Ash Fouling Free Regenerative Air Preheater for Deep Cyclic Operation

Final Technical Report

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Principal Authors:
Pengfei He, Heather Nikolic, Kunlei Liu

University of Kentucky, Lexington, KY

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University of Kentucky Research Foundation
109 Kinkead Hall, Lexington, KY 40506-0057

PRINCIPAL INVESTIGATOR
Dr. Kunlei Liu
859-257-0293
kunlei.liu@uky.edu

DOE PROJECT MANAGER
Katelyn Ballard
katelyn.ballard@netl.doe.gov

SUBMITTED TO
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Liechun Liu

Chengguo Ma

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1) EXECUTIVE SUMMARY

The University of Kentucky (UKy) project titled "Ash Fouling Free Regenerative Air Preheater for Deep Cyclic Operation", DE-FE0031757, was conducted from 8/15/2019 to 8/14/2024 in two Budget Periods. Other participants included PPL Corporation and Black Dragon Double Boiler. The overall goal was to investigate the proposed self-cleaning technology to achieve ash fouling free air preheater operation in a coal-fired power plant, especially during deep cycling. All project deliverables, milestones, and success criteria were met. UKy obtained the following scientific findings.

- Temporary and periodic high temperature of heating elements (450 ~ 500 °F) can prevent ash accumulation and maintain air preheater free of clogging.
- The ash samples analysis and unit operation provide solid evidence of ABS formed during low load with SCR ammonia slip being the major cause of ash accumulation, and air preheater clogging can be prevented by raising the heating element temperature up to 450 °F~ 500 °F at which ABS is decomposed.
- In-situ self-cleaning can be controlled by monitoring temperature and/or presetting fixed number of cleanings per day. Both approaches in pilot testing show positive results for maintaining an ash free state for the air preheater.
- Temperature criteria (cold end or gas outlet temperature) for entering self-cleaning service is critical to balance the number of cleaning cycles with maintaining the ash level.
- Temperature criteria (cold end or gas outlet temperature) for exiting self-cleaning service is critical to balance the duration of the cleaning cycles with maintaining the ash level.

1.1 Overview

The scope of work is a thorough study that will result in a self-cleaning, ash fouling free air preheater to increase the capacity and capability of a coal-fired power plant for load following. Increased use of alternative energy sources presents a challenge to fossil fuel-based power plants, particularly solid-fired units, when generating load is below 50% of the nameplate. The technology developed in this study offers a solution to this, especially during deep cyclic operation. This is accomplished by installing auto-controlled blinder-type vanes at the air inlet of the air preheater. Whenever the load is below 70%, one or more of the inlet blinder-type vanes will be closed to restrict the air flow and provide an annular high-temperature zone inside the metal basket for ammonia bisulfate decomposition, then will transform the sticky, fouling ash to loose dry ash, followed by a cleaning with high-temperature flue gas when it rotates to the flue gas side as shown in **Exhibit 1.1.1**.

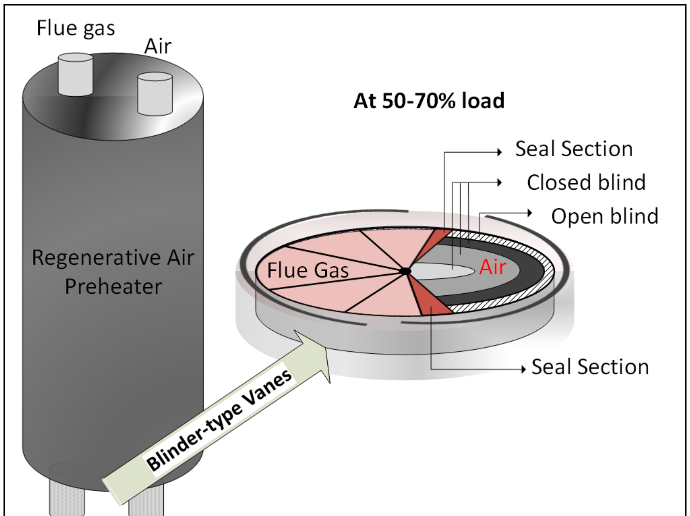


Exhibit 1.1.1. UKy-IDEA Self-Cleaning Ash Fouling Free Technology.

Successful development of the proposed technology will have a multitude of public benefits including continued utilization of abundant, low-cost fossil fuels for the production of reliable electricity while affordably meeting and managing environmental concerns. With less than \$500K investment to a normal 550 MW_e unit retrofit, the potential benefit to existing coal-fired power plants will be three-fold: (1) The stable minimum load could be as low as 25-30% of baseload. (2) 2-3% boiler efficiency improvement could be realized due to low air leaks, low gas pressure drop across the air preheater, and reduced or eliminated use of an in-line gas heater. (3) De-NO_x efficiency improvements can be achieved and maintained with relatively high ammonia injection flowrates without the concern of air preheater blockage resulting from ammonia bisulfite/bisulfate formation due to high ammonia slip.

The UKy-IDEA self-cleaning ash fouling free technology addresses four scientific challenges targeted by Funding Opportunity Announcement (FOA) DE-FOA-0001989: (1) Testing technologies which will better equip key components such as pulverizers, boilers, and emissions control systems to handle load changes, (2) Testing methodologies and/or automation techniques for optimizing the operation of key components under low load and/or cycling conditions, (3) Testing technologies (including materials) that permit a wider temperature range of operation for emissions control components, and (4) Testing techniques which shorten the length of time-consuming repairs and reduce downtime. The demonstrated technology uses auto-controlled blinder-type vanes that restrict air flow at the air inlet during partial loads to periodically raise heating element temperature and maintain the air preheater ash fouling free. The technology targets to permit broader temperature range operation of boiler and SCR under low load and deep cyclic conditions, while still allowing air preheater performance of effective heat recovery without heavy blockage and minimizing the downtime.

In power industry, the air-side gas pressure drop can double in months caused by ash fouling from high ammonia slip at partial loads (particularly <50%), which lead to four detrimental consequences: (1) Instability of coal combustion and boiler operation due to high fluctuation of boiler pressure from a typical -50Pa ~ 200Pa to -100Pa ~ 500Pa results from non-uniform blockage and the slow blower response against a downstream pressure drop fluctuation. (2) Approximately 20% capacity reduction from full load results from a limited air flow rate for given primary draft fan due to high air preheater back pressure. (3) An estimated 2-3% boiler efficiency drop results from the high temperature of flue gas exiting the air preheater and high air leakage between air and flue gas chambers due high differential pressure. (4) Frequent forced outages are required for off-line cleaning (Chen et al, 2017; Nie, 2017).

Maintaining ash fouling free operation of the regenerative air preheater could positively impact the boiler/steam generator under low load and deep cyclic conditions and widen the temperature range of operation for emission control components. The demonstrated process including blinder-type vanes departs from traditional efforts, focusing on periodically restricting air flow during partial loads with a low cost retrofit and to form the local high temperature zones for ammonia bisulfate decomposition, transforming underutilized air flow area during partial loads for ash removal. Additionally, the auto-controlled blinder-type vanes location at the inlet of air preheater widens the material selection and simplified the device design and construction due to the low temperature and low solid loading.

1.2 Key Results

In BP1, ash was sampled and crystallography, mineralogy and chemical analysis as well as other surface characteristic analysis was performed. Information on host site maintenance plan and operation schedule was collected for the period coinciding with UKy's APH installation and testing. The SCR catalyst had approximately 10,000 hours in-service at the beginning of 2022. The 250 kW_{th} air preheater unit was designed, sized, and fabricated. The required instruments were evaluated, selected, and purchased. The control system was designed and built to achieve alternative air/gas flow and automatic cleaning control. The integrated unit with supporting structure was successfully installed and connected to host site plant guided from a 3D CAD model with consideration of tightness of onsite space. In BP2, the unit operation was commissioned. Parametric studies were complete at the beginning to test the unit functionality. The cleaning sequence was applied with adjustable criteria of entering and exiting the cleaning sequence, which was fine tuned to achieve reasonable number of cleanings per day. Long term operation campaign was continued for over 8000 hours to demonstrate the reliability of the technology.

The chemical analysis of ash particles revealed the following.

- The Energy-dispersive X-ray spectroscopy (EDS) maps identify the existence of high sulfur content resulting from SO_3 in flue gas condensation around dew point temperature, which acts as a bonding agent and promotes adhesion at the interface of the agglomerated ash particles.
- The analysis of ion chromatography via water leaching of ash deposits determined concentration of ammonium, sulfates etc. The presence of high content ammonium and sulfates verified the formation of ammonium sulfate/bisulfate in the air preheater (APH) region.

The integrated process was evaluated with self-cleaning control. A flue gas/metal surface temperature parametric campaign of >1000 hours, and long-term campaign of >8000 hours for all four seasons, were conducted along with host site plant operation. The BP2 temperature parametric and long-term campaigns demonstrated the following.

- Operation with self-cleaning in service could periodically raise up the unit temperature and prevent ash build-up. Accrual of over 8000 operating hours with self-cleaning demonstrated its reliability to prevent continuous heavy ash build-up.
- With the assistance of UKy technology in place, higher temperature operating condition (Gas outlet temperature > 250 °F) could allow air preheater to operate smoothly without concern of ash build-up. The typical state-of-the-art APH operates with the flue gas exhaust temperature between 280-300 ºF.
- Lower temperature operating condition (Gas outlet temperature < 200 °F) could quickly lead to ash build-up over time.
- Corrosion coupon analysis showed that very minimum pitting corrosion, if any, was found over 3000 hours of operation.

1.3 Key Challenges

Three key technical challenges were encountered.

1. Temperature measurement inside heating element area.

To understand the temperature variations within the heating element, thermocouples needed to be inserted horizontally between the corrugated heat element plates. With properly packed heating elements, an open-ended ¼" tube was forced and jammed between two of the metal plates to create the space for thermocouple, as shown in **Exhibit 1.3.1**. The 1/8" thermocouple was then inserted into the open-ended tube shell for operation measurement. Two thermocouples were placed with one at the center of the hot end, the top section of metal element, and the other at the center of the cold end, the bottom metal section. When ash accumulated above the tube shell, where there is a flow dead zone, the temperature reading could be delayed for a longer time than the alternate elapse time and thus less swing between heating and cooling cycle was measured, as shown in **Exhibit 1.3.2**. Specifically, the data in the right column of **Exhibit 1.3.2** shows the temperature measurement of four different locations during the

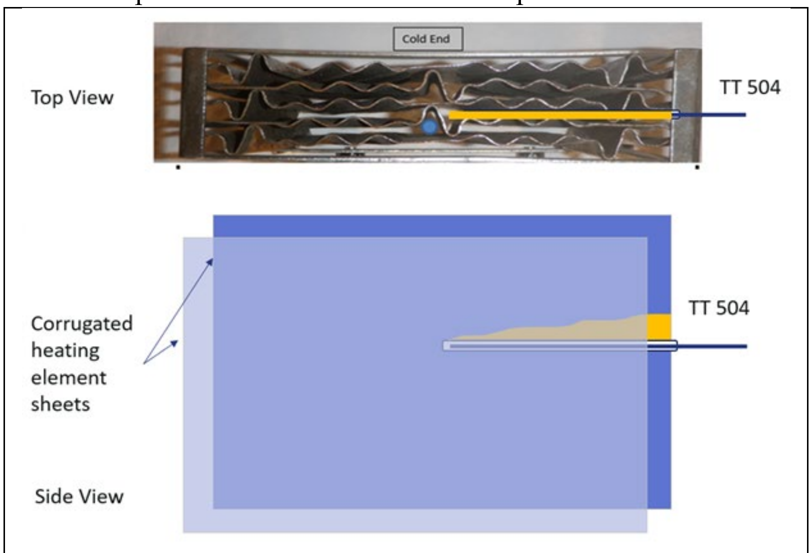


Exhibit 1.3.1. Schematics of Thermocouple with Accumulated Ash (Yellow Area)

operation after the unit experienced a

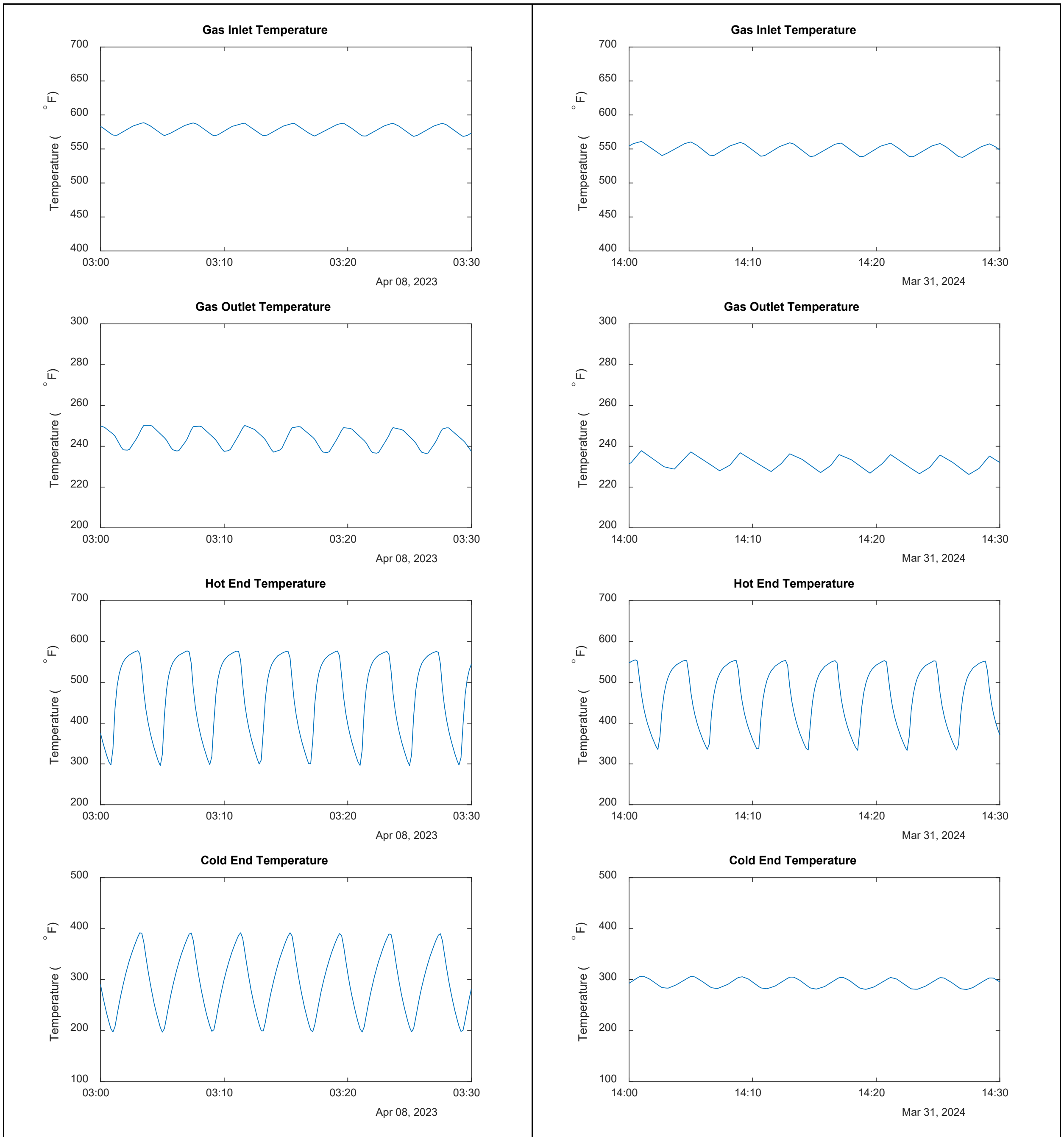


Exhibit 1.3.2. Cold End Thermocouple Reading Affected with Accumulated Ash

heavy ash buildup and water wash cleaning, and the data in the left column shows the same measurements before ash buildup and water wash cleaning. As we see in the right column, the cold end thermocouple experienced a delayed response reading and thus less temperature swing. The reason is the water wash cleaning could flush ash into the dead zone above the thermocouple and form mud that decreased the sensitivity of the temperature reading, schematically shown in **Exhibit 1.3.1**. The hot end temperature swing did not reduce as much as the cold end temperature swing, indicating that ash mainly accumulated at the cold end of the heating elements. The solution of removing the accumulated ash above the tube shell was limited without taking apart each heating element. The delayed response reading of the thermocouple does not affect the conclusion on effectiveness of cleaning control.

2. Existing valves that could potentially affect flow.

For this pilot scale unit with fixed heating element, a total of 4 auto-control valves and 4 manual valves at the inlets/outlets of gas and air flow are facilitated to mimic rotational movement per recommendation from LJUNGSTRÖM, the OEM of the APH installed on the host unit. Manual valves were used to isolate the testing unit from power plant and kept open during the testing. Auto-control valves are used to achieve alternating flow. Such design could prevent significant air leakage associated with rotating heating element at the pilot scale, with a tradeoff of restricted flow to certain extent due to existence of valve disk at fully open position. Especially for the gas outlet manual valve, the valve disk tended to accumulate ash when its temperature falls below 200 °F during operation of alternating between heating and cooling cycle. An image showing half blocked gas outlet manual valve is shown in **Exhibit 1.3.3**. This could potentially constrain the flue gas flow rate and promote ash build up in heating elements.

