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Reliability and Integrity Management of Fired Heaters, Boilers and Furnaces in Upstream Oil and Gas: A Review

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Abstract- Fired heaters, boilers and furnaces are among the most safety-critical and failure-prone classes of static equipment in upstream oil and gas facilities. They supply the process heat required for crude stabilization, dehydration, glycol and amine regeneration, steam generation for enhanced oil recovery, and heavy oil processing, and they do so under conditions of high temperature, cyclic loading, aggressive combustion environments and, in many upstream settings, variable fuel quality. Failures of fired equipment carry disproportionate consequences: loss of containment of hydrocarbons at a live ignition source, tube ruptures, firebox explosions and extended production deferment. This paper reviews the state of practice and the published literature, up to 2019, on the reliability and integrity management of fired equipment in upstream service. It surveys the dominant damage mechanisms, including creep, high temperature hydrogen attack, external and internal corrosion, oxidation, carburization, thermal fatigue, fouling and flame impingement damage. It then examines the governing codes and recommended practices, principally API 560, API 530, API 573, API 579-1/ASME FFS-1, API 580 and 581, and the ASME Boiler and Pressure Vessel Code, and reviews inspection and condition monitoring techniques ranging from conventional non-destructive examination to infrared thermography, intelligent tube inspection tools and online tube-skin temperature monitoring. The review further evaluates risk-based inspection, fitness-for-service assessment and reliability-centered maintenance as the organizing frameworks of modern integrity management, and considers emerging digital approaches such as predictive analytics and digital twins. Gaps identified include the scarcity of upstream-specific reliability data, limited treatment of aging fired equipment in remote and offshore locations, and the immaturity of prognostic models for combined damage mechanisms. Directions for future research are proposed.

Keywords: fired heaters; boilers; furnaces; asset integrity; reliability; risk-based inspection; fitness-for-service; upstream oil and gas; damage mechanisms; non-destructive examination.

I. INTRODUCTION

Upstream oil and gas facilities depend on fired equipment to deliver heat wherever produced fluids must be stabilized, dried, sweetened or thermally mobilized. Direct-fired and indirect-fired heaters raise the temperature of crude oil ahead of stabilization columns, reboil glycol and amine solutions in dehydration and gas sweetening units, and prevent hydrate formation in gas processing. Steam boilers, including once-through steam generators, provide the motive steam for thermal enhanced oil recovery schemes such as cyclic steam stimulation and steam-assisted gravity drainage. In heavy oil and oil sands operations, fired furnaces are integral to upgrading and diluent recovery. Across all of these applications the equipment operates continuously at elevated temperature, frequently in remote or offshore locations where maintenance access is constrained, spares logistics are slow and the workforce is limited. Procurement and supply chain research on energy facilities underlines this constraint, linking strategic procurement optimization, inventory availability and vendor governance directly to plant uptime and maintenance cost (Okonkwo, Ogunwole and Okeke, 2018a, 2018b; Agbabiaka et al., 2019; Okonkwo et al., 2019), while work on heat stress risk in extreme industrial environments highlights the additional human constraints on inspection and repair activity at desert and tropical sites (Arumosoye and Obriki, 2018).

The consequence profile of fired equipment failure is severe. Unlike most static equipment, a fired heater combines pressurized hydrocarbon inventory with a continuous open flame in a confined firebox. A tube rupture releases process fluid directly into an ignition source; a burner management failure can accumulate unburned fuel and produce a firebox explosion; and chronic underperformance of heat transfer surfaces erodes throughput and energy efficiency long before any catastrophic event occurs. Industry loss statistics and insurer analyses have repeatedly identified fired heaters and boilers as leading contributors to large property damage losses in the hydrocarbon processing industries, a pattern consistent with the case history record of the process safety literature (Kletz, 2009; Mannan, 2012). In upstream settings the picture is complicated further by variable and often untreated fuel gas, produced-water carryover, sour service, sand and solids in process fluids, and operating regimes that swing with well deliverability.

The economics of fired equipment reliability reinforce the safety argument. A single radiant tube failure on a crude heater typically forces an unplanned facility shutdown measured in days to weeks, combining direct repair cost with deferred production whose value at upstream margins dwarfs the maintenance budget of the equipment itself. Chronic underperformance is costlier still because it is invisible: a heater running with fouled coils and poorly tuned burners consumes several percent more fuel continuously, restricts throughput at the facility bottleneck and accumulates creep damage that shortens the interval to the next major retube. Insurance market analyses of hydrocarbon industry losses place fired equipment persistently among the top equipment categories by loss value, and the pattern within those losses, a long tail of tube failures punctuated by rare but very large explosion events, matches the damage mechanism structure reviewed in this paper. The implication drawn consistently across the literature is that fired equipment rewards proactive investment unusually well, because both the frequent small losses and the rare large ones trace back to the same manageable precursors of overheating, fouling, chemistry excursion and safeguarding decay.

Over the last three decades the management of fired equipment has migrated from time-based inspection and reactive repair toward structured asset integrity management built on risk-based inspection (RBI), fitness-for-service (FFS) assessment and reliability-centered maintenance (RCM). A substantial body of standards, recommended practices and published research now underpins this practice, yet much of it is written from the perspective of downstream refining, where fired heaters are most numerous. Upstream applications differ in duty, fuel quality, remoteness, manning and regulatory context, and the literature addressing these differences remains fragmented. The contribution of this paper lies in that consolidation: to the best of the authors' knowledge, no prior review has integrated the damage mechanism, combustion, water chemistry, inspection, assessment and management system literatures for fired equipment from a specifically upstream perspective, and doing so surfaces the cross-domain interactions and upstream-specific gaps that single-domain treatments miss.

The objective of this paper is therefore to review, as of 2019, the reliability and integrity management of fired heaters, boilers and furnaces with specific attention to upstream oil and gas service. The review is organized as follows. Section 2 characterizes the fired equipment population found in upstream facilities, its duty cycles and its operating context, including thermal recovery steam generation and offshore installations. Section 3 reviews the damage mechanisms and failure modes reported for this equipment class. Section 4 summarizes the governing codes, standards and recommended practices. Section 5 examines combustion systems, burners and burner management safeguarding, which sit at the root of many severe fired equipment events. Section 6 reviews inspection and condition monitoring techniques together with inspection planning and data management. Section 7 examines RBI and FFS as decision frameworks. Section 8 addresses water treatment and chemistry control for upstream boilers and steam generators. Section 9 covers reliability-centered maintenance and integrity management systems. Section 10 reviews repair, rerating and life extension practice. Section 11 addresses performance, efficiency and emissions management as leading indicators of mechanical health. Section 12 surveys emerging digital technologies. Section 13 identifies gaps and future research directions, and Section 14 concludes.

A note on scope and method frames what follows. The review covers direct-fired process heaters, indirect wellsite heaters, fired boilers and once-

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through steam generators, together with the closely coupled systems, fuel gas conditioning, burner management, water treatment and hot oil circuits, without which their integrity cannot be discussed coherently; unfired waste heat recovery equipment is included where it shares mechanisms and management with the fired population. The source base comprises the governing standards and recommended practices, the established monographs on high temperature damage and boiler failure analysis, the combustion engineering literature, published operator and practitioner experience from industry conferences and journals, and, where cross-sector methods illuminate upstream practice, literature from adjacent domains of safety governance, risk modeling, data engineering and infrastructure delivery. Material is synthesized thematically rather than chronologically, and the treatment is deliberately integrative: the recurring argument of the paper is that fired equipment reliability emerges from interactions among combustion, chemistry, metallurgy and management, so each section is written with its couplings to the others made explicit.

II. FIRED EQUIPMENT IN UPSTREAM OPERATIONS

2.1 Equipment Classes and Duties

Fired equipment in upstream service can be grouped into three broad classes. The first comprises direct-fired process heaters, in which process fluid flows through tubes exposed to radiant and convective heat from burners, as codified for general refinery service in API Standard 560. In upstream facilities these appear as crude heaters upstream of stabilizers, regeneration gas heaters in molecular sieve dehydration, and hot oil heaters serving closed-loop heat transfer systems. The second class comprises indirect heaters, ubiquitous at wellsites and gas gathering stations, in which a fire tube immersed in a water or water-glycol bath heats process coils without direct flame contact; these are commonly built to smaller vendor standards and are frequently unmanned. The third class comprises steam generators and boilers, ranging from packaged fire-tube boilers for utility steam to large once-through steam generators dedicated to thermal recovery, falling under ASME Boiler and Pressure Vessel Code Section I and, in operation and inspection, under jurisdictional boiler regulations and the National Board Inspection Code.

