Boiler System: Detailed Technical Revision Notes

Introduction to Boiler Systems

- Boiler systems are fundamental to steam generation in the oil and gas industry, supporting power generation and crucial plant operations.
- The main goal: Convert water into steam, transfer it efficiently, and utilize steam for turbine operation and energy production.

Key Components and Flow Path

- **Typical system components (in order of flow):**
  - **Deaerator**: Removes dissolved gases from feedwater.
  - **Economizer**: Recovers residual heat from flue gases to preheat feedwater.
  - **Evaporator**: Converts preheated water into steam.
  - **Steam Drum**: Separates saturated steam from water; stores DM water and facilitates chemical dosing and blow down.
  - **Superheater**: Boosts temperature of saturated steam to produce superheated steam.
  - **Reheater**: Increases temperature of steam returning from High-Pressure Turbine (HPT).
  - **Water Walls**: Carry feedwater and act as the primary heat absorption surface within the furnace.
  - **Condensate & Polishing**: Ensures quality of return water.
  - **Turbine**: Converts steam energy to mechanical/electrical energy for plant use.
  - **Stack**: Discharges combustion gases to atmosphere.
  - **Attemporator**: Controls steam temperature by spraying water.

Boiler Pressure Parts: Functions & Types

- ### Economizer
  - Preheats feedwater to recover heat from flue gases.
  - Construction: Carbon steel; may be finned and staggered or bare tube and inline.
  - Main Functions:
    - Reduce coal consumption by 15–20%.

- 1% increase in thermal efficiency for every 6°C rise in temp.
        - Accelerates conversion of feedwater to steam.
        - Reduces boiler stress, enhances life and reduces combustion rate.
- **Superheaters**
    - Increases main steam temperature using flue gas, producing dry, superheated steam for turbine operation.
    - Sections:
        - **Pendant Spaced:** Behind screen; convective heat transfer.
        - **Platen:** Above furnace; radiant absorption.
        - **Rear Horizontal:** Second pass; convective counterflow.
        - **Steam Cooled Wall & Roof Section:** Second pass enclosure and roof.
    - Functions:
        - Remove moisture from steam to protect turbine blades from corrosion/breakage.
- **Reheaters**
    - Raise the temperature of steam returning from HPT using flue gas temperature.
    - Functions:
        - Increase thermal efficiency and energy content of the steam before entering Low-Pressure Turbine (LPT).
- **Water Walls**
    - Carry feedwater from ring headers to boiler drum.
    - Advantages:
        - Efficiency improvement, better heat transfer.
        - Quick and easy erection.
        - Enhanced boiler availability.
- **Safety Valves**
    - Operate as protection devices during emergencies, preventing over-pressurization.
- **De-superheaters (Attemporators)**
    - Control main steam temperature within safe design limits by injecting water or adjusting heat absorption.
- **Boiler Drum**
    - Stores DM water, limits solids, enables chemical dosing to maintain pH, and supports controlled blowdown cycles.

Boiler Tube Materials per ASTM

Material	Maximum Temp (°C)	Alloy Content
SA210 Gr.A1	425	Carbon Steel: C 0.27% Mn 0.93%
SA209 T1	480	0.5% Mo Steel: C 0.10–0.20%
SA213 T11	550	1% Cr, 0.5% Mo
SA213 T22	580	2.25% Cr, 1% Mo
SA213 TP304H	700	Stainless Steel: 18% Cr, 8% Ni
SA213 TP347H	700	Stainless Steel: 18% Cr, 10% Ni

Current Industry Scenario & Challenges

- High-performance expectations, deteriorating fuel quality, introduction of new/imported fuels.
- Pressure to produce cheaper power due to government regulation and availability-based tariffs.
- Plant operators aim for:
  - Higher plant availability and optimal performance.
  - Load flexibility to meet dynamic targets.
  - Improved combustion techniques for variable fuel quality.
  - Lower pollution, better positioning in availability-based tariff (ABT) markets.
  - Low gestation period and extended plant/equipment life.

Boiler Reliability and Impact of Failures

- Optimal plant heat rate requires adaptability to fuel changes and minimizing deviations/damage.
- Tube failures directly cause forced outages, decreasing reliability and availability:
  - Each tube failure in a 500 MW utility can cost approximately USD 1 million due to replacement, power charges, 3–4 days of downtime, plus morale and reputation impacts.

Boiler Tube Failures: Mechanisms & Locations

Primary Failure Mechanisms

- **Stress Rupture**
- **Short-Term Overheating**
- **High-Temperature Creep**
- **Dissimilar Metal Weld Failures**
- **Fatigue/Vibration/Thermal Stresses**
- **Water-Side Corrosion**
- **Caustic Corrosion**
- **Hydrogen Damage**
- **Pitting/Stress Corrosion Cracking**
- **Erosion (Flyash, Falling Slag, Soot Blower, Coal Particle, etc.)**
- **Fire-Side Corrosion (Low Temp, Waterwall, Coal Ash, Oil Ash)**
- **Defects:** Material, maintenance, welding, chemical excursions.

Notable: Some listed issues (e.g., certain corrosion/fatigue modes) have not been reported in India.

Specific Case Mechanisms and Corrective Actions

- **Short-Term Overheating**
  - Causes: Tube blockages (debris/scale), high heat transfer due to improper firing, low water or steam flow from poor circulation/upstream leaks.
  - Actions: Prevent blockages, maintain drum levels and coolant flow, avoid overfiring, redesign tubing for improved flow, reposition horizontal/inclined tubes to avoid film boiling.

