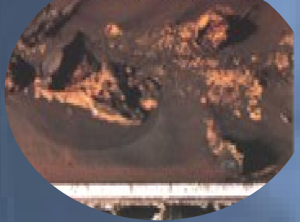
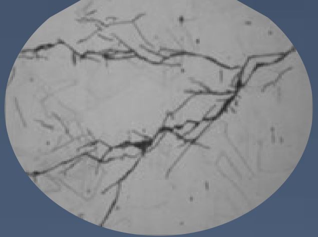






Enhancing Boiler Life: Leveraging Tube Failure Insights

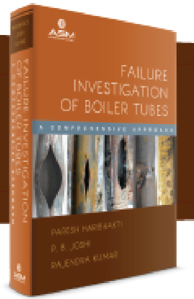
Significance of knowledge based Inspection and Advanced NDT techniques

Paresh Haribhakti
MD

TCR Advanced Engineering P. Ltd

Reliability through Knowledge Based Inspection (KBI)

- Profit 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**
- Change in service demand on the integrity of **Boiler components**



FAILURE INVESTIGATION OF BOILER TUBES: A COMPREHENSIVE APPROACH

BY PARESH HARIBHAKTI, P.B. JOSHI, AND RAJENDRA KUMAR

Scheduled Release: August 31, 2018

Product Code: 05243G | ISBN: 978-1-62708-156-6
Hardcover | Estimated Pages: 500

Non-Member: ~~$220~~ $199

ASM Member: ~~$165~~ $149

Prepublication prices good through August 31, 2018

Failures or forced shutdowns in power plants are often due to boilers, and particularly failure of boiler tubes. This comprehensive resource deals with the subject of failure investigation of boiler tubes from basic fundamentals to practical applications.

Coverage includes properties and selection of materials for boiler tubes, damage mechanisms responsible for failure of boiler tubes, and characterization techniques employed for investigating failures of boiler tubes in thermal power plants and utility boilers of industrial/commercial/institutional (ICI) boilers. A large number of case studies based on the actual failures from the field are described, along with photographs and microstructures to allow for easy comprehension of the theory behind the failures.

This book is geared to practicing engineers and for studies in the major area of power plant engineering. For non-metallurgists, a chapter has been devoted to the basics of material science, metallurgy of steels, heat treatment, and structure-property correlation. A chapter on materials for boiler tubes covers composition and application of different grades of steels and high temperature alloys currently in use and future materials to be used in supercritical, ultra-supercritical, and advanced ultra-supercritical thermal power plants. A comprehensive discussion on different mechanisms of boiler tube failures is the heart of the book. Additional chapters detailing the role of advanced material characterization techniques in failure investigation and the role of water chemistry in tube failures are key contributions to the book.

The authors have long-standing experience in the field of metallurgy and materials technology, failure investigation, remaining life assessment (RLA), and fitness for service (FFS) for industrial plants and equipment. They have conducted a large number of failure investigations of boiler tubes and have recommended effective remedial measures in problem solving for power and utility boilers.

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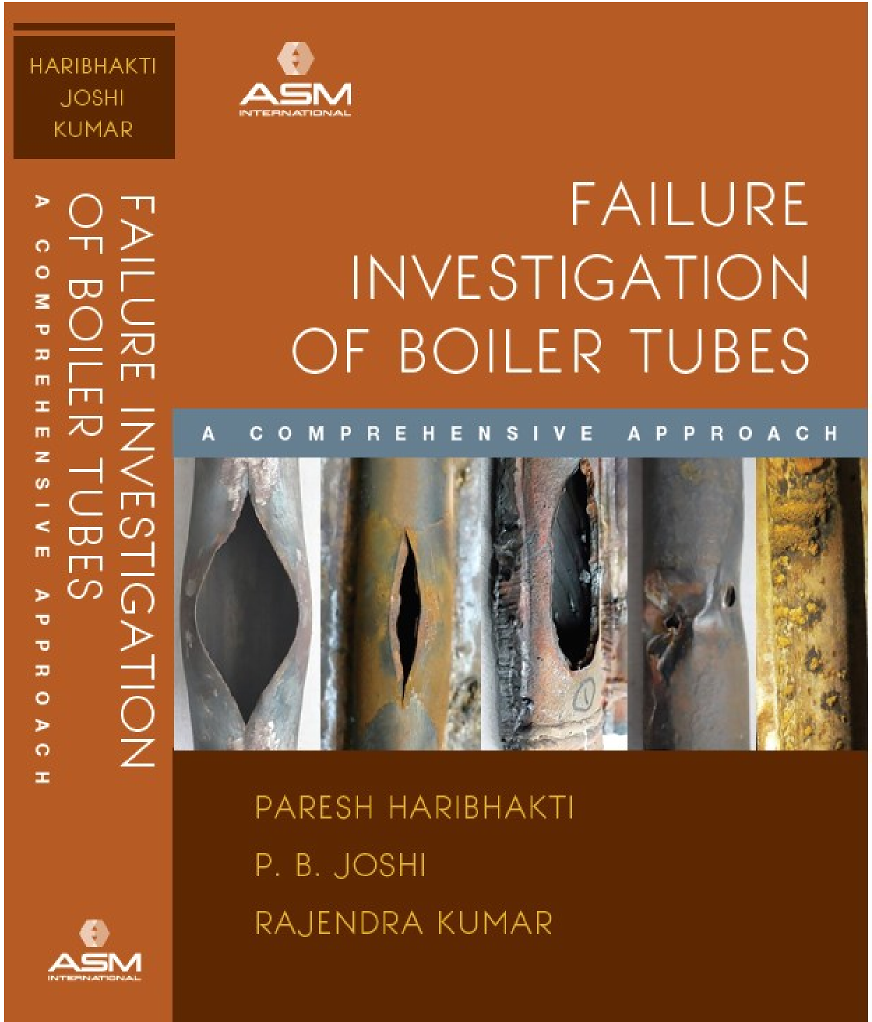

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ASM Handbook, Volume 11A, *Analysis and Prevention of Component and Equipment Failures*
B.A. Miller, R.J. Shipley, R.J. Parrington, D.P. Dennies, editors
DOI 10.31399/asm.hb.v11A.a0006825

Failure of Boilers and Related Equipment

Paresh Haribhakti and P.B. Joshi, TCR Advanced Engineering Pvt. Ltd.

