Components of a Solid Piping Reliability Program

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Presentation Overview

- Introduction/Historical Perspective/Industry Practices
- Overview of Available Tools (RBI, FFS/Engineering Analysis, IDMS, Stat analysis, MOEs)
- Isolating a Special Emphasis Mechanism – Piping Vibration
- Supercharging the Piping Review – The MOE (material operating envelope, aka integrity operating envelope)
- Bringing the Elements Together
- Summary
“The Goal”

Assure regulatory and corporate compliance, and ensure reliable use of piping (and equipment) for finite run times, while measuring, managing and minimizing risks and eliminating non-value adding activities and costs.
Introduction

• Historical statistics attribute piping failure as leading cause of large property losses (Marsh and McLennan study mid-1990s and 2001).

• Data from numerous corporations indicate that the most frequent failures (approximately 35-40%) are from piping systems.

• In a significant number of plants, there is no criticality or risk based analysis beyond the API 570 classification system to prioritize the piping inspection program.

• In most plants inspectors, software (IDMS) vendors or 3rd party inspection companies decide where to place TMLs (CMLs)
Introduction


Losses in the refinery industry have continued to increase over the last few years and the causes highlight the aging facilities in this category. A significant number of larger losses (over $10,000,000) have been caused by piping failures or piping leaks, leading to fires and/or explosions. Several large losses due to piping failures were due to corrosion issues or using the wrong metallurgy.....
Introduction

The explosion occurred when employees were attempting to isolate a leak on a condensate line between the NGL plant and the refinery. Three crude units were damaged and two reformers were destroyed. The fire was extinguished approximately nine hours after the initial explosion. Five people were killed and 50 others were injured. Initial investigation into the loss indicates a lack of inspection and maintenance of the condensate line.

June 25, 2000
Mina Al-Ahmadi, Kuwait
$412,000,000 (2000 dollars) $433,000,000 (2002 dollars)

Introduction

• Routine straight beam ultrasonic inspection (UT) is by far the most common method (and often the only method utilized) of inspection independent of the expected damage mechanism.

• Typically there is no detailed analysis of the UT data to determine the quality of the data, adequate coverage of inspection points, etc.
Introduction

• CMLs (corrosion monitoring locations) not in the correct locations, inappropriate NDE use and an over abundance of CMLs (i.e. they are non-value adding)
  – Corrosion engineers not involved in placement decisions
  – Statistical analysis not used to determine optimal sampling
  – RBI not used to quantify risk reduction/investment payback

• Little to no integration and definition of the relationships of corrosion review, Fitness for Service, RBI and statistical analyses within the overall process to achieve optimal effectiveness

• The Roadmap to Improved Piping Reliability
Introduction
Database Management Programs

• IDMS
  - How much change has occurred
  - How much being used
  - How accurate are CRs
  - How much do we believe retirement dates
  - How was the program instituted
  - How were circuits chosen
  - Was a corrosion engineer used to guide selection of inspection scope, type and location
**Introduction**  
**Improvement is Needed**

- Plants are aging  
  - Failure rates will increase without effective change

*The significant problems we have cannot be solved at the same level of thinking with which we created them.*

A. Einstein
Introduction
Perspective – Level of Thinking

• Shift – Why, where, when, how to inspect
  – RBI Principles
    • Likelihood
      – Scatter in the projection
    • Consequence
  – FFS Principles
    • Engineering Analysis
    • Limiting flaw size perspective
  – Pro-active approaches - Systems
    • MOEs
    • MOCs
  – Corrosion systemization and circuitization
Available Tools

• Codes and Standards Improvement
  – For example, latest editions of API 570, 574, 579, 580, 581

• RBI
  – Critical element – DM (damage mechanisms review)

• FFS
  – Engineering Analysis
  – Critical Element - DM

• Corrosion and materials review
  – Basic RBI
  – MOE (Material Operating Envelope)
  – Systemization and circuitization
Available Tools
Codes and Standards

• Now permit use of and provide minimum guidelines
  – RBI
  – FFS
  – Jurisdictional

• Support documents
  – 580
  – 581
  – API/ASME ISIJC
Available Tools
New Joint API and ASME FFS Standard

- The release of the new joint standard designated as API 579-1/ASME FFS-1 occurred in July, 2007
- API 579-1/ASME FFS-1 2007 supersedes API 579-2000
- API 510, 570 and 653 point to API 579-1/ASME FFS-1 2007 for FFS decision making
- The agreement to produce a joint standard on FFS technology is a landmark decision that will permit the focusing of resources in the US to develop a single document that can be used by all industries that utilize pressure containing equipment
- In addition, a joint API/ASME FFS standard will promote uniform acceptance of FFS technology by regulatory bodies
Available Tools

RBI

• Risk-based prioritization
  – Probability of Failure
  – Consequence of Failure
• Use on Piping
• Damage Mechanisms Review
  – Critical to success of any RBI program
• Addressing Special Emphasis Mechanisms
Available Tools
RBI Damage Mechanisms Review

- Critical to the success of any equipment reliability program
- Critical to success of any RBI process
- Required by codes, standards and regulators
- Should include special emphasis mechanisms
Available Tools

Damage Mechanisms
Special Emphasis
Piping Vibration

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Piping Vibration

- Vibration Fundamentals
- Types of Piping Vibration
- Resonance
- Sources of Piping Vibration and Their Effects
- Measuring Vibration Characteristics
- Methods to Mitigate Piping Vibration
- Using Analysis Programs in Evaluating Piping Vibration
Vibration Fundamentals - Definitions

F = Frequency (cycles/sec)

Fn = Natural Frequency (cycles/sec)

ω = Circular Frequency = 2\pi F (radians/sec)

T = period = 1 / F (sec/cycle)
Vibration Fundamentals

- Harmonic Displacement
  
  \[ \text{Displacement} = A \cdot \sin(\omega t) \]

- Harmonic Velocity
  
  \[ \text{Velocity} = A \cdot \omega \cdot \cos(\omega t) \]