- **High-Temperature Creep**
  - Typical in steam cooled tubes, partially choked tubes, radiant heat zones, gas blockages, material transitions, weld attachments.
  - Actions: Conduct Remaining Life Assessment (RLA)/Inspection of Tube (IOT), fluid flushing, material upgrades.

- **Dissimilar Metal Weld Failures**
  - Occur at SH (Superheater)/RH (Reheater) weld joints exposed to stress or temperature excursions.
  - Actions: Repair/replace welds, relocate them, use Ni-base filler, frequent inspections.

- Detailed Mechanism: Carbon-depleted zone forms at transition from ferritic to austenitic structure, constrained by surrounding harder material; exposed to strain, creep, and eventual cracking along the weld interface.

Water-Side Corrosion Mechanisms

- **Caustic Corrosion (Gouging)**
  - Typically occurs on water-cooled tubes at points of flow disruption or high heat flux.
  - Causes: Localized concentration of NaOH due to boiler water chemicals, corrosion products, condenser leakage, temperature rise due to deposits.
  - Actions: Control water chemistry, chemical cleaning, reduce product ingress, reweld irregular welds, use T11 steel/rifled tubes.
  - Mechanism: NaOH removes Fe_3O_4 protective layer, iron reacts with water/NaOH, leading to parent metal loss.

- **Pitting Corrosion**
  - Localized attack, leading to pinholes, pits, and cavities when protective film fails locally.
  - Results from breakdown or cracking of the protective film at specific points — small anodic/large cathodic zones form.

- **Stress Corrosion Cracking**
  - Occurs in SS 304H and other stainless at SH/RH (esp. bends, attachment welds), generally due to high-stress fabrications, chemical carry-over, or attemperator spray.
  - Actions: Replacement, carry-over surveillance, bend heat treatment, careful chemical cleaning, use of 347H tubes.

Fire-Side/Erosive Failures

- **Fly Ash Erosion**
  - Occurs at gaps between tube banks and duct walls, gas by-pass channels, protrusions, or high ash accumulation areas.
  - Causes: Non-uniform/excessive gas flow, high-ash coal with quartz, tube misalignment.

- Actions: Adjust load, reduce excess air, install shields/baffles, conduct flow modeling studies for optimization.

- **Erosion by Falling Slag**
  - Recommendations: Adjust fuel if fouling is an issue, optimize combustion regime, weld wear bars to disrupt ash boulders, increase tube wall thickness.

- **SB Steam Erosion**
  - Recommendations:
    - Maintain a minimum superheat of 15°C at blower.
    - Ensure necessary piping gradient/slopes.
    - Conduct wall thickness surveys for SB zones, replace eroded tubes.
    - Ensure proper nozzle alignment, temporary shielding.
    - Provide thermal drain system if not available.

Design Improvements to Reduce Tube Failures

- Select materials compatible with working pressure/temperature and proper design of steam flow, velocity, heat transfer, thermal expansion, radius of bends, and weldments.
- Best practices:
  - Lower flue gas velocity over tube banks.
  - Use plain tube inline arrangements.
  - Optimize end gaps to avoid preferential gas flows.
  - Erosion shields/cassette baffles.
  - Erosion allowance for lead tubes in a bank.
  - Flexible connectors for pendant SH coils, improved supports for superheaters/economizer coils, improved seal plate and tube connections for hoppers.

Recommendations for Failure Mitigation

- **For Flue Gas (Flyash) Erosion:**
  - Conduct thorough inspections, verify condition of shields/baffles, map thickness, repair/replace as needed.
  - Implement baffling/shielding at erosion-prone points.

- Operational adjustments such as reduced load and excess air. Conduct flow model studies regularly.

- **For Long-Term Overheating (Creep):**
    - Monitor/maintain temperatures within specified limits, ensure adequate flow, follow proper startup firing rate curves.
    - Assess tube life via oxide scale thickness, tune boiler air temp/excess air, utilize upgraded materials, enforce strict quality control during replacements to prevent foreign material ingress.

Conclusion: Failure Investigation & Reliability

- Correct failure mechanism diagnosis is complex, involving metallurgists, chemists, combustion experts, and boiler designers, with operating records and failure histories as vital resources.
- Joint task force between plant, boiler designers/manufacturers, and experts is recommended to drive root cause analysis and implement corrective actions.
- Improved investigative collaboration reduces failures and enhances overall boiler availability and reliability.

Magnetite Formation & Water Circuit Condition

Magnetite Basics

- Magnetite (Fe_3O_4) forms as a protective barrier when steel is oxidized by pure water at high temperature.
- Features:
  - **Black, thin layer** with minimal impact on heat transfer.
  - Acts as a barrier to further oxidation in boiler tubes and surfaces.

Chemistry of Magnetite Formation

- **High temperature passivation:**

$$3Fe + 4H_2O \rightarrow Fe_3O_4 + 4H_2 \text{ (Protective)}$$

- **Low/moderate temperature reactions:**

$$2Fe + O_2 + 2H_2O \rightarrow 2Fe(OH)_2$$

  - FeO and Fe_2O_3 may also form, which are less protective than Fe_3O_4.
- Ensuring the stable formation of magnetite is crucial for equipment longevity.

Magnetite Film Damage

- Damaged by:
  - **Oxygen (high O_2 levels)**
  - **High alkalinity (high pH)**
  - **Acidity**
  - **Corrosion-fatigue or mechanical stresses**
- Visual clue: Brown stains after ambient exposure signal improper magnetite formation.

