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ASSESSMENT AND ANALYSIS OF THE PERFORMANCE OF COMBINATION BOILER

Omical Asanta[1], Dedi Priadi[2] and Desiran Sembiring[3]

[1]Student of Department of Metallurgy & Materials Engineering UNIVERSITY OF INDONESIA (UI) Jakarta, Indonesia
Email: omicalasanta@gmail.com

[2]Lecturer Faculty of Metallurgy, UNIVERSITY OF INDONESIA (UI) Jakarta, Indonesia
Email: ir.dedi@ui.ac.id

[3]Engineering - PT Medatama, Jakarta, Indonesia
email: desmuham@gmail.com

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ABSTRACT

This study evaluated the performance and condition of a combined water-tube and fire-tube boiler system. The boiler, with a design capacity of 20 t/h, has been in operation since 2011 and utilizes a circulating fluidized bed (CFB) combustion system fueled by low-grade coal. The assessment included visual inspection, material thickness measurements, ultrasonic testing of weld joints, non-destructive testing (Dye Penetrant Testing), hardness testing, and in-situ metallography. The objectives of the assessment were to determine the extent of wall thinning due to corrosion, erosion, or creep; to identify defects in the boiler material and welds through non-destructive testing; to assess metallurgical and mechanical degradation caused by thermal aging, overheating, fatigue, creep, stress corrosion cracking (SCC), or other degradation mechanisms; and to evaluate the current condition and estimate the remaining life of the boiler to determine whether it is still serviceable, repairable, or requires replacement or depressurization. The assessment results indicated that the boiler frame, fire tube, water tube, pipe sheet, and header were in good condition. Visual inspection revealed minor rust and dirt but no significant defects. Material thickness measurements met the Maximum Allowable Working Pressure (MAWP) requirements, and hardness tests showed no significant changes in material properties. Non-destructive testing (NDT) and in-situ metallography confirmed no material degradation or structural changes. Recommendations include cleaning the surfaces of the fire tube and water tube, ensuring boiler feedwater meets required standards to prevent corrosion, reinstalling previously blocked water tubes, repairing external corrosion and damaged insulation on the header, and repairing cracked and peeling refractory walls in the furnace. Furthermore, it is recommended to conduct a boiler assessment every five years to ensure continued reliability and safety. This comprehensive assessment aims to provide baseline data for making informed decisions regarding repairs, replacements, and optimization of the boiler system to improve its performance and ensure compliance with safety regulations. The findings and recommendations from this study are critical to maintaining the operational efficiency and safety of the boiler, thus supporting a sustainable and efficient production process.

Keywords: Fire Tube Water Tube Boiler (Combi Boiler), Thickness, Non-Destructive Testing (NDT), Hardness Test, Metallography, Remaining Life Assessment (RLA)

1. INTRODUCTION

Boilers are critical assets across various industries, serving as the backbone for vital operations by supplying reliable thermal energy and steam required for manufacturing, chemical processing, and food production [1], [2]. As the primary source of thermal energy, boilers facilitate essential processes such as heating, sterilization, and power generation [3]. Among various configurations, the integration of water-tube and fire-tube designs in a combination (hybrid) boiler offers synergistic advantages that optimize both operational efficiency and load flexibility. The water-tube section provides an expansive heating surface for steady-state heat transfer, while the fire-tube section enables rapid steam generation to accommodate fluctuating production demands [4].

However, operating these assets continuously under high temperatures and pressures over extended periods such as the approximately 15-year operational lifespan of the combination boiler investigated in this study exposes them to severe material degradation and structural fatigue. Prolonged operations precipitate thermodynamic and mechanical issues, including scaling, electrochemical corrosion, localized overheating, and creep [5]. Preliminary visual inspections of the studied boiler revealed critical anomalies: two intentionally plugged water tubes on the fireside, extensive refractory damage on several headers, and significant scale accumulation that inherently impedes heat transfer. Evaluating the performance and structural condition of such equipment is imperative to uphold operational efficiency, mitigate catastrophic safety risks, and ensure regulatory compliance [6], [7]

A critical review of contemporary literature reveals several fundamental research gaps in the domain of boiler integrity management. Theoretically, previous studies exhibit a tendency to oversimplify failure mechanisms by investigating corrosion, overheating, or thermal fatigue in isolation [2], [8]. In reality, boiler material degradation occurs simultaneously through the synergistic effects of these mechanisms. Methodologically, earlier evaluations often rely on partial approaches, such as utilizing solely ultrasonic thickness mapping or macroscopic visual observations [9]. Furthermore, relying exclusively on surface hardness tests to estimate tensile strength in high-temperature environments is fundamentally flawed, as microstructural degradation does not always correlate linearly with surface hardness. Practically, conventional industry maintenance still adheres to rigid, time-based inspection (TBI) schedules inherited from outdated 1930s-1980s regulations, which ignore real-time material degradation and result in either costly over-inspection or highly risky under-inspection [6], [10].