- Harmonic Acceleration
  
  \[ \text{Acceleration} = -A \cdot \omega^2 \cdot \sin(\omega t) \]
Vibration Fundamentals

- Periodic Vibration

\[
\text{Displacement} = \sum_{i=0}^{n} A_i \cdot \sin(\omega_i t + \phi_i)
\]
Vibration Fundamentals
Vibration Fundamentals
Types of Piping Vibration

- Steady State, Harmonic (mechanically induced, acoustic pulsation, vortex shedding)
Types of Piping Vibration

- Steady State, Periodic (acoustic pulsations with multiple harmonics)
Types of Piping Vibration

- Transient Vibration (water hammer, slug flow)
Types of Piping Vibration

- Random Vibration (earthquake, acoustically induced)
Piping Vibration Concerns

- Fatigue leading to cracking of pipe or supports and restraints
- Large displacements from transient or periodic loading resulting in pipe “jumping” off supports or impacting surrounding equipment (i.e., pipe whip)
- Problems with reliability of connected equipment, particularly rotating equipment
- Unacceptable sound levels (noise)
- Perception of field personnel
Structural Resonance

![Diagram showing the relationship between magnification factor and F/Fn for different magnification factors (0%, 5%, 10%, 20%, 30%) through a series of curves. The x-axis represents F/Fn, and the y-axis represents the magnification factor. The curves peak at different points corresponding to the different magnification factors, demonstrating the resonant behavior.](image-url)
Acoustic Resonance

![Graph showing the relationship between Magnification Factor and F/Fn]
Sources of Piping Vibration

- Mechanically Induced
- Acoustic Pulsations
- Vortex Shedding
- Fluid Transients in Liquid Filled System
- Acoustically Induced, from Gaseous Pressure Letdown
- Slug Flow
- Earthquake
Mechanically Induced Vibration

- Vibration occurs due to a piping connection to machinery or vessels that are vibrating
- Examples include:
  - Centrifugal pumps or compressors that have shaft imbalance or misalignment with driver
  - Reciprocating pumps or compressors with worn or loose connectors
  - Improperly restrained anchored equipment
  - Fluid solids surge in FCCU reactors or regenerators
- Usually results in harmonic or periodic displacements
- Vibration usually limited to vicinity of machinery of vessels
Acoustic Pulsations

- Pulsations can result from:
  - Reciprocating (positive displacement) pumps and compressors
  - Internal turbulence at connections to the pipe or piping components
    - Branch connection
    - Valve Internals
    - Pressure, temperature or flow instruments that extend into the flow path
  - Relief valve chatter
Acoustic Natural Frequency

- Quarter Wave Equation (Open–Closed)

\[ F_n = \left( 2n - 1 \right) \frac{c}{4L} \]

- Half Wave Equation (Open-Open or Closed-Closed)

\[ F_n = \frac{n \cdot c}{2L} \]

where:
- \( n \) = harmonic number, (1, 2, 3, ...)
- \( c \) = speed of sound of fluid, ft/sec (m/sec)
- \( L \) = effective length of pipe segment, ft (m)
Acoustic Pulsations

• Result in harmonic or periodic forces and pipe vibrations

• May occur anywhere along piping system; harmonic or periodic pipe vibration remote from obvious source often caused by acoustic pulsations

• Harmonic force magnitude equal to pressure pulsation magnitude multiplied by the inside pipe area

• Can lead to large displacements and stresses if resonant with the acoustic natural frequency or structural natural frequency or the piping system
Modeling Acoustic Pulsation

- May be modeled as harmonic applied forces (or displacements if measured) in piping stress analyses to determine stresses
- Stresses from analysis should be evaluated with regard to fatigue
- May need to combine with thermal stresses in cyclic life evaluation
Vortex Shedding

- A pipe in a velocity flow field with the flow perpendicular to the pipe axis, will interrupt the flow
- The interruption of the flow creates vortices (like the ones you see in a stream where an object is just below or penetrates the free surface)
- The vortices will shed from the pipe at a frequency that depends on the pipe diameter, the fluid density, and the flow velocity
- The shedding vortices are accompanied by periodic changes in pressure
- The pressure fluctuations place forces on the pipe in a direction perpendicular to the plane formed by the pipe axis and the fluid velocity vector
Vortex Shedding

- If the shedding / force frequency is close to the pipe’s structural natural frequency, resonance can cause the pipe to vibrate.
- This phenomenon is most often associated with above ground pipelines between the supports. It rarely occurs in most process plants but could affect offsites piping.
Vortex Shedding Frequency

- The frequency of vortex shedding (and the harmonic force) is given by:

\[ F_{shed} = S \frac{V}{D} \]

where:

- \( S \) = Strouhal number, dimensionless
  - = 0.2 for a cylinder in air
- \( V \) = Flow velocity, ft/sec
- \( D \) = Pipe diameter, ft
Pipe Structural Natural Frequency

For a pipe simply supported over multiple spans, the natural frequency can be approximated by:

\[ F_n = n^2 \frac{\pi}{2} \sqrt[4]{\frac{gEI}{wL^4}} \]

where:
- \( F_n \) = natural frequency, hertz
- \( n \) = Mode number (1, 2, 3, ...)
- \( g \) = Gravitational constant = 386.1 in/sec\(^2\)
- \( E \) = Modulus of elasticity, lb/in\(^2\)
- \( I \) = Pipe moment of inertia, in\(^4\)
- \( w \) = Pipe total weight per unit length, lb/in
- \( L \) = Pipe length between spans, in
Transient Liquid Flow

- Plant operations require control of the motion (flow) of process fluids (both liquids and vapors)
- The control can involve changing the direction of the flow, starting flow, or stopping flow
- All of these require a change in the fluid’s momentum
- For steady state flow through piping the momentum change occurs mainly at pipe elbows and tees where the fluid direction changes
- Equal and opposite forces are exerted by the pipe (on the fluid) and by the fluid (on the pipe)
- The forces will be in proportion to the mass of the fluid and the rate of velocity change, Force = Mass x dV/dt
Transient Liquid Flow

• Similarly, when starting or stopping flow a force must be applied to change the momentum of the fluid