Water Circuit: Clean vs Deposited Operation

- **Clean Circuit:**
  - Operates with controlled nucleate boiling and efficient heat transfer.
- **Deposited/Scaled Circuit:**
  - Heavy deposits on water side reduce efficiency.
  - Larger steam bubbles form, heat transfer drops, tube temperatures rise.

Scale vs. Deposit

- **Scale:** Hard, glassy, formed by selective precipitation (on hot surfaces).
- **Deposit:** Material precipitated elsewhere and transported to the tube/drum surface.

Impact of Scales and Deposits

- Increased risk of overheating, reduced efficiency, potential tube failure.
- **Failure causes (statistical):**
    - Long-term overheating: 15%
    - Short-term overheating: 66%
    - Corrosion (including from feedwater): 19%.

Water Chemistry – Control Parameters & Standards

Major Boiler Water Problems

- **Deposits:** Reduce heat transfer, risk tube overheating.
- **Corrosion:** Damage to material, increased maintenance.
- **Carryover:** Transport of impurities with steam.

Feedwater & Boiler Water Control

- Water quality controlled by:
    - **External treatment:** For removal of hardness, dissolved gases, etc.
    - **Internal treatment:** Chemical dosages to reduce effects of remaining contaminants.

Typical Feedwater (BFW) Internal Operating Windows (IOW)

- Oxygen: < 20 ppb
- Conductivity: < 0.2 µS/cm
- Conditioned with volatile alkalies (e.g. ammonia, morpholine, hydrazine) or phosphates (e.g. sodium phosphate, caustic)
- pH (BW): 9.5–11
- Iron: < 50 ppb
- Silica: < 20 ppb.

International Specifications

- Organizations determining boiler water standards include:

- British Standards Institute (BSI)
    - VdTUV (<68 bar)
    - VGB (>64 bar)
    - EN 12952 (Shell Global recommended for latest guidance).

Main Corrosion Mechanisms and Influencing Factors

Key Boiler Corrosion Issues

- pH variations
- Oxygen corrosion
- Caustic corrosion/gouging/cracking
- Flow-assisted corrosion (FAC)
- Erosion/corrosion-erosion
- Chelant corrosion
- Scaling
- Corrosion fatigue
- Overheating/stress rupture/creep
- Fireside corrosion
- Flue gas and condensate corrosion.

Common Causes of Corrosion

- Poor pH control
- Oxygen ingress/pitting
- Insufficient chemical dosing/blowdown
- Poor deaerator performance/condensate quality
- Stress and deposition mechanisms
- Inadequate external water treatment
- Condensate contamination
- Embrittling water characteristics.

pH and Corrosion

- **pH Impact:**
    - Low pH: Acid corrosion of feedwater lines, boiler surfaces, and exchangers.
    - High pH: Favours scaling or caustic corrosion in local concentrations.
- Safe pH range at 25°C: Refer to provided chart/data.
    - Boiler feedwater: pH ~9 (IOW)

- Boiler water: pH 9.5–11 (IOW)
- pH Control Methods:
  - Non-volatile (for both BFW and BW): Sodium phosphate, caustic
  - Volatile (mainly BFW): Ammonia, Morpholine, Hydrazine.

Oxygen Corrosion

Mechanisms

- High oxygen levels convert protective Fe_3O_4 to Fe_2O_3 (soft and non-protective).
- Leads to pitting (localized cell reactions at anode/cathode).
- Attack can occur system-wide but most often at feedwater and economizer locations—especially if under deposits or with thermal cycling.

Reaction Equations

- Magnetite with oxygen:

$$4Fe_3O_4 + O_2 \rightarrow 6Fe_2O_3$$

- Bare steel surface with oxygen:

$$4Fe + 2nH_2O + 3O_2 \rightarrow 2(Fe_2O_3 \cdot nH_2O)$$

- Hematite (Fe_2O_3) is non-protective.

Control and Removal Strategies

- Reduce dissolved O_2 using:
  - Mechanical deaeration
  - Chemical scavenging: e.g. hydrazine (N_2H_4), hydroquinone, sulphite, carbohydrazides
- Maintain O_2 levels below 20 ppb for safe operation.

High Alkalinity (Caustic) Attacks

Caustic Corrosion/Gouging

- Local concentration of caustic soda (NaOH) under deposits or in crevices leads to:
  - Dissolution of Fe_3O_4 protective layer, followed by steel loss as ferrates.
  - Caustic embrittlement: A form of stress corrosion cracking (usually above 150°C).
- Mitigation:

- Control caustic concentrations.
- Use coordinated phosphate treatments.
- Maintain congruent sodium phosphate/low hydroxide operation.

- Key reactions:
  - Magnetite removal at high pH:
    $$Fe_3O_4 + 4NaOH \rightarrow 2NaFeO_2 + Na_2FeO_2 + 2H_2O$$
    (soluble products)
  - Bare steel at high pH:
    $Fe + 2NaOH \rightarrow Na_2FeO_2 + H_2$ (soluble products)
  - At moderately high pH:
    $3Fe + 4H_2O \rightarrow Fe_3O_4 + 4H_2$ (yields a porous oxide).

Flow-Assisted Corrosion (FAC)

- Occurs when high-purity, low-oxygen water erodes the oxide layer through:
  - Relative fluid movement/turbulence
  - Velocities above 2.1 m/s
  - Exacerbated at pH < 9.3, with maximum damage at:
    - 140°C (one-phase flow)
    - 180°C (two-phase flow)
- Mitigation:
  - Adjust water chemistry (minimum/buffered changes)
  - Select materials with Cr, Cu, Mo additions; favor 1.25Cr/2.25Cr or 12Cr steel.