The most fundamental gap, however, is the scarcity of empirical studies specifically examining the structural integrity of combination boilers. While existing literature predominantly focuses on standard water-tube or fire-tube architectures [11], combination boilers possess a unique hybrid heat-transfer architecture that triggers asymmetric thermal stress, localized overheating, and accelerated degradation in transition areas.

To address these multi-dimensional gaps, this study presents a holistic integrity assessment and Remaining Life Assessment (RLA) specifically tailored for a combination boiler. By integrating layered inspection methodologies encompassing visual macroscopic inspection, volumetric Ultrasonic Thickness (UT) measurement, non-destructive testing (DPT and Ultrasonic Scan), and metallurgical validation through in-situ metallography and hardness testing this research aims to evaluate material degradation precisely. Ultimately, this comprehensive framework seeks to facilitate the industry's paradigm shift from time-based to condition-based maintenance, providing strategic recommendations to ensure sustained operational reliability and industrial safety [12], [13].

2. MATERIALS AND METHODS

2.1. Boiler Specifications

The equipment under investigation is a combination boiler integrating both water-tube and fire-tube designs, manufactured in 2010 (permit number 566/363/404.3.3/2011, serial number CX200/19/1). Designed to accommodate various industrial applications, the boiler operates with a steam capacity of 20 t/h. The system is engineered for a maximum allowable working pressure of 19 kg/cm², with operating temperatures reaching 236°C in the furnace/bed and 211°C for the generated steam.

The chemical composition, nominal dimensions, and mechanical properties of the critical boiler components including the shell, water tubes, fire tubes, tube sheets, headers, and downcomers are detailed in Table 1. All materials conform to established industrial standards, satisfying the specified requirements for tensile strength and hardness [6], [13]

Table 1 Boiler Component Specifications and Mechanical Properties

No	Component	Nominal Dimension(mm)	Thickness Measurement	Outside Diameter	Material Specification	Tensile Strength - Hardness
1	Body (Shell)	3.100	25	25.21	SA 515 Class 70	Tensile Strength, 49.21 kgf/mm Hardness ≥ 143 HB
2	Water Tube	3.407	25	25.00	BS : 3059 PART 1 : 1987 Gr.320 ERW	Tensile Strength, 32.63 kgf/mm Hardness ≥ 108 HB
3	Fire Tube	88.9	4.5	4.35	BS : 3059 Part 1 : 1987 Class 320 ERW	Tensile Strength, 32.63 kgf/mm Hardness ≥ 108 HB
4	Tube Sheet				SA 515 Class 70	Tensile Strength, 49.21 kgf/mm Hardness ≥ 143 HB
5	Header	50.8	4.06	3.07	SA 106 Gr.B	Tensile Strength, 42.18 kgf/mm Hardness ≥ 121 HB
6	Down Comer	219.1	12.7	12.65	SA 106 Class B	Tensile Strength, 42.18 kgf/mm Hardness ≥ 121 HB.

2.2. Boiler Specifications

Data collection was executed through a comprehensive, structured approach under controlled environmental conditions to ensure analytical accuracy and reliability. The scope of the integrity assessment comprised the following methodologies:

1. Visual Inspection: Conducted to examine the macroscopic condition of both the internal (waterside) and external (fireside) components.

2. Dimensional Analysis: Involving material thickness and outer diameter measurements utilizing ultrasonic thickness indicators to evaluate the degree of wall thinning due to corrosion, erosion, or creep.
3. Non-Destructive Testing (NDT): Employing Dye Penetrant Testing (DPT) to identify surface discontinuities and Ultrasonic Testing (UT Flaw Detector) to assess weld joint integrity.
4. Mechanical Evaluation: Utilizing portable hardness testing to detect mechanical degradation and estimate the material's current tensile strength.
5. Microstructural Analysis: Applying in-situ metallography (replica technique) to assess metallurgical degradation, such as thermal aging or structural changes.
6. Water Quality Assessment: Laboratory testing of boiler feedwater samples to evaluate chemical compliance and corrosion potential.

The collected data were subsequently analyzed to determine the active degradation mechanisms, evaluate the current physical condition of the pressure parts, and calculate the remaining safe operational life of the boiler [5], [11].

3. RESULTS AND DISCUSSION

The integrity assessment and testing of the combination boiler were conducted over a seven-day period, focusing on primary pressure-retaining components: the shell drum, tube sheets, fire tubes, water tubes, and headers.