Two adjacent equipment families belong in the same integrity conversation even where they blur the definition of fired equipment. Hot oil and thermal fluid systems couple a fired heater to a circulating organic heat transfer fluid that distributes heat to multiple consumers; their integrity behavior adds fluid degradation to the usual mechanisms, since thermal cracking of the fluid at film temperatures above its limit produces both light ends that flash in the expansion system and carbon that fouls the coil, so fluid condition analysis becomes a condition monitoring technique for the heater itself. Waste heat recovery units, which raise steam or heat process fluid from gas turbine exhaust, contain no burners of their own in unfired configurations yet share the convection section damage mechanisms, water chemistry sensitivities and inspection challenges of boilers, and supplementary-fired variants add full burner management obligations. Upstream facilities increasingly pair gas turbines with waste heat recovery to displace direct firing, which shifts rather than removes the fired equipment integrity workload and is properly captured within the same management framework.

2.2 Distinctive Features of Upstream Service

Several features distinguish upstream fired equipment from its downstream counterparts and shape its degradation behavior. Fuel is typically produced gas whose composition varies with reservoir behavior and processing; hydrogen sulfide, heavier hydrocarbon fractions, and entrained liquids promote burner fouling, flame instability, afterburning in convection sections and accelerated fireside corrosion. Feed streams may carry produced water, salts and solids that foul and corrode tube internals. Duty cycles follow production, so units experience more frequent starts, stops and load swings than continuously run refinery heaters, aggravating thermal fatigue and refractory degradation. Many units are installed in remote, desert, arctic or offshore locations where inspection windows are short, scaffolding and access are difficult, and specialist

NDE resources must be mobilized at high cost. Finally, indirect wellsite heaters are numerous, individually low in value and often excluded from the rigorous inspection regimes applied to plant equipment, even though their aggregate risk contribution, particularly regarding fire tube failures and bath loss, is significant.

2.3 Steam Generation for Thermal Enhanced Oil Recovery

Thermal enhanced oil recovery is the single largest concentration of fired equipment duty in the upstream sector. Cyclic steam stimulation, steam flooding and steam-assisted gravity drainage all demand very large continuous steam rates, and the workhorse of these schemes is the once-through steam generator. Unlike a drum boiler, the once-through steam generator has no steam drum and no internal recirculation; feedwater passes once through a serpentine coil arranged in radiant and convective sections and leaves as wet steam, typically at a quality of seventy to eighty percent. The residual liquid fraction is deliberate: it keeps the highest-solids water moving as a film on the tube wall and carries dissolved solids out of the generator rather than allowing them to deposit. This design choice permits the use of softened but otherwise high-solids feedwater, frequently recycled produced water, which no conventional drum boiler could tolerate, but it also makes the generator acutely sensitive to any disturbance that dries out the tube wall locally, since dryout concentrates solids at the wall and initiates under-deposit corrosion and overheating.

The reliability behavior of once-through steam generators is therefore governed by the interaction of water chemistry, firing distribution and hydraulic stability. Field experience reported in the thermal recovery literature identifies convection section fouling from feedwater hardness excursions, radiant tube hot spots from burner maldistribution, and quality measurement error as the principal precursors of tube failure, and the boiler engineering texts covering industrial steam generation supply the design context for these units (Ganapathy, 2003; Rayaprolu, 2009). Because a single thermal recovery project may operate dozens of generators, fleet effects matter: common feedwater treatment plants create common cause failure potential across the fleet, and fleet-wide inspection findings, when pooled, provide a statistically useful degradation dataset that individual heaters elsewhere in the upstream sector rarely generate. Several operators have exploited this by standardizing tube sampling, deposit weight density measurement and retubing criteria across their generator fleets, effectively running an internal reliability program of a rigor that the wider industry has not matched for other fired equipment classes.

2.4 Offshore and Remote Installations

Offshore platforms and floating production storage and offloading vessels carry their own population of fired and heated equipment, including direct-fired and waste-heat variants of process heaters, fired reboilers for glycol regeneration, and in some cases fired steam generators. The offshore context changes the risk calculus in several ways. Congestion places fired equipment in close proximity to wellheads, risers, separators and living quarters, so consequence modeling drives stringent segregation, fire and gas detection and emergency shutdown requirements under safety case regimes. Weight and space constraints favor compact designs with less access for inspection, and structural motion on floating facilities imposes loads on tube supports, refractory and casing that land-based designs never see. Salt-laden atmospheres accelerate external corrosion of casings, stacks and structural attachments, and corrosion under insulation is a chronic finding on heated equipment in marine service, a mechanism now addressed by dedicated practices including API RP 583 and NACE SP0198.

Remote onshore installations, including desert gas plants, arctic facilities and jungle flowstations, share many of these constraints in different form. Mobilization of scaffolding, refractory crews and specialist non-destructive examination technicians to such sites is slow and expensive, which pressures operators to stretch inspection intervals and to complete opportunistic scopes whenever a unit is down for any reason. Climatic extremes affect both equipment and people: low ambient temperatures embrittle casing steels and complicate refractory dryout, while high ambient temperatures constrain confined space entry durations and elevate heat stress risk for inspection personnel (Arumosoye and Obriki, 2018). The practical consequence, visible in published integrity program descriptions, is that remote fired equipment tends to be inspected less frequently, less intrusively and with more reliance on external and online techniques than comparable equipment at accessible plants, which places a premium on the quality of the monitoring and assessment methods reviewed later in this paper.

III. DAMAGE MECHANISMS AND FAILURE MODES

API RP 571 catalogs the damage mechanisms affecting fixed equipment in the refining and petrochemical industries, and most of its high temperature mechanisms apply directly to upstream fired equipment. The mechanisms of greatest practical significance are reviewed below, drawing also on the failure analysis literature for boilers and high temperature components.

3.1 Creep and Stress Rupture

Radiant tubes, tube supports and hangers operate in the creep range for common tube materials. Long term exposure above the design metal temperature, whether from fouling-induced overheating, flame impingement or loss of internal flow, accumulates creep strain that culminates in bulging, sagging and eventual stress rupture. API Standard 530 provides the design basis for heater tube thickness using the Larson-Miller parameter approach (Larson and Miller, 1952) and remains the reference for remaining life estimation from operating temperature histories. Viswanathan’s treatment of damage mechanisms and life assessment of high temperature components remains a foundational reference for creep cavitation metallography, hardness-based screening and life fraction rules. Short term overheating, by contrast, produces thin-lipped fishmouth ruptures with heavy deformation, a morphology well documented in the boiler failure literature.

Practical creep life management rests on three measurement families whose combination is stronger than any alone. Dimensional measurement tracks the macroscopic symptom: diametral growth of tubes against retirement criteria of accumulated strain, commonly a few percent depending on material, with intelligent pigging now supplying full-coil strain maps in place of sampled strapping. Metallographic examination by in-situ replication reads the microstructure directly, grading creep cavitation from isolated cavities through oriented chains to microcracking on established classification scales, and revealing the carbide spheroidization and phase changes that mark long thermal exposure; hardness testing provides a cheap field proxy for the same thermal history. Calculation ties the evidence together, converting operating temperature and stress history into consumed life fraction through Larson-Miller based rules, with the assessed remaining life then setting reinspection intervals rather than serving as a precise prediction. The literature is candid about the scatter inherent in creep data and the sensitivity of life estimates to temperature error, a twenty degree Celsius error in assumed metal temperature commonly altering calculated life by a factor of two or more, which is why the measurement and inference of tube metal temperature recurs throughout this review as the central practical problem of fired equipment life management.

3.2 High Temperature Corrosion, Oxidation and Carburization

Fireside surfaces suffer oxidation and, where fuels contain sulfur, sulfidation and ash-related corrosion. In upstream units burning untreated produced gas, hydrogen sulfide in the fuel accelerates fireside sulfidation of tubes, tube sheets and burner components. Vanadium and sodium species in liquid fuels, still used in some remote operations, cause fuel ash corrosion of tube supports and refractory anchors. Process-side mechanisms include naphthenic acid corrosion in some crude heating services, sulfidation of carbon and low alloy steels above roughly 260 degrees Celsius in sour streams, and carburization of coil materials in reducing, carbon-rich environments. Selection of chromium-molybdenum and austenitic stainless tube materials, guided by API 530 and operator material selection standards, is the primary preventive barrier, with the general corrosion engineering handbooks providing the broader framework for mechanism identification and materials response (Roberge, 2012), while inhibitor chemistry continues to develop, including a growing literature on green corrosion inhibitors derived from agricultural extracts for steel protection in aggressive media (Atta, Asomani and Adenuga, 2018).

3.3 Waterside Mechanisms in Boilers and Steam Generators

Boilers and once-through steam generators in thermal recovery service are dominated by waterside chemistry-driven mechanisms. Oxygen pitting, caustic gouging, hydrogen damage, phosphate hideout related corrosion and under-deposit corrosion are extensively documented in the boiler failure analysis literature (Dooley and McNaughton, 1996). Thermal recovery steam generators typically accept softened but high solids feedwater at high hardness removal duty, and operate at steam qualities around eighty percent, which concentrates dissolved solids in the residual liquid film and makes deposition control and rigorous water treatment surveillance central to tube reliability. Scale deposition insulates the waterside surface, elevates tube metal temperature and converts a chemistry problem into a creep problem, illustrating the coupling between mechanisms that complicates life prediction.

