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ENHANCING HEAT RECOVERY STEAM GENERATOR INTEGRITY: A FITNESS-FOR-SERVICE APPROACH USING ASME FFS-1/API 579 FOR REMAINING LIFE ASSESSMENT

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ABSTRACT
Assessment of the remaining life of a Heat Recovery Steam Generator (HRSG) that has been in operation for 24 years is crucial to ensure operational reliability, with the ASME FFS-1/API 579 standard as the primary reference. Analyze the material condition and assess the remaining life of HRSG Unit 2 based on the ASME FFS-1/API 579 standard. Data were collected through Non-Destructive Testing (UTM, LPT, MPT, UFD), visual inspection, borescope examination, and in-situ metallurgical tests to obtain microstructure and hardness profiles. The analysis was conducted by comparing inspection results with design specifications, evaluating microstructural changes, assessing hardness degradation, calculating remaining wall thickness, and performing fitness-for-service assessment according to ASME FFS-1/API 579. No significant cracks were found, but there was material thinning of up to 16.6% in some areas. The material condition is still good and meets design standards. The estimated remaining operational life is 10–15 years. HRSG Unit 2 is declared safe and reliable to operate. The ASME-based assessment method has been proven effective for estimating the remaining life and supporting a risk-based maintenance strategy.

Keywords: ASME; heat recovery steam generator; remaining life assessmen

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INTRODUCTION
Power generation plays a crucial role in supporting activities in various sectors, particularly oil and gas exploration. Combined-cycle power plants, a combination of steam and gas power plants, have high efficiency, generating additional energy by utilizing residual heat from gas turbines to produce steam, which is then used in steam turbines (Mansouri et al., 2012). One component of a combined-cycle power generation system, the Heat Recovery Steam Generator (HRSG), plays a crucial role in utilizing residual heat from the turbine to produce high-pressure steam, which can then be used to generate additional electricity or support other industrial processes (Arpit & Das., 2023).

Heat Recovery Steam Generators (HRSGs) are crucial components in combined-cycle power plants (Norouzi et al., 2019). It has been reported that using HRSGs for steam production can achieve system efficiencies of up to 75–85% (V. Ganapathy, 2017). HRSGs absorb heat from exhaust gases through water flowing through pipes in each unit. Several stages, such as an economizer to heat the water, an evaporator to convert the water to steam, and a superheater to increase the steam temperature to a higher temperature suitable for driving the steam turbine (Jouhara et al., 2018). Waste heat recovery (WHR) refers to methods that capture and recycle heat from exhaust gases, flue gas, or other waste-heat streams, converting it into useful energy to improve overall system efficiency. Recent reviews show that WHR technologies are increasingly adopted across industrial processes to reduce fuel consumption and energy waste (Ononogbo et al., 2023). The steam generates additional electrical energy, increasing the overall efficiency of the plant. After the heat is absorbed, the flue gas, at a much lower temperature, is released into the atmosphere. HRSGs in combined cycle systems are increasingly used because they can maximize energy resource utilization, reduce emissions, and reduce operational costs (Balku., 2017).

Corrosion, fouling, and thermal fatigue pose serious threats that can degrade the performance and design life of HRSGs (Dooley, 2024). Several standard approaches are used in the industry, each with its own advantages and limitations. Two common methods are corrosion rate calculations and stress rupture analysis. Corrosion rate calculations are one of the most basic approaches to estimating the remaining life of components experiencing material thinning. This data is typically obtained from periodic inspections using techniques such as Ultrasonic Thickness Measurement (UTM), as was done for the HRSG in this document. By knowing the average thinning rate, the remaining life can be estimated by projecting when the component thickness will reach the minimum required thickness. Its limitations include assuming a linear rate (assuming that the corrosion rate is constant over time, even though operating conditions can change and accelerate or slow the corrosion rate), not accounting for localized corrosion, and being ineffective for non-corrosive damage (this method is not suitable for assessing damage due to creep, fatigue, or cracking).