3.1. Visual Inspection

Visual examinations of both internal and external components indicated that the boiler is generally well-maintained. The waterside of the wall tubes and the internal surface of the shell drum were free from significant corrosion, validating the effectiveness of the current boiler feedwater treatment. However, several critical anomalies requiring corrective action were identified:

- Furnace and Refractory: A significant gap was observed between the furnace door and the adjacent wall, presenting a critical risk of heat leakage. Furthermore, extensive cracking and peeling were documented across the refractory lining, compromising the structural insulation.

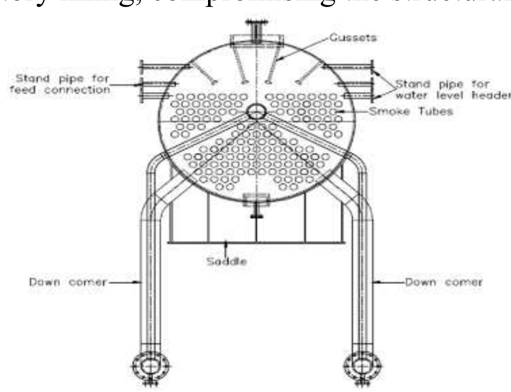


Figure 1 Combi boiler construction layout

Figure 2 Boiler Shell

(A) (B)

Figure 3(A). Visual inspection of the water tank in Compartment 1 (West) and (B) Visual inspection of the water tank in Compartment 1 (East) - Furnace

- Tube Conditions: An anomaly in the tube configuration was discovered in Compartments 1 and 2, where one tube was intentionally cut and blocked. Fireside surfaces of the water and fire tubes were coated with extensive layers of coal combustion residue. Minor abrasion and corrosion (±0.5 mm) were observed on the water tubes over 14 years of service.

(A) (B)

Figure 4(A). Visual inspection of Wall Tubes in the furnace and (B) Visual inspection of Header 1 (West)

(A) (B)

Figure 5 (A). East side of the Pipe Plate and (B) The West side of the pipe plate is filled with crust from combustion residue.

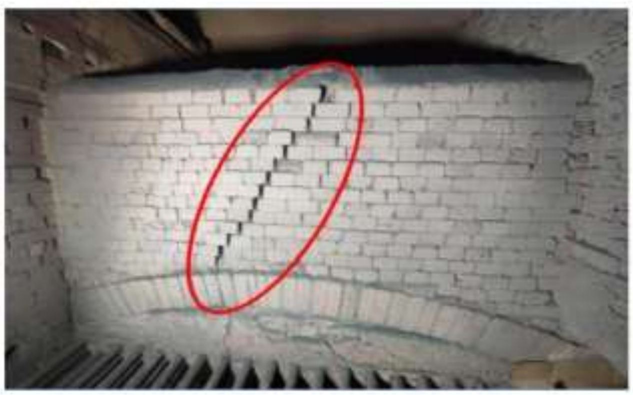


Figure 6 Cracks in the wall in the furnace area in the partition area.

(A) (B)

Figure 7 (A). Fuel Line Plate Compartment (Coal) 1 (North) (B) Fuel Line Plate Compartment (Coal) 2 (North)

- Header and Nozzle Integrity: Severe external corrosion was detected on the header. Deformation was observed on the nozzle plate at the fuel feed port (North side), likely attributed to localized overheating.
- Structural Welds: The supporting structure and nozzle welds were found to be in optimal condition.

3.2. Thickness Measurement and MAWP Assessment

Ultrasonic Thickness Indicator measurements were performed to evaluate wall thinning against the Maximum Allowable Working Pressure (MAWP) requirements stipulated by ASME BPVC Section VIII, Division 1. The data confirms that all primary components maintain structural thicknesses well above the minimum permissible limits.

Table 2 Results of Water Tube thickness measurements

(Dimensi Nominal: Ø 63.5 mm X 3.66 mm).