3.4 Thermal Fatigue, Mechanical Damage and Refractory Degradation

Cyclic operation drives thermal fatigue at tube-to-header attachments, terminal tubes, casing penetrations and fire tube inlets of indirect heaters. Flame impingement from misaligned or damaged burners produces localized hot spots, accelerated oxidation and local creep. Tube supports and hangers crack and distort, allowing tube sagging and contact damage. Refractory linings degrade by thermal cycling, spalling, hot gas bypassing and anchor corrosion; refractory failure exposes casing to overheating and is a frequent finding in upstream heater inspections. Vibration induced damage in convection sections, erosion by soot blowing in boilers, and external corrosion under insulation on casings and external piping complete the picture of mechanical and external mechanisms.

3.5 Failure Modes and Consequence

The dominant reported failure modes across the equipment class are tube leaks and ruptures, fire tube failures in indirect heaters, firebox explosions associated with burner management deficiencies, refractory and casing failures, and stack and breeching corrosion. Published incident reviews and insurer loss data consistently attribute a large fraction of severe events to tube rupture caused by overheating, with burner management and fuel gas quality contributing to the ignition and explosion events. In upstream facilities the consequence of any of these modes is amplified by co-location with wellheads, separators and storage, and by limited firefighting resources at remote sites.

3.6 High Temperature Hydrogen Attack and Decarburization

Where fired heaters serve hydrogen-rich streams, as in gas processing units with hydrogenation duties or in upgrading service associated with heavy oil, high temperature hydrogen attack becomes a credible mechanism. Atomic hydrogen diffuses into the steel, reacts with carbides to form methane at internal interfaces, and the accumulating methane pressure generates fissuring and blistering that degrade toughness and strength with little external evidence. Susceptibility is governed by the combination of hydrogen partial pressure, metal temperature and material chemistry, historically screened using the Nelson curves maintained in API RP 941. The mechanism deserves emphasis in a fired equipment review for two reasons. First, tube metal temperature, not bulk fluid temperature, controls the attack rate, so fouling or flame impingement can push a nominally safe operating point across the susceptibility boundary without any change in process conditions. Second, industry experience up to 2019, including a widely studied fatal heat exchanger rupture attributed to hydrogen attack of carbon steel operating below the then-accepted curve (U.S. Chemical Safety and Hazard Investigation Board, 2014), prompted a general tightening of screening margins and renewed attention to the accuracy of design temperature assumptions, lessons directly transferable to fired heaters in hydrogen service. Decarburization, the surface loss of carbon in high temperature oxidizing or hydrogen environments, accompanies these exposures and serves inspectors as a metallographic marker of thermal history even where hydrogen attack itself is absent.

3.7 Dew Point Corrosion and Cold End Mechanisms
While most attention concentrates on the hottest parts of fired equipment, a persistent family of failures originates at the cold end. Flue gas containing sulfur oxides forms sulfuric acid vapor that condenses on any surface below the acid dew point, typically in the range of one hundred ten to one hundred fifty degrees Celsius depending on sulfur trioxide concentration and moisture. Economizer tubes, air preheaters, convection section cold rows, casing penetrations, breeching and stacks are the usual victims, suffering aggressive wastage that is easy to miss because it develops on external tube surfaces and internal casing surfaces hidden from routine view. In upstream units burning sour or variable fuel gas the acid dew point moves with fuel composition, so a unit designed with adequate cold end margins on sweet design gas can slide into chronic dew point attack when field conditions change. Water dew point corrosion, distinct from acid dew point attack, affects units on frequent standby, where humid air breathing through an idle firebox condenses on cold surfaces and drives oxygen corrosion of tubes and casing. Operational countermeasures, including maintaining stack temperatures above dew point, sealing casing leaks that create cold spots, and dehumidified or heated standby preservation, are well established but demand a discipline that unmanned and cycling upstream units often lack, which is why cold end wastage features prominently in upstream heater inspection findings.

3.8 Erosion, Flow-Accelerated Corrosion and Internal Flow Effects
Flow-related mechanisms complete the damage picture. On the process side, produced fluids carrying formation sand or proppant erode tube bends, return bends and coil inlets, thinning pressure boundaries preferentially at locations of flow impingement; the combination of erosion with corrosive fluids produces erosion-corrosion rates far exceeding either mechanism alone. In boilers and steam generators, flow-accelerated corrosion attacks carbon steel in single phase and two phase water systems within a specific window of temperature, chemistry and hydrodynamics, dissolving the protective magnetite layer and producing characteristic scalloped thinning in economizers, feedwater piping and wet steam lines. The mechanism is chemistry sensitive, accelerating at reducing conditions and low pH, and its management is one of the strongest arguments for the rigorous feedwater chemistry control reviewed later in this paper. On the fireside, soot blower erosion in boiler convection banks and fly ash erosion in units firing liquid fuels thin tubes locally along blower paths and gas lanes. Finally, internal maldistribution deserves mention as a degradation multiplier rather than a mechanism in its own right: unequal flow among parallel heater passes, whether from inlet manifold design, partial plugging or control valve behavior, starves individual passes, elevates their tube metal temperatures and concentrates creep and fouling damage on a subset of tubes, a pattern that intelligent coil inspection surveys have made newly visible by mapping wall loss and diameter growth pass by pass.

IV. CODES, STANDARDS AND REGULATORY FRAMEWORK

The integrity management of fired equipment rests on a mature framework of design codes, inspection codes and recommended practices. API Standard 560 governs the design of fired heaters for general refinery service and is widely applied by analogy to upstream process heaters. API Standard 530 establishes the calculation of heater tube thickness and provides the creep rupture design curves used both for design and for remaining life assessment. API RP 573 addresses the inspection of fired boilers and heaters, covering inspection intervals, methods, typical deterioration and record keeping, and is the primary inspection practice for this equipment class. API RP 571 supplies the damage mechanism taxonomy that underpins inspection planning, while API RP 577 and related welding practices govern repair quality. A wider family of practices completes the technical framework: API 510 and API RP 574 cover the vessels and piping bound to fired equipment circuits, API RP 578 governs material verification, API RP 535 addresses burner selection for fired heaters, API RP 583 and NACE SP0198

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address corrosion under insulation and fireproofing, API RP 584 codifies integrity operating windows, API RP 585 structures pressure equipment incident investigation, NFPA 86 covers ovens and furnaces adjacent to the process heater population, and ASME PCC-2 provides accepted repair methods for pressure equipment.

Fitness-for-service assessment is standardized in API 579-1/ASME FFS-1, whose assessment procedures for general and local metal loss, creep damage, dents, bulges and laminations are directly applicable to heater tubes and boiler pressure parts. Risk-based inspection is framed by API RP 580, with quantitative methodology in API RP 581, which includes damage factor models relevant to fired equipment circuits. Boilers fall under ASME Boiler and Pressure Vessel Code Section I for construction and under the National Board Inspection Code for in-service inspection and repair, supplemented by jurisdictional regulation. Burner and combustion safeguarding is governed by NFPA 85 for boilers and NFPA 87 for fluid heaters, together with API RP 556 on instrumentation and control of fired heaters, and functional safety of burner management systems is addressed through IEC 61511. At the management system level, API RP 754 process safety indicators, jurisdictional safety case regimes the risk based process safety framework of the Center for Chemical Process Safety (2007), the general risk management principles of ISO 31000, and the emerging ISO 55000 asset management series provide the governance envelope within which fired equipment programs sit. A recurring observation in the literature is that indirect wellsite heaters often escape this framework because they fall below pressure equipment thresholds or outside plant inspection registers, a gap that several operators have addressed through dedicated wellsite heater integrity programs. Comparable lessons on delivering and regulating high risk infrastructure in developing economy contexts are reported outside oil and gas, including capital project delivery models for high risk healthcare infrastructure and regulatory compliant design systems for highly controlled laboratory environments (Aminu-Ibrahim, Ogbete and Ambali, 2018, 2019; Ogbete, Aminu-Ibrahim and Ambali, 2018, 2019), and these reinforce the argument that codes alone do not assure integrity without delivery capability.

The jurisdictional layer deserves explicit attention for upstream operators working across borders. Boiler law is among the oldest safety regulation in industrial countries, and its requirements, registration, authorized inspection, certificated operators in some jurisdictions, and prescriptive internal inspection intervals, apply to upstream steam plant regardless of how modern the risk-based philosophy of the owner may be, so RBI conclusions must be reconciled with statutory minima rather than substituted for them. Process heaters, by contrast, frequently fall under general pressure equipment or occupational safety law whose fired-equipment specificity is limited, leaving recommended practices to carry the technical burden. In developing regions hosting much upstream activity, regulatory regimes may adopt international codes by reference while lacking enforcement depth, which transfers responsibility onto operator internal standards and self-verification; international operators typically respond by applying a single corporate integrity standard globally at the level of the most demanding jurisdiction in which they work, while national operators exhibit wider variation documented in integrity maturity studies. The practical guidance emerging from published experience is unambiguous: the governing framework for any specific unit must be established in writing at the equipment register level, because units misclassified between boiler law and pressure equipment law, or assumed exempt as package equipment, are recurrent findings in integrity audits and occasionally in incident investigations.