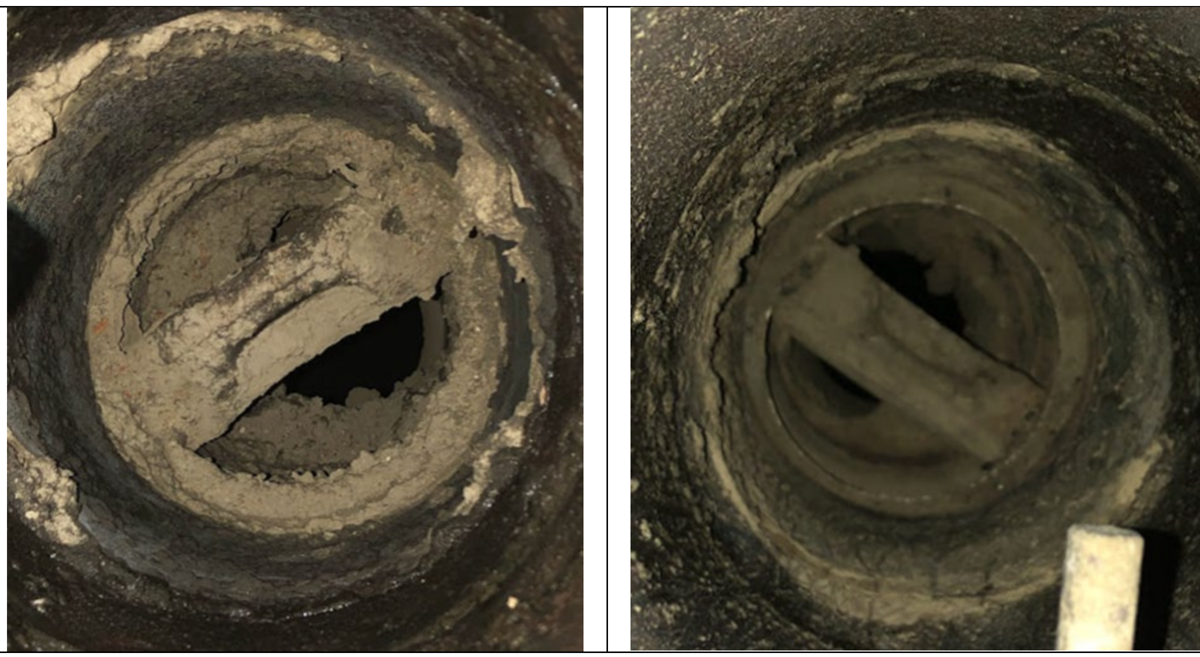
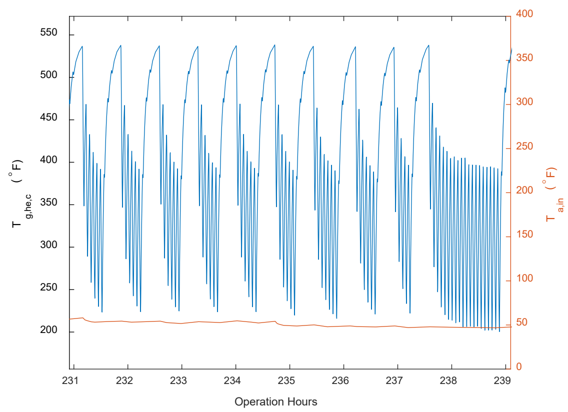


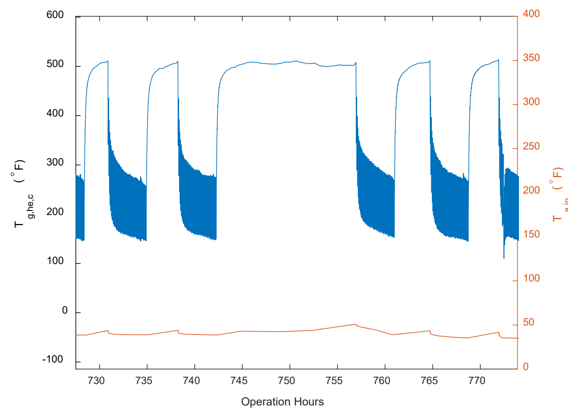
Exhibit 1.3.3. Gas Outlet Manual Valve Ash Accumulation (Left) and After Ash Removal (Right)

3. Achieve balance of periodical cleaning and maximize heat recovery operation during the cold weather and low load.

The cleaning sequence can be controlled by monitoring the cold end and gas outlet temperature. The unit enters cleaning mode when the temperature reaches a preset temperature criteria and exits cleaning mode when the temperature reaches a higher preset temperature criteria. Alternatively, the unit can also enter cleaning mode for a fixed preset number of times per day or prescheduled a fixed number of cleanings per day at certain times of the day, say midnight, or any particular time during the valley of electricity demand. The goal is to undergo the cleaning service enough times to achieve ash fouling free operation, without hurting the heat recovery efficiency by excessive time spent in cleaning. **Exhibit 1.3.4** shows examples of cleaning operation based on temperature (Left) as well as fixed number of cleanings (Right). For temperature-based cleaning control, the cleaning frequency can vary by adjusting the temperature criteria to enter the cleaning sequence. Specifically, higher enter-cleaning temperature criteria will lead to more frequent cleaning. The cleaning frequency may also be relatively higher during winter season with heat loss affecting the system temperature. The duration of cleaning is determined by the temperature criteria to exit the cleaning sequence. Specifically, higher exit-cleaning temperature criteria will require longer cleaning time. For the fixed number of cleanings control, the cleaning frequency remains constant, and the cleaning duration is determined by the temperature criteria to exit the cleaning. For both types of control, the duration of cleaning can vary by adjusting the temperature criteria to exit the cleaning sequence. These preset value of temperature criteria need to be carefully fine-tuned along with the air preheater operation to achieve self-cleaning while ensuring the unit remains well functional and maintains efficient heat recovery.



Temperature Based Control
Cleaning in service when:
TI301<=225 °F OR TI504<=380 °F after flue gas cycle;
Cleaning off service when:
TI301>=415 °F OR TI504>=520 °F after flue gas cycle.



Fixed Number of Cleanings Control
Cleaning in service when:
Count every 5-6 hours;
Cleaning off service when:
TI301>=415 °F OR TI504>=520 °F after flue gas cycle.

Exhibit 1.3.4. Operational Data of Temperature Based and Fixed Number of Cleanings Control

1.4 Project Deliverables, Milestones and Success Criteria

All project deliverables, milestones and success criteria were met as summarized in **Exhibits 1.4.1-1.4.3**.

Exhibit 1.4.1. Task Progress Summary

Task Name	Percent Complete	Accomplishments
1.0 Project Management Planning and Reporting	100%	• Final project presentation made on 8/1/2024 and project ended on 8/14/2024.
1.1 Project Kickoff Meeting Held	100%	• This task is complete on 10/9/2019.
2.0 Information Collection for 1) Unit 3 Operating Conditions Anticipated for 2021 and 2022, and 2) Ash Property and ABS Destruction Kinetics	100%	• This task is complete in Q2FY2020.

3.0 Process Design Package, Risk Analysis and Tie-in Requirement	100%	• This task is complete in Q3FY2020.
4.0 Procurement, Fabrication, Shipping and Installation of Bench-scale Unit	100%	• This task is complete in Q4FY2021.
5.0 Test Condition Selection and Data Analysis Plan	100%	• This task is complete in Q1FY2021.
6.0 Operational Procedure and Safety Protocol	100%	• This task is complete in Q2FY2022.
7.0 Process and Balance of Plant Testing, Start-up, and Commissioning	100%	• This task is complete in Q2FY2022.
8.0 Test Campaign	100%	• This task is complete in Q3FY2024 • Long-term test campaign continued. Smooth operation with self-cleaning for >8000 accrued operating hours with negligible ash build up. • Both temperature based and fixed number of cleanings control modes have been considered and implemented.

Exhibit 1.4.2. Project Milestone Log.

BP	Milestone Number	Milestone Title/Description	Verification Method	Planned Completion Date	Actual Completion Date
1	1	Project Kickoff Meeting Held	Quarterly Report	9/30/2019	10/9/2019
1	2	Completed Air Preheater Design Package	Topical Report	7/31/2020	7/30/2020
1	3	Air Preheater Installed	Quarterly Report	8/14/2021	9/6/2021
1	4	Completed Air Preheater Commissioning	Quarterly Report	1/31/2022	10/11/2021
2	5	Test Campaign Complete	Quarterly Report	8/14/2024	7/10/2024

Exhibit 1.4.3. Success Criteria Summary

Success Criterion	Percent Complete	Accomplishments
Complete analysis on the collected ash from Unit 3 air preheater	100%	• Experimental results and data analysis on IC, ammonia extraction, pH, XRD, XPS, XRF, SEM, EDS spectral analysis & mapping have been collected.

The ash deposited is breakable and in a loosened form after ABS destruction	100%	• According to data analysis using numerous techniques (IC, XRD, XRF, XPS, SEM-EDS and ammonia extraction), a high amount of ammonia and sulfates were detected in the ash fouling sample. • After the heat treatment experiments up to 350 and 400 °C, the ash samples become loose and easily breakable. • IC data show a reduced (2-3 times) ammonium concentration after heating, compared to the original non-heated sample, for all samples (cold and hot side of APH). • The in-situ high temperature XRD experiments show the concentration of NH_4^+-sulfates phases being reduced at elevated temperatures up to 500 °C compared to ambient temperature sample. • SEM-EDS images and elemental analyses show that after heat treatment the ash deposit consisted of round, fine particles a with limited amount of sulfur, compared to a thick, flocculent surface observed on unheated ash. The smaller ash particles are found to penetrate the voids of the soft and easily breakable larger particles meaning that the majority of the ash deposit is more fragile than the non-heated deposit.
Development of an appropriate execution system to control the blinds	100%	• The execution system to control the blinder-type vanes has been completed with three sections that are controlled by each actuator.
Completed process, piping and equipment engineering specifications	100%	• The design basis report is complete and submitted. • Process design package is complete and finalized, including the equipment sizing and general arrangement drawings, the APH engineering drawing, process flow diagram (PFD) and piping and instrumentation diagrams (P&ID) drawings, three-dimensional (3D) modeling drawing, and piping-fitting-flange-accessories list. • The hazard and operability (HAZOP) analysis is complete.

		• The instrument and equipment lists are complete with process electrical utility and air supply requirements identified. • Host unit tie-in points and engineering specifications are complete.
Fabricated bench-scale unit installed	100%	• APH Unit installation complete on 9/6/2021. • UKy SOW complete on 9/30/2021. • Control programming on DeltaV workstation is completed on 9/30/2021.
Startup and commissioning	100%	• Commissioning completed on 10/11/2021. • Auto sequence control operation tested. • Clogging issue observed and solution identified and exercised. • Unit can be operated smoothly.
Completed experimentation with both parametric and long-term studies	100%	• >1000 hours of parametric operation accrued. No notable ash build-up has been observed for high temperature condition. Unit experienced clog for low temperature condition. • >8000 accrued hours of smooth operation and no heating element clogging with in situ self-cleaning mode active. Criteria of automatic cleaning established with reasonable service frequency and sufficient cleaning time.
Completed final technical report	100%	• Final report completed with project findings and achievements.

2) BACKGROUND AND TECHNOLOGY DESCRIPTION

2.1 Project Objective and Background

The overall project goal is to improve power plant efficiency and reliability, with UKy-IDEA proposed self-cleaning, ash fouling free air preheater technology to increase the capacity and capability of a coal-fired power plant for load following. With the fast deployment of intermittent electricity from wind and solar sources and the installation of smart meters, the electric grid, as a whole, has been used as an energy surge tank with the balance provided by the stationary power generation dominantly consisting of nuclear, natural gas and coal-based units. Different from a gas turbine which has excellent load following capacity, a coal-fired unit typically runs into operating challenges at low load that frequently leads to forced outages due to the formation of ammonium bisulfate (ABS) inside the air-preheater at low temperatures when SCR is in service to meet EPA regulations on NO_x emissions. Additionally, a portion of SO_2 will be catalytically converted to SO_3 on the catalyst surface as a side reaction. It has been reported that 10-25 ppm SO_3 can be measured at SCR outlet when high sulfur coal is combusted. Also, air preheaters are typically operated at minimum metal temperatures above 320 °F (H_2SO_4 acid dew point is approximately 250 °F for coal-derived flue gas) to avoid cold-end metal corrosion due to sulfuric acid condensation onto the metal surface. There are 2-5 ppm of ammonia which normally passes the SCR unreacted, which can combine with sulfur trioxide (SO_3) and/or sulfuric acid (H_2SO_4) to produce ammonium bisulfate (NH_4HSO_4, ABS) at temperatures below 500 °F, as shown in **Exhibit 2.1.1**. For a slip of 10 ppm of ammonia with the presence of 25 ppm of SO_3, the ABS formation temperature is around 437 °F. During the heat transfer cycle of the air preheater, if the metal temperature is in the range of 300-390 °F, ABS will deposit on the heating elements in the form of a sticky liquid, starting from the cold end (due to low gas velocity, typically 7-8 m/s) and moving to intermediate layers of the air preheater.

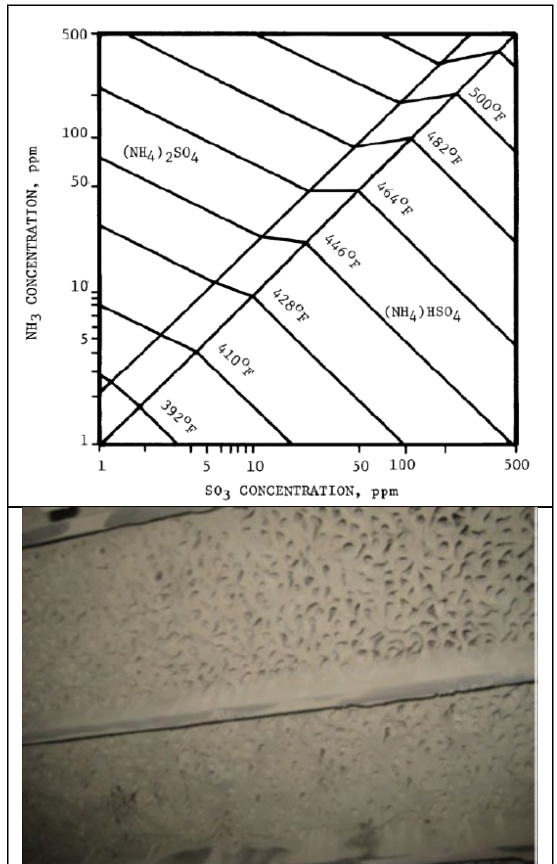


Exhibit 2.1.1. Hitachi-Zosen Map of Ammonium Bisulfate Formation Temperature (Counterman et al, 1998) and Air Preheater Ash Fouling.

At partial load, particularly during deep cycling with loads below 50% of nameplate, the SCR is operated at a lower temperature than it is designed for, and the catalyst has a reduced reactivity. To maintain 90% NO_x reduction a relatively high NH_3/NO ratio (> 0.9) is typically used to counter-balance the catalyst deactivation. Unfortunately, the high NH_3/NO ratio will result in more ammonia slip. It has been reported that within one month operation, the air-side gas pressure drop across the air preheater increased from 0.9 kPa to 1.9 kPa due to ash fouling (Datang Power Company, 2018). In addition, higher concentrations of NH_3 and SO_3 at partial loads shifts the ABS formation temperatures higher (Nie, 2017; Menasha et al, 2011), meaning that the ABS will form much deeper towards hot end of the air preheater, making it very difficult to clean by soot blowing. This leads to serious fouling and plugging problems, as illustrated in **Exhibit 2.1.1**, and results in significant impact to the unit's efficiency and reliability and for most cases, ends with a forced outage before the operator can take the air preheater off-line to conduct a thorough water wash.

Reaction Equations of Forming ABS:

$$SO_2 + O_2 \leftrightarrow SO_3$$

$$SO_3 + H_2O \leftrightarrow H_2SO_4$$

$$NH_3 + SO_3 + H_2O \leftrightarrow NH_4HSO_4 \text{ (g/l), ammonium bisulfate (ABS).}$$

To address heavy ash fouling resulting from SCR operation below design temperature, a few new technologies have been developed such as bypassing a portion of heated air from the air preheater exhaust to the air inlet (flue gas recirculation), or an installation of steam or a hot water recirculating system (HWRC) to use drum saturated water to heat the flue gas after the economizer to a certain temperature to maintain the SCR activity thereby reducing the ammonia slip. A third option is shown in **Exhibit 2.1.2.** For this technology (Chen et al), a corner of the secondary air duct is removed to provide space for a newly installed hot-temperature recycling system as illustrated in green. By providing hot air to the air preheater, the metal surface temperature will be maintained at above 500 °F which is above the ammonium bisulfate decomposition temperature, resulting in destruction of ABS and loosening the sticky deposited ash, which when dry is carried out by the air. This modification has been demonstrated for its effectiveness to resolve the ash fouling but will require significant physical hardware for retrofit and installation of a high temperature blower for air recirculation.

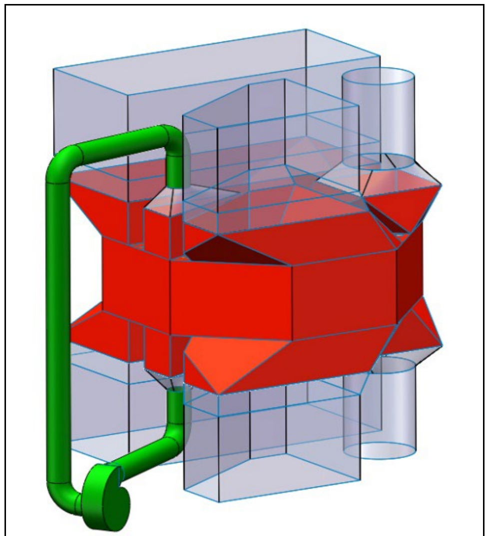


Exhibit 2.1.2. Ash Fouling Cleaning Technology - Hot Water Recirculation System.

Taking a similar principle, UKy-IDEA proposed an innovative mechanism to simply install a series of annular blinder-type vanes (4 sets as indicated in **Exhibit 2.1.3** at the air inlet duct prior to the rotary wheel without requiring major air duct modifications or new blower installation as indicated in **Exhibit 2.1.2**. The working principle for the UKy-IDEA technology is briefly: (1) at high load (80-100% of full load), all of the blinder-type vanes are fully open to ensure the air heater is at full capacity; (2) at medium load (50-70% of full load), one fourth of sets of blinder-type vanes are alternatively closed to provide a no-flow (heat transfer) zone to maintain the metal surface temperature at the flue gas side so deposited ammonium bisulfate can be destructed and ash fouling can be loosened and cleaned; and (3) at low load (25-50% of full load), two sets of blinds will be closed and perform a similar sequence and function as (2).