No.	PARTS	Tube No.	Thickness Point of Measurement (mm)				Thickness (mm)	
			0°	90°	180°	270°	Minimum	Nominal
Water Tube/ Pipa Air (Compartement 1)								
1		1	-	3.31	3.25	-		3.66
2		2	-	3.61	3.37	3.69		3.66
3	*Layer 1*	3	-	3.55	3.17	3.25		3.66
4		8	-	3.48	3.39	3.46		3.66
5		15	-	3.57	3.44	3.66		3.66
6		1	3.49	3.37	-	-	**3.07**	3.66
7		2	-	-	-	-		3.66
8	*Layer 4*	3	3.21	3.17	-	3.07		3.66
9		12	3.63	3.48	-	3.34		3.66
10		17	3.26	3.45	-	3.64		3.66
Water Tube/ Pipa Air (Compartement 2)								
11		1	-	3,37	3.57	-		3.66
12		2	-	3,45	3.44	3.55		3.66
13	*Layer 1*	3	-	3,37	3.48	3.61		3.66
14		7	-	3,58	3.62	3.48		3.66
15		16	-	3,55	3.43	-		3.66
16		1	3.40	3.45	-	-	**3.33**	3.66
17		2	-	-	-	-		3.66
18	*Layer 4*	3	3.33	3.64	-	3.52		3.66
19		14	3.46	3.44	-	3.39		3.66
20		19	3.60	3.66	-	3.59		3.66

Table 3Results of measuring the thickness of the Fire Tube

No.	PARTS	Tube No.	Thickness Point of Measurement (mm)				Thickness (mm)	
			0°	90°	180°	270°	Minimum	Nominal
Fire Tube								
21	*FIRE TUBE / PIPA API*	1	4.67	4.62	-	4.48	4.21	4.50
22		3	4.58	4.51	-	4.65		4.50
23		5	4.60	4.48	-	4.55		4.50
24		7	4.42	4.65	-	4.42		4.50
25		9	4.51	4.55	-	4.32		4.50
26		11	4.46	4.53	-	4.35		4.50
27		13	4.37	4.67	-	4.29		4.50
28		15	4.56	4.39	-	4.33		4.50
29		17	4.47	4.49	-	4.21		4.50
30		19	4.68	4.65	-	4.37		4.50

Table 4Results of measuring the thickness of tube sheet and header

(Dimensi Nominal: Ø 3100 mm X 25 mm).

No.	PARTS	Spot No.	Thickness Point of Measurement (mm)				Thickness (mm)	
			0°	90°	180°	270°	Minimum	Nominal
Shell								
31	*Shell 1*	1	25.21	25.41	-	25.66	25.21	25.00
32		2	25.57	25.47	-	25.43		25.00
33	Shell 2	3	25.59	25.38	-	25.35		25.00
34		4	25.74	25.62	-	25.44		25.00
Tube sheet (timur)								
35	Tube Sheet (Timur)	A	25.41	25.33	25.08	25.27	25.00	25.00
36		B	25.32	25.00	25.31	25.28		25.00
37		C	25.34	25.22	25.18	25.02		25.00
Header 1								
38	Header 1	A	12.56	12.35	12.28	12.46	12.28	12.7
39		B	12.67	12.25	12.34	12.51		12.7
40		C	12.38	12.45	12.41	12.33		12.7

3.3. Non-Destructive Testing (NDT)

Dye Penetrant Testing (DPT) applied to the pipe-to-shell sheet, pipe-to-tube sheet, and drum nozzles revealed an absolute absence of surface defects, cracking, or porosity. Similarly, Ultrasonic Flaw Detector testing on the critical "T" joint welds of the steam-side shell confirmed high-quality workmanship with no detectable sub-surface flaws.

(A) (B)

Figure 8 (A). Dye Penetration Test on Tube Sheet (East) and (B) Dye Penetration Test on Nozzle

Figure 9 Ultrasonic Test on steam side shell "T" connection

3.4. Mechanical and Microstructural Evaluation

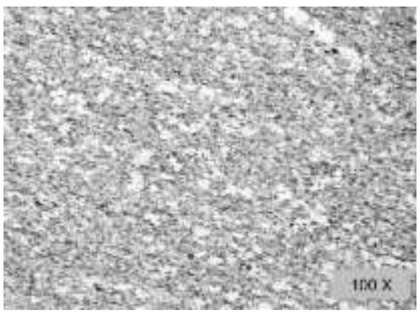
Portable hardness testing was utilized to evaluate mechanical degradation. The findings are summarized in Table 5. The hardness assessment reveals that the primary structural components exhibit mechanical properties consistent with their design specifications.