FAILURES IN BOILERS and other equipment taking place in power plants that use steam as the working fluid are discussed in this article. The discussion is mainly concerned with failures in Rankine cycle systems that use fossil fuels as the primary heat source. In a Rankine cycle system, the steam is generated in a boiler, followed by its expansion in the prime mover and condensation in the condenser; finally, it is fed into the boiler again. Although, many of the principles that apply to Rankine cycle systems also apply to systems using other steam cycles or to systems using working fluids other than steam.

Boilers/steam generators work on the principle of conversion of the chemical energy in fuel into thermal energy to generate steam or hot water. Power boilers using pulverized coal, fuel oil, or natural gas as the fuel are used in thermal power plants to produce steam for generation of electricity. They are very large in size and are operated at high pressure and temperature in order to produce high-pressure, high-temperature superheated steam for power generation.

The other category of boilers termed as the industrial, commercial, and institutional (ICI) boilers are relatively small in size and are used to cater to captive demand of steam or hot water for the intended application. Boilers installed in chemical industries, petrochemicals and refineries, food processing, paper, textile, and similar other industries belong to this category. Their main function is to provide steam, hot water, or electricity, depending on the nature of the requirement. Institutions and commercial establishments such as hospitals, schools, colleges, hotels, restaurants, and office buildings use boilers for generation of steam and/or hot water.

Likewise, there are boilers termed as heat-recovery steam generators (HRSGs) and kraft-recovery boilers. As the HRSG name indicates, the waste heat released by the exhaust gases or hot air from combustion processes of gas turbines, diesel engines, or other industrial processes is effectively used to produce hot water or steam to improve the process economy. The kraft-recovery boilers (also known as black-liquor-recovery boilers) produce steam that can be used in the kraft process to generate electricity or for heating purposes.

Most boiler/steam generator failures occur in pressurized components, such as the tubing, piping, headers, and pressure vessels that constitute the steam-generating portion of the system. With very few exceptions, failure of pressurized components is confined to relatively small-diameter tubing (such as the water-wall, superheater, reheater, and economizer tubes) making up the heat-transfer surfaces.

This article discusses the main types of failure that occur in steam-power-plant equipment, with major emphasis on the distinctive features of each type that enable the failure analyst to determine the cause of failure.

Power plants, by and large, make use of various nonrenewable sources of energy such as coal, natural gas, oil, and nuclear for electrical power generation, of which coal is the most common source. Approximately 40% of electricity produced worldwide is still from coal-based thermal power plants. With coal as the fuel, there are two distinct technologies used for power generation: subcritical and supercritical. Supercritical is that state of a substance in which there is no clear distinction between the liquid and gaseous phase (i.e., it behaves as a homogeneous fluid). Water reaches this state at a pressure greater than 22.1 MPa (3.2 ksi) and a temperature equal to 374.15 °C (705.50 °F). *Supercritical* is a generic term used in the power plant industry that also includes ultra-supercritical (USC) and advanced ultra-supercritical (A-USC) boiler technologies.

From a design point of view, the conventional or subcritical thermal power plants have a drum-type boiler wherein steam is separated from a nonhomogeneous mixture of water and steam before it is superheated and fed to the turbine. On the other hand, all supercritical boilers are of the once-through type, wherein the water and steam flow through the boiler circuitry only once. Figure 1 explains the basic difference between the functioning of a subcritical and a supercritical boiler.

For a fossil-fuel-based (such as the coal-based) thermal power plant, the operating steam temperature and pressure decide its efficiency. The operating temperature and pressure in cases of subcritical boilers are below 538 °C (1000 °F) and 22.1 MPa (3.2 ksi),

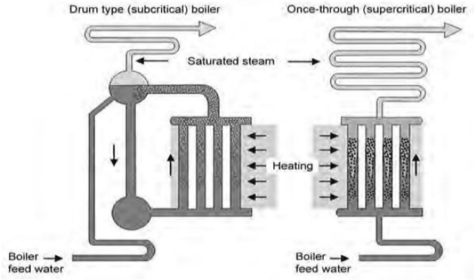
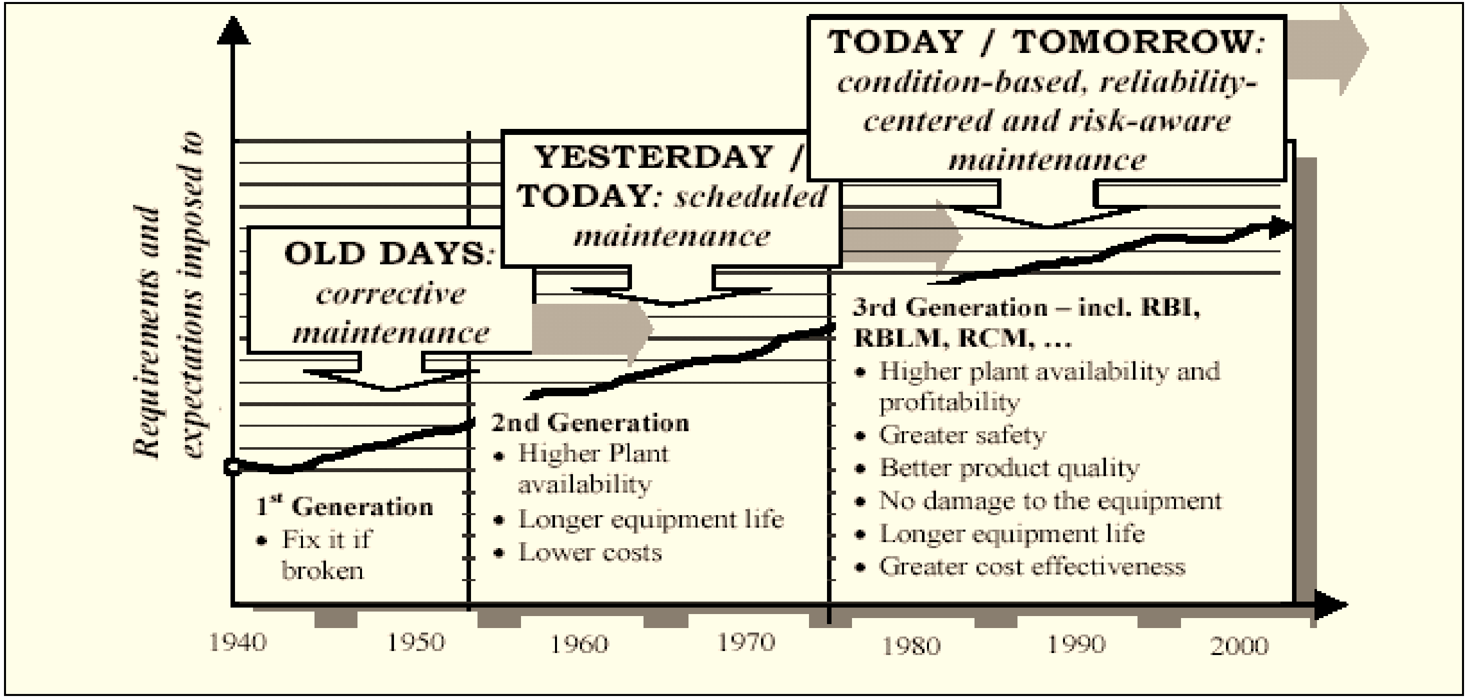