Furthermore, the stress rupture analysis method is used to assess components operating at high temperatures, where the primary damage mechanism is creep (Wahyudi, D., & Iswanto, 2023). However, this method has limitations, including its destructive nature, cost and time-consuming nature, and limited sampling. No single method can provide a complete picture of the effective remaining life assessment of HRSGs. Each method has its own advantages and limitations (Danang Priambada, 2025). Remaining life assessment (RLA) of HRSGs is essential to ensure operational reliability and safety, thus avoiding damage that can lead to costly downtime and safety risks (Smith, J., & Brown, 2020).

ASME standards, such as the Boiler and Pressure Vessel Code (BPVC) and API 579-1/ASME FFS-1, provide guidance on design measurements, mandatory periodic inspections, and component integrity assessments based on in-depth analysis. The use of the ASME approach is considered appropriate because this method has been proven effective in identifying potential forms of damage including cracking, corrosion, and thermal degradation allowing corrective actions to be implemented early before they compromise system safety and reliability (Utomo et al., 2024). PT. X, a power and steam power generation company that uses HRSG components, has operated safely and reliably for 24 years after the commissioning of CT #2 in 2000. Assessment of the remaining life of HRSG is an important aspect in ensuring operational reliability and safety. One way to measure the remaining life of HRSG is by using the standards of the American Society of Mechanical Engineers (ASME). Overall, there is no single method that can provide a complete picture of the remaining life assessment of HRSG. The most effective approach is to combine several methods to obtain more accurate and comprehensive results. In addition, it is very important to consider factors such as specific operating conditions, maintenance history, and material characteristics in assessing the remaining life of HRSG.

Therefore, this study aims to analyze the material condition, evaluate the degradation mechanisms, and estimate the remaining operational life of HRSG Unit 2 using ASME FFS-1/API 579 standards through a combination of Non-Destructive Testing, in-situ metallurgical examination, and hardness measurement.

METHOD

This type of research is a descriptive study with a quantitative approach that aims to describe and evaluate the condition of HRSG (Heat Recovery Steam Generator) materials and assess the remaining life of HRSG using in situ metallurgy methods according to ASME standard guidelines (Zhao, Y., Guo, W., dan Zhang, 2022). In this study, researchers not only measure or calculate the remaining life or hardness of the material, but also describe and analyze these findings to draw broader conclusions about the performance and condition of HRSG (Feng, Z., Xie, Z., dan Li, 2020). The quantitative approach of this study is to measure certain values, such as hardness test results, grain size in the microstructure, and to calculate the estimated remaining life of HRSG based on ASME guidelines (Nashit & M, 2019). PT. X is an electricity generation company that supplies the operational needs of oil exploration and is able to produce electricity. PT. X is an electricity and steam generation company that supplies the operational needs of oil exploration and produces electricity by 70% or around 280 MW in the Y system which also produces steam with a 70% contribution to exploration needs in Y or 46,850 tons / day. PT. Products The power generated by PT X is generated by 3 x 100 MW Combustion Turbine (CT) units, each equipped with Heat Recovery Steam Generators (HRSG) capable of producing a total of 350 MBCWEPD (Mega Barrel of Cool Water Equivalent Per Day, equivalent to 2,318,565 liters/hour) of steam. PT X, as an electricity and steam generation company that uses HRSG components, has operated safely and reliably for 24 years after the commissioning of CT #2 in 2000.

Available Non-Destructive Testing (NDT) inspection data includes visual data and measurement instruments such as ultrasonics, pressure testing, or radiography. JSA forms for Liquid Penetrant Test (LPT) and Magnetic Particle Test (MPT). Ultrasonic Thickness Measurement (UTM) testing procedures. Material Sampling: HRSG material sampling in situ (on-site) for further laboratory testing. In Situ Metallurgical Testing: Microstructural testing (such as microscopy) and material hardness testing (e.g., Brinell, Rockwell, or Vickers tests) are performed to directly evaluate material properties. Microstructural analysis uses an optical microscope or electron microscope to study the internal structure of the material. Hardness testing uses hardness test methods to evaluate the physical properties of the material. ASME FFS-1/API 579 Standard: Uses ASME-based HRSG remaining life analysis guidelines (Level 2 and Level 3) to evaluate damage and estimate the remaining life of equipment.