V. COMBUSTION SYSTEMS, BURNERS AND BURNER MANAGEMENT

5.1 Burner Design, Fuel Quality and Fuel Gas Conditioning

The burner is the point at which most fired equipment problems either begin or are prevented. Burner selection fixes the flame envelope, heat flux distribution, turndown capability and emissions signature of the unit, and the combustion engineering literature provides extensive design guidance on natural draft and forced draft configurations, staged fuel and staged air low NOx designs, and flame stabilization (Baukal, 2013; Mullinger and Jenkins, 2014), with the classic furnace operation and process heat transfer texts remaining useful references for natural draft practice (Kern, 1950; Reed, 1981). In upstream service the dominant practical issue is not burner design but fuel quality. Produced fuel gas varies in composition, heating value and Wobbe index as wells decline, as gas lift and flash gas streams mix, and as process upsets occur. Heavier components shift flame length and heat flux, raising the risk of flame impingement on tubes sized for a design gas that no longer represents reality. Hydrogen sulfide corrodes burner tips and gas passages, and liquid carryover from inadequate knockout fouls tips, distorts spray patterns and can deliver slugs of liquid into a hot firebox with dangerous energy release. For these reasons the fuel gas conditioning train, comprising knockout drums, filtration or coalescing, superheating above the hydrocarbon dew point and pressure regulation, functions as integrity-critical equipment even though it contains no flame, and its maintenance is repeatedly identified in reliability studies as among the highest leverage activities for fired equipment availability. Burner condition itself degrades progressively: tip erosion and coking, diffuser and tile damage, register seizure and gasket leakage each distort combustion long before they cause alarm, and routine burner inspection and tuning programs recover both efficiency and tube life at modest cost.

5.2 Burner Management Systems and Combustion Safeguarding

The catastrophic failure modes of fired equipment, firebox explosions foremost among them, are governed less by metallurgy than by the burner management system. A firebox explosion requires the accumulation of a flammable mixture within the enclosure and an ignition event, a sequence almost always traceable to failures of purge discipline, fuel isolation integrity or flame supervision. Codified defenses are mature: NFPA 85 for boilers and NFPA 87 for fluid heaters prescribe pre-ignition purge requirements, proven ignition sequences, flame detection, safety shutoff valve arrangements with double block and vent on fuel gas, and mandatory trip functions for low fuel pressure, loss of flame, high firebox pressure and loss of combustion air. API RP 556 addresses the instrumentation and control architecture for gas fired heaters, and IEC 61511, built on the general functional safety standard IEC 61508, provides the framework under which burner management trip functions are assigned safety integrity levels, designed, validated and proof tested. Adaptive safety management implementation models developed for aviation oversight in developing economies offer a useful template for phasing such safeguarding upgrades across legacy fleets where full compliance cannot be achieved at once (Adeyelu, 2018, 2019).

The upstream fleet presents a specific safeguarding problem: a large legacy population of small heaters, particularly indirect wellsite heaters, built before modern burner management requirements and often fitted with little more than a thermocouple-based flame safeguard and a single fuel valve. Incident histories for this equipment class feature delayed ignition events during manual lighting, flame-outs with continued fuel flow into hot bath enclosures, and fire tube explosions, all preventable by modern safeguarding. Upgrading thousands of distributed small units is an economic and logistical challenge, and published operator practice converges on risk-ranked retrofit programs that prioritize units by fuel rate, proximity to personnel and history, installing self-checking flame scanners, double block and bleed fuel trains and automated purge sequencing on the highest ranked units first. Equally important is the human element: manual relight procedures, lockout of defeated trips and the normalization of operating with failed flame scanners recur as causal factors in investigation reports, placing burner management proof testing and trip defeat control among the most safety-significant maintenance activities on any upstream facility.

5.3 Combustion Tuning, Draft Control and Operational Practice

Between the design of the burner and the safeguarding of the flame lies the daily operational practice of combustion management, which exerts a quiet but powerful influence on both efficiency and integrity. Excess air control is the central lever: too little air produces combustibles breakthrough,

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afterburning in the convection section and the risk of fuel-rich excursions, while too much air wastes fuel, cools the radiant section, shifts duty to the convection section and increases the mass flow available to carry acid gases to cold end surfaces. Flue gas oxygen and carbon monoxide measurement, with analyzers maintained in calibration, enables operation near the optimum, and the difference between a well tuned and a neglected heater commonly amounts to several percentage points of fuel efficiency. Draft management matters equally on natural draft heaters, which dominate upstream service: excessive draft pulls tramp air through casing leaks and distorts the air register balance, while insufficient draft risks positive pressure at the arch, flame rollout and casing damage. The disciplined practice of holding a slightly negative arch pressure, balancing registers across burners and sealing casing leaks is well documented in operating guidance yet is among the first practices to decay at lightly manned facilities. Operational monitoring rounds out the picture: bridgewall temperature trends reveal fouling and burner degradation, pass outlet temperature spreads reveal maldistribution, and visual flame observation, for all its subjectivity, remains an irreplaceable early detector of impingement and burner malfunction, which argues for retaining combustion competence in field operator training programs even as automation increases.

VI. INSPECTION AND CONDITION MONITORING TECHNIQUES

6.1 Offline Inspection

Conventional outage inspection of fired equipment combines visual examination of tubes, supports, refractory, burners and casing with quantitative NDE of pressure boundaries. Ultrasonic thickness measurement remains the workhorse for wall loss, supplemented by profile radiography where access is limited. Tube diameter measurement by strapping or go/no-go gauges detects creep swelling, with API RP 573 offering guidance on bulging acceptance. In-situ metallography by replication reveals creep cavitation and microstructural degradation such as spheroidization in carbon and low alloy steels, and hardness testing screens for both softening and hardening. Boiler internal inspection targets drum internals, waterside deposits, and tube sampling for deposit weight density measurement, which drives chemical cleaning decisions. Advanced volumetric methods have matured considerably: intelligent pigging tools for heater coils, using ultrasonic or laser-based measurement, now map wall thickness, internal diameter, bulging and fouling over the full coil length, converting inspection from sampling to census and materially improving the input quality for remaining life assessment.

Method selection deserves comment because each technique carries limitations that matter at fired equipment temperatures and geometries. Conventional ultrasonic thickness measurement requires surface preparation through external scale whose thickness itself biases readings if not removed, and couples poorly to rough cast components such as tube supports. Radiography penetrates insulation and scale but resolves wall loss less precisely and imposes exclusion zones that conflict with parallel turnaround work. Eddy current and remote field techniques serve finned convection tubes that ultrasonics cannot practically access, while magnetic particle and dye penetrant examination remain the workhorses for surface cracking at welds, supports and casing attachments. Emerging at the time of this review were phased array ultrasonics for creep damage screening at critical welds, and laser scanning for casing and coil deformation mapping. The recurring practical lesson in published inspection experience is coverage honesty: reporting which tubes, rows and components were actually examined, at what grid density, with which technique and preparation, because assessment engineers repeatedly discover that historical records claiming full inspection reflect sampled campaigns whose gaps concealed exactly the localized damage, dew point wastage on cold rows, erosion on blower paths, impingement scars behind burners, that later produced failures.

6.2 Online Monitoring

Because tube metal temperature is the dominant variable in creep life, its measurement is the highest value online monitoring activity. Welded tube-skin thermocouples remain standard despite their limited life and localized coverage, and infrared thermography through inspection ports has become routine for surveying radiant sections during operation, detecting hot spots, flame impingement and scale-related temperature elevation. Corrections for furnace background reflection and tube emissivity are essential for quantitative use, and the thermography literature offers established procedures for this. Combustion monitoring by flue gas oxygen, combustibles and carbon monoxide analyzers supports both efficiency and safety, with draft measurement guarding against positive pressure excursions. For boilers, online chemistry analyzers, acoustic leak detection and steam quality measurement are established. Research and early industrial practice up to 2019 report growing use of permanently installed ultrasonic sensors, distributed fiber optic temperature sensing on selected geometries, and drone-based visual and thermographic inspection of stacks and external surfaces, drawing on the UAV inspection frameworks developed for power transmission infrastructure (Dagodzo, 2018a, 2018b), although validation and standardization of these techniques remained incomplete at the time of this review. The dependability of such remote monitoring also rests on communications and site electrical infrastructure, where studies of telecommunication network quality, voltage control with distributed generation, and hybrid solar load management in developing economies are directly relevant to unmanned upstream sites (Amayo and Popoola, 2017b; Oshevire, Eyenubo and Amayo, 2017; Sunday and Omoegun, 2018, 2019).