Fig. 1 Schematic showing difference in functioning of subcritical and supercritical boilers

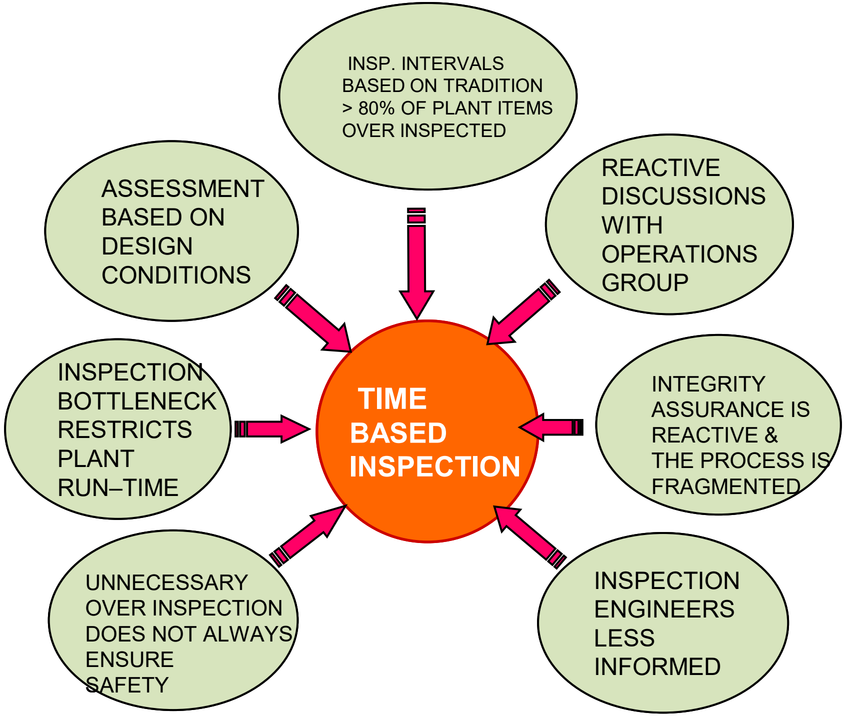
Survey of maintenance practices

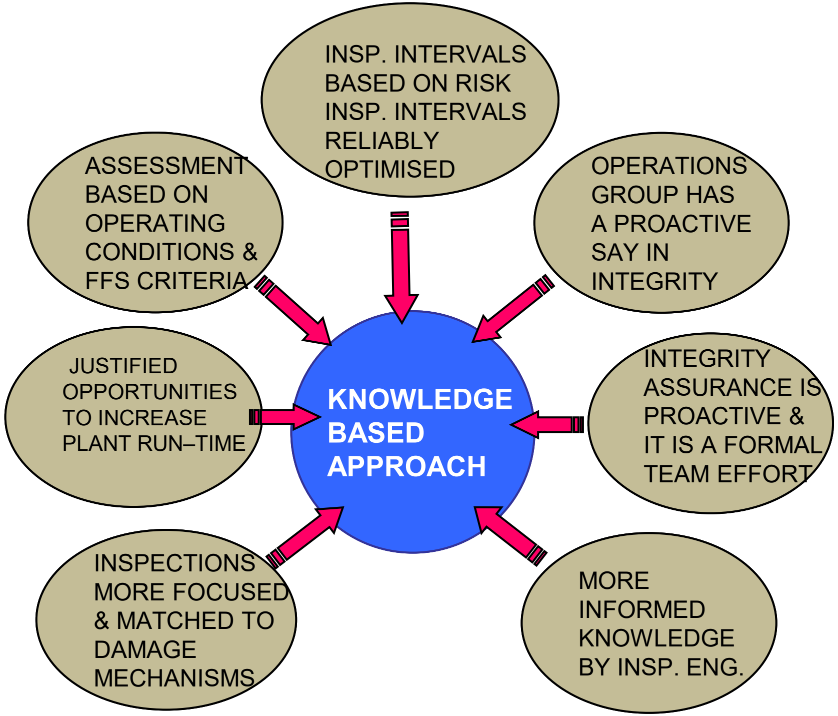


Summary: Need for KBI

- Most inspection codes/standards based on LOF not COF
- Improve reliability and safety of each item and Reduce risk of high consequence failures of ageing plants
- Improve the cost effectiveness of inspection and maintenance resources
- Provide a formal justification to extend plant run-length time
- Provide a basis optimizing each item inspection interval and for shifting resources from lower to higher risk equipment
- Measure and understand the risks associated with current inspection programs & operational practices
- Measure risk reduction as a result of inspection practices