Table 5 Results of hardness testing materials

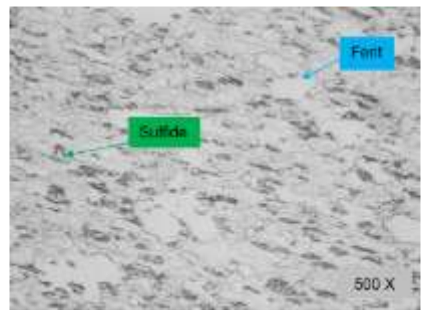
No	Component Name / Test Location	Hardness Value (HB)				Estimated Tensile Strength Value		HB (Certificate)
		Point 1	Point 2	Point 3	Average	(kgf/mm2)	Mpa	
1	Shell	147	149	143	151	52,8	518.28	49.21
2		163	145	140				
3		151	156	165				
4	pipe plate	144	154	149	152	53.2	521.71	49.21
5		162	157	148				
6		155	153	146				
7	Fire Tube	81	86	84	87	30.4	298.12	32.63
8		91	88	83				
9		86	89	94				
10	Water Tube	95	92	101	97	33.8	331.46	32.63
11		96	98	102				
12		97	93	97				
13	Header 1	103	116	105	105	36.9	361.86	42.18
14		98	104	107				
15		102	108	106				

Following the mechanical evaluation, In-Situ Metallography (replica technique) was performed to characterize the microstructural integrity of the boiler components. Analysis confirms that the materials exhibit a normal ferritic and pearlitic microstructure with no evidence of critical degradation.

Figure 10 Hardness testing on Water Tube compartment 1

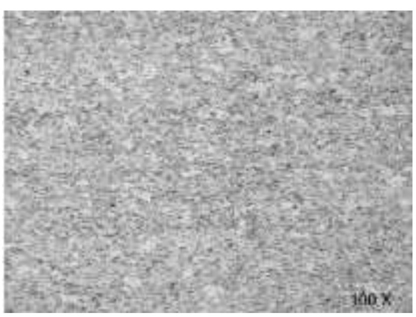


(A)

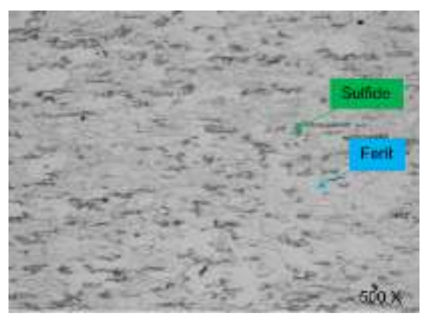


(B)

Figure 11 In-situ metallography of Water Tube Compartment 2 (East), Tube No. 2 Layer 1 (Material: BS 3059 Part 1:1987 Gr.320 ERW). (A) Microstructure at 100X magnification showing a normal ferritic matrix with sulfide impurities (Hardness: 97 HB; Etchant: 8% Nita

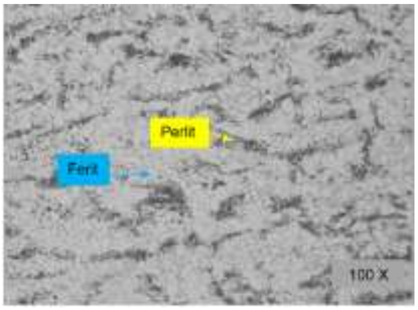


(A)

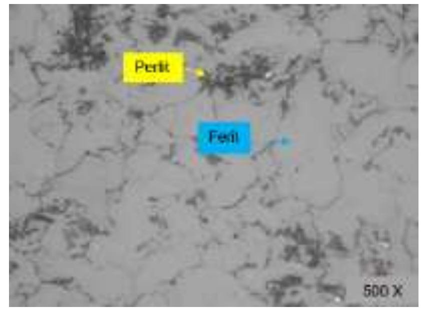


(B)

Figure 12 In-situ metallography of Water Tube Compartment 2 (West), Tube No. 2 Layer 1 (Material: BS 3059 Part 1:1987 Gr.320 ERW). (A) Microstructure at 100X magnification indicating a normal condition with a ferritic matrix (white) and sulfide impurities (black)

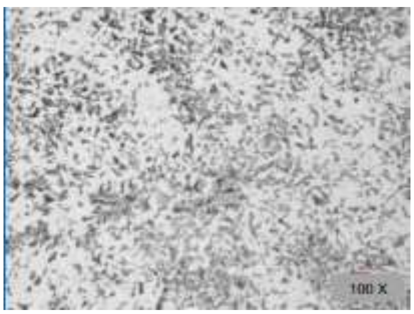


(A)

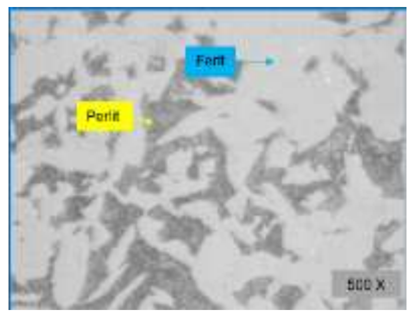


(B)

Figure 13 In-situ metallography of Header (Material: SA 106 Gr.B). (A) Microstructure at 100X magnification indicating a normal condition with ferrite (white) and spheroidized pearlite (black) (Hardness: 108 HB; Etchant: 8% Nital). (B) Enlarged view at 500X magni