Monitoring value is realized or lost in the surveillance architecture that surrounds the sensors. Points must land in the historian with correct ranges and maintained calibration, alarms must be rationalized so that a genuine tube-skin excursion is not buried among nuisance annunciations, and someone must own the response: published operating experience contains repeated examples of tube failures preceded by days of visible temperature trend that no one was tasked to watch. Effective programs therefore pair instruments with explicit surveillance routines, daily review of pass outlet spreads and bridgewall trend by operations, periodic infrared survey comparison against a baseline atlas by inspection, and defined operating envelope limits whose breach triggers documented response rather than informal judgment. Integrity operating windows, the formalization of these limits with defined ownership and escalation as codified in API RP 584, extend naturally to fired equipment variables, and their adoption converts monitoring from data collection into barrier management. The architecture question grows more pointed as unmanned operation spreads: remote surveillance centers can watch more units more consistently than site crews ever did, but only when the alarm philosophy, the communications reliability discussed above, and the authority to intervene are engineered as deliberately as the sensors themselves.

6.3 Inspection Planning, Access and Turnaround Execution

Techniques deliver value only through executable inspection plans. Fired equipment inspection is turnaround-bound to an unusual degree because meaningful internal access requires cooling, refractory protection, tube cleaning and often scaffolding within a confined firebox, so the planning cycle begins a year or more before execution with a scope built from the damage mechanism review, previous findings, RBI outputs and operating history since the last entry. API RP 573 provides the checklist backbone for such scopes, covering tubes, supports, hangers, refractory, casing, burners, stacks and appurtenances. Good practice reported by operators includes pre-turnaround infrared surveys to target suspect areas while the unit still runs, laser or ultrasonic intelligent pigging scheduled early in the outage so that findings can drive repair scope within the same window, and contingency planning for discovered work such as staged tube stock and pre-qualified welding procedures. The scheduling tension is real: fired equipment competes for turnaround duration with columns and exchangers, and inspection scopes are vulnerable to compression when outages overrun. Remote and offshore units add mobilization risk, where a single delayed specialist crew can force deferral of an entire scope to the next opportunity years away. These realities explain the steady migration toward non-intrusive and online techniques reviewed above, and they argue for treating access engineering, permanent platforms, inspection ports and rope access or drone access provisions, as an integrity investment in its own right.

6.4 Inspection Data Management and Records

The inspection function generates a growing volume of heterogeneous data: thickness grids, intelligent pig maps, thermography archives, replication micrographs, deposit analyses, refractory condition reports and photographic records. The value of this data compounds only if it is stored against a stable equipment and component hierarchy, trended across campaigns and made available to the assessment engineers who convert it into remaining life. Reviews of integrity program failures repeatedly identify data loss and fragmentation, records held by departed contractors, thickness locations that cannot be re-found, and paper archives destroyed or dispersed, as root contributors to poor decisions. Inspection data management systems address this by binding condition monitoring locations to equipment registers, automating corrosion rate and retirement date calculation and flagging overdue inspections, and their governance benefits from the same disciplines described in the enterprise data engineering literature on extract, transform and load design and platform governance in regulated environments (Badmus, Dosunmu and Ozowara, 2019a, 2019b). For fired equipment specifically, the highest value dataset is the tube-by-tube history: wall thickness, diameter, temperature exposure and repair record per tube, which intelligent pigging now populates efficiently and which transforms retubing decisions from judgment calls into evidence-based fleet management.

VII. RISK-BASED INSPECTION AND FITNESS-FOR-SERVICE

7.1 Risk-Based Inspection

RBI allocates inspection effort in proportion to the risk of each equipment item, combining probability of failure derived from damage mechanism assessment with consequence of failure derived from inventory, fluid and location; the broader risk-based maintenance literature formalizes the same allocation logic and documents its quantitative development (Khan and Haddara, 2003; Arunraj and Maiti, 2007). Applied to fired equipment, RBI methodologies segment heaters into circuits by material and operating condition, assign damage factors for creep, thinning and external mechanisms, and set inspection intervals and techniques accordingly. API RP 581 provides quantitative procedures, including a heater tube module that links operating temperature history to rupture probability. Published case studies from refining and, increasingly, from upstream operators report that RBI implementation on fired equipment concentrates effort on radiant coils, reduces intrusive inspection of low risk convection circuits, and improves outage scoping. Critiques in the literature note that RBI quality is limited by the quality of temperature history data, that generic failure frequencies for fired equipment are sparse, and that upstream indirect heaters are poorly represented in commercial RBI software damage models, all of which argue for operator-specific calibration. Parallel work in the financial sector on risk based internal control models and data driven risk evaluation for institutions in emerging markets illustrates how risk scoring frameworks are calibrated and governed under sparse data, and offers transferable lessons for RBI programs facing the same limitation (Akomolafe and Agu, 2019a, 2019b).

Implementation process determines outcome as much as methodology. A creditable fired equipment RBI study assembles a multidisciplinary team spanning inspection, process operation, materials engineering and combustion, because no single discipline holds the data the damage models require: process engineers supply the true operating envelope and excursion history, operators supply firing practice and fuel quality reality, materials engineers assign mechanisms and rates, and inspectors supply findings and their confidence. Corrosion loops and circuits are then defined so that each carries homogeneous conditions, a step where fired equipment demands finer segmentation than vessels, since a single coil traverses radically different temperature and flux regimes from convection inlet to radiant outlet. The output is not a risk number but an inspection plan: technique, coverage, interval and acceptance criteria per circuit, with the evergreen requirement that findings, excursions and process changes reenter the study on a defined cycle. Audits of stalled RBI

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programs report common failure patterns, studies completed as one-time consultancy deliverables and never updated, damage models left at software defaults, and inspection plans disconnected from the turnaround scoping process, all organizational rather than technical failures, and all avoidable by owning the study as a living element of the integrity management system described later in this review.

7.2 Fitness-for-Service and Remaining Life Assessment

FFS assessment translates inspection findings into run, repair or replace decisions. For heater tubes the central assessment is remaining creep life, performed to API 579-1/ASME FFS-1 Part 10 using operating temperature and stress histories, the Larson-Miller based material data of API 530 and the Omega method where strain data are available (Prager, 1995). Level 1 screening based on time-temperature exposure is commonly followed by Level 2 assessments using measured wall thickness and diametral growth, with Level 3 finite element analysis reserved for complex geometries such as tube supports and header boxes. Metal loss on boiler pressure parts is assessed under Parts 4 and 5 of API 579-1, while dents, bulges and laminations have dedicated procedures. The literature emphasizes two recurring difficulties: the reconstruction of credible tube metal temperature histories, for which infrared survey archives and process data inference methods have been proposed, and the treatment of interacting mechanisms, such as internal fouling accelerating creep, for which current codified procedures offer limited guidance and which remains an active research area.

7.3 Application Experience and Practical Lessons

Published application experience, though dominated by refining, offers transferable lessons for upstream implementation. RBI programs on heater populations consistently report an initial redistribution of effort: radiant coils in creep service and cold end circuits in dew point service rise in priority, while low temperature convection circuits and utility boiler economizers in well controlled chemistry regimes fall, with net inspection cost frequently reduced even as coverage of high risk circuits increases. The credibility of these outcomes rests on input honesty. Case discussions note a tendency to record design rather than actual operating temperatures, to overlook excursion history and to treat fouled operation as an anomaly rather than a duty condition, all of which bias creep damage factors optimistically; programs that institutionalize the feedback of infrared survey data and pass outlet temperature history into the RBI record avoid this trap. FFS application experience carries a parallel lesson about conservatism management: Level 1 creep screenings on heater tubes frequently fail conservative inputs and, if acted upon directly, drive premature retubing, whereas Level 2 assessments with measured wall, measured diameter growth and reconstructed temperature history routinely justify continued operation with defined reinspection intervals. The economic stakes are significant, since a radiant coil replacement on a large heater is a multi-million dollar scope with long lead alloy material, and the assessment discipline that separates necessary from unnecessary retubes pays for itself many times over. Analogous experience in financial risk governance, where risk model quality depends on data lineage and calibration discipline under sparse observations, reinforces the general point that risk based frameworks are only as good as their inputs and their governance (Akomolafe and Agu, 2019a, 2019b).

VIII. WATER TREATMENT AND CHEMISTRY CONTROL FOR UPSTREAM BOILERS AND STEAM GENERATORS

8.1 Feedwater Treatment Trains

For boilers and thermal recovery steam generators, water chemistry is the dominant integrity variable, and the treatment train that prepares feedwater is as integrity-critical as any pressure part. Conventional utility boilers at upstream plants follow familiar practice: filtration, softening or demineralization, deaeration for dissolved oxygen removal, and internal treatment with oxygen scavengers, phosphate or all-volatile programs matched to operating pressure. Thermal recovery service is more demanding because economics favor recycling produced water as generator feedwater. Produced water arrives with high hardness, silica, dissolved organics and oil carryover, and the treatment train, typically comprising de-oiling, warm or hot lime softening for hardness and silica reduction, filtration and ion exchange polishing, must deliver near-zero hardness continuously at very large flow rates. Hardness breakthrough is the classic precursor event: a softener train upset that passes even a few parts per million of hardness for hours deposits scale through the generator fleet, insulates tube walls, elevates metal temperatures and initiates the under-deposit corrosion and creep interactions described in Section 3. Published thermal recovery operating experience accordingly treats softener performance monitoring, regeneration quality control and rapid breakthrough detection as frontline reliability activities, and the failure analysis literature documents the tube damage signatures of each chemistry excursion in detail (Port and Herro, 1991; French, 1993), with the standard water treatment handbooks supplying program design guidance (Flynn, 2009).

