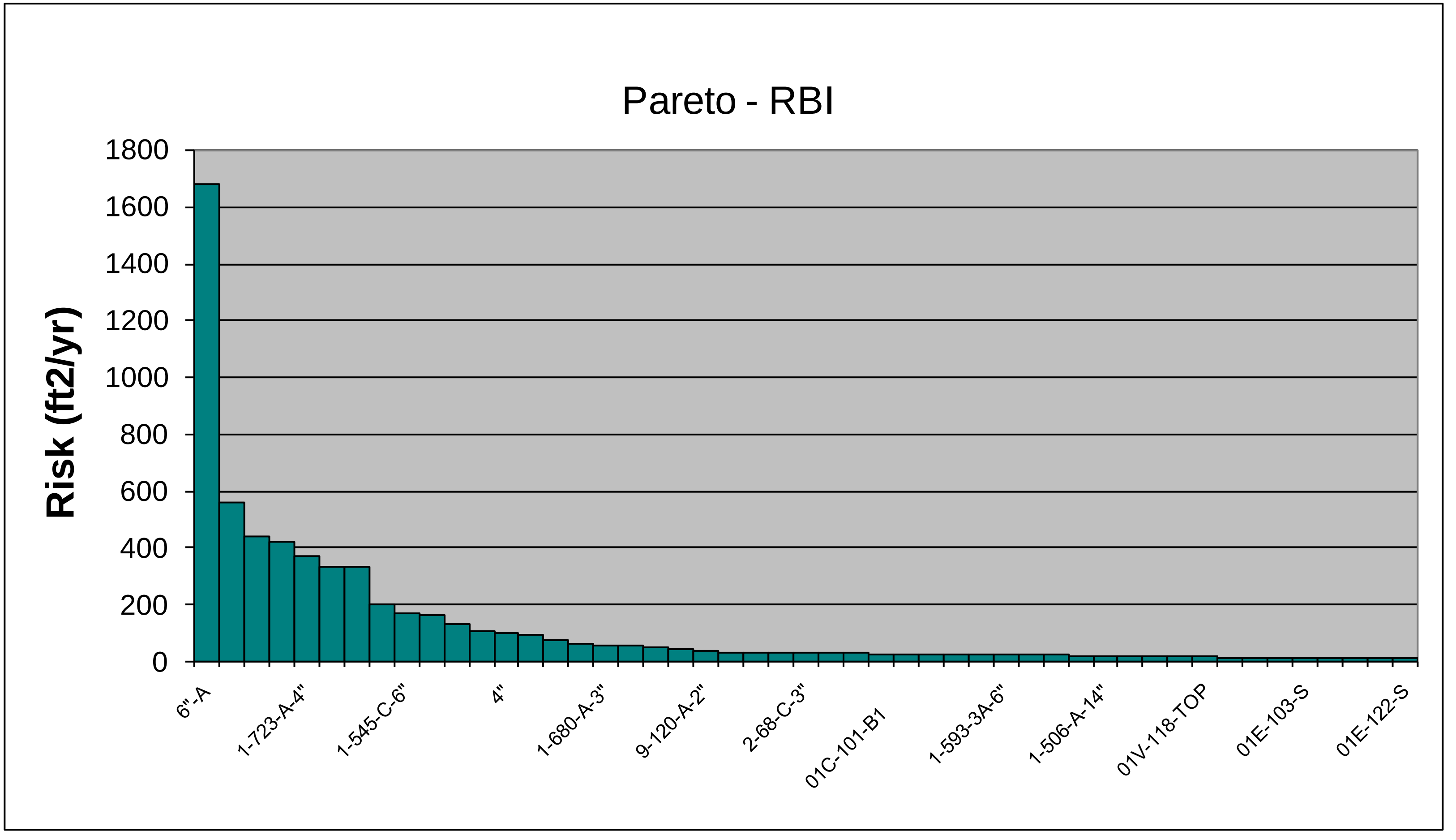
Case Study – Pressure Vessels & Piping

- Risk calculated for RBI Date and Plan Date with and without the planned inspection
- Risk calculated for Condition or Interval-Based inspection (CBI) and Risk-based inspection (RBI)
- Date set for Action, i.e. Inspection, Repair or Replace
  - Repair Efficiency and Cost
  - Replacement Efficiency and Cost
  - Planned Inspection and Cost
- Risk before and after mitigation is calculated for each Inspection, Repair and Replacement option
- Cost Benefit Ratio – Relationship between Risk Reduction as a result of mitigation and the Cost of that mitigation