• Changing the velocity of a fluid changes its momentum and kinetic energy
  – For moving fluids we must convert kinetic energy to potential energy (i.e., velocity to pressure or elevation)
  – For stationary fluids we convert potential energy to kinetic energy (i.e., pressure or elevation to velocity)

• Typically for fluids we exert the force to change the kinetic energy by applying pressure to the fluid

• For liquids a rapid change in velocity is often accompanied by potentially large pressures and forces
  – Liquids have a higher mass than vapors
  – Liquids are less compressible than vapors
Transient Liquid Flow

- The pressure generated due to a rapid change in the velocity of a fluid is a function of the compressibility and density.
- For a liquid, the compressibility is analogous to the modulus of elasticity of a solid and is known as the bulk modulus, $K$.
- $K$ is defined by the equation:
  \[ K = \frac{\Delta P}{\Delta \rho} = \frac{\Delta P}{\Delta Volume/Volume} = \frac{\text{Stress}}{\text{Strain}} \]
- The bulk modulus is a function of the liquid’s temperature and density and typically ranges in value from 30,000 lb/in$^2$ to 400,000 lb/in$^2$.
- $K$ can be found in fluids data bases or from its definition.
Causes and Effects of Liquid Transients

• Actions that result in liquid transients include:
  – Valve closure in a flowing line (most common cause)
  – Vapor pocket collapse
  – Pump start-up or shut-off
  – Relief valve flow into a filled line
  – Steam injection into a cooler fluid

• The potential effects of liquid transients include:
  – Over pressure of the pipe
  – Leaks at gasketed connections
  – Large transient forces that result in damage to piping system components
  – Loud banging noises
Potential Pressure Magnitude

- The potential pressure change due to a rapid change in the velocity of liquid flow such as a fast valve closure is given by:

\[ \Delta P = \frac{\rho \cdot a \cdot \Delta V}{144} \]

where:

\( \Delta P \) = pressure change, lb/in²
\( \rho \) = mass density of the fluid, lb-sec²/ft⁴
\( a \) = sonic velocity of liquid pipe combination, ft/sec
\( \Delta V \) = change in the liquid velocity, ft/sec

- Computer programs exist to better estimate the pressure
Liquid Sonic Velocity in Piping

- The sonic velocity, $a$, of the liquid-pipe in ft/sec is given by:

$$a = \frac{\sqrt{144 \cdot \frac{K}{\rho}}}{\sqrt{1 + \left(\frac{K}{E}\right) \left(\frac{D}{t}\right) c}}$$

where:
- $K =$ Liquid bulk modulus, lb/in$^2$
- $\rho =$ Liquid mass density, lb-sec$^2$/ft$^4$
- $D =$ Pipe inside diameter, in
- $t =$ Pipe wall thickness, in
- $E =$ Pipe metal modulus of elasticity, lb/in$^2$
- $c =$ Constant to adjust for pipe constraint (usually $c = 1 - \frac{\nu}{2}$)
- $\nu =$ Poisson’s ratio of the pipe material
Pressure Magnitude

- For valve closure if the time of closure is much greater than twice the time it takes for the pressure wave to reach a mitigating boundary (e.g., a constant pressure vessel) then the pressure rise will usually be less than the potential value.

- For pump start-up and shut-down the pump curves and equation for $\Delta P$ are used to estimate the potential pressure change.

- For pressure relief valve (PRV) operation the potential pressure downstream of the PRV is the PRV set point.

- Pressure changes from vapor pocket collapse are more difficult to estimate since they depend on the piping system hydraulic configuration.
Pressure from Pump Operation

![Graph showing pressure from pump operation vs flow (gpm)]
Pressure Wave

- Liquid transients result in a pressure wave that propagates at the sonic speed away from the source.

- The wave can actually be two waves, a positive wave traveling in one direction from the source and a negative wave traveling in the opposite direction:
  - Valve closure: + upstream, - downstream
  - Pump shut-off: + upstream, - downstream
  - Pump start-up: + downstream, - upstream
  - Vapor collapse: + next to vapor pocket
  - Relief valve: + downstream, - upstream

- The negative pressure wave may create a vapor pocket if the total pressure drops below the liquid’s vapor pressure at the operating temperature.
Liquid Transient Force

- The pressure wave traveling in the piping system creates an unbalanced force in the piping that can cause large transient displacements.
- The force acts in a segment between two pipe bends for the time that the wave is in the segment between the bends.
- The direction of the unbalanced force is opposite to the direction of wave propagation and its magnitude equals:

\[
Force = \Delta P \cdot \frac{\pi D^2}{4}
\]
Application to Piping Analysis

- Forces are applied as a “square wave” time history to consecutive nodes along the piping system in a dynamic analysis to get displacements and stresses.

- Duration is given by $L/a$ where $L$ is the segment length between bends and $a$ is the sonic velocity.

- The magnitude of the force is that given earlier.

- Alternative to full dynamic analysis is to use twice the estimated force as a static load to calculate stresses.

- Calculated stresses may be treated as an occasional load for evaluation.
Acoustically Induced Vibration

- Occurs when high pressure gaseous flow undergoes a pressure reduction, usually at a valve.
- Potential and kinetic energy of the gas pressure is transformed into sound and some heat.
- The sound consists of a wide range of frequencies (i.e., broad band noise).
- Sound energy downstream of pressure reduction will resonate with the pipe wall causing it to vibrate in a two dimensional pattern.
- The pipe wall displacements do not usually result visually perceptible pipe motion.
- Interruptions to the pipe wall displacement pattern result in stresses that can lead to fatigue failure, sometimes in hours.
Pipe Wall Radial Displacements – 103 Hz
Sound Power Level

- Measurement of the amount of energy being converted to sound per unit time
- A function of the following flow parameters:
  - Differential pressure upstream to downstream
  - Mass flow rate through pressure letdown device
  - Molecular weight and temperature of gas
  - Whether sonic velocity exists or not
  - Distance from the pressure letdown location (attenuation)
Design Curve

![Design Curve Graph]