8.2 Operating Chemistry Control and Surveillance

Once quality feedwater is delivered, operating chemistry control maintains the protective magnetite layer on waterside surfaces and manages the concentration mechanisms inherent to steam generation. In drum boilers this means controlling boiler water within program limits for pH, phosphate or alkalinity, conductivity and silica, blowing down to control cycles of concentration, and scavenging oxygen to protect the feed train; failures of this control produce the caustic gouging, hydrogen damage, phosphate hideout effects and oxygen pitting cataloged in the boiler failure literature. In once-through steam generators the absence of blowdown transfers the control burden to feedwater quality and to steam quality management, since the exit quality setpoint fixes the concentration factor experienced by the liquid film at the tube wall; overshooting quality, whether from measurement error or firing imbalance among passes, locally dries the wall and precipitates the full dissolved solids load at the point of dryout. Surveillance practice therefore centers on reliable online analyzers for hardness, pH, conductivity and dissolved oxygen, on per-pass steam quality measurement for once-through units, and on periodic tube sampling with deposit weight density measurement, which remains the ground truth for waterside cleanliness and the codified trigger for chemical cleaning. Reviews of boiler reliability programs emphasize organizational as much as technical factors: chemistry limits are only protective when excursions generate alarms that operators act upon, when analyzer maintenance is resourced, and when the water treatment function holds standing authority to reduce firing or shut down generators on sustained excursions, an authority that production pressure at upstream facilities tests constantly.

8.3 Chemical Cleaning, Preservation and Layup

Even well controlled units accumulate waterside deposit over years of service, and the restoration activity is chemical cleaning: solvent circulation programs, classically inhibited hydrochloric acid for hardness scales with alternatives such as chelant and organic acid programs for mixed deposits, engineered from tube sample deposit analysis and executed with rigorous inhibitor control, spent solvent handling and post-clean passivation. Cleaning is not without risk, since aggressive solvents attack base metal if inhibition fails and cleaning residues left in dead legs cause later corrosion, so the decision to clean, its timing against deposit weight density thresholds, and its execution quality are integrity decisions in the full sense. Preservation and layup complete the chemistry lifecycle. Upstream boilers and steam generators experience frequent and sometimes extended idle periods driven by well work, production curtailment and seasonal demand, and idle corrosion during poor layup rivals operating corrosion as a life consumer. Established practice distinguishes wet layup, with treated, deoxygenated water under nitrogen blanket for short outages, from dry layup with dehumidified or desiccant air circulation for extended storage, and inspection findings of oxygen pitting in units with a history of unprotected standby confirm what the guidance predicts. For remote and unmanned upstream units, practical layup discipline is the recurring weakness, and simple engineered aids, nitrogen connections, dehumidifier skids and layup checklists embedded in shutdown procedures, return outsized reliability value for their cost.

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IX. RELIABILITY-CENTERED MAINTENANCE AND INTEGRITY MANAGEMENT SYSTEMS

Where RBI governs the pressure boundary, reliability-centered maintenance provides the framework for the balance of the asset: burners, fans, dampers, soot blowers, burner management systems, fuel gas conditioning and instrumentation. RCM analysis, following the classical methodology of Nowlan and Heap and its later standardization, identifies failure modes and assigns condition-based, time-based or run-to-failure strategies. Published applications to fired equipment highlight burner inspection and tuning, combustion air system maintenance, fuel gas filtration and knockout, refractory inspection routines and proof testing of burner management safeguards as the tasks with the greatest reliability leverage. Reliability data compilations such as OREDA provide upstream failure rate context for rotating and instrumented subsystems, although fired equipment as a class is thinly covered, a gap noted repeatedly in the literature. The reliability of motor driven auxiliaries such as combustion air fans and pumps also benefits from the electrical machines literature on induction motor loss and design optimization (Amayo, Ubeku and Oshevire, 2015; Amayo, 2017; Amayo and Popoola, 2017a), and control oriented studies of thermodynamic efficiency in heating and cooling systems inform the tuning of combustion and heat recovery controls (Sunday et al., 2019).

At the system level, operators embed these programs in asset integrity management systems, for which consolidated guidance exists in the mechanical integrity and asset integrity literature (Center for Chemical Process Safety, 2006, 2017), that define accountabilities, performance standards, inspection registers, deferral controls and key performance indicators. Regulatory drivers include safety case regimes for offshore installations and jurisdictional boiler codes onshore. Studies of integrity management maturity in national and international operators report that fired equipment programs succeed or fail less on technical method than on data management, competence and the discipline of closing corrective actions, echoing the broader process safety literature after major accident inquiries. This finding is consistent with governance research beyond oil and gas: studies of technology enabled internal audit, integrated governance and compliance strategy, and reporting and reconciliation workflow discipline all show that assurance quality depends on data integrity and closure of findings (Akomolafe and Agu, 2018, 2019c; Dogbatsey and Ebhojie, 2018; Dogbatsey, Ebhojie and Oyeleye, 2019), and adaptive safety management system implementation models from aviation oversight in developing economies offer a template for phased SMS maturity at upstream facilities (Adeyelu, 2018, 2019). Human and organizational factors, including operator response to burner trips and the normalization of running with failed tube-skin thermocouples or degraded analyzers, are identified as recurring causal threads in fired equipment incidents. The occupational safety literature reinforces this: leadership driven safety culture transformation, structured management safety walkthroughs, systematic hazard identification and the exploitation of near miss and observation data are repeatedly shown to shape frontline risk control outcomes on large industrial and construction workforces (Obriki and Arumosoye, 2018, 2019; Arumosoye and Obriki, 2019; Obogo, Ozobu and Uduokhai, 2019a, 2019b; Obogo, Uduokhai and Ozobu, 2019).

Two management system elements bear specifically hard on fired equipment. Management of change is the first, because the equipment is exquisitely sensitive to changes that other equipment tolerates: a fuel gas source swap alters flame geometry and dew point, a throughput increase moves tube metal temperatures, a feed change alters fouling propensity, and a control system migration can silently alter trip logic, so integrity review of process and fuel changes belongs formally within the change process rather than being discovered at the next inspection. Deferral management is the second. Inspection and maintenance deferrals are a fact of production operations, but unmanaged deferral is the classic slow path to fired equipment failure, and mature systems therefore require that any deferral of an inspection, a proof test or a corrective action on fired equipment carries a documented technical risk

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assessment, a defined expiry, escalating approval authority with accumulating deferral, and visibility in the performance indicators reviewed below. Investigation reports repeatedly reconstruct incident timelines in which each individual deferral appeared reasonable while the accumulated stack removed every barrier, a pattern the governance controls exist precisely to interrupt.

9.1 Performance Standards and Key Performance Indicators

Mature integrity management systems define, for each barrier and activity, a performance standard and a measurable indicator against it. For fired equipment the leading indicator set reported in operator practice includes inspection plan attainment, corrective action closure within due date, tube-skin thermocouple availability, analyzer availability for flue gas oxygen and boiler chemistry, burner management proof test attainment, trip defeat count and duration, and the count of operating hours above design bridgewall or tube metal temperature. Lagging indicators include tube failure count, unplanned outage hours attributable to fired equipment and loss of primary containment events, aligned with the process safety event tiers of API RP 754. The reporting discipline that makes such indicators trustworthy, stable definitions, reconciliation of data sources and audit of self-reported attainment, mirrors the reporting and reconciliation control literature from financial governance (Dogbatsey and Ebhojie, 2018; Dogbatsey, Ebhojie and Oyeleye, 2019), and audits of integrity programs repeatedly find that indicator quality, not indicator choice, separates effective from cosmetic performance management.

9.2 Contractor Management and Competence Assurance

Fired equipment work is contractor intensive: refractory installation, specialist NDE, burner servicing, chemical cleaning and tube welding are almost universally executed by third parties, frequently mobilized to remote sites. The integrity outcome therefore depends on contractor selection, qualification and supervision as much as on any owner activity, and the safety governance literature on multi-contractor projects documents how fragmented supervision and interface ambiguity degrade risk control on exactly such work (Obogo, Ozobu and Uduokhai, 2019b). Practical controls reported by operators include qualification of refractory installers with witnessed material testing, performance demonstration requirements for NDE techniques beyond written certification, welding procedure and welder qualification control under API RP 577, and owner witness points at irreversible stages such as refractory dryout schedules and post weld heat treatment. Competence assurance extends to the owner team: combustion tuning, heater operation and inspection assessment are specialist competencies that thin out as experienced personnel retire, and structured development programs, drawing on the general competence management literature from resource constrained settings (Bobga et al., 2018; Yeboah et al., 2019), are increasingly formalized within integrity management systems rather than left to informal mentoring.