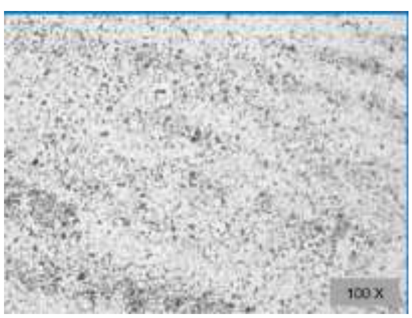


(A)

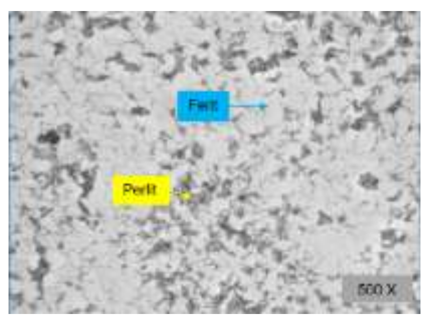


(B)

Figure 14 In-situ metallography of Tube Plate/Tube Sheet (Material: SA 515 Gr.70). (A) Microstructure at 100X magnification indicating a normal condition with coarse-grained ferrite (white) and pearlite (black) (Hardness: 157 HB; Etchant: 8% Nital). (B) Enlarged

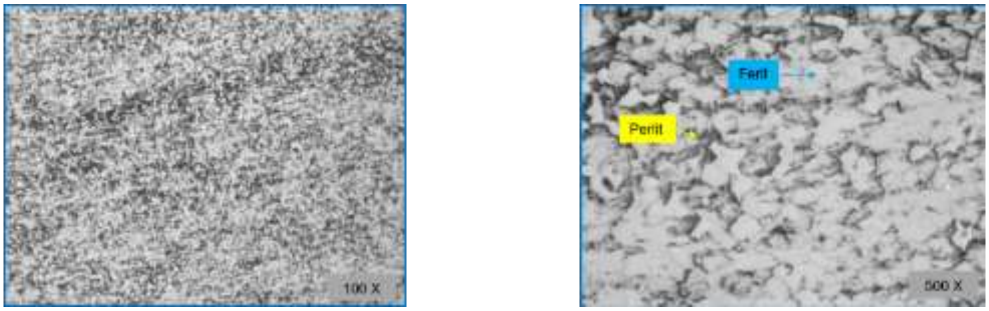


(A)



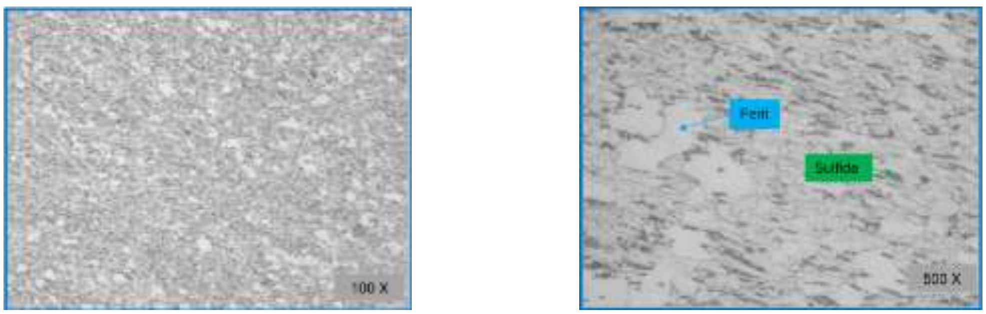
(B)

Figure 15 In-situ metallography of Shell Drum (Material: SA 515 Gr.70). (A) Microstructure at 100X magnification indicating a normal condition consisting of ferrite (white) and pearlite (black) (Hardness: 151 HB; Etchant: 8% Nital). (B) Enlarged view at 500X magn



(A) (B)

Figure 16 In-situ metallography of Fire Tube (Material: BS 3059 Part 1:1987 Gr.320 ERW). (A) Microstructure at 100X magnification indicating a normal condition with ferrite (white) and pearlite (black) (Hardness: 91 HB; Etchant: 8% Nital). (B) Enlarged view at 50



(A) (B)

Figure 17 In-situ metallography of Water Tube No. 3 Layer 4 (Material: BS 3059 Part 1:1987 Gr.320 ERW). (A) Microstructure at 100X magnification indicating a normal condition with ferrite (white) and sulfide impurities (black) (Hardness: 102 HB; Etchant: 8% Nital

3.5. Water Quality and Combustion Residue

Chemical analysis of the deposits and feedwater using EDS and XRF indicates that the crust on the fireside of the tubes is primarily composed of corrosive elements (Fe, Si, S compounds). The boiler feedwater laboratory analysis confirms that water quality is currently maintained within safe operational limits.