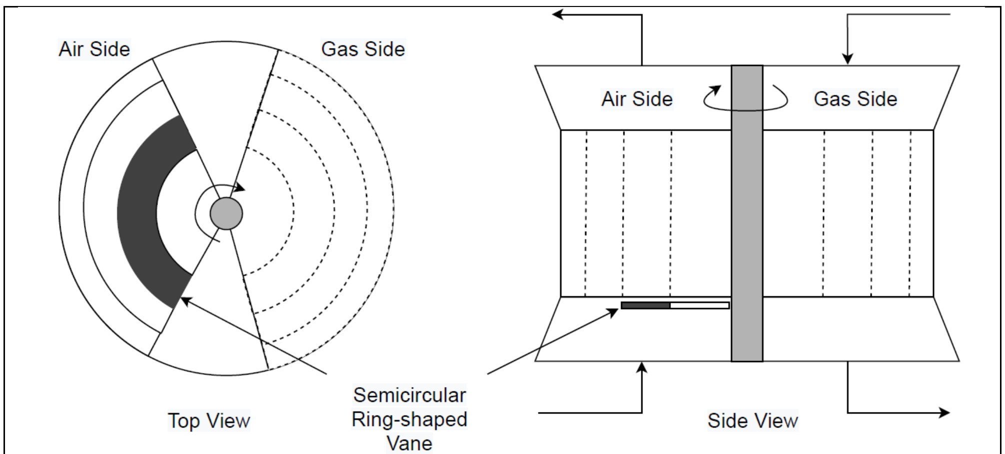


Exhibit 2.1.3. Ash Fouling Cleaning Technology – UKy-IDEA Approach.

Reaction Equations of Decomposing ABS:

$$NH_4HSO_4 \leftrightarrow NH_3 + SO_3 + H_2O$$

It is important to remember that the reaction for decomposition of ABS takes place dominantly when temperature is above around 500 °F. Thus, the targeted temperature of heating elements during self-cleaning is set close to 500 °F for a sufficient amount of time.

In this project, the pilot-scale unit, 250 kW_{th}, equivalent, was designed and installed to attach to a commercial 450 $MW_{e,net}$ pulverized coal unit (PPL Corporation's E.W. Brown Unit 3) that burns bituminous coal. Based on consultation with the original equipment manufacturer (OEM) of host unit regenerative air preheater, LJUNGSTRÖM , the pilot unit was designed as a fixed heating element, one segment of the host unit, to avoid significant air leakage associated with the pilot scale, with flue gas and air flows being automatically switched to alternate through the test unit, as shown in **Exhibit 2.1.4**. The effectiveness of the self-cleaning from auto-control blinder-type vanes was investigated in terms of flue gas pressure drop across the air preheater and the flue gas exhaust temperature as a function of time. The reliability of the technology is evaluated by over a year-long operation campaign.

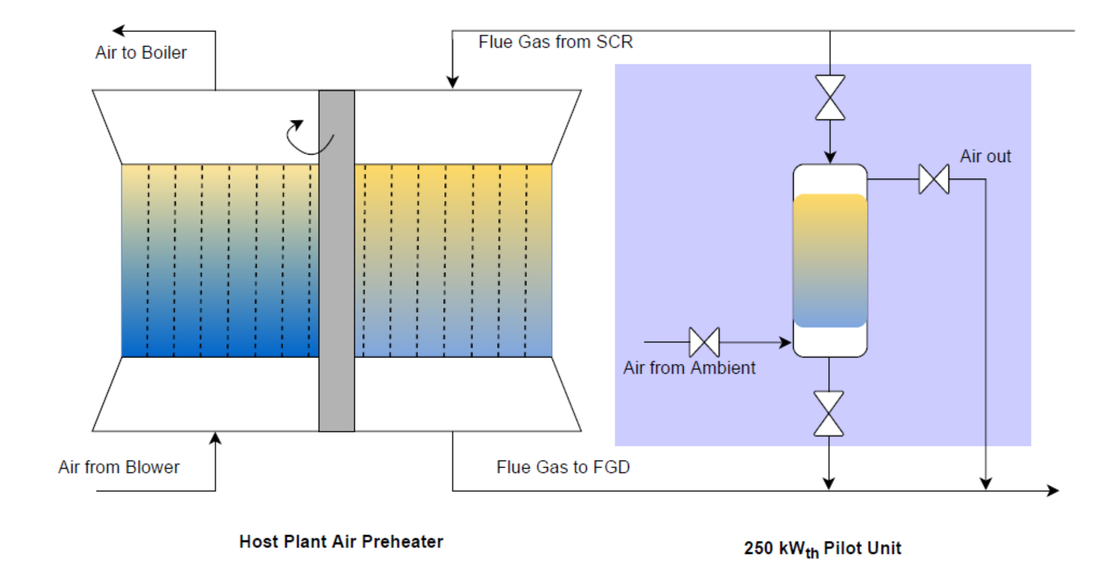


Exhibit 2.1.4. Schematic of 250 kW_{th} Pilot Unit Installation in Host Plant.

2.2 Performance Targets

Summarized in **Exhibit 2.2.1**, targets of unit performance were set for conventional operation as well as operation with self-cleaning service. Performance criteria of conventional operation was set to be identical and representative of industrial traditional regenerative air preheater. The cleaning the self-cleaning air preheater were set to meet or exceed baseline performance of a traditional regenerative air preheater. Pressure drop and gas outlet temperature performance criteria were set for the self-cleaning air preheater to ensure practical application and operability of the technology during scale-up.

Exhibit 2.2.1. Summary of Performance Targets.

Air Preheater Operation	Gas Flow Rate = 1000~3000 lb/hr (Varies from Low to High load) Gas Inlet Temperature = 550~700 °F (Varies from Low to High load) Gas Side Pressure Drop = 1~3 in wc (Varies from Low to High load) Gas Outlet Temperature = 200~300 °F (Varies from Low to High load) Air Flow Rate = 1000~3000 lb/hr (Varies from Low to High load) Air Inlet Temperature = 30~80 °F (Varies from seasons) Air Side Pressure Drop = 1~3 in wc (Varies from Low to High load)

	Air Outlet Temperature = 350~400 °F (Varies from Low to High load) Hot End Temperature Swing = 300~550 °F Cold End Temperature Swing = 200~400 °F
Air Preheater Operation w/. Self-Cleaning	Gas Outlet Temperature w/. Cleaning = 400 °F Air Outlet Temperature w/. Cleaning = 300 °F Cold End Temperature Max w/. Cleaning = 500 °F

Exhibit 2.2.2. 250 kW_{th} Pilot Unit, as Installed at E.W. Brown Power Plant, a PPL facility.

Gas Side / Gas Cycle: As shown in **Exhibits 1.1.1 and 2.1.4**, the gas side of a regenerative air preheater is the side where flue gas passes through and heats the rotating heating elements basket. For the 250 kW_{th} pilot unit, the gas side or gas cycle is defined as the time during which flue gas passes through the fixed heating elements.

Air Side / Air Cycle: As shown in **Exhibits 1.1.1 and 2.1.4**, the air side of a regenerative air preheater is the side where air is heated as it passes through the rotating heating elements basket. For the 250 kW_{th} pilot unit, the air side or air cycle is defined as the time during which air passes through the fixed heating elements.

Pilot Unit Performance Criteria and Targets: The complete pilot-scale unit before insulation is shown in **Exhibit 2.2.2**. It measures 10"x7" rectangular with a heating element section 42" in height, connected with NPS 8 pipe for a total height of 254" between plant flue gas ducts. Various sized ports are included for observation and access, gas sampling, temperature and differential pressure measurement. The pilot-scale unit is operated by alternating the flow between gas and air. The flow rate of both gas and air is adjustable via the inlet control valve. To simplify the system, the pilot-scale unit is directly tied-in with flue gas ducts entering and exhausting from the host unit. The pressure drop across the host unit is the driving force for gas/air flow to the pilot-scale unit. The flow rates, gas inlet temperature and pressure drops across heating element are also affected by host plant operation loads. The pilot-scale unit should be able to function with 1) gas flow rate 1000~3000 lb/hr, 2) air flow rate 1000~3000 lb/hr, 3) gas inlet temperature 550~700 °F, 4) gas outlet temperature 250~300 °F.

Pilot Unit Parametric Campaign Performance Criteria and Targets: The performance of pilot unit is further evaluated using system temperature (referenced by gas outlet temperature) by adjusting the ratio of the gas side and air side flow. The performance requirements during the parametric campaign were established to meet the baseline performance of a regenerative air preheater at traditional operating conditions. The pilot unit should be able to show ash build up phenomenon which aligns with a conventional air preheater.

Self-Cleaning Performance Criteria and Targets: The pilot unit should be able to function with the periodical restriction of air flow automatically during the air cycle. The performance of self-cleaning is evaluated by the temperature of the gas outlet and cold end heating metal surface. The pilot unit should be able to boost heating element temperature > 450 °F (gas outlet temperature >350 °F).

Pilot Unit Self-Cleaning Parametric Campaign Performance Criteria and Targets: The performance of the self-cleaning of pilot unit is evaluated using cleaning frequency (number of cleanings per day), duration of each cleaning, gas outlet temperature and pressure drop across heating elements. The pilot unit must be able to perform self-cleaning with reasonable cleaning frequencies and durations.

Pilot Unit Self-Cleaning Long-term Campaign Performance Criteria and Targets: After the parametric campaign, the performance of the self-cleaning of pilot unit is evaluated for yearlong operation, with the target being to maintain the pressure drop, flow rate and average gas outlet temperature. A dimensionless index may be developed to indicate ash level over time.

3) 250kW$_{th}$ PILOT UNIT DESIGN AND FABRICATION

3.1 Ash Properties and ABS

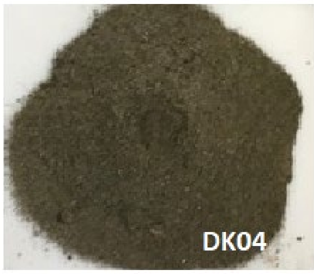
3.1.1. Ash Sample Collection

Understanding the chemical composition and physical properties of the air preheater ash deposits is necessary in order to determine the ash fouling formation process and optimize the operational conditions of the air preheater. Chemical and physical analyses were performed using a combination of XRF and XRD characterization to determine the mineralogy and chemistry (bulk), SEM-EDS to identify the morphology, IC in order to measure the ammonium and sulfate contents, and XPS to determine the surface chemistry and interfacial characteristics between the agglomerated ash particles.

Due to accessibility constraints, five ash samples (instead of six) were collected after a few days of shutdown from different regions of the air preheater by E.W. Brown plant personnel. E.W. Brown includes two duct systems, 3-1 and 3-2. To cover a full spectrum of samples, they were collected at gas outlet and inlet side from Duct 3-1 (sample names DK_02, DK_05) and Duct 3-2 (sample names DK_03, DK_04). An additional sample at the gas outlet of Duct 3-1 (sample name DK_01) was collected for relatively easier access. The samples were collected for a detailed mineralogical and chemical analysis in order to understand the underlying mechanism that promotes the formation of ash deposition, and to establish a decomposition process of ammonium bisulfate, which tends to block the heating elements of the air preheater. Details regarding the locations and description of ash deposits (physical appearance) of the air preheater at the E.W. Brown Station are provided in **Exhibit 3.1.1**.

Exhibit 3.1.1. Description, Position in the Air Preheater and Sample ID of the Collected Ash Deposits.

Sample location at EW Brown Station (APH)	Physical characteristics	Sample description	Sample ID
Air heater gas cold side (gas outlet)	Dark grey particles, mainly in a loose form (fine particles) or partially aggregated in bigger structures. Additional irregularly shaped and thicker/larger structures mixed with the fine particles.	Solid ash around the perimeter and on top of some of the braces near the air heater. This sample was collected from these areas near the baskets.	Sample 1: 3-1 (DK_01) 

Air heater gas cold side (gas outlet)	Dark grey particles. Mainly in a loose form, mixed with large and crispy structures.	This sample was collected from the ductwork under the air heater. There may be some air heater basket material (pieces breaking off the air heater baskets that may have been collected with the shovel).	Sample 2: 3-1 (DK_02) 
Air heater gas cold side (gas outlet)	Similar appearance to Sample 2 (DK_02).	This sample was collected from the ductwork under the air heater. There may be some air heater basket material (pieces breaking off the air heater baskets that may have been collected with the shovel).	Sample 3: 3-2 (DK_03) 
Air heater gas hot side (gas inlet)	Dark grey fine particles. There is no aggregation.	This sample was collected from flatter surfaces around the perimeter of the air heater.	Sample 4: 3-2 (DK_04) 
Air heater gas hot side (gas inlet)	Mixture of brown to yellowish fine particles. Mainly in a fine powder form, with a few larger structures due to agglomeration of fine particles.	Sample from ash that was laying in piles on the air heater basket on 3-1 side. It may have fallen after soot blowing was collected.	Sample 5: 3-1 (DK_05) 

3.1.2. Crystallography, Mineralogy and Chemical analysis

The elemental and proximate analysis for ash composition, fraction of volatile matter and fixed carbon, as well as other alkali metals, was determined based on the minerals and oxides (e.g. aluminosilicates, hematite, aragonite) via XRF and XRD measurements. The presence and content of different minerals helped to elucidate the ash properties, flue gas conditions, and their contribution in the deposition/formation mechanism at different positions of the air preheater. Furthermore, quantitative XRD analysis provided information and useful crystallographic parameters of the mineral phases and byproducts/melting phases (mainly crystallized phases and minerals) that are formed during the deposition process within the heating elements of the air preheater (validation and identification of the deposition processes). **Exhibit 3.1.2** presents the XRF results of the ash deposits.

Exhibit 3.1. 2. XRF Results and Proximate Analysis of Ash Samples (Results in wt%)

Sample	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	P_2O_5	TiO_2	SO_3	Ash	Moisture	C	F (ppm)
DK_01	40.87	18.93	29.02	2.03	0.87	0.67	2.2	0.12	0.92	2.37	87.44	2.32	1.54	108
DK_02	47.96	21.68	19.01	2.08	0.98	0.72	2.77	0.12	1.09	1.53	96.68	1	0.95	71
DK_03	47.99	22.78	18.09	1.71	0.97	0.7	2.8	0.18	1.14	1.53	95.25	1.31	0.97	122
DK_04	42.47	19.74	28.18	2.37	0.89	0.39	2.17	0.1	0.89	0.89	98.85	0.19	0.77	<1
DK_05	48.72	22.77	16.87	1.5	0.95	0.74	2.85	0.23	1.14	2.04	85.99	1.93	0.78	37

By applying theoretical deposition indices and models for ash fouling and slagging, the ash deposition or condensation of volatile inorganic components on air preheater surfaces can be predicted. The oxides in ash samples, as determined from the XRF results, can be categorized to acidic and base components. The ratio of the base to acidic (B/A) contents serves as an indicator for fouling and slagging tendency of ash products. In addition, more complicated indices, such as the fouling index, can also predict the fouling propensity of ash products. **Exhibit 3.1.3** reports the results of the predicted fouling and slagging indices for the ash deposits as collected from different locations in the air preheater. The results suggest a significant fouling tendency in both the cold (outlet) and hot (inlet) side of the air preheater, especially for the samples DK_01 and DK_04, as shown in **Exhibit 3.1.3**.

Exhibit 3.1.3. Ash Fouling Indices and B/A Ratio Based on XRF Results of Ash Deposits.

Sample	Slag Ratio (SR)	B/A	Fouling Index (Fu)	B/A simp	B/A(+P)	Hw (slag/fouling index)
DK_01	56.15	0.57	1.64	0.53	0.57	10.00
DK_02	68.48	0.36	1.26	0.32	0.36	6.21
DK_03	69.79	0.34	1.18	0.29	0.34	6.75
DK_04	57.46	0.54	1.38	0.50	0.54	8.64
DK_05	71.60	0.32	1.13	0.27	0.32	6.89

Further analysis, via XRD measurements and Rietveld Refinement, was performed in order to determine the crystallographic characteristics for all samples based on crystallographic structures and phase determination during the ash deposition. Control experiments on pure $(NH_4)HSO_4$ and $(NH_4)_2SO_4$ were also performed for comparison reasons. **Exhibit 3.1.4** shows the XRD pattern of sample DK-05, and the main crystallographic phases as detected via refinement. As the XRD analysis showed, the sample consisted of mullites, ardealite, whewellite, silicon dioxide, ammonium sulfates, as well as hematite, Al-, Ca, NH_4-and K- sulfates, such as $KAl(SO_4)_2(H_2O)_{12}$. The latter may be formed by the reaction of condensed sulfuric acid with ash particles, while the presence of Fe_3O_4 and Fe_2O_3 in the ash samples is evidence for corrosion phenomena that occur within the flue gas and the heating elements of the air preheater.

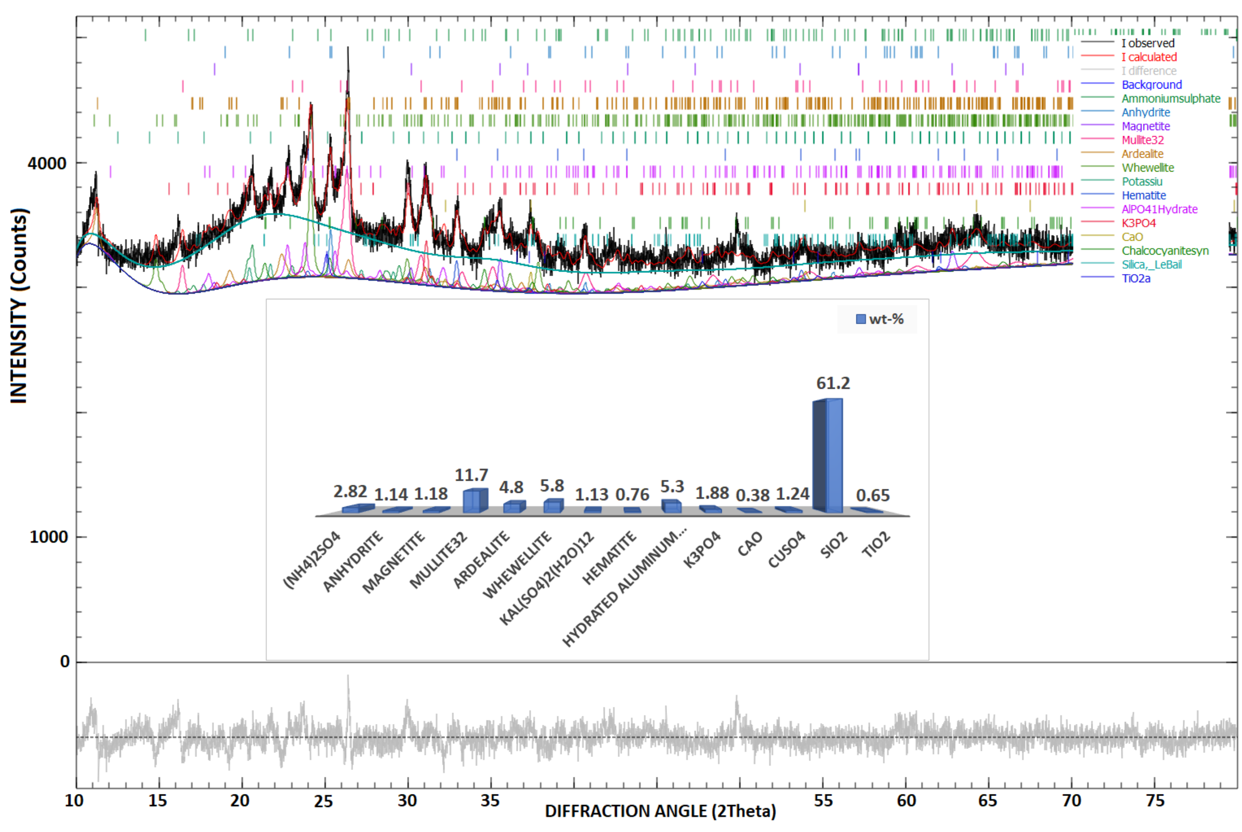


Exhibit 3.1.4. A Representative XRD Diffractogram (Experimental and Simulated) and Phase Determination of Sample DK_05.

