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Enhancing Boiler Asset Performance

A Scientific Approach Integrating **Knowledge-Based Audit (KBA)** for Asset Integrity, Efficiency, and Reliability

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Abstract

Boiler reliability is the cornerstone of coal-fired power plant performance, yet boiler tube failures (BTFs) remain the primary cause of forced outages, unplanned downtime, and efficiency losses. This paper presents a conceptual framework for Damage Mechanism-Based Diagnostics using TCR Advanced Engineering's proprietary Knowledge-Based Audit (KBA) methodology. Drawing on over 1500 boiler tube failure inavestigations and 500+ remaining life assessments (RLA), this approach integrates metallurgical, operational, and NDT data to proactively identify and mitigate high-risk failure mechanisms in both sub-critical and supercritical boilers. Case studies illustrate practical applications, including life extension strategies and alignment with ESG objectives.

Introduction

Boiler tube failures (BTFs) are consistently identified as the leading cause of unplanned outages in coal-fired power plants, contributing to mid-single-digit reductions in annual plant availability. These failures not only disrupt generation but also reduce efficiency, increase fuel consumption, and pose safety hazards.

1.1. Sub-Critical vs. Super-Critical Boilers

Super-Critical Boilers

- Operate at higher pressures/ temperatures using advanced materials/ designs.
- Face more aggressive creep, oxidation, and flow-accelerated corrosion (FAC).
- Require stricter water chemistry (e.g., oxygenated treatment).
- Need close monitoring of tube metal temperatures, as design margins assume finite creep life.

Sub-Critical Boilers

- Operate at lower parameters but still suffer fatigue and corrosion, especially beyond 25–30 years of design life. Many 200–500 MW Indian units are >20 years old.
- CEA mandates Renovation & Modernisation (R&M) and Life Extension.
- Residual Life Assessment (RLA) after ~20 years (~160,000 hrs) checks for creep, fatigue, corrosion.
- Repairs/replacements can extend unit life by 15–20 years.
- Must also comply with stricter emission norms (NOx, SO_2) and enable flexible operation to support renewables.

1.12 Boiler Integrity Management

Traditional Practices

- Relied on time-based overhauls.
- Statuary compliances.
- Reactive approach.

1.13 Knowledge-Based Audits (KBA)

Damage mechanism-specific, knowledge-driven approach.

Leverages decades of empirical failure data.

Enables prediction and prevention of failures.

Improves asset integrity, efficiency, and reliability.

Plant Life Extension

Retains Knowledge with in the company

Knowledge-Based Audit (KBA) Methodology

KBA is a structured, data-driven audit framework developed by TCR Advanced Engineering. It leverages the collective knowledge from 1500+ BTF investigations and 500+ RLA projects to identify high-risk boiler components and mitigate failures.

2.1 KBA Workflow

Data Gathering
Collect design, operational, and historical failure data.

Damage Mechanism Identification
Analyze each component for plausible mechanisms (creep, corrosion-fatigue, FAC, oxidation, erosion, thermal fatigue).

Likelihood and Consequence Assessment
Quantitative or qualitative evaluation of PoF and CoF.

Criticality Ranking
Prioritize components based on combined risk metrics.

Targeted Inspections and RLA
Focused NDT and metallurgical studies on critical zones.

Mitigation & Operational Recommendations
Implement material upgrades, operational adjustments, and monitoring systems.

01

Data

Collection & Validation
Design Data Operating
History Inspection Results

02

Analysis

Damage Mechanism
Identification
Metallurgical
Degradation
Trend & Correlation

03

Risk Ranking

Failure Probability
Consequence Criticality
Prioritization

04

Targeted RLA

Remaining Life Level
1/2/3 Assessments
Monitoring Strategy

05

Mitigation

Repair/Replacement
Process Operating
Adjustments Protective
coatings/treatments

06

Life Extension

Optimized
Maintenance Reliability
Improvement
Efficiency Recovery

Major Damage Mechanisms and KBA Diagnostics

3.1 Corrosion-Fatigue in Boilers

3.11 Mechanism:

A combined action of cyclic stress (fatigue) and corrosive environment. Common in water-touched tubes (waterwalls, economizers) under fluctuating thermal/pressure stresses with poor water chemistry (e.g., oxygen pitting, acidic condensate).