Materials and spares strategy is the third leg of execution readiness. Fired equipment repair material is unforgiving of substitution: alloy tube, matching welding consumables, cast supports, refractory within shelf life and burner spares are all long lead items whose absence at a discovered defect converts a day of repair into a season of deferral. The procurement research on energy facilities quantifies what operators experience, that inventory availability policy is a direct determinant of plant uptime and that strategic procurement optimization and vendor governance materially reduce both cost and mobilization delay for exactly this class of critical spares (Okonkwo, Ogunwole and Okeke, 2018a, 2018b; Okonkwo et al., 2019), while supply chain risk modeling for gas processing projects addresses the upstream reality of long, fragile logistics chains to remote sites (Agbabiaka et al., 2019). Practical measures reported in operator practice include engineered critical spares lists derived from the RBI and RCM analyses rather than from vendor recommendations alone, positive material identification on receipt under API RP 578 to prevent alloy mix-ups whose consequences surface years later as premature failures, shelf life management for refractory and welding consumables, and pooling arrangements for high value long lead items such as alloy tube across sites or with neighboring operators, an application of fleet thinking to the warehouse.

X. REPAIR, RERATING AND LIFE EXTENSION

10.1 Tube Repair and Replacement Practice

When inspection and assessment conclude that a tube or coil cannot remain in service, the repair pathway is governed by material, geometry and code context. Individual tube replacement in heaters requires cutting out the affected length, preparing and aligning replacement tube of matching specification, and executing butt welds to qualified procedures with the preheat, interpass control and post weld heat treatment that the material demands; chromium-molybdenum grades are unforgiving of shortcuts, and hydrogen cracking of hastily welded repairs is a documented cause of repeat failures. Welding practice draws on API RP 577, on the accepted repair methods of ASME PCC-2, and for boilers on the repair provisions of the National Board Inspection Code, which governs repair method acceptance, documentation and stamping for jurisdictional equipment. Component-level decisions accompany tube work: return bends, headers and terminal fittings suffer their own thinning and cracking, and support and hanger replacement is routinely the largest discovered scope in heater turnarounds, since castings crack and creep at temperatures above those the tubes themselves see. Full or partial retubing is the endpoint decision, typically triggered when assessment shows a large tube population approaching retirement together; here the fleet-level tube history described earlier becomes decisive, because selective replacement of the worst passes can defer full retube cost by years when the data supports it, while data-poor programs default to conservative wholesale replacement.

10.2 Refractory, Casing and Structural Repair

Refractory repair is the perennial companion of every fired equipment outage. Failure modes, spalling, anchor corrosion, hot gas bypass behind linings and shrinkage cracking, are diagnosed visually and by external casing thermography during operation, and repair quality determines whether the fix survives one campaign or five. The critical variables are documented and repeatedly violated: material storage within shelf life and moisture limits, water quality and dosage in castable mixing, installation technique matched to material, anchor layout and welding quality, and above all a controlled dryout schedule, since free and chemically bound water driven off too quickly generates steam spalling that destroys new lining before it ever sees service. Casing and structural repair follows conventional practice, plate replacement, seal welding of leaks and stack repair, with the reminder that casing leaks are combustion and cold end problems as much as structural ones, admitting tramp air that distorts draft and creating local cold spots for dew point attack. External corrosion management, painting programs, insulation and fireproofing repair with attention to corrosion under insulation, closes the scope. The consistent lesson from published refractory reliability reviews is that specification and supervision, not material selection, dominate outcomes, reinforcing the contractor management emphasis of Section 9.

10.3 Rerating, Modification and Life Extension Decisions

Beyond like-for-like repair lies the family of engineered life extension decisions. Rerating adjusts documented design conditions, sometimes downward to reflect a permanently reduced duty and recover assessment margin, sometimes upward following detailed analysis where original design proves conservative, in either case under management of change control with fitness-for-service assessment as the technical basis. Material upgrade at replacement is a common life extension lever: substituting a higher chromium grade or an austenitic alloy at retube in a coil with a demonstrated sulfidation or creep problem converts a recurring failure mode into a solved one for modest incremental cost. Convection section modifications, extended surface changes, shield tube upgrades and soot blower additions, address fouling-driven duty loss, and burner replacement with modern low NOx designs pairs emissions benefit with improved flame quality and reduced impingement risk. Aging fleet decisions ultimately reduce to repair versus replace economics, in which remaining life assessment, forward inspection and maintenance cost, efficiency gap against modern equipment and obsolescence of controls and safeguarding are weighed against replacement capital, with regulatory attention to ageing and life extension, exemplified by the UK offshore Key Programme 4, formalizing the expectation that such decisions be demonstrable (Health and Safety Executive, 2014); the analytics-driven decision frameworks described in enterprise financial planning literature (Lawal and Oduleye, 2018a, 2019b) map naturally onto these evaluations, and several operators report formalized end-of-life review gates for fired equipment beyond a threshold age, ensuring that continued operation of legacy units is a decision rather than a default.

10.4 Failure Investigation and Organizational Learning

Every fired equipment failure, and every significant near miss such as a detected hot spot or a trip on genuine demand, is an information asset whose value depends entirely on the investigation applied to it. Technical failure analysis of tubes follows well established metallurgical practice: documentation of rupture morphology distinguishing short term from long term overheating, deposit and scale analysis on both surfaces, microstructural examination for creep cavitation, carburization, decarburization and hydrogen damage, and hardness traverses, with the boiler and high temperature component literature supplying the diagnostic atlases that make these examinations conclusive (Port and Herro, 1991; French, 1993; Viswanathan, 1989). The organizational half of the investigation matters equally: tracing why the precursor, the chemistry excursion, the failed thermocouple, the deferred inspection, the defeated trip, survived the management system, using structured root cause methods that resist stopping at operator error, as framed for pressure equipment incidents by API RP 585. Learning transmission completes the loop, through fleet-wide checks for the same vulnerability, updates to RBI damage assumptions and inspection plans, and incorporation into training. Published integrity maturity assessments distinguish organizations precisely on this loop: mature operators convert each failure into fleet-level prevention, while immature ones repair the symptom and repeat the event, and the near-miss and observation data literature confirms that the richest learning stream is the one below the failure threshold, provided the organization is instrumented to capture it (Arumosoye and Obriki, 2019).

XI. PERFORMANCE, EFFICIENCY AND EMISSIONS MANAGEMENT

11.1 Thermal Efficiency as an Integrity Indicator

Fired equipment efficiency and mechanical integrity are tightly coupled, and performance monitoring earns a place in an integrity review because efficiency loss is usually the earliest visible symptom of developing mechanical problems. Heater and boiler efficiency is measured directly by fuel and duty balance or indirectly by stack loss method from flue gas temperature and composition, and its degradation decomposes into causes that are all integrity relevant: rising stack temperature signals fouled heat transfer surfaces on either side of the tube wall, rising excess air signals casing leakage, analyzer drift or burner deterioration, and rising fuel consumption at constant duty integrates all of them. The energy stakes are material, since fired equipment dominates fuel consumption at most upstream facilities and steam generation dominates operating cost in thermal recovery, so efficiency programs are self-funding; the integrity dividend is that the same monitoring detects the fouling that drives tube overheating and the casing leakage that drives dew point attack. Studies of thermodynamic efficiency and control strategy in heating and cooling systems, though developed for building energy applications, illustrate the general method of decomposing efficiency loss into actionable causes and of closing the loop through control adjustment (Sunday et al., 2019), and the same logic applied to heater bridgewall temperature, pass balance and stack oxygen constitutes practical daily surveillance of both performance and health.

11.2 Emissions Compliance and its Interaction with Reliability

Emissions regulation increasingly shapes fired equipment operation even in upstream jurisdictions historically lightly regulated. NOx limits drive the retrofit of staged combustion and low NOx burners, which narrow stable operating envelopes and demand better fuel gas conditioning and tuning discipline than the robust conventional burners they replace, a reliability interaction operators learn quickly after retrofit. Sulfur oxide emissions track fuel gas hydrogen sulfide and drive fuel treating decisions whose integrity side effects, on burner corrosion and cold end attack, have been noted throughout this review. Carbon monoxide and combustibles limits enforce exactly the combustion tuning discipline that Section 5 identified as integrity protective, an example of regulation and reliability pulling in the same direction. Monitoring obligations, whether continuous emissions monitoring systems or periodic stack testing, add instrumentation whose maintenance joins the analyzer availability indicators of Section 9. In the background, greenhouse gas intensity pressure on the upstream sector was, by 2019, already directing capital toward heat integration, waste heat recovery and electrification studies that reduce fired duty altogether; where such projects displace aging fired equipment they resolve integrity problems by retirement, and where they add waste heat recovery units they import a new inspection population, both outcomes properly considered within integrity planning.