Erosion and Scaling

- **Erosion–Corrosion:** Combined effect; depends on velocity, medium hardness, and material resistance.
  - Key sites: Soot blowers, steam cutting, fly-ash attack.
  - Preventative design: Modified geometry, correct material selection.
- **Scaling:**
  - Silica, iron, copper main contributors.
  - Silica encourages sodium–iron–silicate scales. Limit in BFW: 20 ppb.
  - Iron: < 50 ppb recommended.

- Copper: Accelerates ongoing corrosion; mainly from recovered condensate.

Corrosion Fatigue & Overheating

- **Corrosion fatigue:** Mechanical/thermal cycling or testing can degrade/strip protective Fe_3O_4 layer, leading to fatigue cracks.
- **Overheating & Stress Rupture:** Localized overheating causes tube bulging/permanent deformation. Key risk factors: temperature, time at stress. Thinner walls increase failure speed.
    - Main sources of fouling: silica, iron, copper.

Inspection, Testing, and Quality Assurance

Industry Standards for Inspection

- ASME Section 1: Boiler and Pressure Vessel Code
- ASME Section VII: Power Boiler Care
- NBIC: National Board Inspection Code
- API RP 572/573/574/576: Inspection and care for boilers, fired heaters, pressure vessels, piping, and relief devices.

Preparation for Inspection

- Scheduled at least every two years; intervals may vary with duty and experience.
- Review all:
    - Original design drawings and P&IDs (covering pressure, temperature, inspection points, access).
    - Boiler log and maintenance records.
    - Safety Instruction Sheets (SIS).
    - Hydrostatic test diagrams and previous results.

Boiler Inspection Procedures

General Principles

- Boiler inspections assess maintenance requirements and verify operational safety.
- Inspection intervals: At least every two years, or as dictated by service history and risk factors.
- Inspections integrate visual examination, historical record review, and scientific judgment; focus on prior problems and high-risk locations.

Records to Review Before Inspection

- Original design drawings (pressure, temperature, inspection points, access notes).
- Piping and instrumentation diagrams (P&IDs): Cover pipe sizes, construction materials, vent/drain locations, blinds, original thickness.
- Boiler log: Chronicles inspections, maintenance, and operational notes.
- Maintenance records: Indicate previous issues needing follow-up.
- Safety Instruction Sheets (SIS): Specify allowable pressures, test parameters, and retirement thicknesses of critical piping.
- Hydrostatic test diagrams and past results: Highlight past test areas and observed problems.

External Boiler Inspection

When to Inspect

- May be performed with boiler in operation or shutdown.
- Start external inspection before shutdown when possible to observe hot spots and leaks under load.

Main External Inspection Points

- **Ladders, stairways, platforms:** Check for physical integrity, tightness of fasteners, paint condition, tread safety, crevice corrosion, and rail security.
- **Air/flue gas ducts:** Look for oxidation, paint degradation, refractory breaches, joint/seam cracks, thin spots (hammer test), and possible internal corrosion or misalignment.

- **Support structure/boiler casing:** Inspect for bending, corrosion, poor connections, wall bulging, discoloration (hot spots/refractory loss), foundation cracks, spalling, and settlement.
- **Stack:** Evaluate for risk of collapse, explosive buildup, corrosion, cracks, hot spots, damaged fasteners, guy wire corrosion, and check ground resistance (<25 ohms).
- **Piping:** Examine for leaks, check retirements, corrosion (external and internal via ultrasonic/X-ray/visual methods), support condition, and settling movement.
- **Instrumentation:** Inspect for leakage (especially around water glasses/level indicators), verify safety device function (no bypasses), alarm/shutdown setpoints.

Internal Boiler Inspection

Entry Preconditions

- Ensure all fuel lines blocked/blinded, unit purged/tested gas-free, pumps off/tagged, feed valves blocked/tagged/padlocked, system drained (with vents/drains open), manhole/handhole plates removed.
- No entry until full isolation and gas clearance confirmed.

Main Internal Inspection Points

- **Corrosion/Erosion:** Identify any locations with excess thinning, pitting, deposit formation; characterize as material, operational, or chemical in cause.
- **Metallurgical/Physical Changes:** Look for cracks (macro, micro), graphitization, carbide precipitation, intergranular corrosion, embrittlement, or mechanical deformation (bending, bulging from overheating).
- **Mechanical Forces:** Evidence of thermal shock, vibration, pressure surges, or unusual loading.
- **Firebox Refractory and Insulation:** Inspect for spalling, crumbling, breakage, joint integrity, fluxing of fly ash with refractory, and potential exposure of support steel.
- **Fans/Dampers:** Inspect forced and induced draft fans, bearings, alignment, dampers for corrosion and operability.

Inspection of Tube Sections

External Tubes

- Inspect for corrosion, pitting (may need pit gage), wear at supports, binding, and overheating (bulging, oxidation scale).
- Use ultrasonic thickness testing for average wall thickness (pitting not always detected).
- In severe cases, remove tube samples for direct inspection or chemical analysis.

Internal Tubes

- Internal inspections for corrosion, pitting, cracks, and scale are typically limited by borescope or fiberscope reach (~100 feet). Not all deposits or scale build-up may be detected, especially compact/dense iron oxide.
- Tube ends are inspected during steam/mud drum inspection.
- Use Turner gage for in-situ measurement of internal deposit thickness (>600 microns [0.024 in] may warrant tube removal/chemical cleaning assessment).