Time based v/s Knowledge based





PLANT RELIABILITY & SAFETY CAN BECOME DOUBTFUL & CREATE UNCERTAINTY IN *ROI*

ENHANCED SELF-ASSURANCE IN PLANT RELIABILITY & SAFETY & DISTINCTLY IMPROVED *ROI*

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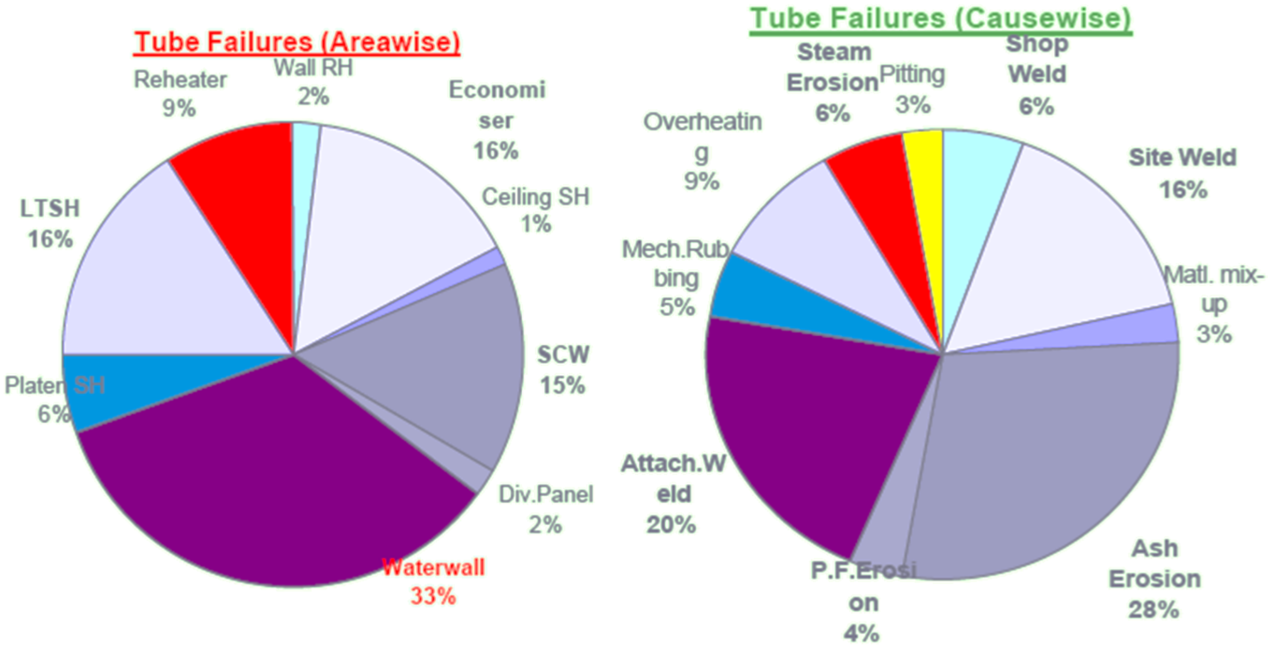
Life limiting factors

- Material defects
- Fabrication practices
- Stress, stress concentration and stress intensity
- Temperature
- Thermal and mechanical fatigue cycles
- Corrosion concerns
- Improper maintenance, inspection practices

Failure investigation - challenge

- Boiler tube failure is an effect and not the cause.
- Minimizing the or eliminating the failure of tubes in India like the rest of the world represents the significant opportunity.
- According to EPRI power generation through fossil fuel it provides 3% of generation loss due to tube failure.

Boiler tube failure: Categorized



Based on NTPC 500 MW boiler tube failure data

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Challenge for Power Plants

The challenge is that for most fossil power plants in operation today—which were designed and manufactured to be operated under baseload conditions—cycling to meet fluctuating demand levels causes disproportionate wear and tear on boiler and plant components, which often leads to damage.

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Damage mechanisms

Fluid side corrosion

- Oxygen pitting
- Under deposit corrosion—caustic gouging
- Under deposit corrosion—hydrogen damage
- Under deposit corrosion—phosphate corrosion
- Acid cleaning corrosion
- Internal deposit/corrosion product build-up
- Flow accelerated corrosion

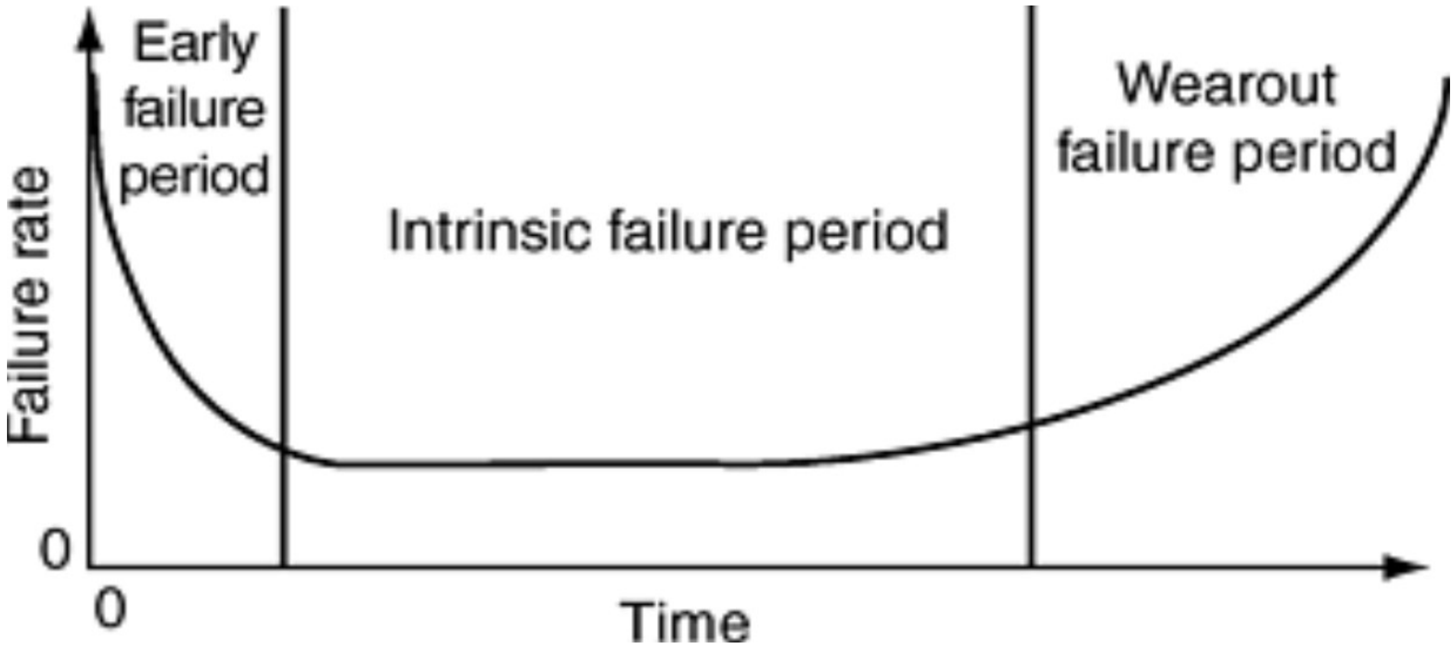
Fireside

- Fireside oxidation
- Fireside corrosion of super heater and re-heater tubing
- Fly ash corrosion
- Soot blower erosion
- Coal particle corrosion
- Steam impingement
- Fireside corrosion of water wall tubing
- Erosion
- Low temperature (dew point) fireside corrosion
- Falling slag damage
- Tube rubbing