3.1.3. Morphology and Interfacial and Surface Characteristics

The surface characteristics and morphology on a microscopic level were detected via SEM-EDS. SEM micrographs of the ash deposits provided evidence for the presence of agglomeration, as well as information regarding the deposition process on the metal surface of the air preheater. EDS combined with the SEM micrographs reported on the ash composition by mapping the surface of each deposit at selected regions, as shown in **Exhibit 3.1.5**.

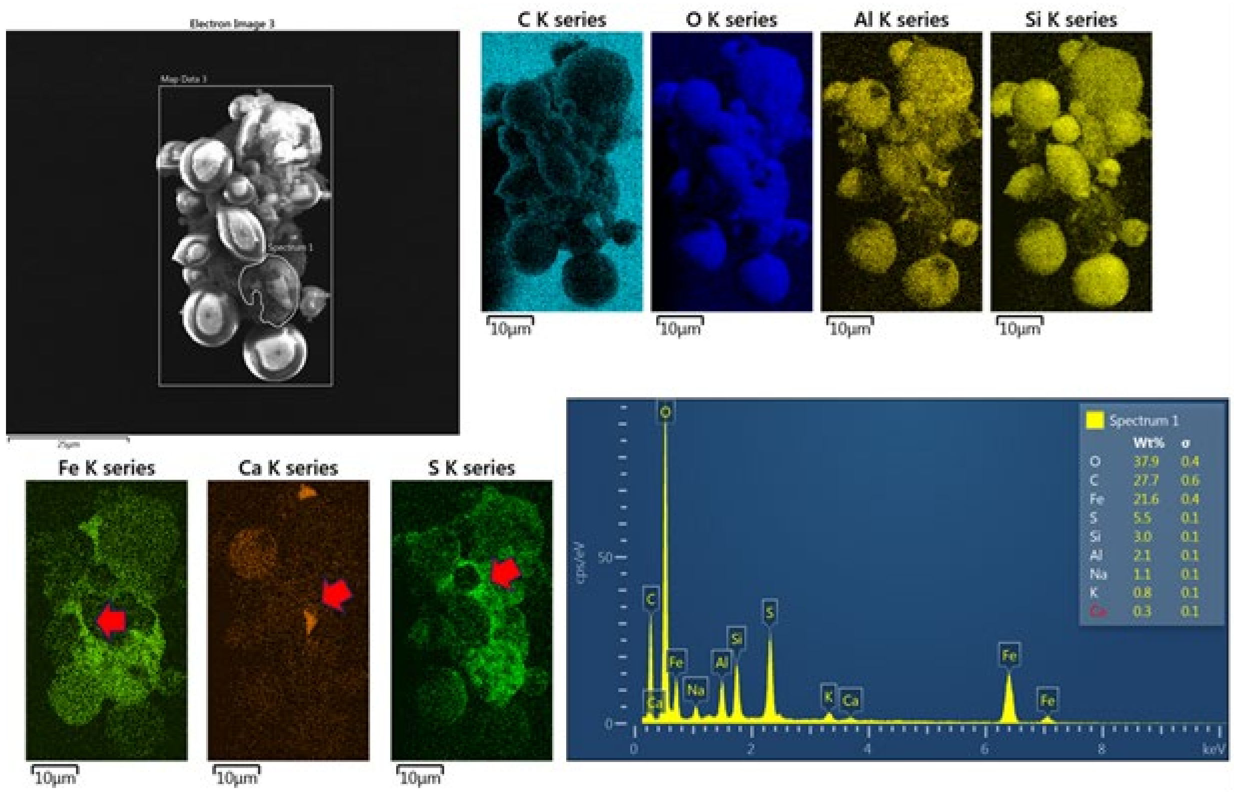


Exhibit 3.1.5. Representative SEM Image and EDS Spectral/Mapping Analyses of Sample DK_01.

The **Exhibit 3.1.5** is a representative example of the SEM-EDS analysis of sample DK_01 that was located in the cold side (gas outlet) of the air preheater. The ash particles showed spherical as well as irregular shaped agglomerated structures. The EDS spectral analysis and EDS mapping at different positions suggested the presence of unburnt carbon, corrosion products (Fe), Ca and sulfur (S). Furthermore, EDS mapping of different elements unveiled the presence of increased sulfur and iron content at the interface of the agglomerated ash particles, acting as adhesion agents during the ash deposition.

The surface chemistry of the ash deposits was further determined by performing XPS measurements. As shown in **Exhibit 3.1.6**, the presence of high sulfur and nitrogen content on the surface of all samples confirmed the formation of ammonium sulfates and other ammonium salts during the ash deposition.

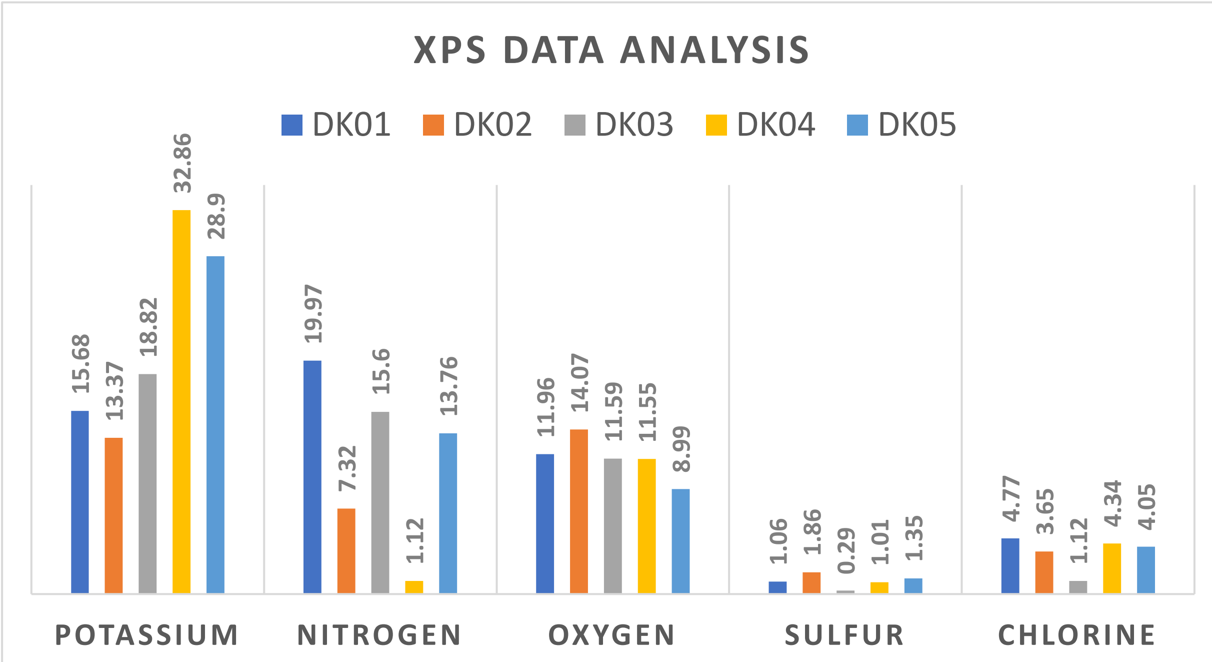


Exhibit 3.1.6. XPS Results of Ash Deposits.

Finally, Ion Chromatography via water leaching of the ash deposits was also performed in order to determine the volatile matter, such as ammonia, immediately after the ammonia extraction procedure. The IC analysis of the test samples determined the concentration of ammonium, sulfates, sodium, potassium, magnesium, chloride, fluoride, and calcium (simultaneous anion and cation analysis). The presence of a high content of ammonium and sulfates verified the presence of ammonium sulfate/bisulfate, and the detection of magnesium, fluoride and calcium provided information regarding the ash deposition rate and thickness, since these elements act as cementing/adhesion agents in the deposition process in the air preheater. The results are shown in **Exhibit 3.1.7.**

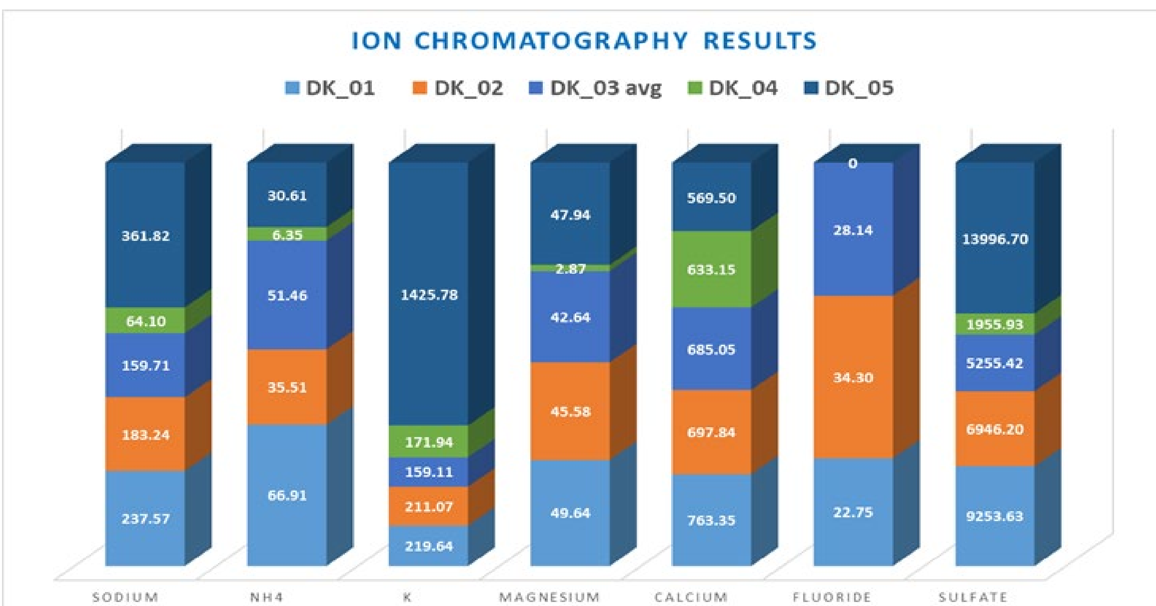


Exhibit 3.1.7. IC Results of Ash Deposits (Results Expressed in ppm).

Similar to the XPS, EDS and XRF aforementioned results, the IC data confirmed the presence of high ammonia and sulfate contents for the samples DK_01 (gas outlet) and DK_05 (gas inlet). Moreover, a very high amount of calcium, fluoride and potassium was detected in all samples, in accordance to the SEM-EDS and XPS results, showing their cementing action between the different shaped and sized ash particles, as shown in **Exhibit 3.1.8**.

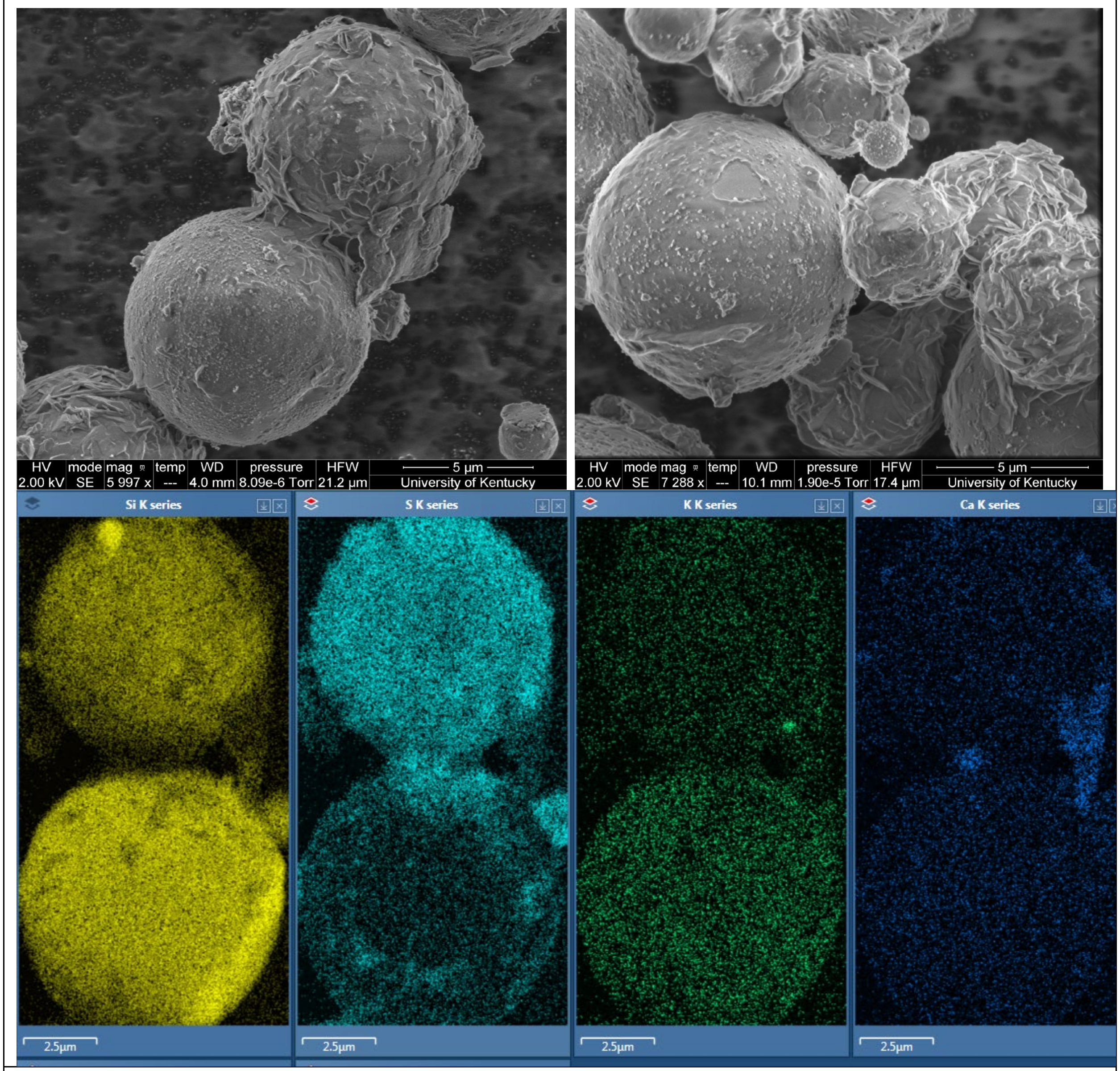


Exhibit 3.1.8. SEM Images and EDS Mapping of Ash Sample DK_03, Showing that High Sulfur and Calcium Contents Act as Adhesion Agents Between Agglomerate Ash Particles.

3.1.4. Thermogravimetric Analysis and Heat treatment

The thermal properties and volatilization processes have been measured for the cold side of the APH as shown in **Exhibit 3.1.9**.

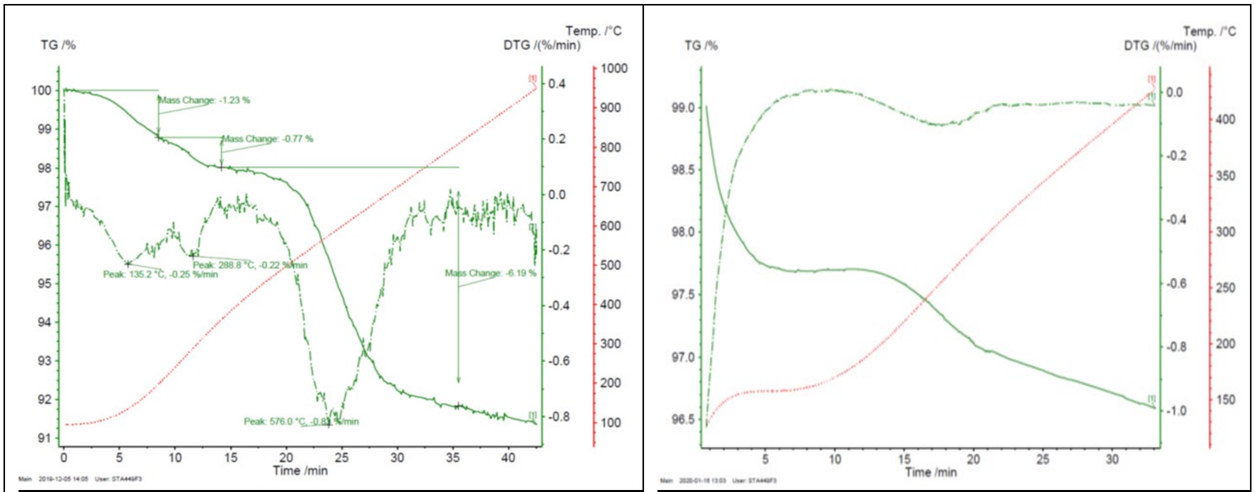


Exhibit 3.1.9. TGA Curves of Ash Sample DK_01 and Total Thermal Decomposition of NH_4-sulfates, that Takes Place Around 380-500°C.