Welds and Supports

- Visually examine welds for cracks, conduct magnetic particle/dye penetrant inspection (especially for austenitic steels).
- Inspect supports for corrosion, cracking and functional integrity.

Additional Inspection Aspects

- **Convection sections** (economizer, superheater): Inspect for deposit accumulation (soot not removed), fin damage, support wear, overheating.
- **Burners:** Inspect (when operating) for correct operation, orifice plugging, tile cracks, and required adjustments.
- **Drums (steam/mud):** Ultrasonic thickness, deposit/corrosion checks, tube end projection/flaring condition.

Hydrostatic Pressure Test Procedures

Definitions

- **Pressure test:** Any test applying hydraulic or pneumatic pressure to prove integrity.
- **Strength test:** Pressurize vessel/piping above normal operating pressure.
- **Tightness test:** Pressurize to operating level and verify for leakage.

Preparation Steps

- Review official test procedure, hydrostatic diagram, and SIS; identify required relief valve settings and test pressure (usually 1.5x design pressure, not exceeding material stress limits given the lower test temperature).
- Isolate sections as needed (if design pressures differ, test pressure must use the lowest section rating).
- Select and calibrate proper gages, identify correct test fluid (preferably treated water, not raw or salt water; inhibitors if needed for alloys).

Test Execution

- Isolate heater, ensure all fire/fuel lines are blocked, and all relief valves temporarily removed or isolated.
- Fill vessel/system from the bottom, vent all air, confirm vents closed upon filling.
- Gradually increase pressure up to test value, maintain for specified duration.
- Water temperature: Not less than ambient and never below 70°F (21°C), not above 120°F (49°C).
- Never exceed test pressure by more than 6%.
- Inspect for visible leaks; do not use hammer testing during the pressure test.
- Release pressure slowly, open vent valves before draining fluid to avoid vacuum formation.
- Document every step and any repairs or findings.

Calculating Corrosion Rate and Remaining Life

Corrosion Rate Calculation

Formula:

$$C = \frac{t_O - t_A}{\text{Time}} \times 1000$$

- CCC: Corrosion rate (mils/year; 1 mil = 0.001 inch)
- tOt_OtO: Thickness at beginning of period (inches)
- tAt_AtA: Thickness at end of period (inches)
- Time: Interval between measurements (years)

Example:

- Initial thickness: 1.181 in (Oct 1995)
- Final thickness: 1.135 in (Apr 1998)
- Time: 2.5 years (30 months)

$$C = \frac{1.181 - 1.135}{2.5} \times 1000 = 0.046 \times 1000/2.5 = 18.4 \text{ mils/year}$$

Remaining Life Calculation

- Remaining Corrosion Allowance (RCA): $t_A - t_{min}$

t_{min}: Minimum allowable wall thickness (inches)

$$RL = \frac{RCA \times 1000}{C}$$

- RL: Remaining life in years
- For fluctuating rates, schedule inspection at ¼ to ½ of projected RL depending on inspection requirements and turnaround cycles.

Safety Relief Valves (PZVs): Testing and Maintenance Protocols

Routine Inspection & Test Requirements

- Maintain a tracking program for all PZVs; document their inspection and test outcomes.
- **ASME Code:**
  - Bench test all boiler PZVs at least annually (offline/removed from service): Must "pop" within the lesser of 10 psi or 3% of setpoint. Must reclose tightly at no less than 96% of set pressure.
  - In-place (on-line) test conducted annually, confirming no leaks/vibration post-lift.
  - Written S.O.P. required for all tests; only qualified/certified technicians may test and document per Maintenance Report Form 3750.
  - Disassemble and inspect every third routine interval (3 years).
  - For boilers >400 psig, NBIC may require enhanced frequency.

Boiler Chemical Cleaning

Criteria for Chemical Cleaning (Based on Deposit Density)

Deposit Density (g/m^2)	Required Action
< 250	No cleaning required
250 – 500	Clean within 1 year
500 – 1000	Clean within 3 months
> 1000	Chemically clean before use

Effectiveness Evaluation

Deposit After Cleaning (g/m^2)	Effectiveness of Chemical Cleaning
≤ 10	Excellent
>10 and <20	Good
>20 and <30	Average
>30 and <50	Passing
>50	Not Acceptable

General Recommendations

- Chemical cleaning is not routine; use only if required per inspection.
- Main deposits: calcium/magnesium carbonate from excess boiler water salts.
- Cleaning involves inhibited acid wash, neutralization, and passivation.
- Oil contamination: Remove by alkaline or alkaline-permanganate boil-out prior to acid cleaning.

Chemical Cleaning Procedure

Preparation:

- Blind inlet/outlet, remove screens/baffles from steam drum.
- Install temporary P/T/level gages on steam drum and mud drum.
- Remove/replace PZVs with temporary vents.
- Blind all instrument lines except those needed for cleaning.

Alkaline Boil-Out:

- Add chemicals, fire slowly, reach 200 psig for 24 hr.
- Drain and open for inspection.

Acid Cleaning:

- Fill with condensate, heat to ~180°F, add acid cleaning chemicals.
- Circulate for 4–6 hr; repeat if necessary based on remaining scale.

Neutralization and Passivation:

- Fill with sodium carbonate solution, heat to 200 psig for 2 hr.
- Drain below 200°F; ensures any acid is neutralized and leaves protective film.