Case Study – Pressure Vessels & Piping



Case Study – Pressure Vessels & Piping



Case Study – Pressure Vessels & Piping

- LERU Summary
  - Percent risk Reduction
    - CBI = 16.5%
    - RBI = 85.8%
  - Inspection and Inspection-related Maintenance costs reduced by US$ 291,500
  - Cost of RBI Study US$ 22,500
  - Soft Benefits
    - Reduced Risk exposure over operating period
    - Failure Avoidance avoids unexpected failure cost, damage due to consequence of failure and production losses
    - Reduced Risk in general leads to increased safety and improved equipment reliability

Case Study – Pressure Vessels & Piping

Type of Risk	CBI Plan	RBI Plan
Future Risk w/out Inspection, ft^2/year	45,743.7	45,743.7
Future Risk w/ Inspection, ft^2/year	38,179.5	6,493.3
Risk Reduction, ft^2/year	7,564.1	39,250.3
Percent Risk Reduction	16.5%	85.8%
Total Inspection Cost ($) within plan time	US$ 1,846,220	US$ 1,554,720
Financial Risk w/out Inspection, $	US$ 264,381,947	US$ 264,381,947
Financial Risk w/ Inspection, $	US$ 218,106,985	US$ 38,571,428
Percent Financial Risk Reduction	17.5%	85.4%
Cost Benefit Analysis Ratio=ΔRisk/Inspection Cost	25.1	145.2