Industry View
EPRI identifies it as a major cause of unscheduled boiler downtime due to its multi-factor nature (stress, environment, transients).

Crack Initiation
Typically starts at stress concentration sites (welds, supports, bends, temperature-mixing zones). Poor water chemistry accelerates initiation/growth.

3.12 Detection:

- Cracks usually axial, oxide-filled, with multiple initiation sites.
- KBA flags high-risk areas (waterwall near backstays, economizer bends).
- NDT methods: MPI/DPT (accessible areas), UT at attachments, thermography, and acoustic emission for active growth.

3.13 Mitigation:

Stress side
Use flexible supports/expansion loops; control ramp rates, prewarm feedwater, avoid rapid load swings.

Corrosion side
Maintain strict chemistry (pH, oxygen scavengers), prevent contaminants, perform chemical cleaning carefully.

Material upgrade
Replace carbon steel with Cr-Mo alloys for higher resistance.

KBA Checklist
Supports movement, chemistry excursions, cyclic patterns – optimized to mitigate the mechanism.

3.14 Case Insight (TCR Advanced):

KBA showed stress concentration + frequent cycling + oxygen peaks = corrosion-fatigue cracks

Repeated waterwall tube leaks at weld-clips

Solutions

Weld blending, redesigned sliding supports, tighter oxygen control.

Result

No further leaks, proving the value of knowledge-driven audits.

3.2 High-Temperature Creep and Overheating in Boiler

3.21 Mechanism

- Time-dependent deformation/damage under stress at high temperature.
- Primary life-limiting mechanism for superheater, reheater tubes, headers, and main steam piping.
- Typical service temperatures: 400–550°C (sub-critical), 600°C+ (supercritical).
- Damage evolution: creep voids/cavities → graphitisation (in carbon steels)→ rupture with bulged "fish-mouth" fracture.
- Failures often linked to long-term overheating or operating above design temperature.

3.22 Oxide Scale Effect

- Ferritic steels form internal magnetite (Fe_3O_4) on steam-side surfaces.
- Acts as insulation → raises tube metal temperature → accelerates creep(self-reinforcing).
- Over decades, oxide growth adds tens of °C, consuming creep life faster.
- Increased oxide thickness is a strong indicator of creep damage.

3.23 Detection & Monitoring

Late signs
visible bulging/sagging tubes → near failure.

Early methods (KBA emphasis):
- In-situ metallography (replica testing): reveals creep voids/cracks beforerupture; staged progression (I → II → III).
- Ultrasonic/EMAT oxide thickness measurement: links scale thickness to overheating/creep damage.
- Infrared thermography: maps hot tubes during operation.
- Periodic replication (every ~3 yrs after 100,000 hrs): tracks creep evolution

3.24 Mitigation Strategies

Replacement/Upgrade:
Renew coils with damage; use higher-strength alloys (e.g. carbon steel → T22 → T91).

Reduce stress/temperature:
Adjust setpoints, firing, or attemperator to keep tubes below creep limit.

Hot spot correction:
Optimize burners, shielding, tube screens.

Oxide cleaning (steam side)
Abrasive/chemical methods can restore heat transfer, but must be carefully managed

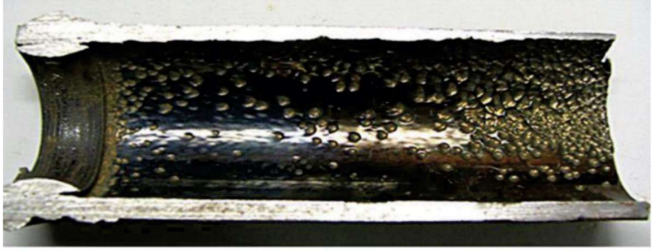
Formal RLA (Residual Life Assessment):
- Uses creep rupture data (Larson-Miller parameters) + observed damage.
- Guides proactive replacement (e.g. tube at 80% life replaced at next outage).