RESULT

Non-Destructive Testing (NDT)

Table 1.
Conclusion of NDT HRSG test results Module 3 dan Duct Burner

NDT Test	Inspection Findings
Modul 3	
Liquid Penetrant Test (LPT)	Most areas, including the Tube Row and Weld Header, showed no cracks. Pores were observed in the welds on the Weld Header Elevation 2 (nearside), although they did not develop into cracks.
Magnetic Particle Test (MPT)	All test points on the tubes, jumpers, and headers were in good condition. No cracks were found in any of the components tested.
Ultrasonic Thickness Measurement (UTM)	Thinning was observed evenly, with values ranging from 3% to 10%. Several areas experienced significant thinning: Row 19 Tube 3: 14.3%, Rows 3–4 Tube 4: 12.9%, and Inlet Circuit Tube 2: 12.5%.
Ultrasonic *Flaw Detection* (UFD)	All components in Module 3 HRSG Unit 2 performed Acceptable. There were no indications of failure; all tested components were acceptable.
Duct Burner 1	
Ultrasonic Thickness Measurement (UTM)	No significant thinning occurred, and the components were deemed safe for continued operation.
Duct Burner 2	
Ultrasonic Thickness Measurement (UTM)	Some elements showed quite severe thinning, for example Burner Elements 2 and 10 with a thinning ratio reaching 15.8%–16.6%.

The LPT test results for Module 3 showed similar conditions, with no cracks found in most of the Tube Row areas (Accepted). However, the Weld Header Elevation 2 (nearside) indicated pores in the weld, although they did not develop into cracks. The Magnetic Particle Test results for Module 3 HRSG Unit 2 indicated all test points were in good condition. No cracks were found on the tubes,

jumpers, or headers, so all components were declared Accepted in accordance with the ASME BPVC standard.
The UTM testing for Module 3 indicated a more even distribution of thinning, with values ranging from 3% to 10%. Several areas with significant thinning were identified, particularly in Row 19 Tube 3 (14.3%) and Rows 3–4 Tube 4 (12.9%). Meanwhile, some tubes, such as Inlet Circuit Tube 2, also showed thinning of up to 12.5%. Although most of the tubes are still in acceptable condition (thinning < 10%), this finding indicates that Module 3 is starting to experience thickness degradation that must be monitored periodically, especially around the return bend and the lower horizontal tube.

In Duct Burner 1, the test results showed relatively good condition. The burner element thickness was slightly above the design value with a negative ratio (-1% to -4.5%). This indicates that no significant thinning has occurred, so the component can be declared safe for continued operation. Different results were obtained in Duct Burner 2. Several elements showed quite severe thinning, for example Burner Elements 2 and 10 with a thinning ratio reaching 15.8%–16.6%. This value is close to the tolerance limit and has the potential to affect the operational life of the components. Therefore, this area is recommended to be entered into the observation category with further inspection in the short term. UFD tests on all components in Module 3 HRSG Unit 2 showed Acceptable results. Showing no indication of failure, all components tested are acceptable.

Table 2.
In-Situ Metallography Test among Modul 3 (Economizer) dan Duct Burner

Area	Material	Magnification	Hardness (HV) Avg ± Std.Dev	Replicas Number	Degradation Level (ERA)
Modul 3					
Farside Return Bend Row 13–14 Tube 6	SA 234 WPC	200×–500×	177.8 ± 2.9	R3.1	D
Farside Horizontal Row 13 Tube 6	SA 106 Gr.C	200×–500×	168.2 ± 2.9	R3.2	C
Nearside Return Bend Row 4–5 Tube 6–5	SA 234 WPC	200×–500×	176.0 ± 1.6	R3.3	C
Nearside Horizontal Row 5 Tube 5	SA 106 Gr.C	200×–500×	157.2 ± 4.1	R3.4	C
Inlet Tube 2	SA 106 Gr.C	200×–500×	192.8 ± 2.6	R3.5	C
Farside Return Bend Row 13–14 Tube 6	SA 234 WPC	200×–500×	177.8 ± 2.9	R3.1	D
Duct Burner					
Duct Burner 1 Element 5 (Nearside)	SS 310	100×–200×	236.2 ± 2.4	R4.1	ISPESL/Neubauer. 1
Duct Burner 1 Element 8 (Nearside)	SS 310	100×–200×	261.4 ± 3.2	R4.2	ISPESL/Neubauer. 2
Duct Burner 2 Element 2 (Nearside)	SS 310	100×–200×	174.2 ± 3.3	R4.3	ISPESL/Neubauer. 3
Duct Burner 2 Element 8 (Nearside)	SS 310	100×–200×	183.8 ± 1.9	R4.4	ISPESL/Neubauer. 3