- **SPL (re. 10^{-12} watt)**
- **Diameter (mm)**
Slug Flow

- In two-phase (liquid-vapor) flow there are conditions that can cause the phases to separate into distinct pockets of single phase fluid.
- The liquid phase in such separated flow is termed a “slug” of liquid, probably for the effect it has on the pipe.
- The vapor and liquid pockets travel at roughly the same velocity.
- When a slug of liquid goes around a pipe bend its direction is changed.
- The change in direction is a change in momentum and thus requires that the pipe and liquid exert equal and opposite forces on each other.
Slug Flow

Liquid Slug
Slug Force

- Total force is the vector sum of the force it takes to stop the flow in one direction and start it moving in the other direction.
- Total Force is then
  \[ \text{Total Force} = 2F \cdot \cos\left(\frac{\theta}{2}\right) \]
- In a dynamic piping analysis the total force is applied as a time history to the bend along a line that bisects the bend.
- The slug force causes transient vibration of the pipe and should be treated as an occasional load.
- In some cases, when the slug flow is periodic, the vibration may also be periodic.
Earthquake

- A form of random vibration
- May be characterized by a response spectrum
  - Measure of the frequency versus amplitude content of the earthquake generated ground waves
  - Response spectra approach looks at how a series of spring-mass systems with varying natural frequencies would respond to the earthquake ground motion
- Treated as an occasional load for determining stresses
Earthquake

- ASCE-7 or the Uniform Building Code provides more information on how to determine the loading and perform the earthquake analysis
  - Static Procedure uses equivalent “g” factor
  - Dynamic Procedure uses response spectra

- In an equivalent static analysis the acceleration is input and the piping program applies it to the mass of the piping; the analysis proceeds as a static analysis

- In a dynamic piping analysis the response spectra are input as support motions in the global directions of the piping system and the piping system’s response is determined
Example of Velocity Response Spectra
Measuring Vibration Characteristics

- For steady state vibration, either harmonic or periodic, the vibration can be characterized by its amplitude and frequency or frequencies.
- Transient vibration is measured by the amplitude and the rate of decay.
  - If the vibration has a periodic aspect this should be also be measured.
- For all but the most simple vibration, manual measurement is impractical.
  - Visual measurement of the vibration amplitude are often overestimated.
  - Even for harmonic vibration the frequency of vibration is difficult to determine if over about 5 hertz.
Measuring Vibration Characteristics

- Multi-Channel Data Analyzer
  - Transducer attached to the piping system, either permanently or via strong magnets
  - Transducer measures amplitude versus time and converts to an electric signal
  - Data analyzer does a Fast Fourier Transform to convert the information from the time domain to the frequency domain
  - Result is a spectral representation that shows the dominant frequency or frequencies and their respective amplitudes
  - The amplitude may be given as displacement, velocity, or acceleration
Measuring Vibration Characteristics

• Measurement Locations
  – Location of maximum observed displacement
  – At attached equipment nozzles
  – At supports / restraints if use of response spectra is desired in a dynamic analysis

• Directions of measurement
  – Desirable to obtain 3 orthogonal measurements for response spectra input
  – May restrict measurement to predominant direction of vibration if known

• Strain gauges sometimes used as a transducer to monitor piping vibration
Judging Severity

[Diagram showing graph with frequency on the x-axis and peak-to-peak amplitude on the y-axis. The graph contains lines labeled A, B, C, and D, each representing different vibration levels. The lines intersect at various points, indicating different severity levels.]

Suggested Limit (one author)
Mitigating Vibration

- Mitigation technique depends on source or cause of vibration, its characteristics, and severity
- If possible mitigate the source by either eliminating it or reducing its magnitude
- If the source cannot be eliminated or reduced, alter the piping system to mitigate the vibration’s effects
  - Restraints
  - Reinforcing
Mitigating Mechanically Induced

- For vibration caused by machinery imbalance or misaligned shafts, treat the machinery to eliminate/reduce the source (it is better for the machine as well)

- For piping attached to vibrating vessels (e.g., piping attached to FCCU reactor or regenerator) the use of snubbers on the piping is usually effective
  - Rigid braces for low temperature systems
  - Flexible snubber for higher temperatures to allow thermal expansion to occur freely while absorbing vibration loads
Mitigating Pulsation Induced Vibration

- Pulsation bottles with or without internal baffles to dampen the magnitude of the pulse
- Detune the piping to eliminate acoustic resonance by changing the length of segments whose acoustic natural frequency is close to the pulsation frequency
- Use Helmholz resonators to absorb energy at a particular frequency or frequency range
- Use rigid restraints or snubbers to absorb the pulsation forces and reduce vibration amplitudes
- For pulsation that occurs due to internal turbulence, where possible consider changing the shape of protrusions in the flow path to make them “aerodynamic”
Mitigating Vortex Shedding

- Design the piping system supports and restraints to keep the structural natural frequency away from the vortex shedding frequency
- May need to consider a frequency range that corresponds to the wind velocity history at a site
- Most effect mitigation is to change the distance between pipe restraints (pipe natural frequency a function of the restraint distance squared)
Mitigating Liquid Transient Vibration

- Close valves slowly (not always a choice)
- Close pump discharge valve before starting pumps
- Use pressure damping, or other relief devices
  - Gas charged bottles with/without bladder
  - Pressure relief valves
  - Rupture discs
  - Proprietary relief devices
- Make structural modifications to absorb the forces from the transient pressure wave
Mitigating Acoustically Induced Vibration

- Divide flow between multiple pressure letdown devices to reduce mass flow through each
- Use multi-stage pressure letdown
- Use low noise pressure reduction valves to convert potential energy to heat instead of sound
- Reinforce connections to pipe to reduce fatigue stresses
  - Thicker pipe
  - Full encirclement wraps at supports, branch connections
  - Avoid non-axisymmetric connections
Mitigating Slug Flow

• Avoiding flow regimes that lead to slug flow is the most effective way to deal with this type of vibration

• If the flow regime is unavoidable, rigid braces or snubbers may be necessary to keep pipe displacements and stresses to within acceptable values
Mitigating Earthquake Induced