3.25 Case Insight (TCR Advanced)

A 30-year-old super-critical unit showed creep voids and heavy oxide in final superheater tubes.

Selective renewal of coils extended safe operation by another decade

3.3 Flow-Accelerated Corrosion (FAC) in Boiler



3.31 Mechanism:

- Thinning of carbon steel due to dissolution of protective magnetite oxide in rapidly flowing water or wet steam.
- Primarily affects feedwater/economizer piping, heaters, and sometimes waterwall or wet-steam turbine regions.
- Common high-risk areas: feedwater elbows downstream of economizers, high-turbulence zones after valves, economizer inlet headers with twophase flow.
- Carbon steel is most vulnerable; low-alloy steels with Cr (0.5–2.25%) offer much better resistance.

3.32 Industry Significance:

- FAC has caused serious incidents, e.g., 1986 Surry Unit 2 pipe rupture.
- Wet-steam carbon steel lines remain a critical degradation concern.
- EPRI guidelines (NSAC-202L) and predictive tools (e.g., CHECWORKS) are widely used.

3.33 Detection & Monitoring:

Indicators
Uniform wall thinning with smooth, scalloped internal surfaces.

KBA Approach:

- Map high-risk locations: elbows, tees, reducers, feedwater heaters, economizer entrances.
- Ultrasonic Thickness (UT): primary NDE method; grid measurements or automated scanning reveal trends.

KBA Approach (CONTD.)

- Trend Analysis: Compare to baseline; calculate metal loss per year and project remaining life.
- Additional techniques: Radiography (RT), spool-piece inspections, wear indicators.
- Water chemistry records (pH, oxygen, hydrazine/ammonia dosing)correlated with thinning events.

3.34 Mitigation Strategies:

Water Chemistry Control:
Maintain proper alkaline pH (~9.2–9.6 for conventional units, oxygenated treatment in supercritical units) to stabilise magnetite film.

Material Upgrades:
Replace susceptible carbon steel with Cr-containing alloys (P11, P22) to reduce FAC rates.

Geometry Optimisation:
Streamlined elbows, flow conditioners, or reduced steam wetness to lower turbulence.

Inspection Planning:
Abrasive/chemical methods can restore heat transfer, but must be carefully managed

3.35 Case Insight (TCR Advanced):

500 MW

Severe FAC in economizer outlet header due to suboptimal pH.

Actions

Header replaced with P11 material, pH control tightened.

Outcome

Further wall loss arrested; unit runs without FAC issues, demonstrating KBA effectiveness

3.4 Oxidation and Scale Formation in Boilers

3.41 Mechanism:

Reaction of steel with oxygen forming oxide scales on fireside (exposed toflue gas) and steam-side surfaces.

Fireside
- Prolonged exposure forms iron oxide scales; sulfur or other corrosivespecies can produce complex scales or pits.
- Thick scales can spall, causing local overheating and tube metal loss.

Steam-side
- Formation of magnetite (Fe_3O_4) scale.
- Excessive scale raises metal temperature (creep risk) and spalled oxide can clog downstream piping or turbines.

3.42 Detection & Monitoring:

Visual signs
Flaky scale, discoloration, especially near burners.
Quantitative methods:
- Oxide thickness replicas or ultrasonic gauging (UT).
- Metallographic sectioning of retired tubes to characterize oxide layers/ morphology.
- Thermocouples and flue gas analysis to detect gradual tube overheating.

Oxide growth generally follows parabolic kinetics (thickness $\propto \sqrt{\text{time}}$).

3.43 Mitigation Strategies:

Material Selection:
Use Cr/Mo alloys or austenitic steels (e.g., T91) in hottest sections to maintain thin, adherent oxide layers.