Testing in Module 3 showed varying results. Most points were at level C degradation, but Farside Return Bend Row 13–14 Tube 6 (R3.1) showed level D degradation, with a ferrite–pearlite microstructure that experienced significant spheroidization. Inspection results on the burner duct showed more varied conditions than the evaporator and economizer. Some points still showed level 1–2 damage (relatively safe), but there were also results of level 3 damage indicating the presence of creep voids at the grain boundaries.

Table 3.
Hardness Measurement Results of Module 3 (Economizer) and Burner Hardness Measurement Results (SS 310)

Part Identification	Measurement (HV)					Average	Std. Dev	Material Spec.
	1	2	3	4	5			
Modul 3								
Farside Return Bend Row 13–14 Tube 6	181	176	178	180	174	177,8	2,9	SA 234 WPC
Farside Horizontal Row 13 Tube 6	173	167	166	169	166	168,2	2,9	SA 106 Gr.C
Nearside Return Bend Row 4–5 Tube 6–5	174	178	175	177	176	176,0	1,6	SA 234 WPC
Nearside Horizontal Row 5 Tube 5	155	151	159	161	160	157,2	4,1	SA 106 Gr.C
Inlet Tube 2	175	175	173	176	177	175,2	1,3	SA 106 Gr.C
Duct Burner								
Duct Burner 1 Element 5	233	238	235	236	239	236,2	2,4	SS 310
Duct Burner 1 Element 8	263	266	261	258	259	261,4	3,2	SS 310
Duct Burner 2 Element 2	176	179	172	173	171	174,2	3,3	SS 310
Duct Burner 2 Element 8	184	183	185	186	181	183,8	1,9	SS 310

Hardness measurements in Module 3 showed lower results, but still within the typical material limits. Farside Return Bend Row 13–14 Tube 6 (SA 234 WPC) recorded 177.8 HV with a deviation of 2.9, still in accordance with the standard. Farside Horizontal Row 13 Tube 6 (SA 106 Gr.C) had an average value of 168.2 HV, approaching the upper limit of the typical material. In the Nearside Return Bend area Row 4–5 Tube 6–5 (SA 234 WPC) obtained an average of 176.0 HV with a deviation of 1.6, indicating good material stability. Nearside Horizontal Row 5 Tube 5 recorded lower, namely 157.2 HV with a deviation of 4.1, approaching the lower limit of the standard. Meanwhile, Inlet Tube 2 showed an average value of 175.2 HV with a deviation of 1.3, still acceptable. Measurement results on burners made of SS 310 show quite wide variations in values. Duct Burner 1 Element 5 recorded 236.2 HV with a deviation of 2.4, while Duct Burner 1 Element 8 reached a high value of 261.4 HV (deviation of 3.2), which is at the upper limit of the SS 310 material standard (160–270 HV). In contrast, Duct Burner 2 Element 2 had a lower average of 174.2 HV with a deviation of 3.3, and Duct Burner 2 Element 8 of 183.8 HV with a deviation of 1.9, both near the lower limit of the typical range. These differences in values indicate variations in the material conditions of the burner, which can be affected by non-uniform heat distribution.