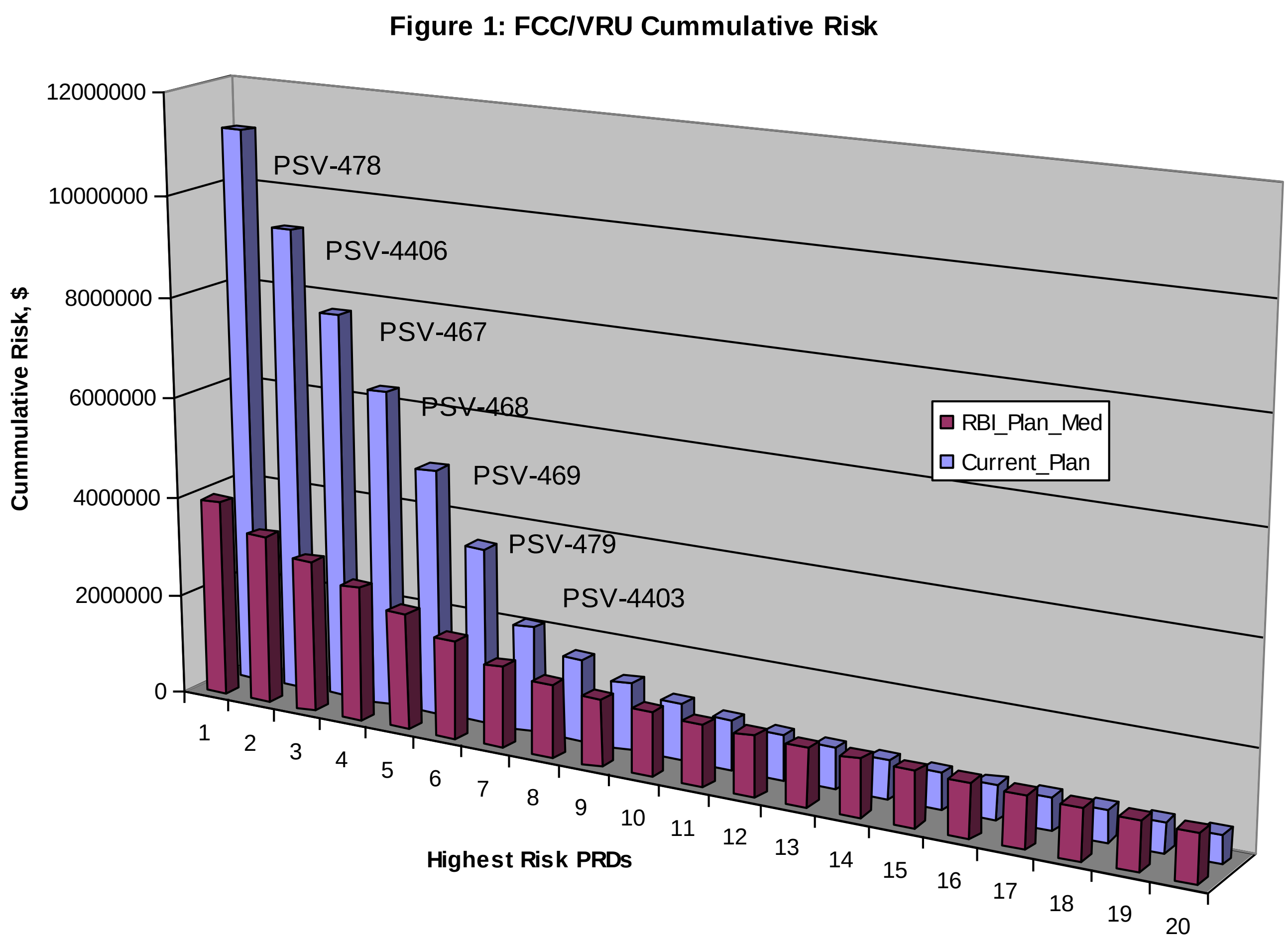
Case Study – Pressure Vessels & Piping

Unit	Type	CBI (% Reduced)	RBI (% Reduced)	Risk Mitigation (% Improvement)
431	DIB/Deprop	11	85	74
866	Heavy HDS	2	50	48
867	SRU	21	93	72
231	Gulfiner	22	50	28
531	Amine	30	68	38
8733	SWS	30	83	53
137	Crude	4	6	2
210B	Crude	53	91	38
210C	Vac	40	68	28
865	Kero HDS	9	49	40
860	Reformer	35	91	56
862	LERU	17	85	68
864	Unifiner	10	63	53
210A	Crude	32	74	42
868	FCC	4	66	62
869	Sulfuric Alky	16	60	44

Case Study- Pressure Relief Devices

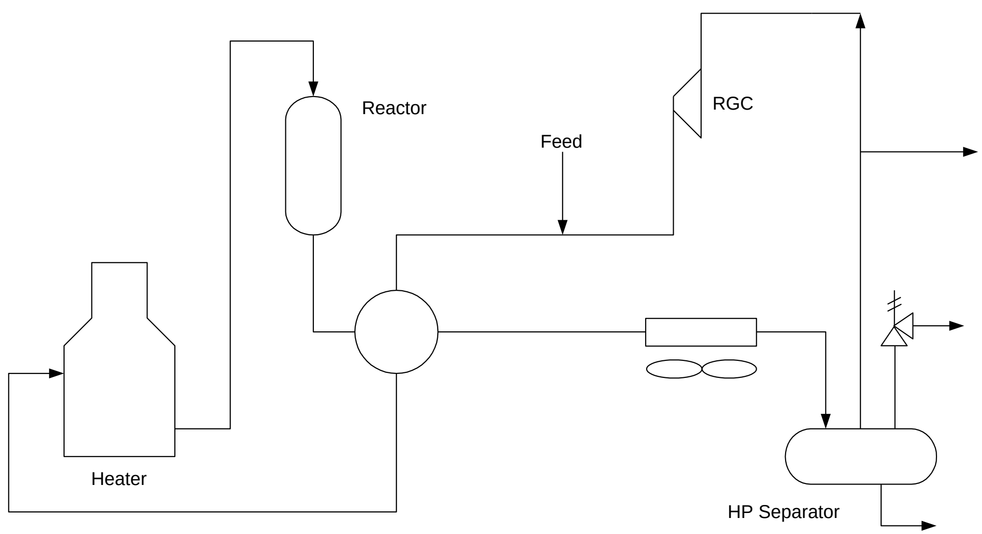
- Fluid Catalytic Cracking (FCC) Unit in a Refinery
  - Risk target of US$ 15,000/year
  - 84 PRDs
  - Intervals originally set according to API 510, typically set at 5 years (60 months)
  - 95% of Risk was related to 17 PRDs, those protecting the major towers in the unit
  - Reduced interval on 14 PRDs, 3 remained unchanged, increased intervals on 67 PRDs
  - Average interval increased from 69 to 97 months
  - Risk reduction of 65%, minor increase in inspection costs