Table 6 Quality feed water table

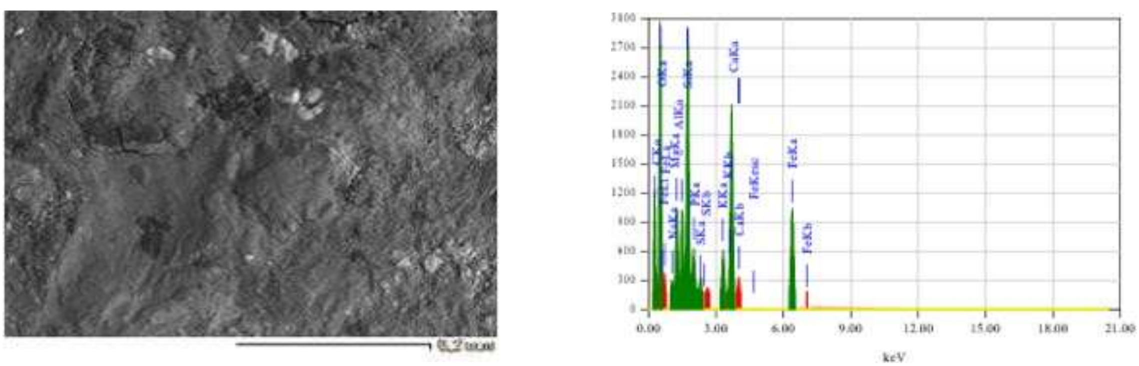
Parameter	Unit	Limit Controlling
Ph	Unit	10.5 – 11.5
Conductivity	Mmhos.cm	5000, max
TDS	Ppm	3500, max
P-Alkalinity	Ppm	-
M-Alkalinity	Ppm	800, max
O-Alkalinity	Ppm	2, 5 x Si O2. Min
Hardness	Ppm	-
Silica	Ppm	150, max
Iron	Ppm	2, max

Phosphate Residual	Ppm	20 – 50
Sulfite Residual	Ppm	20 – 50
pH Condensate	Unit	8.0 – 9.0

Table 7 Composition of XRF water tube crust

FE (%)	Zn (%)	Al (%)	Si (%)	P (%)	S (%)	Cl (%)	Na (%)	Mg (%)
38.7	0.011	0.341	24.823	0.468	0.456	0.342	4.634	4.909
K (%)	Ca (%)	Sc (%)	Ti (%)	Cr (%)	Mn (%)	Ni (%)	Cu (%)	Sr (%)
0.246	24.319	0.067	0.027	0.099	0.251	0.019	0.076	0.177

Sample ID: Water Tube Crust Experiment name: SMART-Element Measurement finished: 26/11/2020



(A) (B)

Figure 18 Results of SEM-EDS crust on the surface boiler tubes at a fireside. (A) SEM results on the surface of the tubes on the fireside; (B) EDS results in the crust on the surface of the tubes on the fireside

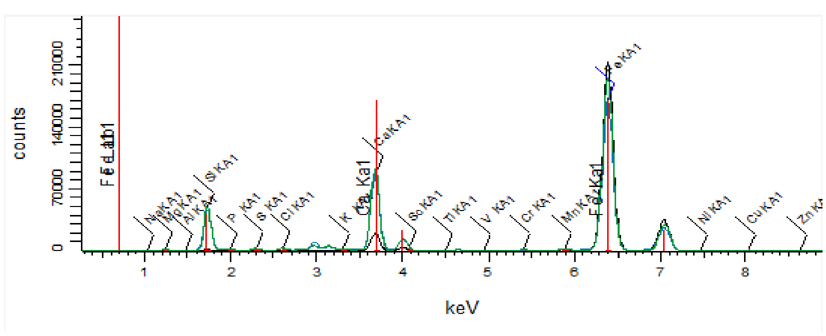


Figure 19 XRF results on the surface of the crust in the water tube boiler

3.6. Boiler MAWP Calculation

Calculations performed according to ASME BPVC Section VIII, Division 1, confirm that all components are categorized as "LAIK" (Acceptable) as the actual thickness remains greater than the required minimum thickness (T_{req}) for the design pressure of 19 kg/cm².