Table 4.
Remaining Life Assessment (RLA) Modul 3 dan Duct Burner

Part/Item Name	OD (mm)	Thickness Measured (mm)	Thickness Design (mm)	Material	Allowable Stress (MPa)	Operating Temp. (°C)	Operating Pressure (MPa)	Operating Hours (Hrs)	Mwt (mm)	Remaining life	Mwt 70% design (mm)	Remaining life
Modul 3												
Farside Inlet Circuit *Tube* 1	114,30	8,18	8,56	SA 106 Gr. C	119	290	9,49	210240	4,95	>200K	5,99	>200K
Farside Inlet Circuit *Tube* 2	114,30	7,49	8,56	SA 106 Gr. C	119	290	9,49	210240	4,95	>200K	5,99	>200K
Farside Inlet Circuit *Tube* 3	114,30	8,25	8,56	SA 106 Gr. C	119	290	9,49	210240	4,95	>200K	5,99	>200K
Farside Inlet Circuit *Tube* 4	114,30	8,25	8,56	SA 106 Gr. C	119	290	9,49	210240	4,95	>200K	5,99	>200K
Farside Inlet Circuit *Tube* 5	114,30	8,06	8,56	SA 106 Gr. C	119	290	9,49	210240	4,95	>200K	5,99	>200K
Farside Inlet Circuit *Tube* 6	114,30	8,12	8,56	SA 106 Gr. C	119	290	9,49	210240	4,95	>200K	5,99	>200K
Farside Inlet Circuit *Tube* 7	114,30	7,97	8,56	SA 106 Gr. C	119	290	9,49	210240	4,95	>200K	5,99	>200K
Farside Inlet Circuit *Tube* 8	114,30	7,99	8,56	SA 106 Gr. C	119	290	9,49	210240	4,95	>200K	5,99	>200K
Farside Inlet Circuit *Tube* 9	114,30	8,05	8,56	SA 106 Gr. C	119	290	9,49	210240	4,95	>200K	5,99	>200K
Farside Inlet Circuit *Tube* 10	114,30	8,01	8,56	SA 106 Gr. C	119	290	9,49	210240	4,95	>200K	5,99	>200K
Farside Inlet Circuit *Tube* 11	114,30	8,14	8,56	SA 106 Gr. C	119	290	9,49	210240	4,95	>200K	5,99	>200K
Farside Inlet Circuit *Tube* 12	114,30	7,96	8,56	SA 106 Gr. C	119	290	9,49	210240	4,95	>200K	5,99	>200K
Farside Header Weld Elevasi 2	219,10	20,29	22,23	SA 106 Gr. C	119	290	9,49	210240	9,50	>200K	15,56	>200K
Farside Return Bend *Row* 11 -12 *Tube* 4	114,30	7,70	8,56	SA 234 WPC	114	290	9,49	210240	5,14	>200K	5,99	>200K
Farside Return Bend *Row* 15 -16 *Tube* 5	114,30	8,03	8,56	SA 234 WPC	114	290	9,49	210240	5,14	>200K	5,99	>200K
Farside Return Bend *Row* 3 -4 *Tube* 4	114,30	7,46	8,56	SA 234 WPC	114	290	9,49	210240	5,14	>200K	5,99	>200K

Part/Item Name	OD (mm)	Thickness Measured (mm)	Thickness Design (mm)	Material	Allowable Stress (MPa)	Operating Temp. (°C)	Operating Pressure (MPa)	Operating Hours (Hrs)	Mwt (mm)	Remaining life	Mwt 70% design (mm)	Remaining life
Farside Return Bend *Row* 5 -6 *Tube* 7	114,30	8,07	8,56	SA 234 WPC	114	290	9,49	210240	5,14	>200K	5,99	>200K
Farside Return Bend *Row* 8 -7 *Tube* 6	114,30	7,96	8,56	SA 234 WPC	114	290	9,49	210240	5,14	>200K	5,99	>200K
Farside Horizontal *Row* 11 *Tube* 4	114,30	7,69	8,56	SA 106 Gr. C	119	290	9,49	210240	4,95	>200K	5,99	>200K
Farside Horizontal *Row* 15 *Tube* 5	114,30	7,76	8,56	SA 106 Gr. C	119	290	9,49	210240	4,95	>200K	5,99	>200K
Duct Burner 1												
Burner Element 2 (dekat Nearside)	114,30	6,10	6,02	SS 310	120	290	0,10	210240	0,62	>200K	4,21	>200K
Burner Element 5	114,30	6,09	6,02	SS 310	120	290	0,10	210240	0,62	>200K	4,21	>200K
Burner Element 8	114,30	6,29	6,02	SS 310	120	290	0,10	210240	0,62	>200K	4,21	>200K
Burner Element 10 (dekat Farside)	114,30	6,08	6,02	SS 310	120	290	0,10	210240	0,62	>200K	4,21	>200K
Duct Burner 2												
Burner Element 2 (dekat Nearside)	114,30	5,02	6,02	SS 310	120	290	0,10	210240	0,62	>200K	4,21	169453
Burner Element 5	114,30	5,15	6,02	SS 310	120	290	0,10	210240	0,62	>200K	4,21	>200K
Burner Element 7	114,30	5,43	6,02	SS 310	120	290	0,10	210240	0,62	>200K	4,21	>200K
Burner Element (dekat Farside)	114,30	5,07	6,02	SS 310	120	290	0,10	210240	0,62	>200K	4,21	189437