Case Study- Pressure Relief Devices



Pressure Relief Device RBI

- Direct Link to Fixed Equipment
  - Recognizes the fact that damaged vessels are at higher risk to failed PRD than undamaged vessels, current PRD module does not consider the protected equipment damage state
  - Risk associated with a PRD protecting fixed equipment increases over time as the damage factor for the equipment increases with time
  - Risk is calculated for EACH piece of equipment or component protected by the PRD

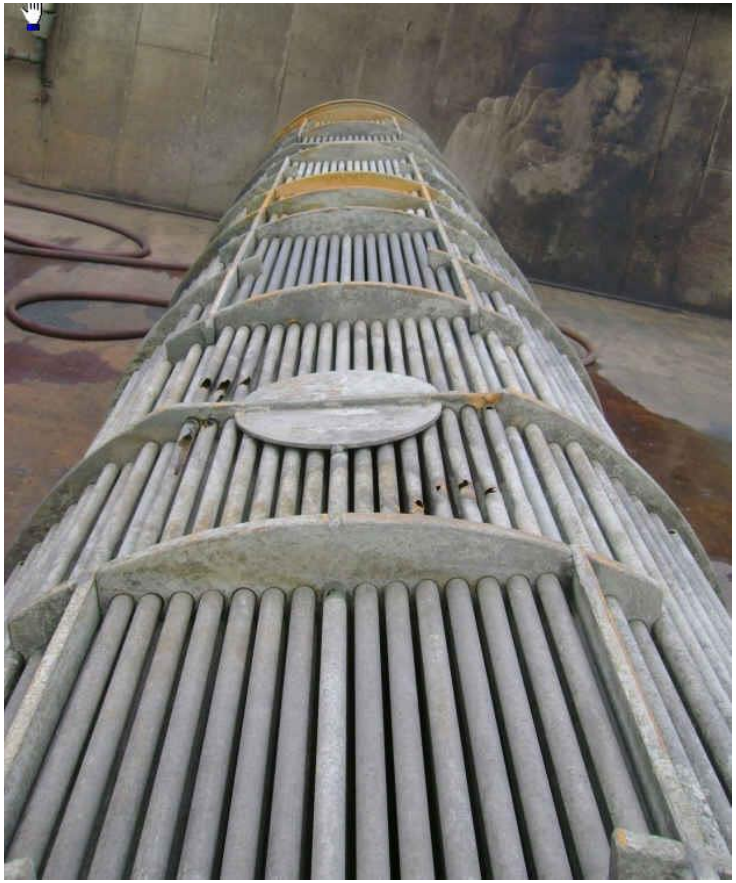


Case Study- Heat Exchanger Bundles

- Crude/Vacuum Unit
  - Refiner had experienced several high profile bundle failures with significant financial loss
  - Upcoming shutdown in 2008
  - Plan date (3/2014, 2^{nd} turnaround date)
  - Risk target of US$ 720,000/year (one days' production loss)
  - Most bundles installed vintage 1975, most inspections historically were limited to visuals and some random UT readings
  - 64 Bundles evaluated
    - 27 bundles - inspection could be deferred until next shutdown
    - 30 required some sort of higher level inspection (eddy current, IRIS or tube sampling)
    - 7 required visual or UT sampling