Superheaters/Economizers

- Normally not cleaned chemically (dry); may need cleaning if steam drum carryover or attemperator present (since it injects water into superheater for temp control).

Fired Heater Comprehensive Revision Notes

Introduction to Fired Heaters

- Fired heaters, or process furnaces, are critical equipment used to heat fluids in refinery and petrochemical processes.
- Common applications include:
  - Distillation: separation of hydrocarbon mixtures.
  - Cracking: breaking large hydrocarbon molecules into smaller ones.
  - Reforming: improving fuel quality through catalytic chemical reactions.
- Types:
  - Fired heaters: direct heating by combustion of fuel inside the furnace.
  - Radiant heaters: heat transfer mainly via radiation.
  - Convection heaters: heat transfer via convective means.
- Operation involves heating fluids inside tubes arranged in furnace walls or roofs by combustion flame and hot gases.

Key Components of Fired Heaters

- **Burners:** Mix air and fuel to create the combustion flame; key for efficient and safe operation.
- **Tubes:** Carry process fluids (gas or liquid) that need heating; exposed to heat flux from combustion.
- **Firebox:** Enclosure where combustion occurs and radiant heat is generated.
- **Stack:** Exhaust system releasing flue gases to the atmosphere.
- **Air Pre-heaters (APH):** Recover heat from flue gases to preheat combustion air and improve thermal efficiency.

Heater Types and Structural Classification

- **Vertical Cylindrical Furnaces:** Large cylindrical radiant section with vertical tubes arranged in a circle; burners fire upward from floor.
- **Box-type Furnaces:** Rectangular or box-shaped with vertical or horizontal tubes; cabin type with horizontal tubes and multiple convection tube banks.
- **Radiant Wall Furnaces:** Employ radiant panels as hot surfaces facing the flame.
- **Multi-cell Furnaces:** Multiple compartments or cells for staged heating.
- **All Convection Furnaces:** Heat transfer predominately by convection.

Heater Sections Overview

- **Radiant Section:** Bottom section where tubes receive about 90% heat from combustion by radiation.
- **Shield or Shock Tubes:** First bare tube rows in convection section protecting finned tubes from direct radiation.
- **Convection Section:** Above radiant section, tubes absorb residual heat mainly through convection with fins or studs to increase surface area.
- **Cross-over Section:** Connects convection outlet to radiant inlet, often outside furnace for temperature monitoring.
- **Stack:** Releases flue gases to atmosphere.
- **Air Pre-Heaters:** Utilize waste heat to warm combustion air.

Heat Transfer Principles in Fired Heaters

1. **Conduction:** Heat transfer within solid tubes due to molecular vibrations.
2. **Convection:** Heat transfer to fluids inside tubes by fluid motion.
3. **Radiation:** Electromagnetic waves emit heat from flame and refractory to tubes; predominant in radiant zone.

Heater Operation Modes and Applications

- **Direct Fired Heaters:** Process fluid heated by direct contact with hot combustion gases.
- **Reaction Heaters:** Filled with catalysts that enable chemical reactions within tubes besides heating (e.g., reformers, methanol heaters).
- **Crude Distillation Unit (CDU) Heaters:** Primarily vaporize hydrocarbons; no cracking or reactions occur.

Heater Performance Objectives

- Maximize heat transfer efficiency to process feed.
- Minimize fuel consumption.
- Maintain operational flexibility with variable fuel quality and feed flows.
- Ensure safe startup, operation, and shutdown.
- Minimize stack emissions (HC, NOx, SOx).
- Achieve high thermal efficiency.

Energy and Environmental Considerations

- Heater energy consumption constitutes ~60-65% of refinery energy use.
- Rising energy costs encourage using waste fuels (off-gases) instead of clean fuels.
- Combustion of waste gases demands careful pollution control.
- Regulations require minimizing contaminant emissions, especially NOx and CO.

Combustion in Fired Heaters

Air Requirements

- **Theoretical Air:** Minimum air needed for complete combustion of carbon and hydrogen.
- **Excess Air:** Air supplied beyond theoretical to ensure complete burning.
- Combustion air supplied via:
  - Natural draft: buoyancy-driven air flow via hot flue gases rising in stack.
  - Forced draft: air supplied by fans or blowers.
  - Induced draft: fans pull combustion gases through furnace.

Air-Fuel Ratio Control and Combustion Efficiency

- Correct air-to-fuel ratio critical:
  - Too little air causes incomplete combustion, high CO and soot.
  - Too much air reduces flame temperature and wastes heat.
- Balanced combustion optimizes flame length, color, and temperature.
- Imbalance leads to:
  - Increased NOx emissions with excess air.
  - Increased CO and hydrocarbons with deficient air.
  - Equipment damage due to soot or flame impingement.

Burners and Their Operation

- Burner types: natural draft, forced draft, ultra-low NOx burners.
- Control of primary and secondary air allows tuning flame shape and stability.
- Precise fuel and gas pressure control ensures uniform heating and prevents flame impingement.
- Burner management systems integrate flame detection, auto ignition, pre- and post-purge functions per NFPA safety protocols.

Combustion Control Strategies and Monitoring

- Use of oxygen (O2) and carbon monoxide (CO) sensors provides real-time feedback for adjusting air-fuel mixture.
- Sensors require frequent calibration to avoid drift.
- Modern control systems use programmable logic controllers (PLCs) for automated adjustments.
- Flame inspection (length, color, stability) assists visual detection of combustion issues.

Effects and Indicators of Excess Air

- Excess air leads to pale yellow or white flame, indicating reduced efficiency.
- Too little air causes dark, smoky flames.
- Excess air wastes heat and increases NOx emissions.