DISCUSSION

The results of the tests and analysis conducted provide a comprehensive overview of the actual condition of HRSG Unit 2 components after 24 years of operation. Non-destructive testing (NDT) indicates that in general, the main components such as tubes, jumpers, and headers are still in good condition and acceptable according to the ASME BPVC standard. Although no significant cracks were found from the Liquid Penetrant Test (LPT) and Magnetic Particle Test (MPT), the LPT results indicated the presence of pores in the weld area in Weld Header Elevation 2, which requires further attention even though it has not developed into cracks. The most significant finding from the NDT was the presence of thinning evenly on several components. Ultrasonic Thickness Measurement (UTM) testing in Module 3 identified thinning between 3%–10%. Some areas showed even more significant thinning, such as in Row 19 Tube 3 (14.3%), Row 3–4 Tube 4 (12.9%), and Inlet Circuit Tube 2 (12.5%). A similar condition was also identified in Duct Burner 2, where elements 2 and 10 experienced thinning of up to 15.8%–16.6%. This pattern of material thinning shows that wall-loss degradation has begun to progress in the affected components, making periodic inspection essential, particularly in zones with the highest reduction in thickness (Setyabudi, 2017).

Conversely, material analysis showed quite positive results. In-situ metallurgical testing in Module 3 did not reveal any significant microstructural degradation. Although spheroidization was identified in Farside Return Bend Row 13–14 Tube 6 (level D) and several points in the Duct Burner showed creep voids (damage level 3), most of the material remained at an acceptable level of degradation(Electric Power Research Institute (EPRI),2011). This is supported by hardness test results, which showed the material hardness value remained within the standard design range (120–220 HV). The hardness values for Module 3 and the Duct Burner, although variable, generally meet the material specifications for SA 234 WPC, SA 106 Gr.C, and SS 310. This good material condition indicates that failure modes due to material degradation are not a threat in the near future.

The final results of the Remaining Life Assessment (RLA) estimate the remaining operational life of the HRSG to be approximately 10–15 years. Given that the HRSG has been in operation for 24 years, out of an initial design of 25 years, this estimate provides significant operational certainty for the company. The assessment indicates that although some components are beginning to show signs of degradation, such as thinning, the HRSG unit still has sufficient reliability to continue operating for that period. These findings provide a strong basis for PT. X to plan a follow-up inspection schedule, maintenance strategy, and long-term investment plan, as outlined in a previous study(Sirohi, S., & Singh, 2015)

This confirms that the approach used has proven effective and aligns with international guidelines, ensuring the results are valid and reliable. All stages of the study, from NDT inspection and material analysis to remaining life calculation, were conducted in accordance with the international standard ASME FFS-1/API 579. The use of this standard ensures that the approach used in this assessment is proven to be effective, valid, and reliable. Compliance with this international guideline strengthens the validity of the remaining life estimation results and provides confidence that the conclusions drawn are technically accurate. Other studies have demonstrated the effectiveness of implementing a risk-based inspection approach that adheres to ASME guidelines. The results of these studies significantly improve the accuracy of HRSG component remaining life assessments and can serve as a reference in HRSG maintenance strategies (Ali & Sabry, 2019).

Specific recommendations based on the findings are provided, such as the importance of consistent preventive maintenance to achieve maximum remaining life estimates. Based on the findings, several technical recommendations can be formulated. First, areas showing significant thinning, such as in Module 3 (Row 19 Tube 3 and Row 3–4 Tube 4) and especially Duct Burner 2 (elements 2 and 10), should be placed under observation with a follow-up inspection scheduled in the short term. Second, even if material degradation is not yet critical, points with damage levels D and 3 (the presence of creep voids) need to be monitored specifically during subsequent inspections. Finally, to achieve the maximum estimated remaining life of up to 15 years, it is important for the company to implement a consistent and disciplined preventive maintenance program (Patel, 2018).