- Have no control over earthquake incidence or severity
- Must mitigate through design of system to withstand the effects of the seismic forces
  - Support spacing
  - Support types (rigid or flexible)
  - Reinforcing high stress locations
General Guidance on Design to Mitigate Vibration

- Eliminate, or 2-Plane brace small bore connections within 20 D of a source of harmonic/periodic vibration

- To reduce vibration magnitudes consider closer spaced supports and restraints (frequency is proportional to unbraced length squared)

- Piping Layout:
  - First bends > 10 D from pumps or compressors
  - Avoid long un-interrupted runs (i.e., > 200 ft)

- Expansion Joints:
  - If possible, avoid use in piping subject to vibration
  - If necessary, use sleeved designs for smooth flow
General Guidance on Design To Mitigate Vibration

- Supports/Restraints must be rigid relative to pipe
  - Recommend factor of 10 in stiffness
  - Can accomplish by keeping restraint stresses low
  - No gaps between support/restraint and pipe since vibration magnitude is typically small
  - May need to change support arrangement to increase stiffness (and natural frequency)
  - Consider dampening type supports
- Could increase mass to keep natural frequency below driving frequency but less effective (and more costly) than increasing stiffness
- Use butt-welded components (tees and elbows)
General Guidance on Design to Mitigate Vibration

- Use Class 6000 couplings for small bore connections
- Use double nuts and/or locking nuts on bolted connections such as valve bonnets and packing glands
- Consider controlled bolting for piping components and for bolted restraint bracing in vibrating service
- When connecting restraints to piping use bolted clamps or weld restraint to full encirclement sleeve that is welded to pipe (sleeve usually needs to be ≥ pipe wall thickness)
- Restraints most effective if attached at location of maximum displacement
- When adding restraints to decrease vibration severity remember the need for adequate thermal flexibility
Using Piping Analysis in Evaluating Piping Vibration

- System natural frequency calculations
- Static analysis using acceleration versus elevation
- Dynamic analysis
  - Harmonic analysis
  - Time history analysis
  - Response spectra analysis
- Interpreting analysis results
  - Examine displacements
  - Evaluate stresses
Structural Natural Frequency

- Build piping model for static analysis (i.e., sustained and thermal loading)
- In the most programs the user can specify the maximum frequency and/or maximum number of modes for natural frequency calculation
- For most systems the default values are adequate
- For other than long, relatively unrestrained pipe (e.g., offsite) first 5-10 modes should suffice
- Most pipe has 1st natural frequency < 10 Hz
- Compare mode shapes / frequencies to known exciters or measured values
Harmonic Dynamic Analyses

• Used for mechanically induced, pulsation, vortex shedding, other harmonic or periodic loading

• Loads usually input at nodes as a combination of amplitude (force, velocity, displacement) and frequency

• Must be cognizant of the phase relation of the harmonic forcing at various nodes
Time History

• Used mostly for liquid transients & slug flow, but may be used for any general loading where force/displacement is known as a function of time.

• Loads usually input at nodes as force versus time pairs.

• Must account for difference in time of loads at each node.
Response Spectra

• Used predominantly for earthquake type analyses
• Can be used for any dynamic analysis where the loading can be represented as a function of frequency
  – Displacement
  – Velocity
  – Acceleration
• Input actual response spectra in global coordinate directions
• Data for response spectra input usually consists of sets of period, and velocity or acceleration that define the spectra
• Spectral values applied to support nodes
Static Earthquake Analysis

- Input accelerations as a function of elevation
- Acceleration applied to piping weight to obtain forces
- Support reactions, member loads, stresses calculated as in static analysis
- May be combined with other static analysis and treated as occasional load case
Examining Dynamic Analysis Results

- Look at displacements first to see that the results make sense
- Next examine the support loads
- Finally, if the displacements and support loads make sense, evaluate the stresses
- Results for time history and response spectra may be in the form of an “envelope” rather than a single value
- Stresses should be evaluated using proper criteria
  - For harmonic type analyses consider fatigue (since cycles can be very high be cautious about the endurance limit)
  - For time history, earthquake treat stresses as “sustained” occasional values
Inspection of Pipe in Vibrating Service

• What to Look for:
  – Cracking
  – Abrasive wear
  – Damaged or failed supports and restraints

• Where to Look:
  – Connection of small bore piping, especially with attached valves in piping subject to periodic excitation
  – Connection points of restraints to piping (all sources)
  – At connection points of restraints (struts, snubbers, etc.) to support structure (restraint integrity)
  – Support points in piping subject to periodic excitation (wear of pipe, damage to spring hangers, pipe off support)
  – Branch connections and other attachments in piping downstream of pressure letdown locations
  – At locations of high stress as indicated by results of piping vibration analysis
Inspection Methods for Vibrating Pipe

• Visual
  – Observation of the vibration
  – Pipe abrasion
  – Cracking at connections
  – Damage to supports/restraints or pipe off of supports

• Dye Penetrant / Magnetic Particle / Ultrasonic
  – Locate and size cracks at points of high stress or subject to fatigue from vibration and/or thermal stress

• Acoustic Emission Testing
  – Used to screen for or locate potential cracks
  – Use piping analysis results to identify most probable locations to reduce cost of implementation

• Other Methods
Inspection of Pipe in Vibrating Service

• Inspection Frequency
  – Periodic observation by operations personnel is first line of defense against problems; inspectors and engineers should be made aware of evidence of vibration
  – Prior to planned shutdown to identify locations for increased inspection emphasis
  – During and after start-up to identify new incidence of piping vibration, particularly when there have been process or equipment changes
  – Periodic inspection of any evidence of in service fatigue cracking; use estimate of fatigue life to determine frequency (piping analysis may be helpful for this)
  – Periodic inspection of locations where changes have been made to mitigate the effects of piping vibration (e.g., at the attachment points of new restraints)
Overall Approach

• Determine source by observation in field or by interviewing operators

• Consider how to best mitigate vibration problem

• If vibration structural analysis necessary, gather required information and start with static analysis
  – Do natural frequency analysis before full dynamic analysis to remove any errors in overall model