Metallurgical damage

- Rupture
- Short-term overheating (stress rupture)
- Long-term overheating (creep rupture)
- Graphitization
- Sigma phase embrittlement cracking
- Corrosion fatigue—waterside
- Corrosion fatigue—fireside
- Thermo mechanical fatigue
- Vibration fatigue
- Dissimilar metal weld stress rupture
- Stress-corrosion cracking
- Stress induced corrosion

Bath tub curve for failures



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Effective implementation to root out boiler tube failures

- Solving BTF problems is best performed by a ‘plant team’ not by a single participant
- Correcting the root cause (‘killing’ the mechanism), rather than ‘managing damage’ from overhaul to overhaul.
- Action plans are prepared for every ‘repeat’ BTF problem or serious single problem. Action plans are separate and distinct to (a) eliminate or mitigate the problem, and (b) to correct the root cause(s) such that problems won’t reoccur in the future.
- Senior corporate and plant management are committed to mechanism identification, root cause analysis and permanent corrective action.
- Clear direction to corporate plant management, engineering operations and maintenance personnel on the conduct of day-to-day activities that influence root cause(s) of significant failures.

Concept of magnetite layer

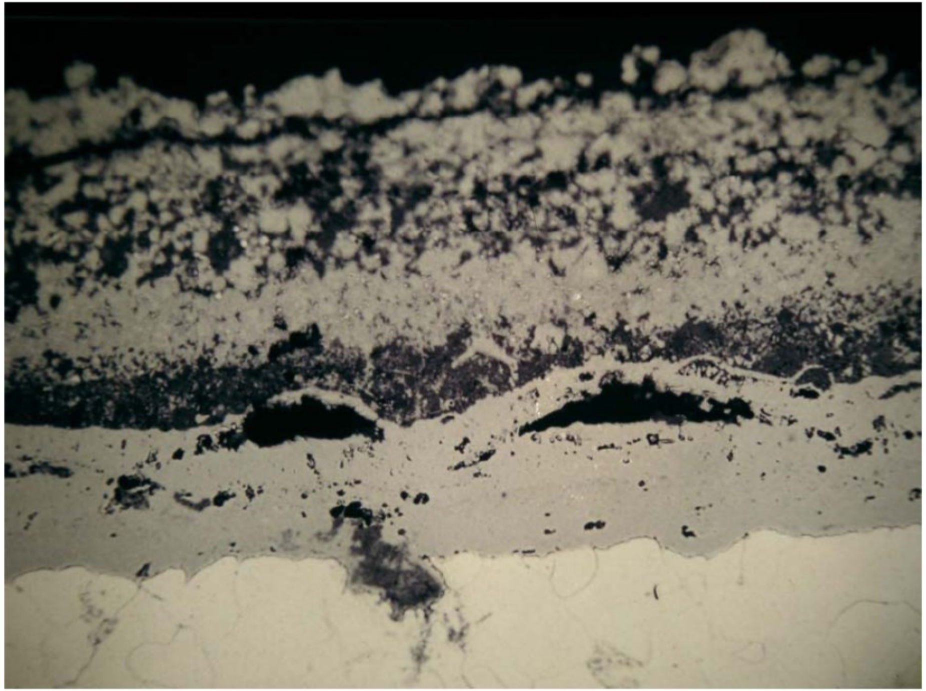
- The primary constituent of boiler scales is magnetite (Fe_3O_4), which is formed as a result of the reaction of metallic iron with high temperature steam. High temperature water and steam that typically range from 150 to 485°C promote fast corrosion reactions. Since no oxygen is normally present, the primary corrosion reaction in an operating boiler is

$3Fe$	+	$4H_2O$		Fe_3O_4	+	$4H_2$
Iron		Water or Steam		Magnetite		Hydrogen Gas

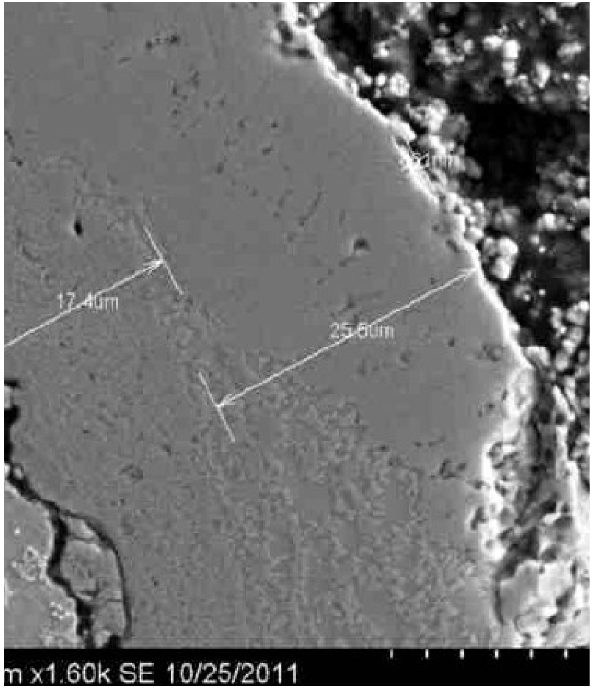
- The product of the process is black iron oxide, or magnetite. This reaction is the cause of all boiler corrosion. Fortunately, this same reaction prevents excessive corrosion.

- When magnetite layer grows to a thickness 0.005 to 0.018 mm, damaging corrosion stops. The magnetite layer which is continually being weakened or damaged by changing temperatures and the dynamic boiler environment.