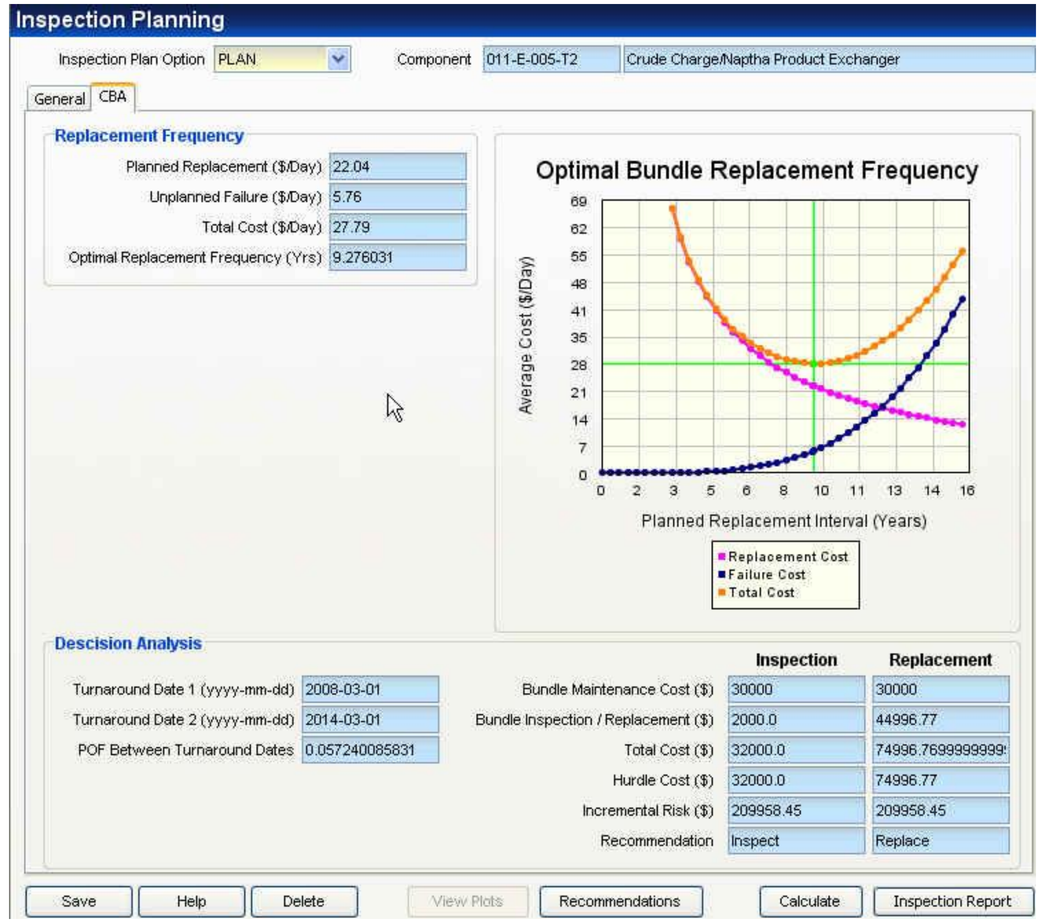
Heat Exchanger Bundle RBI

- Bundle failure definition – Tube Leak
- Condition based inspection programs
  - Limited value since failure data for each bundle and service usually does not exist
  - Not enough failure data to be statistically significant
- API RBI relies on failure database with matching criteria to obtain statistical “cut-set”
- Probability of Failure (POF) as a function of time is determined by:
  - Specific bundle failure history, if enough data to determine MTTF
  - Filtering on Local and Corporate Failure Libraries to obtain Weibull curve of matching bundles



Heat Exchanger Bundle RBI

- Cost benefit analysis
  - Provides economic basis for inspection and replacement decisions
  - Calculates the optimal bundle replacement frequency
  - Compares bundle replacement costs to costs associated with unplanned failures
  - Determines probability of failure at next turnaround



Inspection Benefits from RBI

- Incorporate RBI results into Turnaround (TAR) inspection planning – add, delete or modify prior plans
- Analysis for impact of feed changes on corrosion, monitoring and inspection practices
- Improve specialized inspection programs when incorporated into RBI work process
- Summary/Documentation of corrosion issues for training of new corrosion engineers and use by more experienced corrosion engineers
- RBI in the design stage of new process units (clean fuels) to identify possible risk mitigation and anticipate inspection needs
- Extra effort can be made to identify risk drivers and materials operating envelopes to increase operations awareness of operating practices on equipment integrity and reliability

Inspection Benefits from RBI

- Results in significant reduction in overall unit/plant risk, often with no significant increase in inspection activities
- Shifts attention to most critical equipment, allows less critical equipment intervals to increase
- Identifies non-value adding activities
- Intervals for 60-80% of the equipment can be increased
- 10-20% of the equipment intervals will be reduced
- Identifies other risk mitigation activities (isolation/detection/mitigation for consequence reduction, material upgrades, early bundle replacement, addition of isolation valves, etc.)
- Quantitative approaches generally yield better, more objective results than qualitative approaches

Lynne Kaley, P.E.
Phone: 281-283-6502 • email: lckaley@equityeng.com

2625 Bay Area Blvd.• Suite 325
Houston, TX 77058 USA
Phone: 281-480-0556 • Fax: 281-480-2063
www.equityeng.com