Coatings:
Fireside thermal spray coatings, chroming, or Inconel/alloy coatings to reduce oxidation.

Operational Control:
Maintain proper oxygen levels and avoid exceeding design metal temperatures.

Cleaning:
- Fireside: Soot blowers, water cleaning to remove slag/ash.
- Steam-side: Careful flushing to remove internal scales.

KBA Integration:
- Includes oxide thickness measurements in life assessment.
- Proactive replacement of tubes with excessive oxide (e.g., 0.5 mm internal oxide) to prevent creep rupture.

3.44 Case Insight (KBA Application-TCR Advanced):

210 MW boiler

Reheater outlet tubes showed heavy internal oxide; proactive replacement avoided potential rupture and outage.

Demonstrates how knowledge-based auditing enables proactive life extension and risk mitigation.

3.5 Thermal Fatigue in Boilers

3.51 Mechanism:

- Caused by cyclic thermal stresses due to temperature-induced expansion/contraction.
- Common in thick-walled components: headers, boiler drum internals, large diameter tube welds.
- Triggered by transient operations, rapid heating/cooling, load swings, or differential expansion between tubes, headers, or attachments.
- Increasingly relevant in plants performing load-following or daily startups to accommodate renewables.

3.52 Crack Initiation:

- Occurs at surface stress concentrators: weld toes, sharp corners, mixing zones (e.g., attemperator spray nozzles).
- Often develops from repeated start-stop cycles or rapid temperature changes.

Examples:
- Drum ligaments ("drum crazing") due to water/feedwater temperature difference.
- Header end caps, stub welds, nozzle welds prone to radial/circumferential cracks.

3.53 Detection & Monitoring:

Surface NDT methods:
Magnetic Particle Inspection (MPI) or Dye Penetrant (PT) during overhauls

Instrumentation:
Strain gauges or thermocouples to monitor thermal gradients

Cycle counting software
Tracks hot, warm, cold starts; computes fatigue life usage.

KBA
Identifies critical welds and high-risk components for focused inspection

3.54 Mitigation Strategies:

Operational control:
- Reduce thermal gradients via controlled ramp rates, preheating, bypass lines, or auxiliary heating.
- Avoid abrupt temperature/pressure changes.

Design modifications:
- Improve attemperator spray mixing and nozzle atomization.
- Reconfigure spray arrangements or add liners in mixing tees to reduce thermal deltas.

Repair/Replacement:
- Stop-hole drilling and weld repair for non-critical cracks.
- Replace heavily fatigued headers/drums or upgrade materials/thickness to reset fatigue life.

KBA ensures vulnerable locations are retrofitted, repaired, or closely monitored for safe life extension

3.55 Case Insight (TCR):

Superheater header with tube stub weld fatigue cracks replaced with improved material/thickness

Life extension achieved with safe operation beyond original design life, demonstrating KBA effectiveness.

3.6 Erosion and Erosion-Corrosion in Boilers

3.61 Mechanism:

Erosion:
Mechanical removal of tube material by impinging particles or fluid.

- Common causes in coal-fired boilers: fly ash, soot-blower steam, and high-velocity flue gas.
- High-risk areas: flue gas path, Superheater tubes, waterwalls, soot-blower lanes.

Erosion-Corrosion:
Combined action of mechanical wear and chemical attack.

Examples:

- Economizer/feedwater piping where wet steam or droplets induce both FAC and particle erosion.
- Ash erosion with sulfur corrosion on waterwalls in low-NO_x boilers.

3.62 Detection & Monitoring:

Visual indicators:
“Sand-blasted” or scalloped grooves, localised thinning in flow-facing surfaces.

NDE techniques:

- Ultrasonic thickness measurement (UT) to map erosion grooves and wall loss.
- **Advanced tools:** laser profilometry, high-resolution 3D scanning for precise cross-section loss assessment.

Operational data:
Track soot-blower frequency, pressure, and alignment to correlate with wear patterns.