Undesirable scale



Typical scale pattern in supercritical boiler tubes



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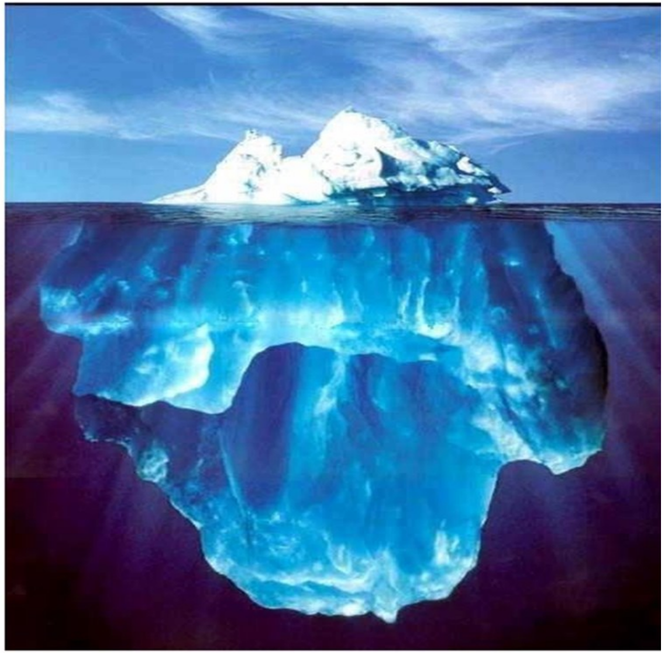
Identification of damage can be a tip of the iceberg



There are primary and secondary failures.
Condenser leakage can cause secondary damage in side the boiler.
Disturbance in water chemistry can lead to serious problems.

Team study TCR & Your company

- Team study facilitator (inspection & integrity assurance experience)
- Plant Inspection Engineer
- Plant Operations Engineer
- Plant Process Engineer
- Metallurgist (with equipment Damage Mechanisms & failure analysis experience)
- Sr. NDT Expert (need basis)

Team Study Process

- Identify ‘Active’ & ‘Potential’ Damage Mechanisms (DMs)
- Evaluate Failure Mode for each DM
- Determine HSE & Business Consequences of Failure (COF) for each DM
- Evaluate or calculate Probability of Failure (POF) for each DM
- Based on COF for each DM, define acceptable HSE and Business Risk positions
- Evaluate or Calculate latest Inspection Date for each DM
- Optimize Inspection Interval so that risk profile of the Item is acceptable
- Define Inspection Methods & Inspection coverage for DMs
- Define Operating Limits and any Maintenance issues that can affect damage rates
- Specify any risk mitigation actions or any anticipated repairs at the next TA, to help plan ahead

Limitation of each NDT Technique

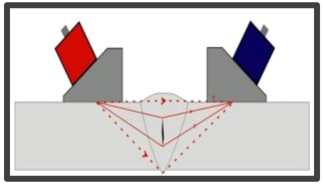
Technique	Applicability	Limitations
DPI	All materials	Surface only
MPI	Ferromagnetic materials	Surface or up to 2 mm subsurface, surface preparation required
UT	Most materials, surface or subsurface	Can be operator dependent, prone to defect sizing errors
Radiography	All materials, surface or subsurface	Defect orientation/size limitations, need access to both sides of component
ECT	Mainly non-magnetic materials, surface and limited subsurface, also crack sizing	Operator dependent, sizing limitations
Potential drop	All steels, surface crack sizing	Limited accuracy and reliability
Replication	All steels, surface, early stage of creep damage, identification of damage type	Highly operator dependent and interpretation expertize required

EFFECTIVE INSPECTION

QUALITATIVE INSPECTION EFFECTIVENESS CATEGORY (API)
***Highly* Effective:** Correctly identify the anticipated in-service damage in nearly every case
Usually Effective: Inspection methods will correctly identify the actual damage state most of the time
Fairly Effective: Inspection methods will correctly identify the true damage state about half the time
Poorly Effective: Inspection methods will provide little information to correctly identify the true damage state
Ineffective: Inspection method will provide no/almost no information to correctly identify the true damage state

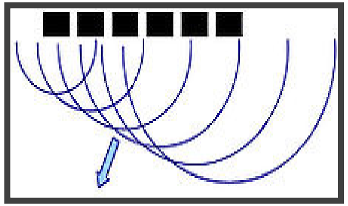
ADVANCED NDT TECHNIQUES FOR
Remaining life Assessment (RLA)

1) TOFD-Time Of Flight Diffraction



- Two longitudinal wave (L-wave) angle beam transducers employs
- One probe acts like a **transmitter** while the other probe **receives** the ultrasound energy.
- The transducer, pulsar and amplifier characteristics are selected to generate as broad distribution of energy as possible over the material under test providing full weld coverage.
- A single-axis scan (that is, along the weld), with a position encoder records the position of the weld and enables the display of digital images in real time.

ADVANCED NDT TECHNIQUES FOR
Remaining life Assessment (RLA)



2. PAUT-Phased Array Ultrasonic Testing

- The PA probe consists of many small elements, each of which can be pulsed separately.
- In the figure- the element on the right is pulsed first and emits a pressure wave that spreads out like a ripple on a pond (largest semicircle).
- The second to right element is pulsed next, and emits a ripple that is slightly smaller than the first because it was started later. The process continues down the line until all the elements have been pulsed.
- The multiple waves add up to one single wave front travelling at a set angle. In other words, the beam angle can be set just by programming the pulse timings.

ADVANCED NDT TECHNIQUES FOR

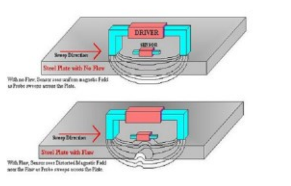
Remaining life Assessment (RLA)

3. Remote visual inspection of headers (Videoscopy)

- It is the inspection of **objects or areas usually inaccessible to the eye** without disassembling surrounding structures or machinery.
- It allows inspectors to **discover hidden discontinuities** before they may cause major problems, e.g. poor welding, surface defects like ligament cracking, corrosion pits, general condition, degradation, blockages and foreign materials
- We can find out nature of defect and location of defect but cannot quantify it. i.e., **qualitative analysis no quantitative** analysis

ADVANCED NDT TECHNIQUES FOR

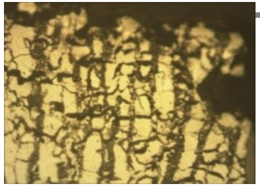
Remaining life Assessment (RLA)