• Carefully examine results of analyses to determine that the results make sense, particularly displacements and support loadings before trusting stress results

• Use restraints in piping analysis model to try solutions to harmonic and time history type vibration problems
Overall Approach

- Use reaction and member force loads to design restraints
- Keep restraint member stresses low to insure proper stiffness
- Check that solution to vibration does not result in excessive thermal stresses
Corrosion Systemization and Circuitization
4.0 HDS PIPING SYSTEMIZATION

The # HDS unit piping was divided into XX process Systems which help to define the process function of a group of equipment. The process function in each equipment group is closely related to the expected materials damage mechanisms. Within each defined system, there are multiple piping corrosion circuits identified. The systems defined for this unit are as follows:

1) HDS Feed  
2) 1st Stage Reactor & Effluent  
3) 2nd Stage Reactor & Effluent  
4) Recycle Hydrogen & Effluent  
5) Make-up Hydrogen  
6) Naphtha Stripper Feed  
7) Naphtha Stripper Overhead & Reflux  
8) Naphtha Stripper Bottoms & Reboiler  
9) CCR Feed  
10) #1 Reactor Feed Effluent  
11) #2 Reactor Feed Effluent  
12) #3 Reactor Feed Effluent  
13) #4 Reactor Feed Effluent  
14) Reformer Recycle Hydrogen  
15) Net Gas Compression  
16) Net Gas Chloride Treaters  
17) LPG Recovery Propane Compression & Chiller  
18) Debutanizer Feed  
19) Debutanizer Overhead & Reflux  
20) Debutanizer Bottoms & Reboiler  
21) Benzene Overhead & Reflux  
22) Benzene Aromatic Product  
23) Benzene Bottoms & Reboiler

Each of these systems has been identified and color-coded on the attached PFD’s. A description of each system and expected problem area is summarized below along with the corrosion circuit within each system.
Circuit Level Summary

- **Circuit 5 – XA-16001A/B to X-16007 SS – Carbon Steel**
- This circuit consists of piping from the Reactor Effluent Air Coolers XA16001A/B to the Shell Side of Reactor Effluent Trim Cooler X-16007.
- **Estimated Corrosion Rate** – 7 mpy
- **Corrosion Type** – Local
- **Primary Damage Mechanism** – Ammonium Bisulfide/Chlorides
- **Specific Location Concerns** – Elbows, high velocity areas (>20 ft/sec);
Available Tools
Materials Operating Envelopes

- “Supercharging” the damage mechanisms review
- Supplies key parameters and ranges
- Enables owner operators proactive operations
- Enables owner operators proactive planning and decision making
Materials Operating Envelopes

2008 IPEIA Conference
Banff, Alberta, Canada

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The Equity Engineering Group, Inc.
Overview

• Another Key Reliability Tool: Materials Operating Envelopes (MOE’s)
• MOE Background
• Damage Mechanisms
• Implementing a MOE
• Lessons Learned
• Documentation
• Commitment and Ownership
• Summary
Profitability Linked to Reliability

• Necessary to maintain units on-line to be profitable
• Unplanned outages/ extended T/A’s can have severe financial impact
• Incidents also affect reputation and have safety consequences
Another Key Reliability Tool: Materials Operating Envelopes (MOE’s)

• RBI and traditional piping inspection programs rely on future operating conditions replicating past operating conditions or being well defined.

• RBI by its nature focuses much more heavily on inspection activities than on controlling operations and monitoring activities.

• Knowledge and control of unit’s operating envelope helps provide an improved chance for reliability and safety, due to improved predictability.

• A MOE defines the envelope for predictable degradation versus specific operating parameters.
Background to MOE’s Process Creep

- Most refining, mid-stream, and chemicals pressurized equipment was designed and built for an operating basis that changed long ago.

- Most plants continuously “tweak” the process to raise throughput or process poorer quality (lower cost) feedstocks (crudes or intermediates).

- Over many years, the effect of this process creep is cumulative. An additional minor change can lead to a much greater rate of damage than previously experienced.
Boundaries

- Plants typically conduct Management of Change (MOC) reviews when process changes are made intentionally. Often changes are made inadvertently.

- In many cases, the people involved either do not have the tools or experience to evaluate the effects of minor process creep or knowledge of the boundaries for materials degradation.

- Ideally, boundaries are established to permit the process to safely operate within set limits without major concerns for the health of the equipment.
Materials Operating Envelopes (MOE’s) Define Limits

- A MOE defines the limits for each part of a unit for operating parameters such as feed contaminant content, pH, flow rate, temperatures, chemical or water injection rates, and acceptable levels of corrosive constituents. Typically covers both the vessels and the connecting piping.

- If limits are not exceeded, degradation should be predictable and, hopefully, reasonably low. However, the outcome depends on getting the model correct and considering some sampling/inspection to verify assumptions about constituents or conditions not being present (e.g. if assume a stream is dry, but water would make it corrosive, need to verify that no water is present).

- If limits are exceeded, excessive equipment degradation due to corrosion, stress corrosion cracking, metallurgical embrittlement, or hydrogen effects, such as high temperature hydrogen attack, could occur.
Drivers to Develop and Implement MOE’s

- Proactive management sees benefits of the technology.
- Reaction to a failure or event that could have been prevented, if such boundaries had been clearly established.
- Discovery of more severe degradation than expected based on past experience due to operating conditions that now place the piping into a much more active degradation zone. Such unexpected degradation is a major cause of piping failure and unreliability.
MOE’s include Controllable and Uncontrollable Items

- MOE’s are similar to KPRP’s (Key Process Reliability Parameters), but differ in that MOE’s contain parameters that may not be controllable, but should be measured and trended.
  - Uncontrollable parameters are reviewed in order to provide ample warning that additional inspection, surveillance, or replacement may be needed.
  - Example: Ammonia content in a crude tower overhead cannot be readily controlled, but it should be trended to alert the refinery if there is a major change in the potential, i.e. salt deposition temperature, for ammonium chloride fouling and pitting in the overhead piping.