The TGA curves for DK_01 present its mass variation between 99°C-500°C. The transition and weight loss around 300°C unveils the start of decomposition process of NH_4-sulfates (e.g. ABS, NH_4HSO_4). Furthermore, the total thermal decomposition of the NH_4-sulfates takes place around 380-500°C, simultaneously with the decomposition of other sulfates, e.g. ardealite (above 450°C) as shown in **Exhibit 3.1.9**. After numerous experiments by adjusting the sample weight, flow rate of the carrier gas (argon) and the heating rate in order to reduce the diffusivity (diffusion resistance by manipulating the operating conditions), kinetic analysis (weight loss rate) via TGA from 99^0C-400^0C at different heating rates of 10, 20 and 30 K min^{-1} under argon atmosphere were measured for reaction kinetic and activation energy determination associated with ash decomposition reactions. The Arrhenius law [$k(T)=A*e^{(-Ea/RT)}$, where A is the pre-exponential factor, Ea is the activation energy and R is the gas constant] is valid and provides the activation energy (110 kJ/mol or 26.3 kcal/mol) of decomposition process of NH_4-sulfates (e.g. ABS, NH_4HSO_4).

Heat treatment of all samples at 350°C and 400°C (30-45 mins) was performed by using a high-temperature tubular furnace. The heat treated samples were collected and chemical analysis via Ion Chromatography, X-Ray Diffraction, Rietveld Refinement, Ammonia Extraction were applied in order to measure ammonium and sulfates concentration.

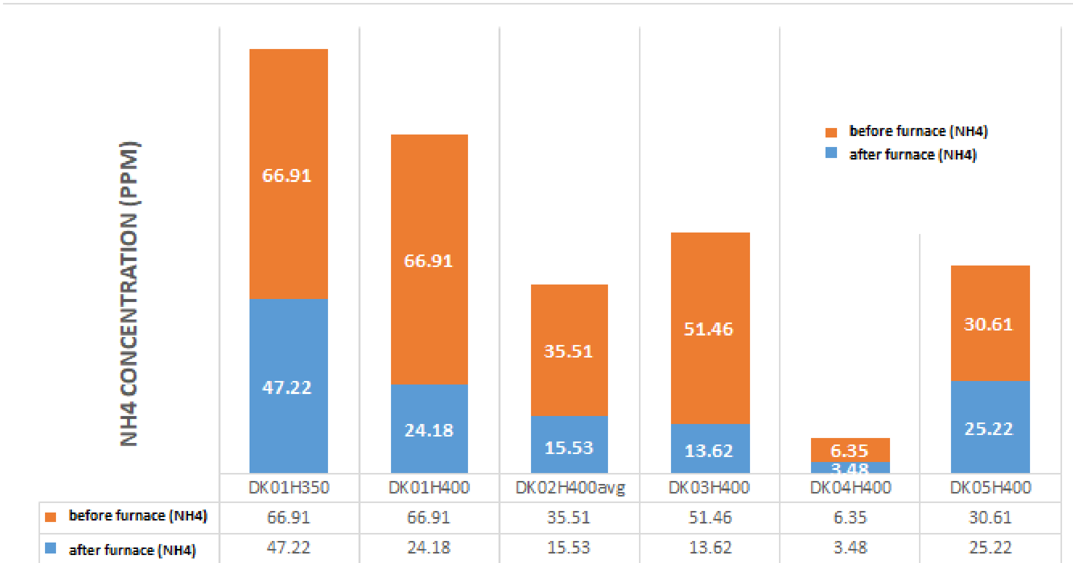


Exhibit 3.1.10. IC Results Reveal a Significant Reduction of Ammonium Concentration after Furnace Experiments.

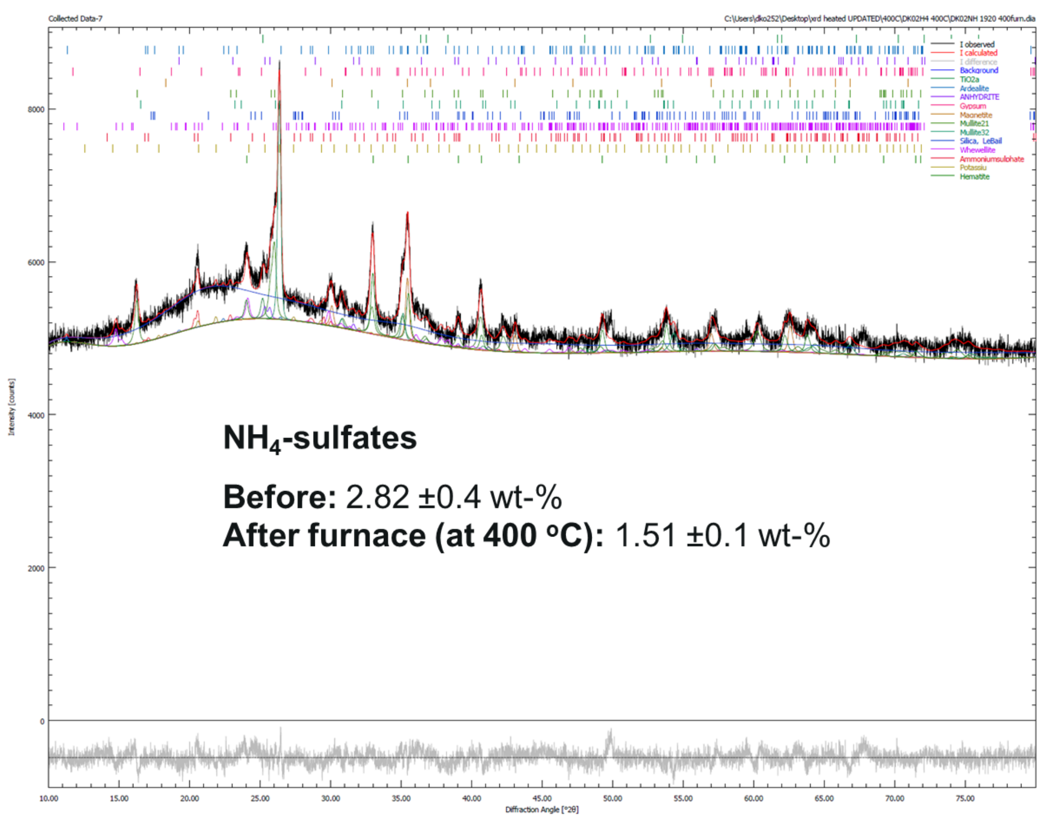


Exhibit 3.1.11. XRD Diffractogram and Analysis Results.

Ion Chromatography shows ammonium concentration to be reduced (approximately 2-3 times) compared to the previously detected, for all samples (cold and hot side of APH) as shown in **Exhibit 3.1.10**. Specifically, after heat treatment, there is 1.5 times (at 350 ºC) reduction of NH_4 content and 3 times reduction after heating at 400 ºC. In addition, XRD analysis microscopically confirms the reduction of ammonium sulfates after the heat treatment at both 350 ºC and 400 ºC at the cold side of the APH (**Exhibit 3.1.11)**. The results reveal a significant reduction (almost 2 times) of NH_4-sulfates after furnace experiments compared to the untreated ash deposits collected from the cold side of the APH. The results after the heat treatment of all samples have been compared to the unheated samples (**Exhibit 3.1.10)**. The significant reduction of ammonium content, after the heat treatment up to 350-400 ºC, will reduce the quick fouling buildup as well as prevent the ABS formation further away from the cold end, into the hotter parts of the air preheater, which is very difficult to be cleaned.

3.1.5. In-Situ XRD with Follow-up SEM and DEM Analysis

In-situ XRD experiments were performed as function of temperature in order to experimentally resemble the operational procedure during the ash deposition within the heating elements of the cold side of the air preheater. In particular, XRD studies, using the high-T stage and controllers on XRD instrument chamber, were performed for studying the decomposition process of NH_4-sulfates of the ash deposits. The in-situ experiments were ranged from ambient temperature up to 500 ºC. Similar experiments were performed by using pure Na_2SO_4 in order to identify the phase transformations that occur during the high-temperature procedure and calibrating the high-temperature stage, accordingly. The determination of the decomposition/deformation temperature of the NH_4-sulfates contained in the deposited ash, based on the crystallographic characteristics was established. **Exhibit 3.1.12** and **Exhibit 3.1.13** present the diffractograms that were obtained as a function of temperature, the main phases' analysis and the reduction of ammonium phase during the in-situ heat treatment.

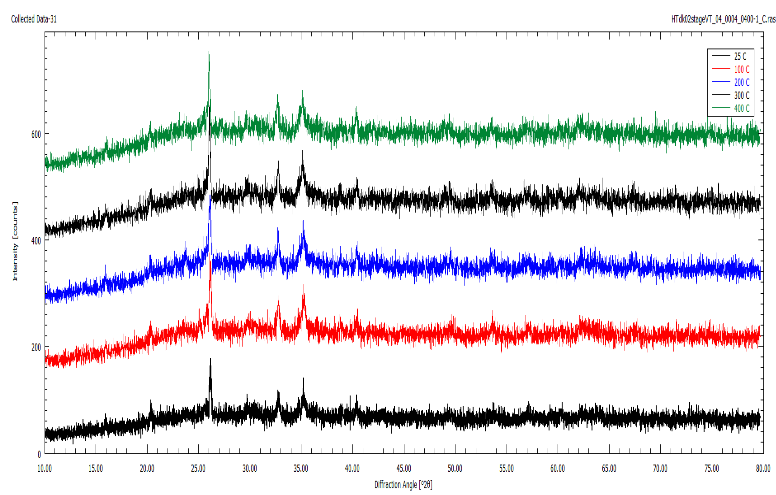
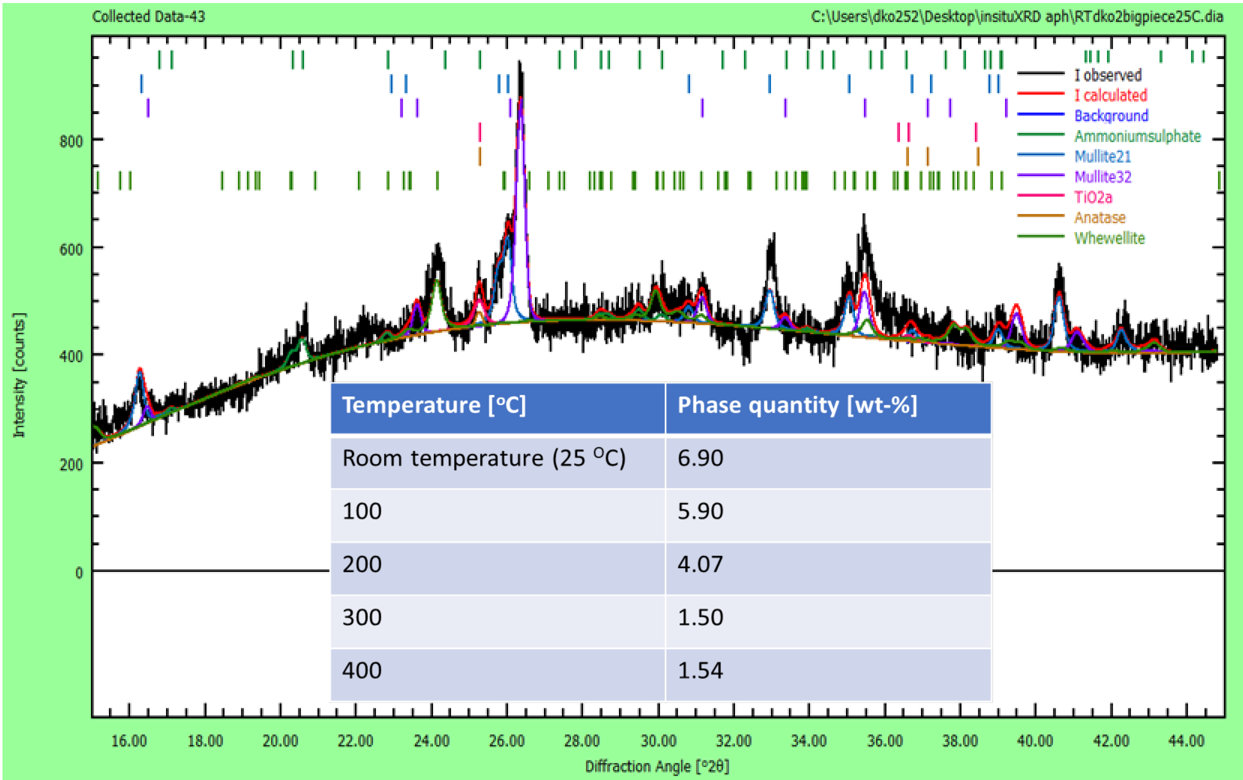


Exhibit 3.1.12 In-situ XRD Diffractograms Ranging Between 25ºC-500ºC.

The main phase is mullite ($3Al_2O_3{\cdot}2SiO_2$ and $2Al_2O_3{\cdot}SiO_2$) which found to systematically transform from $3Al_2O_3 \cdot 2SiO_2$ to $2Al_2O_3 \cdot SiO_2$ (phase transformation) as detected by a gradual change in its lattice parameters (peak shift as the temperature increases). During the heating process the hematite peak also decreases that might be evidence of the formation of new Al- and Si- rich phases that formed during the transformation of mullite. New phases such as $NaAlSi_3O_8$ and $Al_2SiO_4(F,OH)_2$ due to the free Al_2O_3-SiO_2 phases appeared as well as the temperature approached 400 ºC.



Temperature [°C]	Phase quantity [wt-%]
Room temperature (25 °C)	6.90
100	5.90
200	4.07
300	1.50
400	1.54

Exhibit 3.1.13. In-situ XRD Diffractogram Analysis Provide the Main Phases and the Table Reports on the Systematic Reduction in Ammonium Phase during the High Temperature X-ray Experiments.

Hydrated calcium oxalate (whewellite, $CaC_2O_4 \cdot H_2O$) was detected, that serves as evidence of a reaction between the gypsum ($CaSO_4 \cdot 2H_2O$) and unburnt carbon in the ash deposits. During the heat treatment similar to the abovementioned transformations and phase reactions, the XRD diffractograms and analysis results show a systematic reduction of NH_4-sulfates (from 6.90 wt.% to 1.54 wt.%) during the in situ XRD experiments compared to the untreated ash deposit (at ambient temperature). Between the temperature range of 200 °C - 400 °C, NH_4-sulfates formations are melting down and partially decomposed or react with alkali metals and alkaline oxides and so giving new phases, reaffirm the working principle for UKy-IDEA proposed technology demonstrated in this project.

SEM-EDS measurements were performed right after the in-situ XRD experiments in order to detect how the morphology of the ash deposit has been affected after the heat treatment. **Exhibit 3.1.14** presents the SEM images and EDS analyses. The SEM images show that the deposit consists mainly by spherical fine particles with only a small number of flocculent textures on their surface. Larger particles found to be soft and fragile and the smaller particles observed to penetrate within them through the voids. The detected flocculent texture was assigned mainly to sulfur (surficial adsorbed on ash particles and easily act as a cementing/gluing agent after its reaction with alkali metals). EDS spectroscopy confirms that Fe, Al and Si elemental amounts are very high meaning that Fe not only presents as hematite but also may incorporate into mullite ($3Al_2O_3 \cdot 2SiO_2$, main phases) whereas the rest of it reacts with leucite ($KAlSi_2O_6$).

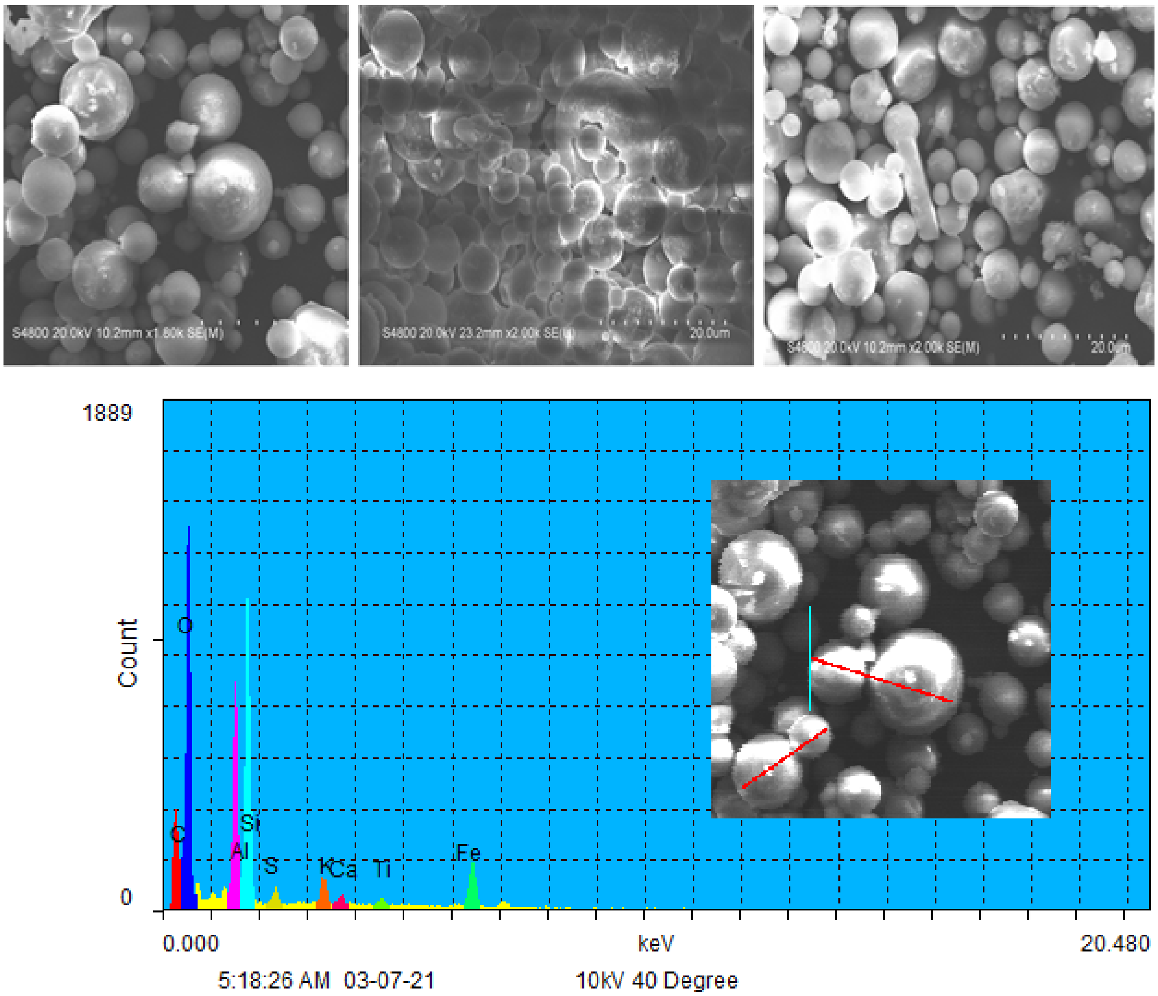


Exhibit 3.1.14. SEM Images and EDS Analysis of Ash Deposit after In-situ High Temperature XRD Study

3.1.6. Brunaeur-Emmett-Teller (BET) Surface Characterization

The Brunaeur-Emmett-Teller (BET) surface characterization method was applied in order to study any difference that may occur between material deposited at the cold and hot ends of the air preheater. The method is based on the sorption (adsorption and desorption) of nitrogen into the pores of the ash deposits and provides an estimation of the isothermal characteristics (isotherm type based on International Union of Pure and Applied Chemistry (IUPAC) classification) as well as a determination of the specific surface area of each sample based on the BET theory.