Consequences of Incomplete Combustion

- Soot formation causes tube fouling and thermal efficiency loss.
- Deposits can cause tube failure and convection corrosion.
- Unburned gases pose explosion risks and increase maintenance.

Emissions and Environmental Impact

NOx Emissions

- NOx consists of nitrogen oxides (NO, NO2) formed at high flame temperatures.
- Environmental effects:
  - Air pollution causing smog and respiratory ailments.
  - Acid rain damaging ecosystems and infrastructure.
  - Contribution to greenhouse gas effects and climate change.
- Regulatory agencies set emission limits, compliance critical.

NOx Control Techniques

- Flue Gas Recirculation (FGR): recycles flue gas to lower flame temperature.
- Low NOx Burners: design to reduce peak flame temperatures.
- Selective Catalytic Reduction (SCR): converts NOx emissions into nitrogen and water using catalysts.

Measurement and Analyzer Considerations

Analyzer Locations

- Radiant Section: most accurate for O2 and combustibles measurement.
- Convection Section: less ideal due to gas mixing.
- Stack: provides overall emissions data but slower process feedback.

Analyzer Types

- Insitu Analyzers: measure gas concentrations directly in process; faster response but prone to fouling.
- Extractive Analyzers: sample drawn outside the heater for analysis; may be more accurate with slower response.

Analyzer Response Time and Calibration

- Fast response provides active combustion control.
- Calibration ensured through regular sensor maintenance.
- Typical response: insitu (seconds to minutes), extractive (minutes to hours).

Combining Oxygen and Combustibles Monitoring

- Using both O2 and PPM combustibles analyzers enhances control precision.
- Detects incomplete combustion more effectively than O2 alone.

Heater Efficiency and Capacity Expansion

Factors Affecting Efficiency

- Proper air-fuel ratio to minimize excess air.
- Maintaining clean tubes to prevent fouling and flame impingement.
- Draft control to optimize air and flue gas flow.
- Use of air pre-heaters to recover heat and reduce flue gas temperature.

Methods for Increasing Heater Capacity

- Increase burner capacity or upgrade to high-efficiency burners.
- Enhance air supply with stronger forced or induced draft fans.
- Add more tubes or finned surfaces for heat absorption.

- Install heat recovery units to capture waste heat.

Feasibility and Safety

- Evaluate cost-benefit of upgrades versus new installations.
- Include safety and operational constraints in expansion decisions.
- Post-upgrade monitoring ensures expected performance.

Inspection and Maintenance of Fired Heaters

Reasons for Inspection

- Check for corrosion, erosion, and material deterioration causes.
- Establish safety and operational reliability.
- Forecast maintenance and replacement needs based on deterioration rate.
- Replace or repair deteriorated components timely.

Inspection Types

1. On-Stream Inspection

- Conducted periodically while heater is in operation.
- Key checks:
  - Burner condition and flame pattern; ensure no tube flame impingement.
  - Tube hot spots or overheating by skin temperature measurement.
  - Tube vibrations and condition of supports/hangers.
  - Visual refractory condition via peep holes and casing temperature checks.
  - Leakage from rolled or plugged tube joints.
  - Tube bowing, sagging, or bulging.
- Additional for hydrogen reformer heaters:
  - Leakage through top and bottom tube flange joints.
  - Proper functioning of tube supports and balancing mechanisms.
- Use of pyrometers and thermographic tools supplements visual inspection.
- Paint discoloration on casing or stack may indicate refractory damage.

2. Shutdown Inspection

- Carried out after heater shutdown; detailed assessment.
- Preliminary inspection as heater is opened:
  - Scale and deposit formation on tubes.

- Refractory and insulation damages.
- Firing pattern abnormalities.

- Cleaning:
    - External tube cleaning manually or by power wire brushing; stainless steel tubes require SS brushes.
    - Grit blasting as needed.
    - Internal cleaning indicated by increased pressure drop or process signs, confirmed by radiography.
    - Internal cleaning methods: steam-air decoking, pigging.
    - Removal and cleaning of loose refractory and burners, soot blowers.
- Thorough visual inspection of entire heating coils (radiation and convection).
- Use of mirrors for refractory inspection behind tubes.

3. Visual Inspection Focus Areas

- Sagging, bowing, distortion, bulging due to structural loss.
- Oxidation, scaling.
- Cracks, creep lines, corrosion, pitting, grooving.
- Tube end erosion and thinning.
- Tube supports, hangers, tube sheets for signs of oxidation or cracks.
- Return headers for corrosion, erosion, and cracks.
- Special attention to welds, heat affected zones.
- Tubes near burners and tube sheet entries/exits.
- Junctions between plain and finned/studded convection tubes.
- Locations of skin thermocouple welds and injection points.

4. Repair Decisions

- Replace tubes sagged or bowed by more than 5 tube diameters.
- Replace tubes with unacceptable bulging (generally above 1%-5% outer diameter increase).

5. Inspection of Convection Coils

- Similar to radiant coils, but limited to accessible tubes.
- More prone to external corrosion.
- Sagging tubes in upper convection rows (nesting) can block flue gas flow and cause overheating; offending tubes must be replaced.
- Sample U-bends may be removed for internal inspection.