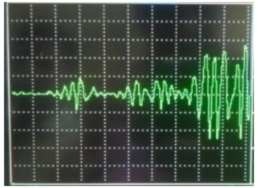


4. Low frequency eddy current testing

- It works on principle of magnetic flux leakage
- It cannot detect defects like lamination and cracks if oriented in direction parallel to the field of magnetic flux
- Thickness loss also may not be accurately obtained – advised to carry out follow up UT at suspected location

ADVANCED NDT TECHNIQUES FOR
Remaining life Assessment (RLA)



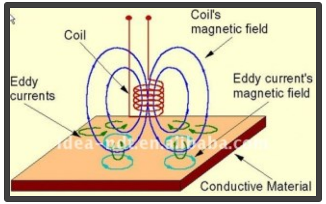


5. AUBT on water-wall tubes

- Microstructure shows presence of fissures from ID due to HTHA
- Other techniques to detect HTHA are as under:
  - Attenuation measurement
  - Spectral analysis
  - Velocity measurement
  - Back scattered technique
  - In-situ metallography
  - WFMPI

ADVANCED NDT TECHNIQUES FOR

Remaining life Assessment (RLA)



6. Remote field eddy current testing (RFET)

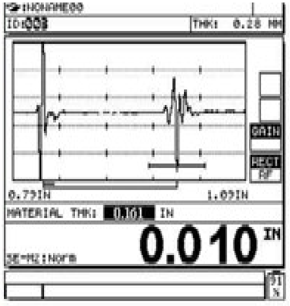
- RFET has been primarily applied to **ferromagnetic**
- Two sources of magnetic flux are created in the tube interior; the primary source is from the coil itself, and the secondary source is from eddy currents generated in the pipe wall.
- At locations in the interior, near the exciter coil, the first source is dominant, but at larger distances, the wall current source dominates.
- A sensor placed in this second, or remote field, region is thus picking up flux from currents through the pipe wall.

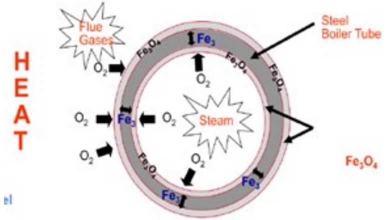
ADVANCED NDT TECHNIQUES FOR

Remaining life Assessment (RLA)

8. In-situ internal oxide scale thickness measurement

- Thickness of oxide helps to predict tube life
- As the internal oxide scale builds above 0.013” (0.33mm) it impedes the heat transfer between the tube metal and the steam
- Transducers: N2091-normal incident shear 20MHz (0.006”)In. or 0.15mm min. internal oxide)
- Measures and displays oxide and tube thickness at the same time

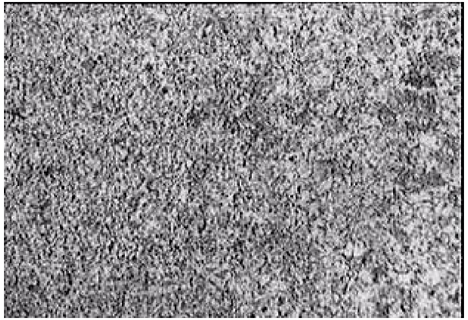


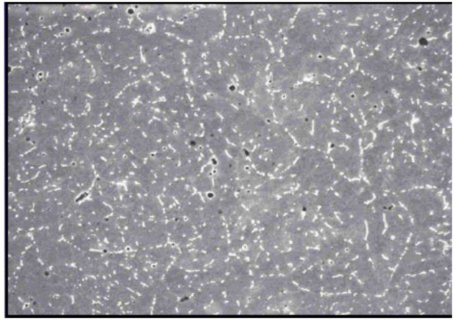


ADVANCED NDT TECHNIQUES FOR

Remaining life Assessment (RLA)

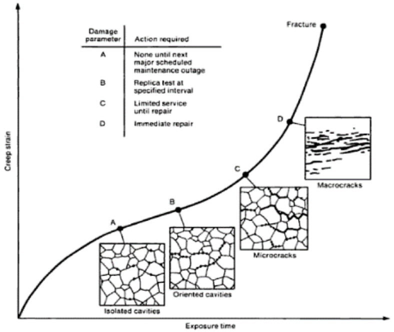
10. In-situ metallography





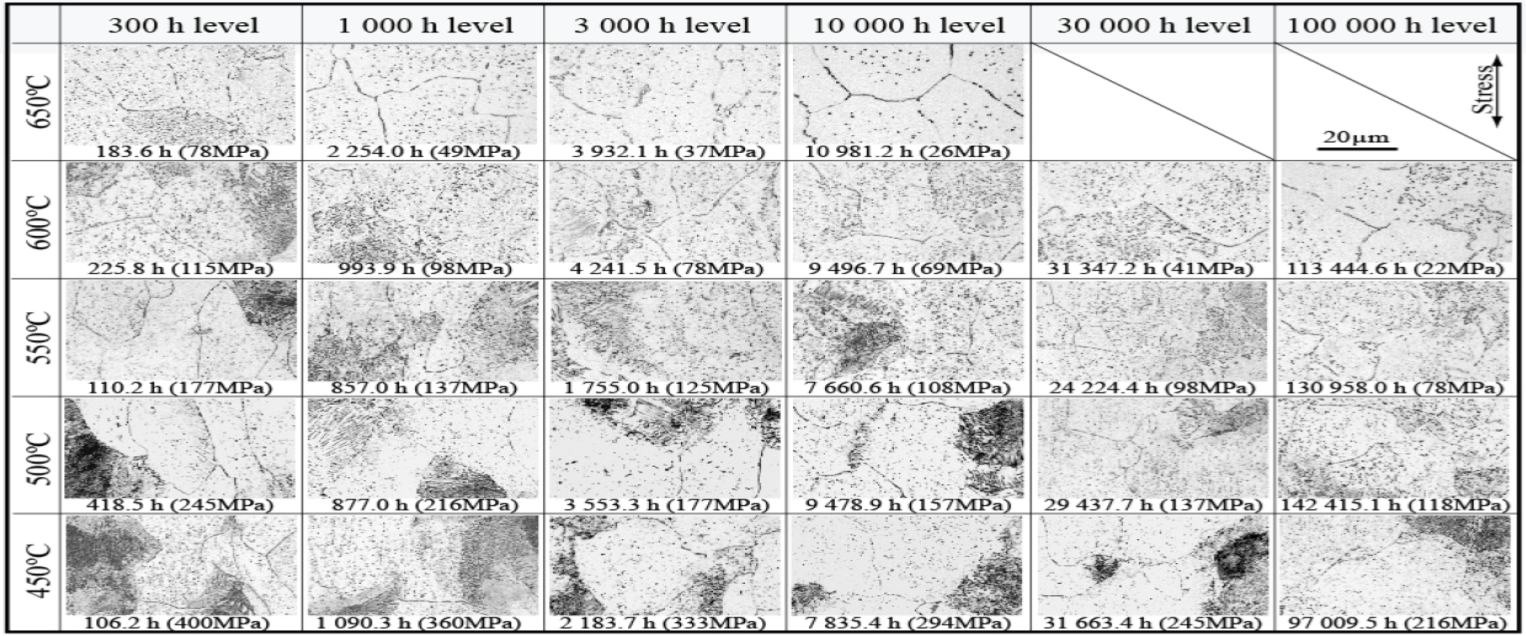
- ❖ Isolated cavitation damage is in the Cr-Mo weld after 25 years of service in the power plant. Carbide formation and cavitation damage is observed.