Furthermore, the inspection and metallurgical findings obtained in this study are consistent with recent global observations regarding degradation patterns in long-operating boiler and heat-exchanger tubing systems. A recent review by (Utomo et al., 2024) highlights that wall thinning above 10% in boiler and HRSG tubing commonly accelerates after 20 years of operation due to thermal cycling, oxidation, and scale spallation an observation that aligns with the thinning values of 12–16% found in Module 3 and Duct Burner 2 of this unit. Similar cases of stainless-steel tube deterioration resulting from long-term exposure to fluctuating thermal loads were also reported by (Yang et al., 2022), supporting the finding that the thinning trend observed in Unit 2 is still within the expected deterioration envelope for heat-exchanger tubing of comparable age and service conditions.

In addition, the non-uniform distribution of thinning observed in Module 3 may be influenced by variations in gas flow velocity and localized thermal gradients. Studies compiled by (Utomo et al., 2024) demonstrate that tubes located in regions with unstable exhaust temperature profiles tend to exhibit accelerated wall loss, particularly near bends and tube intersections patterns that closely resemble the thinning detected in Row 19 Tube 3 and Row 3–4 Tube 4. These findings emphasize the importance of implementing targeted inspection strategies, including flow-based degradation prediction and thermal mapping, to identify future potential thinning hotspots more accurately.

Another critical aspect relates to the early-stage microstructural degradation identified in the burner tubes of Duct Burner 2, where creep voids were detected at several points. A real-world HRSG case study by (Kis Agustin et al., 2025) also reported similar creep-related degradation in superheater tubes after extended high-temperature service, confirming that creep cavity formation can begin even when hardness values remain within acceptable ranges. Although the damage level detected in this unit is still categorized as non-critical, the presence of creep voids indicates the onset of aging mechanisms that require periodic monitoring and trending.

Furthermore, the wide variation in hardness values observed in SS 310 burner elements from lower values around 174–183 HV to values exceeding 260 HV indicates non-uniform thermal exposure and potential thermal fatigue effects. Research on stainless-steel heat-exchanger tubing by (Yang et al., 2022) shows that prolonged thermal cycling can cause localized hardening or softening due to microstructural rearrangement, consistent with the conditions found in this study. This reinforces that thermal loading, rather than corrosion, is likely the dominant deterioration mechanism in Duct Burner 2.

In addition, recent developments in boiler and HRSG asset-management practices emphasize the importance of integrating digital monitoring technologies, including wall-thickness sensors, thermal imaging diagnostics, and data-driven degradation prediction tools, to enhance accuracy in remaining-life assessment. A 2024 review by (Utomo et al., 2024) highlights that combining conventional NDT with real-time operational data can significantly reduce uncertainty in estimating tube degradation progression. Implementing similar digital monitoring approaches in HRSG Unit 2 would allow PT X to detect early-stage deterioration more accurately, optimize inspection intervals, and strengthen long-term reliability planning.

CONCLUSION

Overall, HRSG Unit 2 remains in a safe and reliable condition for continued operation. The assessment showed that, despite 24 years of operation, the major components are generally in good condition and meet acceptable standards. The assessment method used, based on the ASME FFS-1/API 579 standard, proved effective in accurately assessing the actual condition of the equipment. This approach successfully identified areas of early degradation, such as wall thinning on some tubes and burner elements, and pores in weld joints. Although several points requiring monitoring were identified, material analysis did not indicate significant microstructural degradation, and material hardness values remained within design standards. The final Remaining Life Assessment (RLA) results estimated the remaining operational life of the HRSG to be approximately 10 to 15 years. This assessment provides a strong basis for supporting a risk-based maintenance strategy, ensuring operational reliability, and planning future follow-up inspections.

REFERENCES

Ali, A., & Sabry, H. (2019). Implementing a Successful Risk Based Inspection Program. https://doi.org/10.2118/197790-MS

Arpit, S., & Das, P. K. (2023). A state-of-the-art review of heat recovery steam generators and waste heat boilers. Energy Efficiency, 16(8), 99. https://doi.org/10.1007/s12053-023-10179-5

Balku, Ş. (2017). Analysis of combined cycle efficiency by simulation and optimization. Energy Conversion and Management, 148, 174–183.