The specific surface area has been determined for both the cold and hot end of the APH as shown in **Exhibit 3.1.15.** The cold end has a surface area (SA_{BET}) of approximately 1.267 ± 0.016 m^2/g whereas the hot side has surface area is 1.688 ± 0.034 m^2/g. The low cold end surface area is due to enhanced pore blocking by ABS and condensate sulfuric acid as verified with other analytical techniques. The surface area of the ash deposits located at the cold side has a smaller SA_{BET} compared to the ones at the hot end.

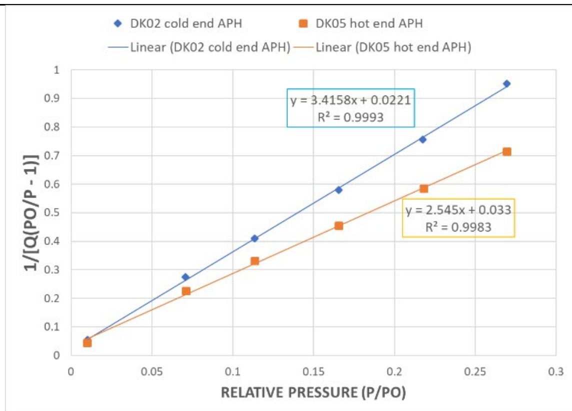


Exhibit 3.1.15. Analysis of Ash Deposits by BET Adsorption/ Desorption for Cold and Hot Side of APH.

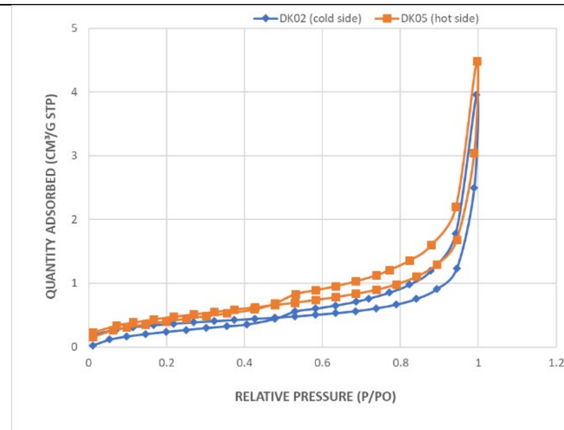


Exhibit 3.1.16. N_2-Sorption Isotherms of Cold and Hot Side of APH.

The N_2-sorption processes will provide information related to the type of pores and their distribution within the tested materials. In the present study on the ash deposits, the obtained isotherms are classified as IV type (based on IUPAC classification). The IV type is an indication of a mesoporous character and this character seems to hold for samples collected on both sides of the air preheater as shown in **Exhibit 3.1.16.** The type IV isotherm (IUPAC) suggests a mesoporous character for both sides of the air preheater.

3.2 Pilot Unit Design

3.2.1 PFD and P&ID

The process flow diagram, the piping and instrumentation diagram and the instrument list of the pilot unit are shown in **Exhibit 3.2.1**, **Exhibit 3.2.2**, and **Exhibit 3.2.3,** respectively. Gas enters unit from top tie-in duct (entering the host APH) and exits to bottom tie-in duct (exiting the host APH). Air enters the unit from atmosphere and exits to bottom tie-in duct. Auto control valves are placed at gas inlet and outlet as well as air inlet and outlet, that are used to control alternating flow between flue gas and air. Four manual valves are placed at upstream of each inlet end and downstream of each outlet end for isolation of the unit when needed. Manual valves remain fully open during operation. Pressure transmitters are placed at the gas and air inlet. Flue gas flow is driven by pressure difference across the host APH between the top tie-in duct and the bottom tie-in duct. Air flow is driven by the pressure difference between the ambient and the bottom tie-in duct. Blower is eliminated for process simplification and easy unit operability. Differential pressure transmitter is placed across heating elements, with high leg connected to the upstream of pilot APH in the direction of gas flow, and low leg connected to the downstream of gas flow. With such connection, one differential pressure transmitter is used for both gas (positive reading) and air flow (negative reading). Thermocouples are placed to measure the temperature at flue gas inlet and outlet, air inlet and outlet, as well as heating element at hot end and cold end. Flow meter is placed on air stream for air flow rate measurement. There is no available flowmeter on the flue gas stream given its high temperature, and high particle-laden condition. Flue gas flow rate for the pilot unit is calculated by heat balance, and verified/confirmed by SO_2 doping method. An MFC is used to dope preset amount of SO_2. Analyzer is used to measure the concentration of SO_2 before and after the doping.

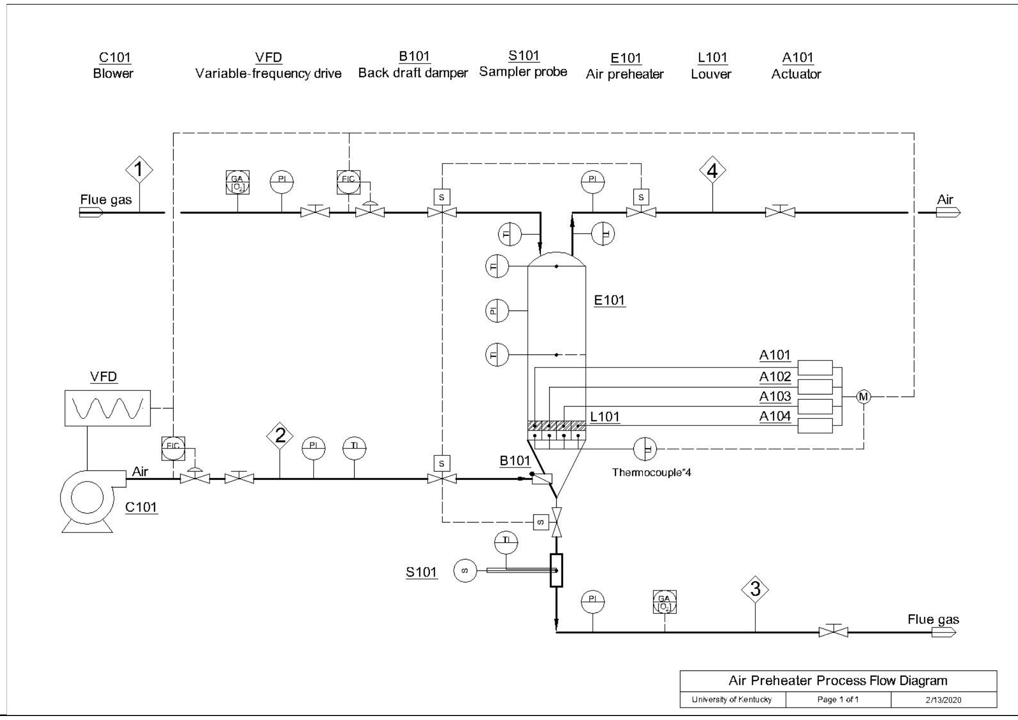


Exhibit 3.2.1. The Process Flow Diagram (PFD) of APH.

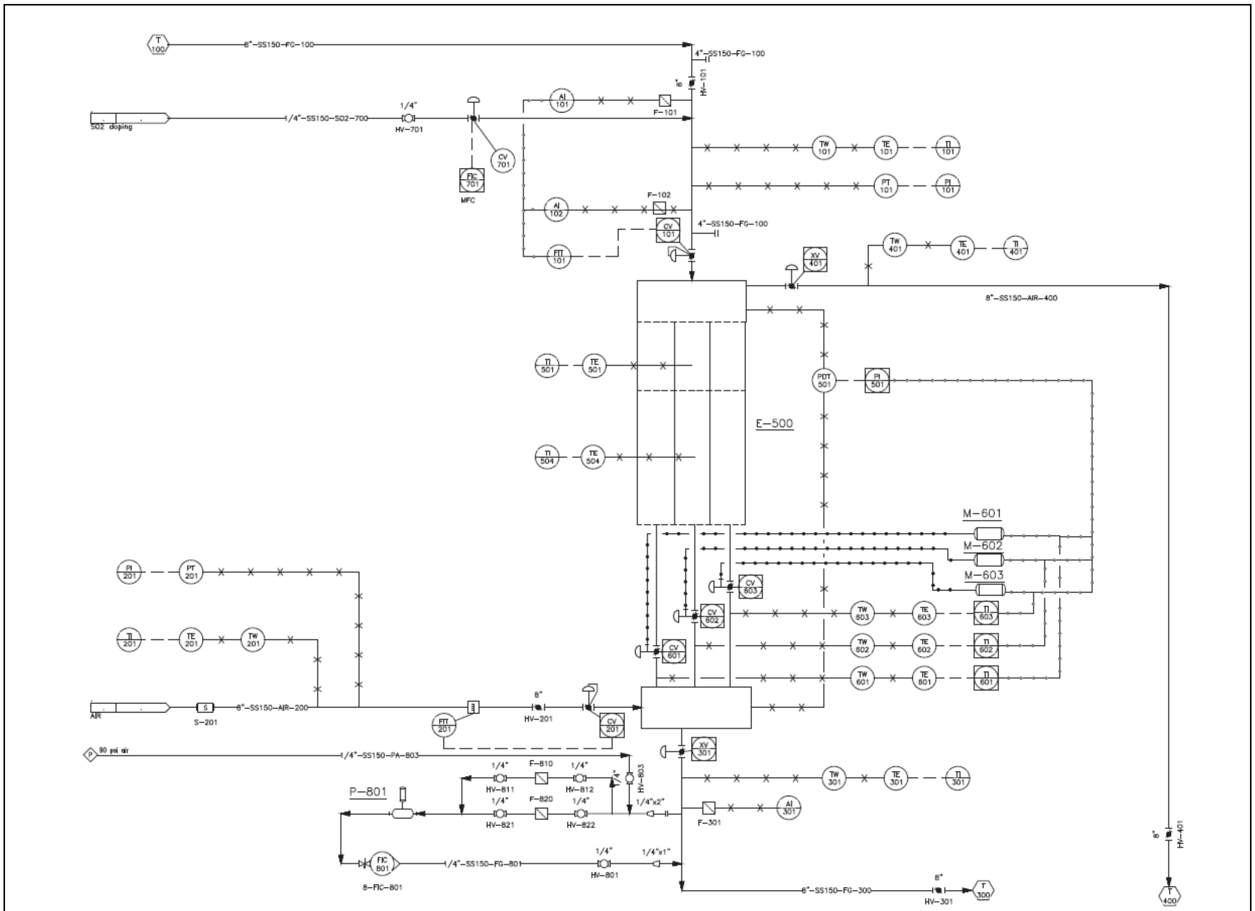


Exhibit 3.2.2. Piping & Instrumentation Diagram (P&ID)

Exhibit 3.2.3. The Instrument List

No	P&ID Tag No.	Items	Manufacture	Type/Model	Qty.	Details
1	FIT-201	Thermal mass flow meter	Endress+ Hauser	T-mass I 300, 6I3BL1	1	0~16500 lb/hr, 4~20 mA
2	AI-101,102, 301	Gas analyzer	Horiba	VA-5111G	1	CO_2, SO_2, O_2
3	PI-101, 201	Pressure Transmitter	Endress+ Hauser	Cerabar S PMC71	2	-12~ 0 in wc
4	PDI-501	Differential Pressure Transmitter	Endress+ Hauser	Deltabar S PMD75	1	-6~ 6 in wc

5	TI-201, 301, 401	Thermocouple	OMEGA	NB1-CPSS-14G-12, Type T	3	1/4” diameter, 12”length, 0-370°C (32-700 °F)
6	TI-101	Thermocouple	OMEGA	NB1-ICSS-14G-12, Type J	1	1/4” diameter, 12”length, 0-720°C (32-1300 °F)
7	TI-501,504, 601,602, 603	Thermocouple	OMEGA	NB1-ICSS-18G-12, Type J	5	1/8” diameter, 12”length, 0-520°C (32-970 °F)
8	CV-101, 201	Butterfly valve	Flowserve	8"FKXCS/CS-B200F, Automax B200s10, Pulsair # 4L93SWM2P4	2	Stop, regulate, and start flow
9	XV-301, 401	Butterfly valve	Flowserve	8"FKXCS/CS-B200F, Automax B200s10, Solenoid, WT8551A001MS-24, Switch Box, NXCLU2M1-14	2	Stop, and start flow
10	HV-201, 301, 401	Butterfly valve	Flowserve	8 FKX RNLG-APA1-A-1AA-G150, Gear	3	Stop, and start flow
11	HV-101	Butterfly valve	Flowserve	8 FKX RNLG-APA1-A-1AA-G150, Chain	1	Stop, and start flow
12	FIC-701	MFC	Aalborg	GFCS-020960	1	THERMAL MFC 316 SS SO2 0-30 STD L/MIN

3.2.2 Process Risk Analysis

The risk analysis is given in **Exhibit 3.2.4**. The entire unit is operating at a negative pressure condition and hence there will be no leak for the flue gas to the outer ambient atmosphere during the unit operation. The main risks of system operation are the loss of the gas from power plant, the malfunction of actuators, the loss of power on the instruments and the loss of air supply. For the loss of flue gas, there no safety issues other than a process restart. All control valves are fail closed (CV-101,201, XV-301,401).

Exhibit 3.2.4. HAZOP Analysis Table

Item No.	Stream No.	What-If	Details	Consequences	Recommendations for Engineering and Administrative Controls
1	1	Loss of flue gas from the power plant	Host plant goes offline, and no flue gas in the flue gas line and a "no flue gas entering" alarm on the control system indicated on FIC-101	No safety issue other than a process operational problem. Unit will be cooled down. Fly ash may accumulate in heating elements.	1) Check the status of the control valve CV-101,201 and XV-301, 401 with respect to the indicator for open and close. 2) Check the Flue gas inlet temperature and pressure drop. 3) Shut down the system. Close all control valves (CV-101,201, XV-301,401).
2		Actuator Malfunction	Auto-control valves all equipped with actuator to achieve automatic operation.	Valves won't be operatable automatically.	1) Remove interlock among valves and try independent operation. 2) Check instrument air. 3) Repair or replace.
3		Loss of Power	All instruments, computer and control need power to function.	Control computer workstation, control I/O, instruments will not be functional.	1) All control valves should be fail to close. 2) Bring back power.

4	1,2,3,4	Loss of Instrument Air	All actuators for control valves need instrument air to function.	Control valves will not be operatable and fail to close.	1) Check and bring back air supply. 2) All control valves should be fail to close.

3.2.3 Unit Design Parameters

The heating elements have two layers, the hot end layer and cold end layer. Both layers of the heating element have the same frontal area (10” x7.2”). The hot end layer of the heating element uses a 14” deep layer of LJUNGSTRÖM’s open channel type heating element. The configuration of the packed heating elements is shown in **Exhibit 3.2.5.** The cold end layer of the heating element uses a 26” deep layer of fully closed channel type of heating element. The selected available heating elements are the same as the existing heating elements baskets used in the air preheater at host site.

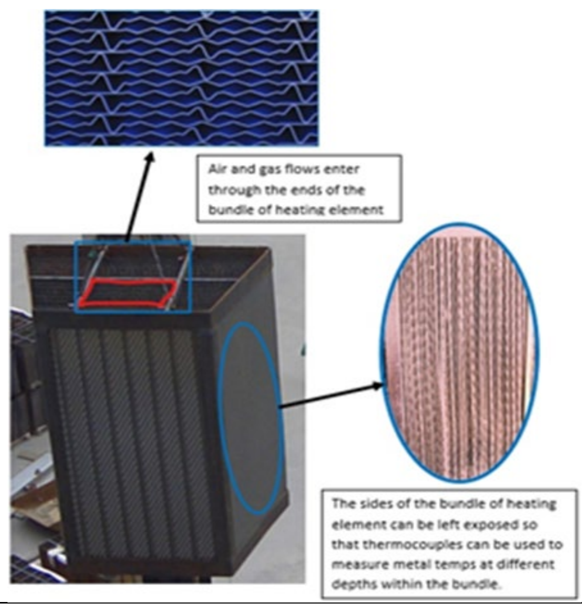


Exhibit 3.2.5. LJUNGSTRÖM’s Heating Element and Configuration.

The detailed mass and heat balance at full-loaded operating conditions of APH is shown in **Exhibit 3.2.6.** The comparison of the calculation between UKy IDEA’s calculation and LJUNGSTRÖM’s prediction shows negligible discrepancies. The gas entering temperature is chosen as 700 °F from the operation of E. W. Brown Station. The gas flowrate is designed as 3000 lbs/hr. The pressure drops on both air side and gas side are predicted to be 1.5 in wc and 2.0 in wc, and these are smaller than the pressure drops for the air preheater in the station without ash deposited.

Exhibit 3.2.6 Dimension and Full-Load Operating Parameters of APH.