CREEP MEASUREMENT AND LIFE ASSESSMENTS



- Metallographic methods have been developed that can correlate cavitation damage.
- In boiler cavitation is the principle damage mechanism.
- Creep cavitation model is developed which measures number of cavities scanning electron microscopy at various stages of creep.
- Ratio of cavitated boundaries to total boundaries of intersect provides creep life.

RLA: APPROACH BASED ON METALLOGRAPHY



MOC: 2.25 Cr Low alloy steel (Typ SA213 Grade T22)

Ref: Metallographic Atlas for 2.25Cr-1Mo Steels and Degradation due to Long-term Service at the Elevated Temperatures

PLANTS ADOPTING KBI: Manifold benefits

- NDT methods effectiveness & capability are better defined
- Identification of potential damage mechanisms (DM)
- Inspection coverage (susceptible locations) for identified DMs
- Identification of key process parameters and assessment of proposed process changes affecting degradation rates
- Operational limits (e.g. temperature, composition) are better defined to prevent increase in damage rates or initiation of new damage mechanisms
- Documentation of current plant configuration and materials of construction
- Improved team working and communication between all departments

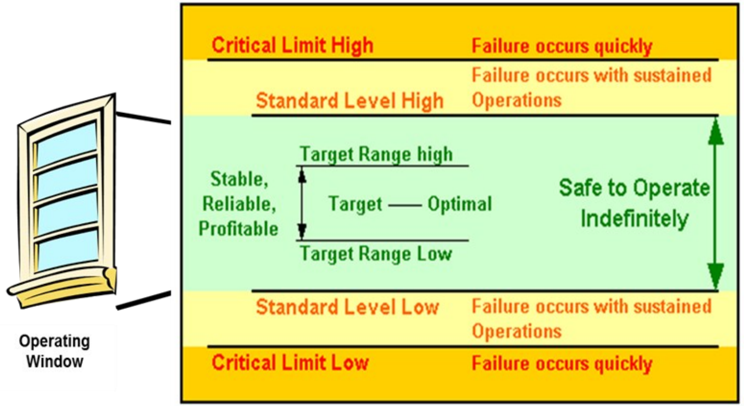
Asset Integrity & Optimization Management (AiOM)

Our prime objective is to help companies achieve
Overall Integrity, Reliability, Safety & Optimization and
Maintenance Excellence

Adding Value to Company's Bottom Line

IOW - INTEGRITY OPERATING WINDOWS

- Integrity Operating Windows (IOWs) are sets of limits used to determine the different variables that could affect the integrity and **reliability** of a process unit.
- IOWs are the limits under which a machine can operate safely.
- Working outside of IOWs may cause otherwise preventable damage or failure. For this reason, it's incredibly important to be aware of the IOWs for each machine that is in operation.
- It is important to develop limits for every possible damage mechanism that is likely to affect a component.
- This way the working within the limits for the machine will be able to prevent most likely types of damage that might affect it.
- To start with, for every piece of equipment, an IOW plan should be created.



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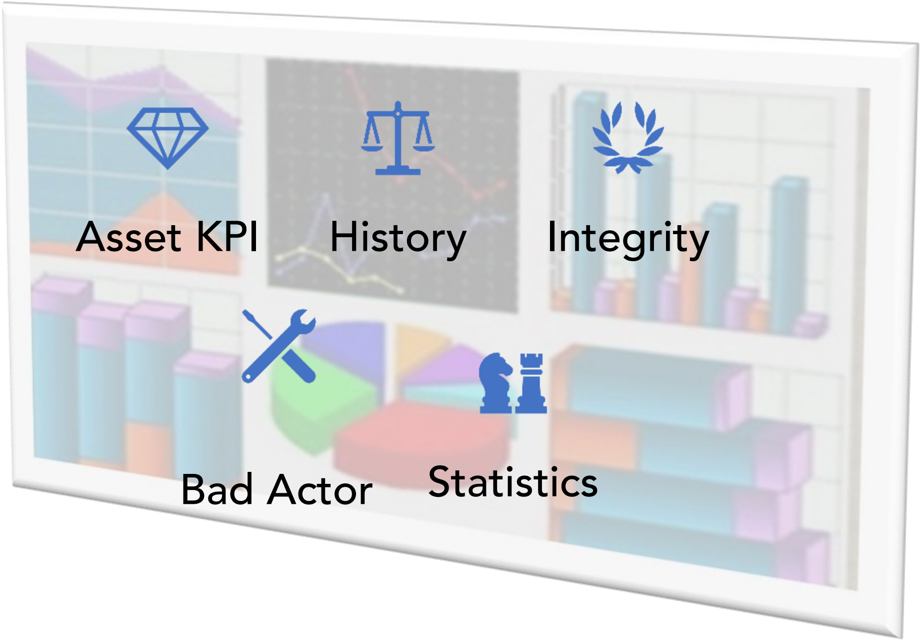
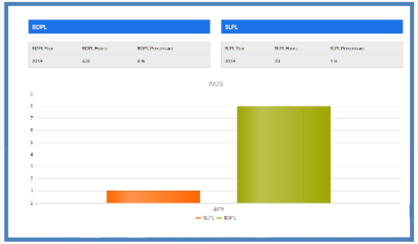
AiOM – Asset ANALYTICS





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Questions?

paresh@tcradvanced.com

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