11.3 Fouling Management and On-Line Cleaning

Fouling deserves distinct treatment because it is simultaneously a performance problem, an integrity accelerant and a partially controllable variable. Process side fouling in crude and heavy hydrocarbon services deposits coke and asphaltenic material on inner tube walls, insulating the process from the flame and forcing firing increases that raise tube metal temperature; the creep consequence has been described, and the management levers include feed filtration and desalting quality, velocity management within design windows, antifoulant chemistry where economic, and decoking by steam air decoking or by mechanical pigging, which has largely displaced thermal methods where coil geometry permits because it cleans more completely with less tube thermal abuse. Fireside fouling from luminous flames, liquid fuel ash or airborne dust settles on convection extended surfaces and is managed by soot blowing in boilers and by offline water washing in heaters, each with its own damage side effects in blower erosion and in chloride-bearing wash water attack on austenitic components if quality is uncontrolled. The monitoring counterpart is fouling factor trending from process and flue gas temperatures, which converts cleaning from calendar-based to condition-based scheduling. Published heater reliability discussions increasingly frame fouling management as the practical center of gravity of fired equipment care between turnarounds, because it is the one degradation driver that operations influences daily, and because every increment of cleanliness purchased is simultaneously an increment of fuel saved and of tube life extended.

XII. EMERGING TECHNOLOGIES AND DIGITALIZATION

The period up to 2019 saw rapid growth in digital approaches to fired equipment reliability. Predictive analytics applied to process historian data has been used to detect coil fouling trends, burner degradation and incipient tube leaks earlier than alarm-based monitoring, using multivariate statistical models and, increasingly, machine learning classifiers trained on historical failures. Digital twin concepts, combining first-principles furnace models with live process data, have been demonstrated for firing optimization and tube metal temperature inference where direct measurement is sparse. Computational fluid dynamics of fireboxes has moved from design into troubleshooting, diagnosing flame impingement and maldistribution that inspection alone cannot explain. Robotics and drones reduce human exposure during internal inspection of fireboxes, stacks and boiler drums. Wireless sensing lowers the cost of adding tube-skin thermocouples and casing temperature points at brownfield and remote sites. The literature is consistent, however, in cautioning that these technologies augment rather than replace the codified inspection and assessment framework, and that their value depends on data quality, model validation and integration with existing integrity management systems, none of which was mature across the industry at the time of writing. Realizing value from digitalization also depends on enterprise data engineering and platform governance, where the literature on ETL design, CI/CD deployment discipline and platform governance in regulated environments is instructive for inspection data management systems (Badmus, Dosunmu and

Ozowara, 2018, 2019a, 2019b), as is work on data driven executive decision systems and analytics led governance and compliance across enterprise functions (Lawal and Oduleye, 2018a, 2018b, 2019a, 2019b). Digital integrity systems further inherit cybersecurity obligations: enterprise data protection governance, comparative data protection regulation, log analytics with automated incident response, security audit and risk assessment frameworks, and hardening of security critical directory services are all directly applicable to operational technology environments at production facilities (Mbonu, Aliliele, Iwuanyanwu and Oluoha, 2018; Mbonu, Aliliele, Uzoka and Oluoha, 2019; Mbonu, Iwuanyanwu, Uzoka and Oluoha, 2019; Ladapo et al., 2018, 2019; Dosunmu and Ogundele, 2019). Finally, cross sector evidence that scientific innovation fails to deliver outcomes without effective delivery infrastructure and sustainable financing is a useful caution for digital integrity initiatives at remote assets (Ilodigwe and Adesemoye, 2019a, 2019b).

The prerequisite beneath every digital ambition is data foundation work that is neither glamorous nor optional. Machine learning models for tube failure or fouling prediction require labeled histories, when did each event occur, on which tube, under what conditions, that most operators cannot presently assemble because failure records live in maintenance text fields, inspection results in scanned reports and process history in a historian with uncalibrated or missing tags for the variables that matter most, tube-skin temperatures above all. Published early applications therefore report that the majority of project effort goes to data engineering, and that the models delivering value first are modest ones, drift detection on analyzers, anomaly detection on pass temperature spreads, fouling factor regression, rather than end-to-end failure prediction. This argues for a deliberate sequencing visible in the more successful programs: instrument the variables that physics says matter, structure inspection and failure records against the equipment hierarchy, deploy simple physics-anchored analytics that build operator trust, and only then attempt more ambitious learned models, evaluated against the sparse-data validation cautions raised in the research gaps below. The alternative sequencing, purchasing a predictive platform ahead of the data foundation, recurs in practitioner accounts as the characteristic failure mode of digitalization initiatives on fired equipment.

XIII. GAPS AND FUTURE RESEARCH DIRECTIONS

Several gaps emerge from this review. First, upstream-specific reliability data for fired equipment are scarce; failure rate compilations underrepresent process heaters, indirect wellsite heaters and thermal recovery steam generators, limiting the calibration of quantitative RBI and the benchmarking of maintenance strategies. A coordinated industry data collection effort, analogous to OREDA for rotating equipment and structured on the reliability data taxonomy of ISO 14224, would materially improve practice. Second, indirect wellsite heaters occupy a regulatory and methodological blind spot despite their numbers and their record of fire tube failures; dedicated inspection guidance and simplified risk screening tools for this equipment class are needed. Third, remaining life assessment under interacting mechanisms, particularly fouling-accelerated creep and waterside deposition-driven overheating, lacks codified treatment, and coupled deposition-thermal-creep models validated against field data represent a clear research opportunity. Fourth, the reconstruction of tube metal temperature histories from sparse and imperfect measurements remains the weakest input to creep life assessment, and inference methods combining thermography archives, process data and furnace models deserve systematic validation. Fifth, the application of machine learning to fired equipment prognostics is promising but immature, constrained by small failure datasets and the absence of agreed validation protocols; transfer learning across fleets and physics-informed models are candidate remedies. Finally, the human and organizational dimension, including competence assurance for combustion operations at increasingly unmanned facilities, has received far less research attention than the technical dimension and warrants dedicated study. Cross sector research on professional development and competence management in resource constrained settings, and on skills development and enterprise finance as

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constraints on capability building in Sub-Saharan Africa, offers transferable insight for structuring competence assurance and local capability programs at remote upstream operations (Bobga et al., 2018; Yeboah et al., 2019; Michael and Ogunsola, 2019a, 2019b).

Beyond the research gaps above, three practice-level gaps deserve statement because they are addressable with existing knowledge. The first is the safeguarding retrofit backlog on legacy small heaters, where the engineering solutions are mature and the barrier is programmatic: risk-ranked retrofit funding models and simplified compliance pathways for small units would accelerate closure of a well understood risk. The second is layup and preservation discipline for intermittently operated boilers and steam generators, where documented practice exists but implementation at unmanned sites fails for want of simple engineered provisions and procedural integration; the cost asymmetry between a dehumidifier skid and a retube argues for treating preservation readiness as a design deliverable on new remote facilities. The third is the loss of combustion and heater craft competence as experienced personnel retire faster than structured programs replace them, a workforce gap amplified at remote operations that already struggle to attract specialists.

Finally, the review suggests a structural observation about the literature itself. Fired equipment knowledge is dispersed across combustion engineering, metallurgy, water chemistry, inspection technology and management system domains, each with its own journals, conferences and standards committees, and the integrating publications that treat the equipment as a system are few and largely practitioner-authored. Upstream-focused synthesis is rarer still. This fragmentation is not merely bibliographic: it reproduces itself in organizations, where combustion, inspection, water treatment and reliability responsibilities sit in different departments and the cross-domain interactions emphasized throughout this review, fouling driving creep, chemistry driving overheating, burner condition driving tube life, fall between them. Research that models these interactions quantitatively, and organizational studies of how operators integrate across them, would both fill a genuine gap and give the practitioner community the systemic treatment the equipment class has lacked.

XIV. CONCLUSION

Fired heaters, boilers and furnaces sit at the intersection of high consequence and high degradation in upstream oil and gas facilities. The technical framework for managing them is mature: damage mechanisms are well characterized, design and inspection codes are established, and RBI, FFS and RCM provide coherent decision structures. The upstream context nonetheless stresses this framework in specific ways, through variable fuels, cyclic duty, remoteness, thin inspection coverage of small heaters and sparse reliability data. The literature up to 2019 shows the industry responding with advanced coil inspection tools, online thermography, RBI adoption and early digitalization, while also revealing persistent gaps in upstream-specific data, interacting-mechanism life assessment and the integrity governance of small wellsite units. Closing these gaps would deliver disproportionate returns, because the cost of prevention for this equipment class is modest against the demonstrated cost of its failures. The research agenda proposed here, centered on data pooling, coupled degradation modeling, temperature history inference and validated prognostics, offers a practical path forward for both researchers and operators.

The breadth of this review carries its own conclusion: fired equipment reliability is a systems outcome, produced jointly by combustion management, water chemistry, metallurgical assessment, inspection execution, repair quality and organizational discipline, and weakened by whichever of these receives the least attention. For the upstream sector specifically, the highest value actions available with existing knowledge are the safeguarding and monitoring retrofit of legacy small heaters, the institutionalization of temperature history capture as the foundation of creep life management, the elevation of fuel gas conditioning and water treatment to integrity-critical status, and the pooling of inspection and failure data across fleets and companies. None of these requires new science; all require the sustained management attention that this equipment class, operating quietly at the heart of upstream facilities, has historically received only after its failures.

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