6. Non-Destructive Examination (NDE)

- Ultrasonic thickness testing (UT) for wall thickness at radiant tubes, bends, and convection tubes/bends.
- Radiography for coking, fouling, and welding inspection.
- Profile radiography at inaccessible convection section locations.
- Advanced NDE techniques: Long Range UT (LRUT), intelligent pigging.
- Tube internal diameter (ID) measured with telescopic gauges.
- Outer diameter (OD) checked with GO-NOGO gauges, with 3% tolerance generally.
- Liquid penetrant examination for welds and skin thermocouple welds.
- Magnetic Particle Inspection (MPI) of 10%-25% of welds on carbon steel and alloy tubes based on conditions/history.
- For austenitic stainless steel tubes, 25%-100% of welds liquid penetrant examined; LP chemicals must be chloride free.
- Hardness tests on overheated or oxidized tubes.
- Intelligent pigging possible for convection tubes inspection.

Incident Case Study: Furnace Tube Rupture at Martinez Renewables Facility

Incident Overview

- Date: November 19, 2023, ~12:21 a.m.
- Event: Rupture of reactor charge furnace tube released hot renewable diesel and hydrogen, causing a fire.
- One employee was seriously injured with third-degree burns.
- Fire extinguished within one hour.

Facility Background

- Joint venture between Marathon Petroleum and Neste, converted from petroleum refinery to renewable fuel facility in 2023.
- Production ramp-up ongoing during incident.
- Renewable diesel produced from plant oils and animal fats.
- Hydrogen used in hydrodeoxygenation (HDO) process.

Operational Context

- Incident occurred during startup of HDO unit.
- Unit heats renewable diesel, recycled diesel, and hydrogen using eleven fuel-gas fired burners.
- Furnace tubes made of ASTM A312 Grade 321 stainless steel to withstand high temperatures.

Cause Analysis

- Excessive furnace tube surface temperatures detected by instruments triggered alarms.
- Attempts to reduce temperature by altering flows and burner operation were unsuccessful.
- Misaligned manual bypass valve upstream of the furnace created an undetected flow path bypassing furnace.
- Flowmeter upstream of valve indicated normal flow, preventing safety interlock activation.
- Tube rupture occurred in convection section; materials ignited causing fire.

Safety Systems and Failures

- Safety interlocks designed to shut down upon excessive temperatures or low flows failed due to bypass valve misalignment and flow measurement errors.
- Incident revealed systemic weaknesses in design and implementation of safety monitoring.

Post Incident Inspection

- Investigation ongoing including metallurgical analysis of tubes for defects or material degradation.
- Internal components—burners, sensors, tube supports—under examination.
- Identification of hazardous scenarios missed in design phase.
- Comparison with industry standards for gaps and improvements.

Lessons Learned

- Critical importance of rigorous safety protocols during startups.
- Risks of repurposing old equipment without adequate system validation.
- Need for continuous monitoring and robust safety interlocks.

- Emphasizes systematic checks and failsafe mechanisms in complex industrial operations.

Future Actions

- CSB continuing detailed analysis including metallurgical failure mode study.
- Enhanced monitoring, stricter interlocks, and operational oversight recommended.
- Industry-wide influence expected to improve safety in renewable fuel sectors.
- Final comprehensive report to include safety improvement recommendations.

Refractory and Insulation

- Refractory materials are essential to protect furnace structure and prevent heat loss.
- Functions:
  - Protect steel cabin structure from high temperatures.
  - Radiate heat back to tubes maintaining uniform temperature.
- Common materials:
  - Fire bricks.
  - Insulating and heat-resistant castables.
  - Ceramic fiber: lightweight, easy to apply, commonly used for roof and walls; not used around oil-fired burners in radiant zone.

Codes and Standards for Fired Heater Design

- API 535: Guidelines for selection/evaluation of burners in refinery fired heaters.
- API 538: Design, operation, and maintenance recommendations for industrial fired boilers.
- API 560: Design, fabrication, inspection, testing, shipping, and erection of fired heaters, air preheaters, and fans.
- API 573: Inspection practices for fired boilers and process heaters.

Summary and Final Recommendations on Fired Heater Practices

Combustion Optimization

- Optimizing air-fuel ratio is critical for efficiency and minimizing emissions.
- Modern analyzers enable real-time adjustments to maintain optimum combustion.
- Regular sensor calibration and maintenance necessary to ensure control accuracy.

Benefits of Analyzer Integration

- Enhances operational control by providing accurate combustion data.
- Enables predictive maintenance and performance optimization.
- Results in reduced fuel consumption, lower operating costs, and extended heater lifespan.

Emissions Compliance and Environmental Impact

- Proper combustion control helps meet current and future regulatory requirements.
- Lowers NOx, CO, and hydrocarbon emissions improving environmental footprint.
- Uses techniques like FGR, low NOx burners, and SCR for emission reduction.

Safety and Operational Reliability

- Early detection of abnormal combustion prevents equipment damage and hazards.
- Burner management systems provide safe start-up, operation, and shutdown.
- Regular inspection and robust safety interlocks are key safety enablers.

Capacity Expansion Considerations

- Feasibility studies necessary before modifying heater capacity.
- Upgrades may involve burner enhancements, improved draft systems, and increased surface area.
- Continuous monitoring post-upgrade verifies efficiency gains.

Investment in Technology

- Upgrading older systems adds control and efficiency improvements.
- Employ new combustion control technologies and digital analytics.

Key Industry Lessons from Incident Investigations

- Industrial incidents highlight the need for diligent safety management.
- Proper design, instrumentation, and safety interlock implementation are critical.
- Continuous system checks and emergency preparedness reduce incident risks.
- Repurposing older equipment requires careful validation to meet new operational demands.