KBA role:
Direct inspections to known erosion zones, analyse trends, and identify tubes nearing critical loss.

3.63 Mitigation Strategies:

Operational control:

- Optimize soot-blower frequency and pressure; avoid dry-tube blows.
- Burner tuning to minimize particle carryover and flame impingement.

Protective measures:

- Erosion shields or sacrificial metal in high-wear zones.
- Hard facing/cladding with wear-resistant alloys (high-chrome, Stellite) or ceramic coatings.

Material & design upgrades:
Thicker tube walls, protective ferrules, or improved alloy selection.

Erosion-Corrosion:
Control fluid chemistry (pH, oxygen) and flow velocity to reduce the chemical component.

3.64 Life Extension & KBA Application:

- Severely eroded tubes (>40% thickness loss) flagged for replacement during next overhaul.
- New tubes may incorporate design or material upgrades.
- Targeted KBA interventions ensure timely detection, preventive measures, and long-term reliability.

3.65 Summary:

Erosion is a continuous degradation mechanism in fossil boilers.

Through KBA-guided inspections, operational optimization, protective materials, and design improvements, its impact can be effectively managed to extend boiler service life.

CASE STUDY

Life Extension of Sub-Critical Power Boiler

Objective

Extend operational life while improving reliability and performance

KBA Overview

Approach:
TCR Advanced conducted a comprehensive Knowledge-Based Audit (KBA) covering the boiler and critical auxiliaries.

Outcome:
High-risk components were identified, prioritized, and addressed through targeted interventions, enabling a 12-year life extension beyond original design life.

Visualization:
A risk-ranking map highlighted components in red/orange, guiding material upgrades, enhanced inspections, and repairs.

Condition Assessment & Key Findings

Operational History
Boiler had operated ~30 years, facing recurrent tube failures and age-related degradation. Conventional RBI had not highlighted specific vulnerabilities.

Damage Mechanisms Identified via KBA:

- Creep fatigue: Final superheater tubes with thick internal oxide scales (~0.4 mm), indicating long-term overheating and significant creep life consumption.
- Flow-Accelerated Corrosion (FAC): Feedwater inlet piping showing advanced wall thinning in previously inaccessible elbows.
- Localized erosion-corrosion: Waterwall tubes near burner throats exposed to particle impingement combined with chemical attack.

Diagnostics Tools:

- Ultrasonic Thickness (UT) Scans: Quantified internal oxide and wall thinning.
- Metallographic Examination: Confirmed creep micro voids and erosion patterns.
- Operational Data Analysis: Correlated transient operation, soot blower
- patterns, and feedwater chemistry excursions with observed damage.

Targeted Interventions

Material Upgrades:

- ~15% of superheater tubes replaced with T91 alloy.

Maintenance Strategy:

- Economizer to be maintained in every two year by replacing refurbished spare.

Erosion Mitigation:
Installation of erosion shields on critical waterwall sections.

Operational Adjustments:

- Feedwater chemistry optimized to slightly higher pH for FAC mitigation.
- Soot blower operation staggered to minimize repetitive impingement.

Results & Impact

Operational Reliability:

- Reduced tube leaks reported in 3+ years post-intervention.
- Thermal profiles stabilized, reducing transient stresses.

Efficiency & Cost Benefits:

- Deferred major capital expenditure for new boiler.
- Improved heat transfers due to cleaner surfaces, reducing auxiliary losses.

Key Takeaway

This case exemplifies how a structured, mechanism-specific KBA can uncover hidden risks, guide targeted interventions, and deliver measurable life extension, operational efficiency, and cost savings—outcomes not achievable through conventional RBI alone.

Strategic Value:

Demonstrates KBA as a proactive, ESG-aligned strategy, maximizing asset utilization, enhancing safety, reliability and financial viability decisions.

12 years,

Life Extension

Confirmed by remaining life assessment calculations and methodologies.