(ASME BPVC Section VIII, Division 1)

Data:

P = 19 Kg/cm2 (269,8 Psi)

D = 3100 mm = 122, 047 inch

S = 37700 Psi

E = 1

CA = 2.997 mm = 0,118 inch

R = 1550 mm = 61,0236 inch

Tebal Pelat badan Original = 25 mm

Shell

$$\text{T. Min Req} = \frac{P.R}{S.E - 0.6.P} + CA$$

$$= \frac{269{,}8 \quad X \quad 61{,}02362}{37700 \quad X \quad 1 \quad - \quad 0{,}6 \quad X \quad 269{,}8} + 0{,}118$$

$$= \frac{16464{,}17323}{37538{,}12} + 0{,}118$$

$$= \mathbf{0{,}56} \ \textbf{Inchi} = \mathbf{14{,}14} \ \textbf{mm}$$

$$\text{T.Min req} = \mathbf{14{,}14} \ \text{mm}$$

$$\text{T. min. Actual} > \text{T. Min. Req}$$

$$\mathbf{25{,}21 \ mm > 14{,}14 \ mm}$$

WATER TUBE

$$\text{T.Min req} = \frac{P.D}{25 + P} + 0.005\,D$$

$$= \frac{269{,}8 \quad X \quad 2{,}5}{26796 \quad + \quad 269{,}8} + 0{,}005 \quad X \quad 2{,}5$$

$$= \frac{674{,}5}{27066} + 0{,}005 \quad X \quad 2{,}5$$

$$= \mathbf{0{,}07} \ \textbf{Inch} = \mathbf{1{,}90} \ \textbf{mm}$$

$$\text{T.Min req} = \mathbf{1{,}90} \ \text{mm}$$

$$\text{T. min. Actual} > \text{T. Min. Req}$$

$$\mathbf{5{,}07 \ mm > 1{,}90 \ mm}$$

FIRE TUBE

$$\text{T.Min req} = \frac{P.D}{25 + P} + 0.005\,D$$

$$= \frac{269{,}8 \quad X \quad 3{,}19}{26796 \quad + \quad 269{,}8} + 0{,}005 \quad X \quad 3{,}19$$

$$= \frac{674{,}5}{27066} + 0{,}005 \quad X \quad 3{,}2$$

$$= \mathbf{0{,}12} \ \textbf{Inch} = \mathbf{2{,}97} \ \textbf{mm}$$

$$\text{T.Min req} = \mathbf{2{,}97} \ \text{mm}$$

$$\text{T. min. Actual} > \text{T. Min. Req}$$

$$\mathbf{4{,}21 \ mm > 2{,}97 \ mm}$$

3.7. Calculation of Remaining Life

Based on the corrosion rates derived from thickness measurements, the remaining service life is projected as follows:

- Water Tubes: 13 years.
- Fire Tubes: 14.09 years.
- Shell Drum: 13 years.

FIRE TUBE

$$\frac{T\ act - T\ Req}{\text{Life Time}}$$

$$= \frac{3{,}07 - 1{,}90}{14}$$

$$= 0{,}09\ \text{mm / year}$$

$$\text{Remaining Life} = \frac{3.07 - 1.90}{0{,}09} = \textbf{13 Year}$$

WATER TUBE

$$\frac{T\ act - T\ Req}{\text{Life Time}}$$

$$= \frac{3{,}07 - 1{,}90}{14}$$

$$= 0{,}083\ \text{mm / year}$$

$$\text{Remaining Life} = \frac{3.07 - 1.90}{0{,}083} = \textbf{14,09 Year}$$

SHELL

$$\frac{T\ act - T\ Req}{\text{Life Time (14)}}$$

$$= \frac{25{,}21 - 14{,}14}{14}$$

$$= 0{,}85\ \text{mm / year}$$

$$\text{Remaining Life} = \frac{25.21 - 14.14}{0{,}85} = \textbf{13 Year}$$

4. CONCLUSION

The comprehensive performance and condition assessment of the 20 t/h combination boiler confirms that its fundamental pressure-retaining components including the shell drum, tube sheets, water tubes, fire tubes, and headers remain in robust operational condition. All components satisfy MAWP requirements, while Non-Destructive Testing (NDT), hardness assessments, and in-situ metallography verify the absence of critical weld defects, mechanical deterioration, or microstructural degradation. While the internal waterside integrity is well-preserved due to excellent feedwater quality, the boiler's optimal performance is currently compromised by external factors. Immediate maintenance interventions are strongly recommended to address severe external header corrosion caused by compromised thermal insulation, extensive refractory wall cracking, and heavy combustion residue accumulation on the fireside tubes. Furthermore, localized overheating has deformed the fuel line nozzle plate. It is imperative to conduct comprehensive fireside cleaning, restore insulation and refractory integrity, upgrade the fuel line compartment with high-temperature resistant materials, and adhere to a strict five-year periodic assessment interval to ensure sustained operational reliability and industrial safety.

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