- Some parameters having predefined controllable limits include:
  - Overhead drum pH (typically controlled by neutralizer)
  - Free CN content (typically controlled by water wash with PS)
  - Ammonium bisulfide concentration of sour water (typically controlled by wash water)
Examples of Process Factors

- Tower reflux rate and temperature can affect the top of a tower or overhead line and cause shock condensation.
- Steam stripping rates can affect $\text{H}_2\text{S}$, $\text{NH}_3$, $\text{CN}$ or $\text{Cl}$ content and lead to corrosion and stress corrosion cracking.
- $\text{CO}/\text{CO}_2$ corrosion and pH
Laying Groundwork

- Key is understanding damage mechanisms
- API and NACE practices and reports
- API RP 571/WRC 489, 488, 490
- JIP’s (MPC, PVRC, etc.)
- Plant experience
Assessing Potential and Specific Damage Mechanisms

- Material (general and specific information including heat treatment, chemistry, strength level, etc.)
- Service exposure (general and specific), normal and upset (trace amounts of corrosives, concentration, cycles, carryover, leaking valves, and particularly human factors, etc.)
- How often and how quickly does damage occur?
- Mitigating factors (coking, crack closure, residual stresses, coatings, chemical additives, water wash)
- Any monitoring data or other warning systems (probes)
- Previous inspections and their effectiveness at targeting the particular mechanisms
- Morphology of the damage
In-Service Damage Types

- General Corrosion
- Localized Corrosion
- Pitting, Crevice, and Grooving Corrosion
- Planar Cracks
- Branched Cracks
- Metallurgical Changes & Hydrogen Effects
- Distortion
In-Service Damage Types

General Corrosion

- High Temperature Sulfidic Corrosion and H₂/H₂S Corrosion
- Moderate Velocity Sour Water
- Oxidation
- Atmospheric Corrosion
- Some Hydrofluoric Acid (HF) Corrosion
In-Service Damage Types

Localized Corrosion

- Low or High Velocity Sour Water
- Naphthenic Acid Corrosion
- Dilute Acid Corrosion
- Galvanic Corrosion
- Corrosion Under Insulation (CUI)
- Erosion/Corrosion
- Injection Point and Dead-leg Corrosion
In-Service Damage Types

Pitting, Crevice, and Grooving Corrosion

• Under deposit corrosion
• Weld knifeline attack
• Water services
• Amine salts
• Stainless steel
• Flashing $H_2S$
In-Service Damage Types

Planar Cracks

- Fatigue cracks of small attachments
- Thermal fatigue
- Long seam weld cracking
In-Service Damage Types

Branched Cracks

- Chloride or Polythionic Acid Stress Corrosion Cracking (SCC)
- Amine, Ammonia, Caustic, or Carbonate SCC
- Liquid Metal Cracking (Hg/Al, Zn/SS)
In-Service Damage Types
Metallurgical Changes & Hydrogen Effects

- Embrittlement (885, Sigma, strain age)
- Graphitization, Spheroidization
- Creep
- High Temperature Hydrogen Attack (HTHA)
- Hydrogen Induced Cracking (HIC)
In-Service Damage Types

*Distortion*

- Bulging
- Blistering (H₂)
- Creep
- Ratcheting
Monitoring Methods

• Corrosion probes
• Hydrogen probes
• Coupons and physical probes
• UT measurements and scanning
• RT
• Stream samples
• Process variable monitoring
• Infrared thermography & thermocouples
Mitigation Methods

- Physically modify the process
  - Change temperature and/or velocity
  - Removal of stream fractions

- Chemically modify the process
  - Water washing
  - Injection of chemicals to change pH or tie up constituents or to form a film barrier

- Isolate the environment from the material
  - Organic coatings and thermal spray coatings
  - Metallic linings
  - Weld overlay

- Upgrade the materials
When to Consider Developing a MOE?

- Proactively or in response to an incident
- In conjunction with a critical Fitness-For-Service assessment
- Next step after doing RBI
MOE’s and FFS

- Having defined MOE boundaries also aids in the implementation of Fitness-For-Service (FFS).
- As stated in API 579-1/ASME FFS-1 *Fitness-For-Service*, the user needs to estimate the future deterioration rate (future corrosion allowance, crack growth rate, etc.).
- The FFS assessment may rely on monitoring to ensure that the degradation rate does not exceed the assumed future damage allowance.
- Having a MOE in place either increases the confidence that the FFS assumptions remain valid, or it can alert the plant that a reassessment may be necessary.
Operating Envelope Development

- Requires multi-disciplined team effort
  - Operations
  - Technical (Materials, Reliability, Process)
  - Inspection

- Key is to have good understanding of the process and the damage mechanisms.
Operating Envelope Development

- Typically work on major lines in a PFD.
- Typically facilitated by experienced materials engineer (a team of off-site materials/process engineers can often bring industry experience to light and speed up the process).
- Questions to the team are geared to identify current practices and problems.
- Historical and future conditions addressed.
- Inspection issues also identified.
- But, no matter how hard we try, there will still be situations where damage occurs unexpectedly, so can’t abandon all inspection and monitoring.
Operating Envelope Development

- Typically, probing of practices and issues is required.
- Cannot rely on impressions – actual data is required
  - Often requires additional monitoring and sampling program to obtain accurate data
Data Requirements

• A function of process unit being evaluated

• Typical data requirements include:
  – Unit feed sources, volumes, and composition
  – Existing sampling program on unit
  – Temperatures at key points
  – Piping and fixed equipment metallurgy
  – RBI results (if available)
  – Inspection records, RCFAs and piping isos /UT data
Examples of Unit Specific Data Requirements

- Crude distillation – desalter efficiency and furnace monitoring
- Hydrotreating - wash water volumes and sources
- FCCUs – polysulfide injection schemes
- Amine – type and loading, filtration, regen overhead bleed rate, etc.
Sampling Program

• Necessary to establish a baseline for comparison.
  – Especially important if changes are being planned for the unit
  – Need to know where you have been before moving forward
  – Typically requires extensive sampling over short period

• Necessary to establish sampling frequency after baseline established.