Framework for Adopting KBA

Knowledge Repository:
Historical failures, inspection reports, RLA studies.

Expert Partnership:
Engage metallurgical and failure analysis specialists.

Comprehensive Audit:
Desktop study → on-site inspections → NDT/metallography → RLA integration.

Actionable Recommendations:
Targeted inspections, replacements, operational changes, monitoring enhancements.

Training & Culture:
Operator/inspector training on damage mechanisms.

Review & Continuous Improvement:
Cyclic feedback, updated risk assessments.

ESG Alignment:

Environmental

Higher efficiency, lower CO2 per kWh, avoiding new boilerconstruction.

Social

Worker/public safety, knowledge sharing, reliability.

Governance

Structured, auditable asset management process.

Conclusion

In today's evolving energy landscape, extracting maximum performance from existing assets is critical. Knowledge-Based Audits (KBA) provide a structured pathway for sub-critical and super-critical power plant boilers to achieve reliable, extended service well beyond their design life. Unlike conventional inspections, KBA applies damage mechanism-specific diagnostics, replacing scattershot approaches with predictive strategies grounded in real failure data.

Refined through thousands of investigations, TCR Advanced's KBA methodology systematically identifies and mitigates critical issues such as corrosion-fatigue, creep, flow-accelerated corrosion (FAC), oxidation, thermal fatigue, and erosion—before they cause costly failures. Case studies prove that every failure mode can be monitored, assessed, and mitigated with the right expertise and tools.

A boiler behaves like a living system, "aging" through metallurgical degradation, corrosion, thermal stress, and wear. KBA acts as a holistic health assessment and life-extension prescription, prescribing targeted treatments such as material upgrades, design optimization, and chemistry adjustments. This reduces tube failures, prevents forced outages, and ensures higher efficiency, consistent generation, lower fuel use, and reduced emissions—directly benefiting financial performance and regulatory compliance.

Successful KBA implementation requires leadership commitment to proactive maintenance and upfront diagnostics for long-term gains. The benefits are compelling: extended asset life, enhanced safety, and alignment with global sustainability goals.

In summary, KBA is the next evolution—transforming decades of operational data into predictive insights. For an industry facing aging infrastructure, stricter regulations, and economic pressures, KBA delivers a timely, ESG-aligned solution that maximizes value, safety, and responsibility.

Sources

Paresh Haribhakti et al., Failure Investigation of Boiler Tubes: A Comprehensive Approach, ASM International (2018) - Comprehensive resource on boiler tube failure mechanisms and case studies.

Paresh Haribahkti & Prakash Joshi. "Failure of Boilers and Related Equipment." In Analysis and Prevention of Component and Equipment Failures, ASM International USA, Handbook Volume 11A, ASM International, 2021, pp. 662-694.

Electric Power Research Institute (EPRI) Guidelines – e.g. Boiler Tube Failures: Theory and Practice (detailed mechanism descriptions); EPRI report on corrosion fatigue indicating it as a leading cause of boiler tube failure downtime; EPRI Boiler Life Extension and Simulation System (BLESS) and life assessment software.

Central Electricity Authority (CEA) of India, R&M and Life Extension Guidelines (2019) – emphasizes need for RLA after 20+ years and outlines procedures for extending life by ~15 years.

API 579-1/ASME FFS-1 Fitness-for-Service Standard – methods for evaluating flaws and remaining life, adopted by ASME for post-construction guidance.

TCR Advanced Engineering case archives and technical papers – e.g. Knowledge- Based Inspection methodology from TCR's newsletter; TCR's Power Plant service profile highlighting KBI approach and advanced diagnostics (magnetite layer analysis, in-situ metallography, etc.).

Babcock & Wilcox (B&W) technical paper, Creep-Rupture Assessment of Superheater Tubes Using Oxide Thickness – describes correlation of internal oxide growth with metal temperature and life consumption.

OECD/NEA CODAP report on FAC – notes carbon steel wet steam lines FAC as industry-wide issue.

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