Switching Regenerator	IDEA/IU	IDEA/U.S.	LJUNGSTRÖM Predicted
Gas entering temperature	371.1 ℃	700.0 °F	700 °F
Gas leaving temperature	148.9 ℃	300.0 °F	239 °F
Gas flow rate		3000 lbs/hr	3000 lbs/hr
Air leaving temperature	318.1 ℃	604.6 °F	605 °F
Air entering temperature	30 ℃	86.0 °F	86 °F
Air flow rate		2857 lbs/hr	2857 lbs/hr
Gas velocity	15 m/s	49.2 ft/s	47.3 ft/s
Air velocity	7.4 m/s		
Width	0.3 m	10.0”	10”
Length	0.3 m	10.0”	~7.2”
Height	1.7 m	68.0”	40”
Gas flowing time	24 /s		
Air flowing time	24 /s		
Gas-side dP*			2 in wc

Air-side dP*			1.5 in wc

The mass and heat stream table is shown in **Exhibit 3.2.7.** Four streams, including flue gas entering line, air entering line, gas leaving line, and air leaving line, show the parameters of mass and heat transfer balance. The inlet/outlet temperatures of both air and gas sides are given with the set pressure and flowrates. The gas and air compositions are collected from E.W. Brown Station, a PPL facility. The fly ash in the flue gas is also considered in the calculation. Due to nature of alternate operation between flue gas and air, there will be no leak on both air and gas sides. The flowrates of flue gas and air are the same between the inlet and outlet. The parameters of the heat transfer balance are shown in **Exhibit 3.2.7**.

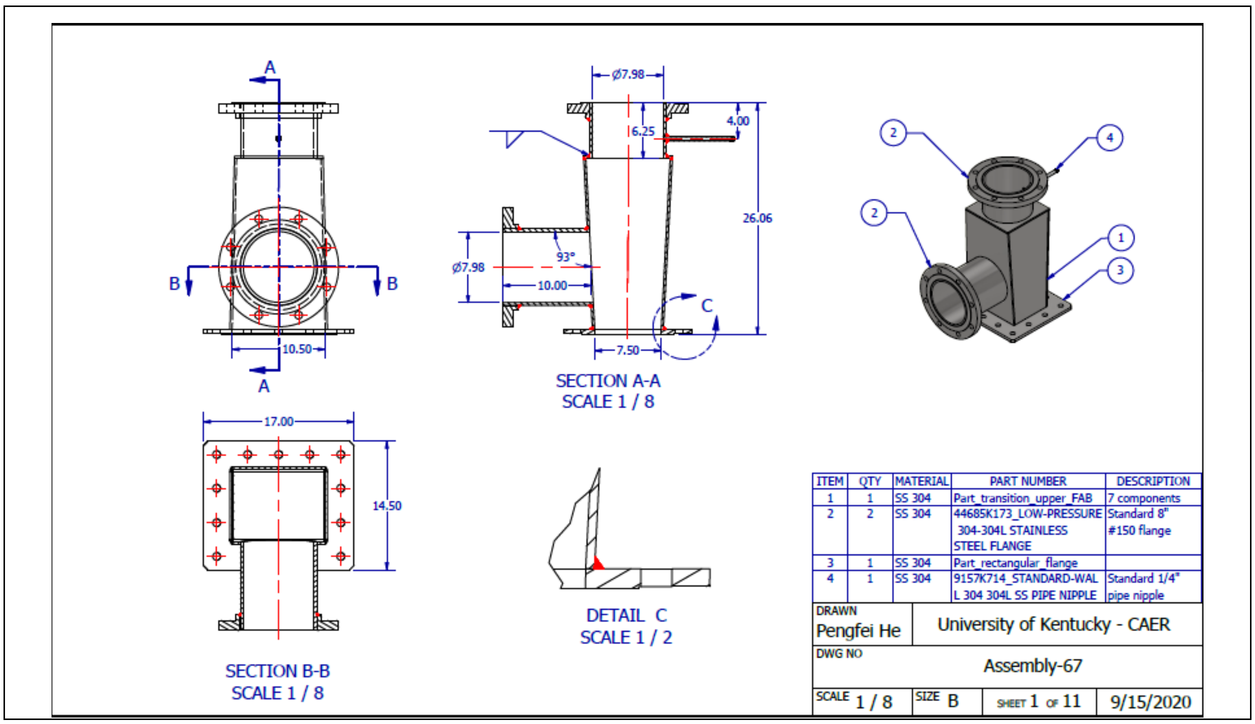
Exhibit 3.2.7. Mass and Heat Transfer Balance Stream Table.

Stream No.	1	2	3	4
Description	Gas entering	Air entering	Gas leaving	Air leaving
Temperature (°F)	700	86	239	605
Temperature (℃)	371	30	115	318
Pressure (Bar)	1.0	1.0	1.0	1.0
Fluid phase	Flue gas	Air	Flue gas	Air
Mass flow rate (lbs/hr)	3000	2857	3000	2857
CO_2	4.934	0.000	4.934	0.000
N_2	35.007	9.412	35.007	9.412
H_2O	2.261	0.000	2.261	0.000
O_2	2.240	35.526	2.240	35.526
SO_2	0.406	0.000	0.406	0.000
NO_x	0.000	0.000	0.000	0.000
Fly Ash	0.370	0.000	0.370	0.000
Total flow (kmol/hr)	45.2	44.9	45.2	44.9
Total flow (lbs/hr)	3000	2857	3000	2857
Total flow (kg/hr)	1361	1296	1361	1296
Gas fraction (%)	99.2	100.0	99.2	100.0
Liquid fraction (%)	0.000	0.000	0.000	0.000
Solid fraction (%)	0.818	0.000	0.818	0.000
Density (kg/m^3)	0.552	1.164	0.920	0.598
Molecular weight (g/mol)	30.094	28.838	30.094	28.838
* * Gas phase * *				
Enthalpy (kJ/kg)	4645.6	269.5	1395.0	2936.7
Viscosity (cP)	0.031	0.019	0.021	0.030
Convection heat transfer coefficient (kW/m^2 K)	0.056	0.040	0.056	0.040
Thermal conductivity (W/m K)	0.047	0.026	0.031	0.045
Velocity/ft/s	47.3	21.4	47.3	21.4
Velocity/m/s	14.4	6.5	8.7	12.7
* * Liquid phase * *				
Viscosity (cP)	-	-	-	-
Thermal conductivity (W/m ℃)	-	-	-	-
* * Solid phase * *				
Fly ash (g/m^3)	12.0	0.0	12.0	0.0
Fly ash (kg/h)	29.6	0.0	29.6	0.0
Enthalpy (kJ/kg)	15.445	-	9.304	-

Total flow (lbs/hr)	3000	2857	3000	2857

3.2.4 Engineering Drawings and General Arrangement

Four components that house the heating elements and direct air and gas flow were designed and sized according to the energy and mass balance calculation as shown in **Exhibit 2.1.6**. The CAD drawing of the four components with detailed dimensions are shown in **Exhibit 3.2.6**. The parts in drawing Assembly-67 and Assembly-11 are designed to connect both air and gas pipes and convert rectangular heating element housing to regular NPS 8 pipes. The parts in drawing Assembly-8 and Assembly-9 are designed to house hot end and cold end heating elements, respectively. Note that to reduce overall weight, ¼" plates thickness were used for rectangular flanges and Sch. 10 pipes were used for air flow side. Sch. 40 pipes were used for flue gas pipe to account for the highly corrosive condition. The 3D model of the air preheater housing and the details of whole air preheater unit is shown in **Exhibit 3.2.7**.



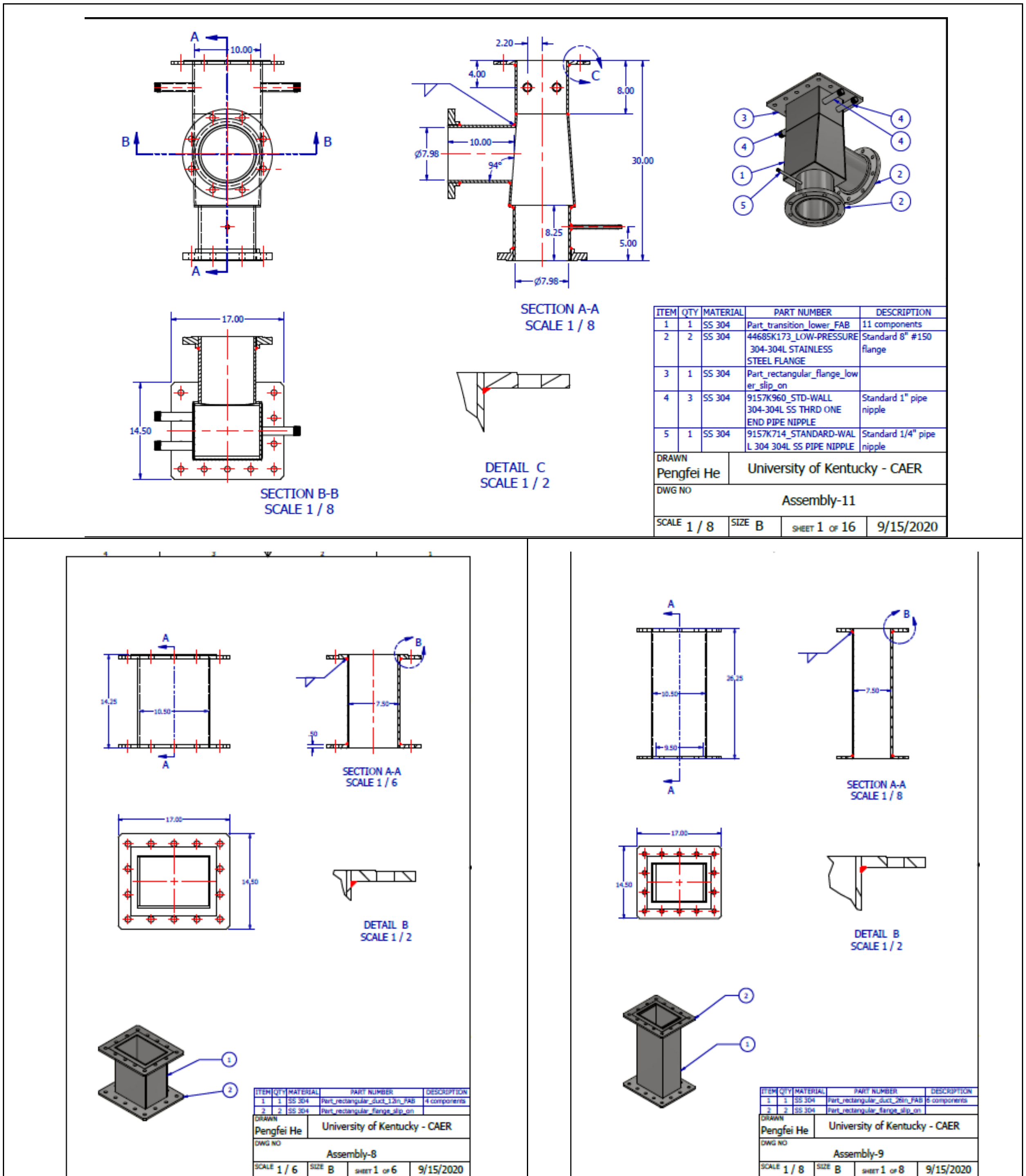
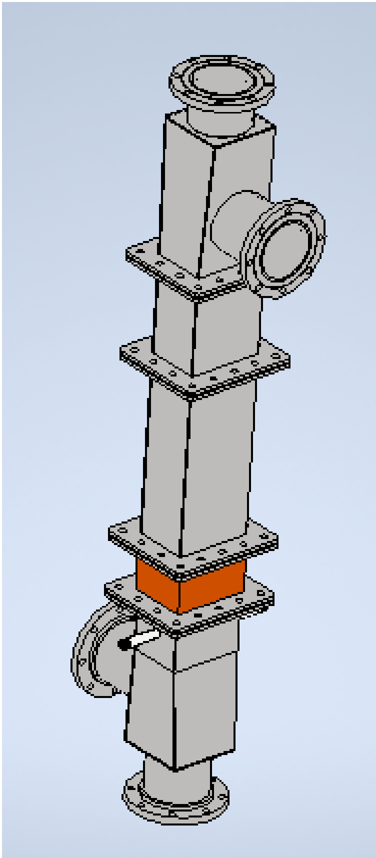
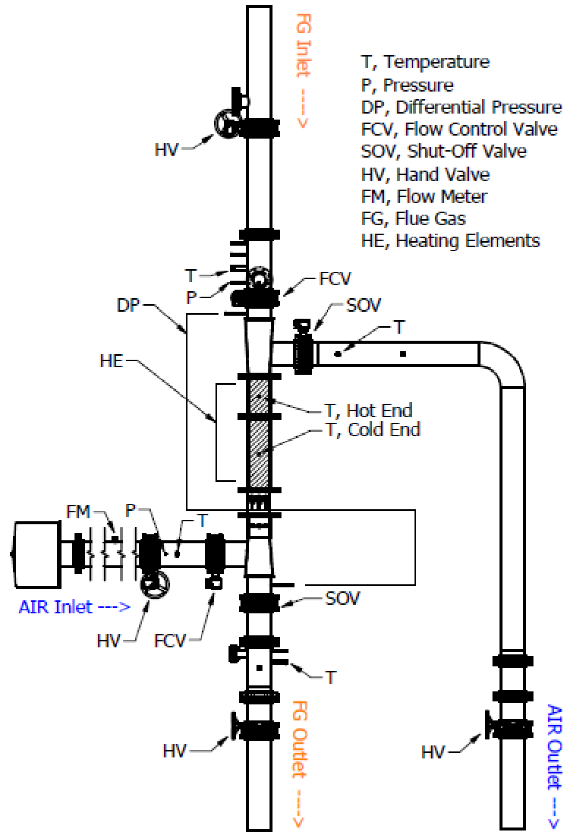


Exhibit 3.2.6. Engineering Drawings of Heating Element Housing Components



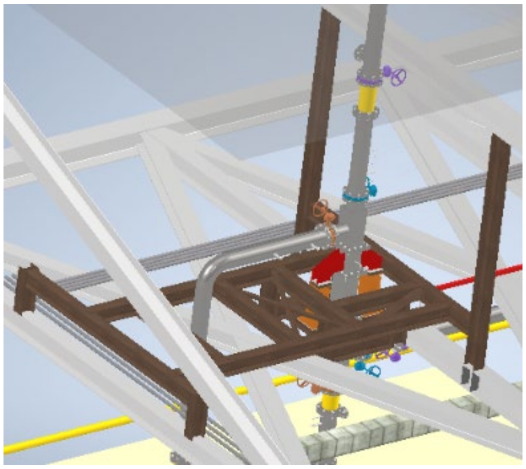
Heating Element Housing Unit



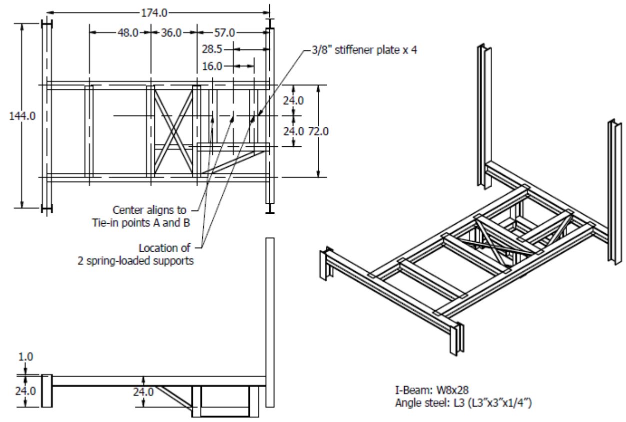
Detailed Air Preheater Unit

Exhibit 3.2.7. 3D Model Drawing of the Air Preheater.

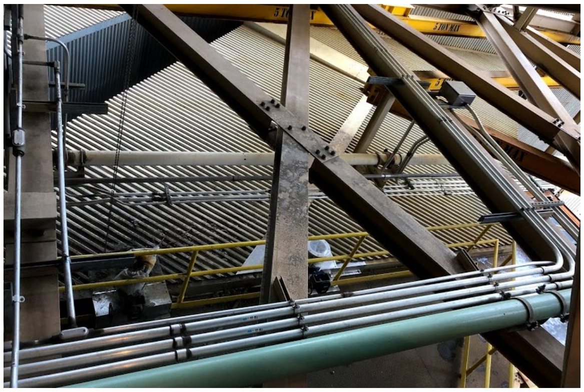
The unit supporting structure and platform was designed by UKy-IDEA, collaboratively with PPL, to suit the host site complex duct and I-Beam structure, as shown in **Exhibit 3.2.8**. The Structural Steel Plan & Detail drawn by Blau the contractor, were reviewed and approved by UKy-IDEA and PPL, shown in **Exhibit 3.2.9**.



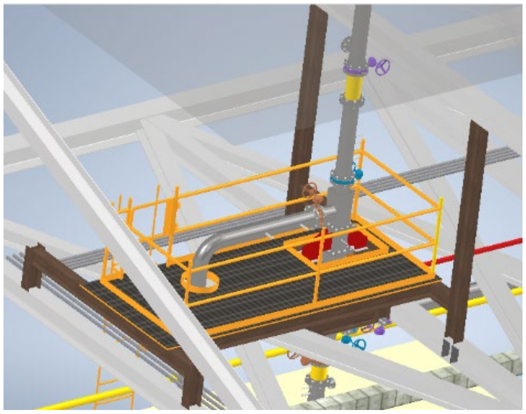
Supporting Frame (Dark Brown Color)



Detailed Dimension of Supporting Beams



On-site Conduit Pipes and I-Beams Considered During the Design



Designed Platform

Exhibit 3.2.8 Complete Design of Supporting Frame and Platform.