• Upper and lower limits set as applicable – other variables trended.

• Typically this effort results in the generation of significant amount of data.

• Need to analyze the data and understand the implications
Lessons Learned from Developing MOE’s

Operations Issues

- Insufficient water being injected into hydrotreater effluent train to force condensation.
- Vendor’s soda ash wash procedure using a water rinse cycle prior to introduction of soda ash solution.
- TAN not recognized as an issue in gas-oil hydrotreater feed circuit.
- Much lower pH observed in a distillate hydrotreater than previously predicted.
- Loading and velocity in an amine unit
Lessons Learned from Developing MOE’s

Inspection Issues

• Need for more UT coverage in some areas and less in other areas.

• Improper inspection procedures being applied – e.g. reliance on straight beam or shear wave UT for HTHA inspection rather than AUBT methods.

• Equipment taken out of service with blinding points that create process deadlegs.

• Equipment being cycled in/out of service creating CUI concerns.
Documentation

- MOE documentation will vary; depends on whether stand-alone, after RBI, or integral part of RBI program.
- The basis and assumptions are summarized. Specific recommendations and limits are provided, typically in tables that include intervals for measurements and commentary regarding whether intervention is possible.
- Recommendation can be assigned a risk-based priority in regards to importance.
- Ideally, the plant’s process information system or process control system can be used to store MOE information and tracks compliance with boundaries.
- Example table: summarizes parameters and limits for a specific process unit.
# Materials Operating Envelope for FCC Light Ends Gas Plant

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Materials Issues</th>
<th>Action</th>
<th>Operating Limits</th>
<th>Interval / Frequency</th>
<th>Intervention Possible?</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-XXX Absorber Deethanizer Feed Drum</td>
<td>Sour water corrosion</td>
<td>Sample sour water for: pH Cl Fe NH₃ H₂S CO₃</td>
<td>Trend. pH &gt; 5.0 pH &lt; 8.5 NH₄HS&lt; 2 wt%, Fe &lt; 1 ppm CO₂&lt;100 ppm</td>
<td>Weekly</td>
<td>N</td>
<td>Expect pH to be alkaline. pH values less than 5.0 can contribute to accelerated corrosion. High pH values can contribute to carbonate cracking. NH₄HS must be low to maintain manageable corrosion rates on carbon steel and to prevent wet H₂S cracking. Fe &gt; 1.0 typically indicative of excessive corrosion. Higher CO₂ levels may be acceptable as a function of system pH.</td>
</tr>
<tr>
<td>Piping Containing Sour Water With or Without Hydrocarbon</td>
<td>Sour water corrosion</td>
<td>Calculate velocity</td>
<td>20 fps for CS.</td>
<td></td>
<td>Y</td>
<td>Piping downstream of wash water injection points and downstream of condensers E-XXX should be evaluated. Calculate velocity in sour water streams from D-XX and D-XX.</td>
</tr>
<tr>
<td>E-XX Compressor Afterstage Condensers</td>
<td>Plugging and under deposit corrosion due to insufficient water wash</td>
<td>Calculate volume of wash water</td>
<td>At least 125% of that required to force dewpoint</td>
<td>One time at max rates and again as unit rates increase</td>
<td>Y</td>
<td>Wash water rates should be monitored.</td>
</tr>
<tr>
<td>T-XX Water Wash Tower</td>
<td>Pitting corrosion</td>
<td>Use oxygen free process water for water washing</td>
<td>NA</td>
<td>Continuous</td>
<td>Y</td>
<td>Pitting has been reported in the upper region of water wash towers when oxygenated wash water was used. Note: process water is currently used.</td>
</tr>
</tbody>
</table>
Commitment

MOE’s require management and plant commitment to:

- Allocate funds, make available knowledgeable plant process / operations personnel, and collect base-line data for the study
- Follow through with the MOE recommendations, which often include:
  - Increasing the stream sampling program and expanding the analyses (load on labs).
  - Some capital investment for corrosion probes or elimination of a constraint by alloy upgrading
- This is not a one-shot deal, but MOE’s need to be evergreened, just like RBI, and need to be periodically reviewed when changes and new findings occur.
Ownership

- Need Management System in place to address ownership and operation outside of the envelope.

- Ideally, the unit process engineer or business unit owner owns the MOE and is responsible for adhering to the envelope limits and taking action as soon as practical when limits are exceeded.

- They also should be responsible for evergreening the MOE program.

- Although Inspection should be advised of MOE boundary exceedences, they typically are not the best group to “own” the MOE program.
Summary

- Creating MOE’s involves time, expertise and funding.
- Requires a plant commitment to expanded work scope (sampling and monitoring).
- The plant needs to identify “owner” and have business process in place to keep unit operations within the limits stated in the MOE.
- MOE process can contribute to increased profitability and improved unit reliability by the prevention of failures due to unexpected materials degradation. May also allow the plant to confidently take advantage of an opportunity by having predefined limits.
- MOE’s should be part of a plant’s reliability “tool-kit”.
Uniting Elements

- Codes and Standards
- RBI
- FFS/Perspective
- Damage Mechanisms
  - SEPs
  - Systemization and Circuitization
    - Corrosion circuits as RBI analyzed and IDMS circuits
    - CML management
- MOEs
  - PIE
  - Notification mechanism
  - Evergreen
- MOC link
- Software platforms
  - IDMS
  - Monitoring
  - Notification systems
  - Evaluation
  - Enterprise
- Management Systems
  - Qualified personnel
  - Systems in place to ensure the programs are working
Summary

- Facilities are aging
- Published data shows increasing rates of failures and larger losses
- Inadequate assessment of piping leading cause
- A new perspective is needed
- Improved tools, engineering approaches and technologies have emerged, exist and are being developed
- These tools are not the “silver bullet” in and of themselves, they complement and provide multiple layers to identify and model potential problems before they result in a loss and identify areas of vulnerability and improvement – Require qualified personnel
- When used in concert by qualified and experienced professionals, in systematic and well managed programs → improved reliability