Danang Priambada, F. E. W. W. (2025). Literature Review : Remaining Life Assessment Method of Heat. 39(1), 9–15.
Dooley, B. (2024). The Importance of HRSG HP Evaporator Tube Internal Deposit Evaluation. Structural Associates.
Feng, Z., Xie, Z., dan Li, L. (2020). Remaining life assessment of Heat Recovery Steam Generators based on the ASME Code and in-situ material testing. Materials Dan Design, 188, 10840. https://doi.org/https://doi.org/10.1016/j.matdes.2020.108406
Jouhara, H., Khordehgah, N., Almahmoud, S., Delpech, B., Chauhan, A., & Tassou, S. A. (2018). Waste heat recovery technologies and applications. Thermal Science and Engineering Progress, 6, 268–289. https://doi.org/10.1016/j.tsep.2018.04.017
Kis Agustin, H. C., Sidharta, I., Wulandari, E., & Sutikno. (2025). Failure Analysis of Superheater Drain Tube in Heat Recovery Steam Generator BT - Smart Innovation in Mechanical Engineering (A. El Kharbachi, I. D. Wijayanti, P. Suwarta, & I. Tolj (Eds.); pp. 447–454). Springer Nature Singapore.
Mansouri, M. T., Ahmadi, P., Kaviri, A. G., & Jaafar, M. N. M. (2012). Exergetic and economic evaluation of the effect of HRSG configurations on the performance of combined cycle power plants. Energy Conversion and Management, 58, 47–58.
Nashit, M., & M, F. (2019). Analysis of material degradation and remaining life assessment in Heat Recovery Steam Generators using advanced metallurgical techniques. International Journal of Pressure Vessels and Piping, 171, 1–9. https://doi.org/10.1016/j.ijpvp.2019.02.001
Norouzi, E., Amidpour, M., & Rezakazemi, M. (2019). Heat recovery steam generator: Constructal thermoeconomic optimization. Applied Thermal Engineering, 148, 747–753. https://doi.org/10.1016/j.applthermaleng.2018.11.094
Ononogbo, C., Nwosu, E. C., Nwakuba, N. R., Nwaji, G. N., Nwufo, O. C., Chukwuezie, O. C., Chukwu, M. M., & Anyanwu, E. E. (2023). Opportunities of waste heat recovery from various sources: Review of technologies and implementation. Heliyon, 9(2), e13590. https://doi.org/10.1016/j.heliyon.2023.e13590
Patel, V. (2018). Preventive Maintenance Strategy for Power Plant Equipment. International Journal of Engineering Research & Technology. International Journal of Engineering Research & Technology.
Setyabudi, I. (2017). ES Mechanical Engineering and Sciences. J ES The International Journal of Mechanical Engineering and Sciences, 1(1), 8–14.
Sirohi, S., & Singh, R. (2015). Remaining Life Assessment of Power Plant Components: A Review. Urnal of Failure Analysis and Prevention, 15(4), 506–523.
Smith, J., & Brown, R. (2020). Evaluation of Creep and Fatigue Damage in HRSG Tubes. International Journal of Energy Systems Engineering.
Utomo, F. F., Rashyid, M. I., Nugraha, A. D., & Muflikhun, M. A. (2024). a Recent Review on the Failure Analysis of Boiler Tube. Jurnal Rekayasa Mesin, 15(2), 619–646. https://doi.org/10.21776/jrm.v15i2.1392
V. Ganapathy. (2017). Heat Recovery Steam Generators (HRSGs), Part 3: Predicting OffDesign Performance.
Wahyudi, D., & Iswanto, P. T. (2023). Analisis Sisa Umur Pakai Tube Heater Pada Heat Recovery Steam Generator (HRSG). Journal of Mechanical Design and Testing, 5(1), 10–1.
Yang, J., Li, C., Pan, Y., & Huang, H. (2022). The Failure Mechanism of the 316 SS Heat Exchanger Tube in the Geothermal Water Environment. Materials, 15(22), 8103. https://doi.org/10.3390/ma15228103
Zhao, Y., Guo, W., dan Zhang, M. (2022). In-situ metallurgical testing and assessment for the remaining life of steam generator tubing in power Plants. Journal of Materials Science & Technology, 128, 59–70. https://doi.org/10.1016/j.jmst.2022.04.017