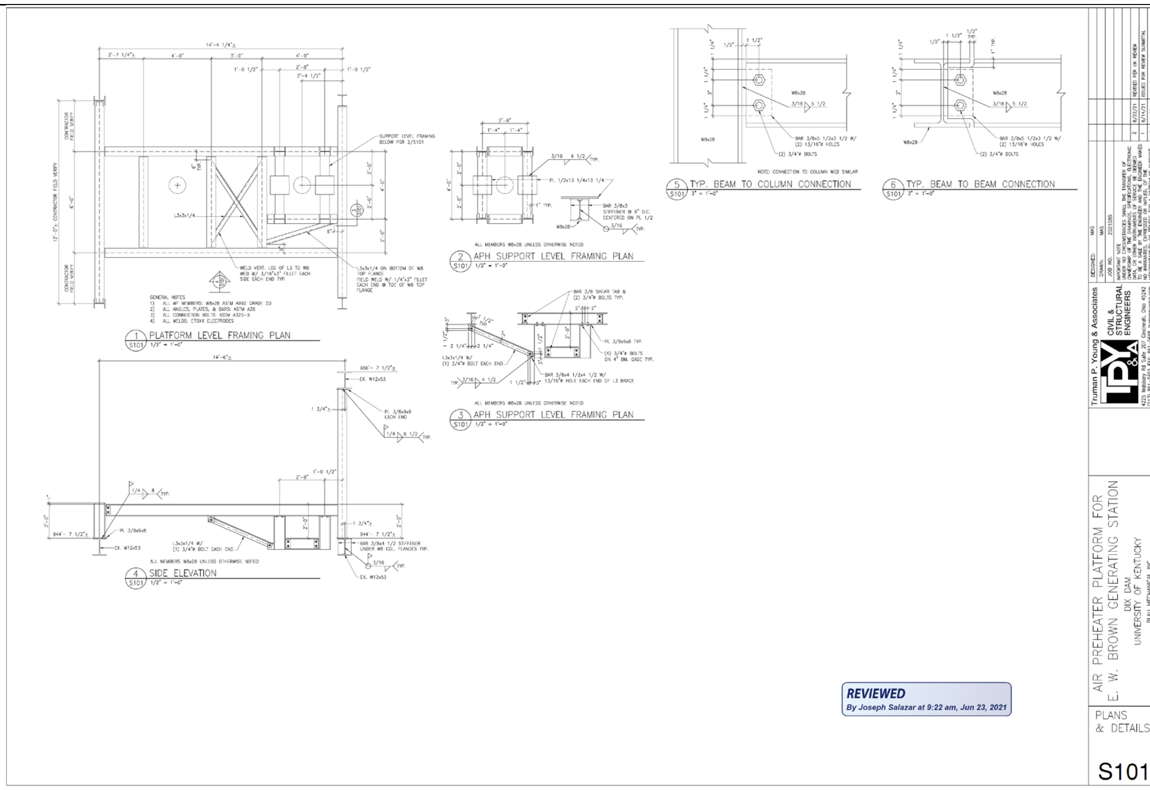


Exhibit 3.2.9. Structural Steel Plan & Details Submitted by Blau Mechanical.

The general arrangement 3D model of the air preheater pilot unit is shown in **Exhibit 3.2.10.** The pilot unit is fit vertically in the 255” height space between two flue gas ducts. Considering thermal expansion, two metal bellows expansion joints are placed at gas and air outlet section of the unit to accommodate the change in length at high temperature. In addition, stainless steel braided flexible hose is used at the gas inlet section of the unit to connect the top tie-in duct and account for any lateral movement due to uneven expansion of gas duct. Two spring load supports are placed underneath the unit (one at each side) to hold weight of the entire unit and account for thermal expansion. Two spring hangers are used to hold the weight of horizontal air inlet piping. Three tie-in points for gas inlet/outlet and air outlet located on Flue Gas Duct 3B are shown in detail in **Exhibit 3.2.11.**

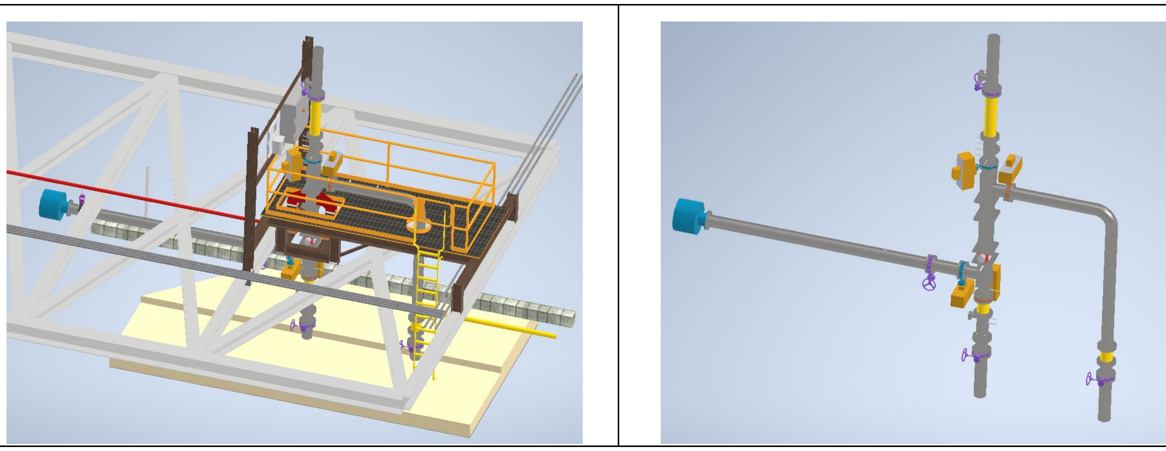
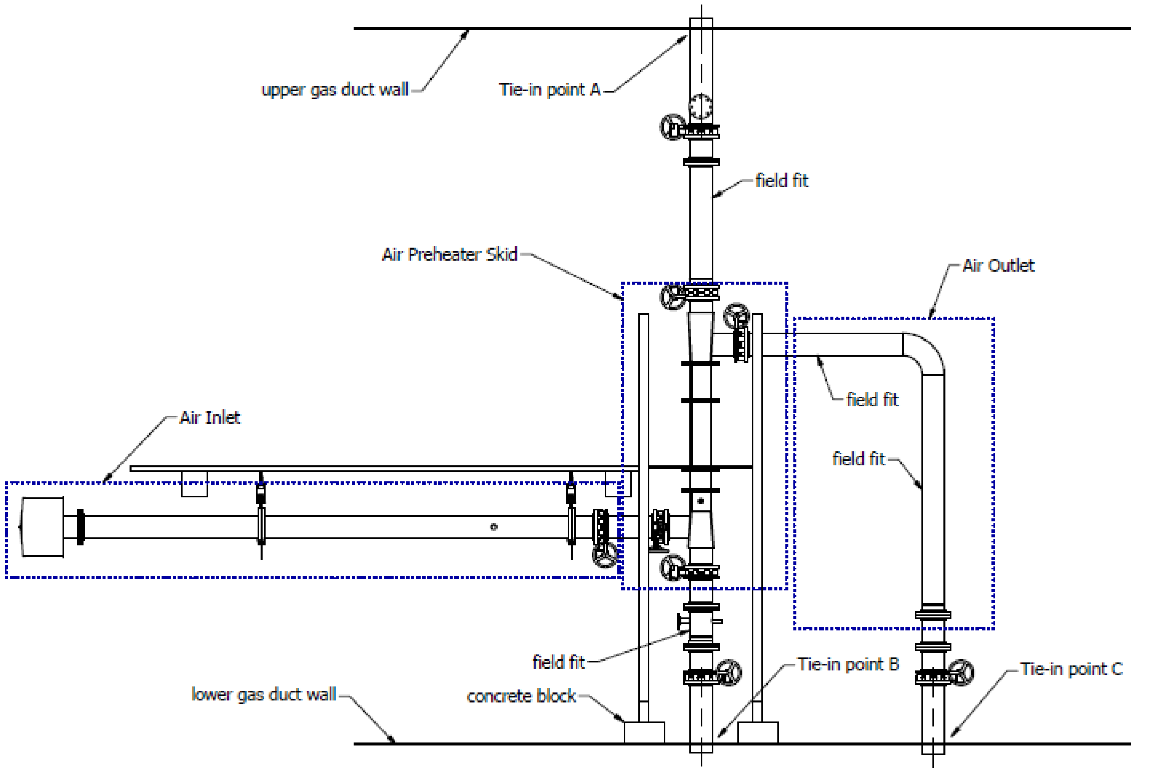
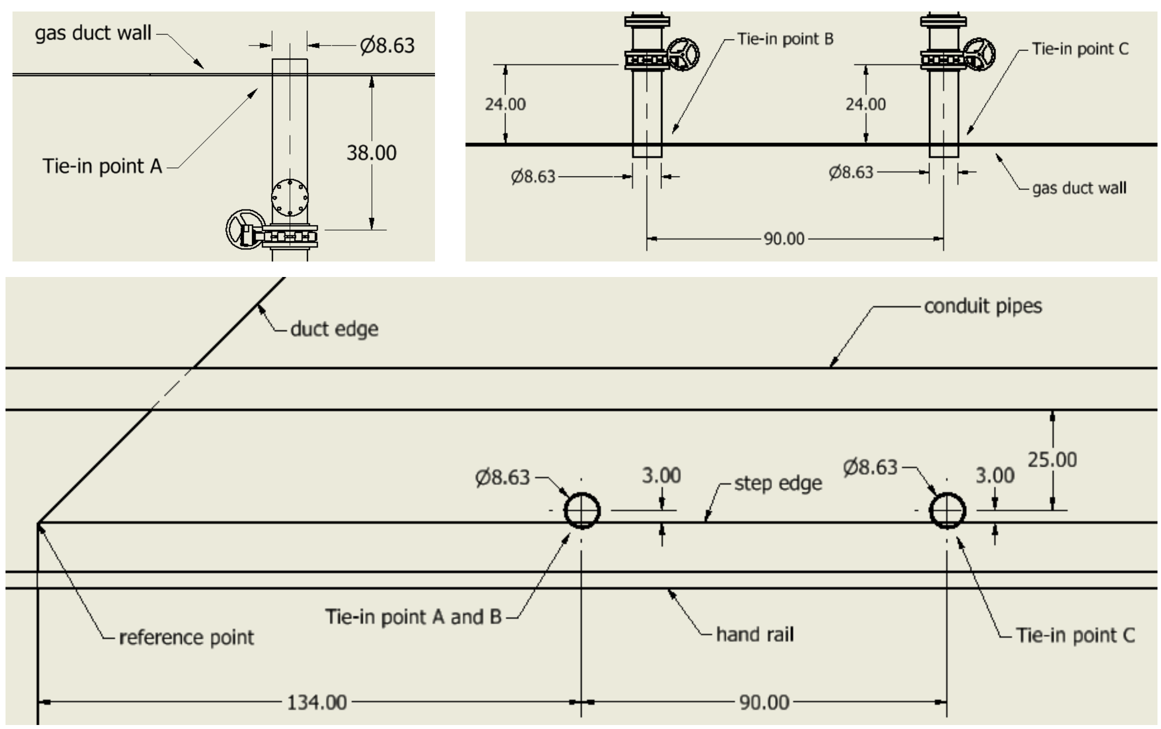


Exhibit 3.2.10. The 3D Model Drawing of the Air Preheater Unit with (Left) and without (Right) Suroundings.



a. Overview Location of Three Tie-in Points

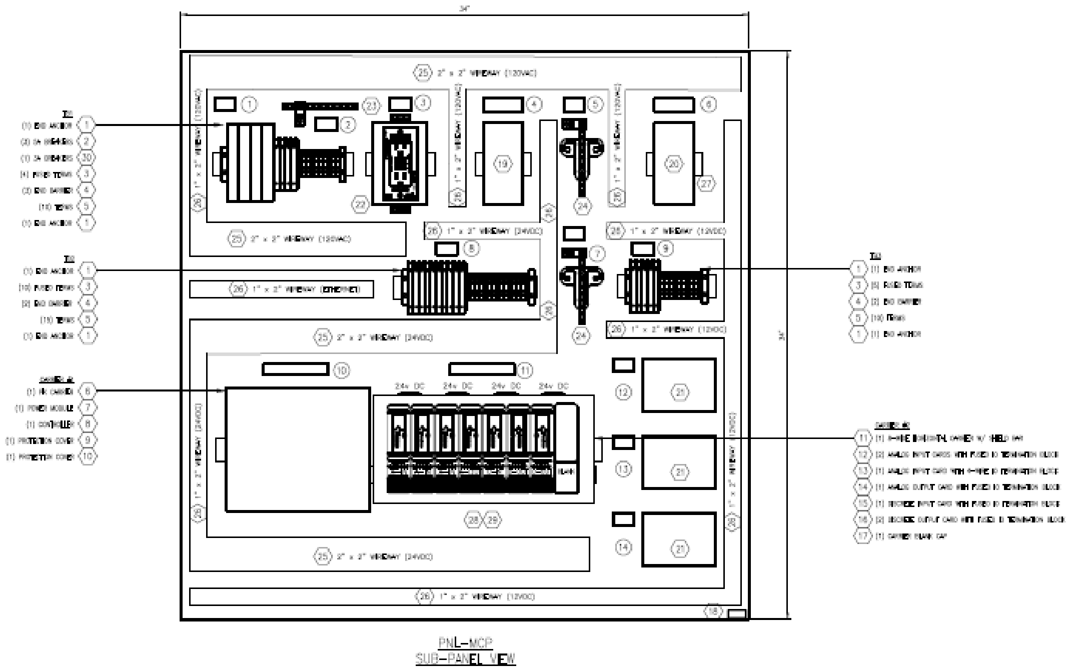


b. Detailed Location of Three Tie-ins (Front and Top View)

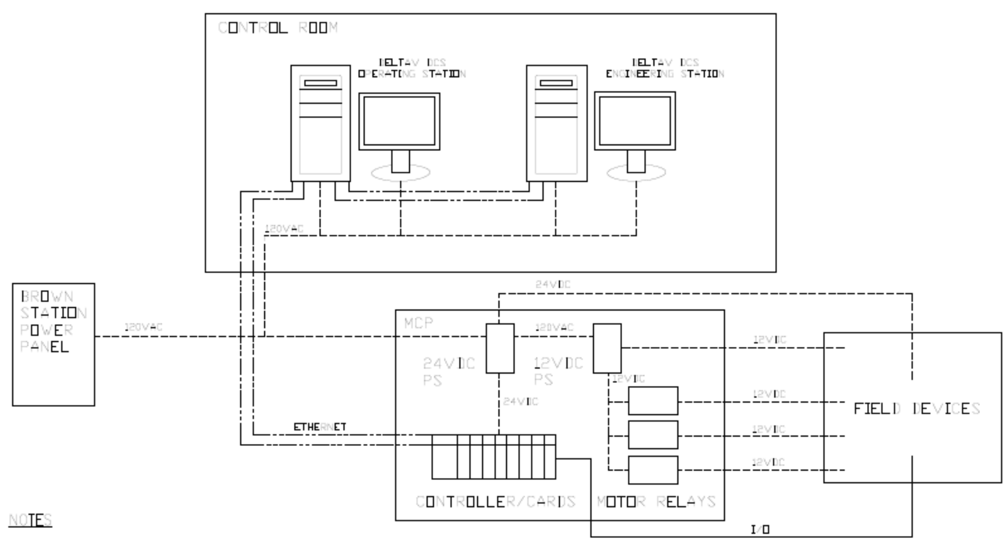
Exhibit 3.2.11. The Location of Three Tie-in Points for Air Preheater System.

3.2.5 Control Panel Design and Logic Sequence

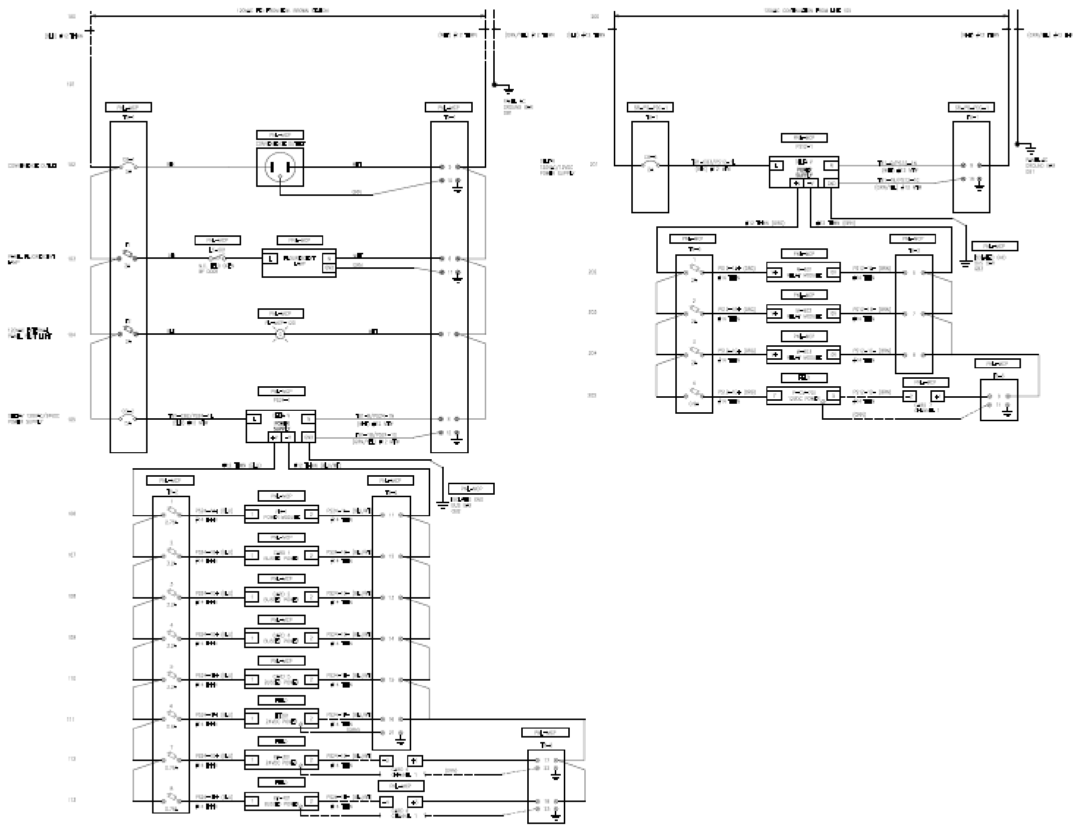
The control system design including the panel layout, system architecture and power distribution are shown in **Exhibit 3.2.12**. The design of analog and discrete I/O card are shown in **Exhibit 3.2.13**. The controller is powered by 24 VDC and extended with 7 I/O cards. Thermocouples, pressure transmitters, flow meter, and analyzer are connected to analog input cards, shut off valves are connected to discrete output cards, and flow control valves are connected to analog output cards.



a. Panel Layout

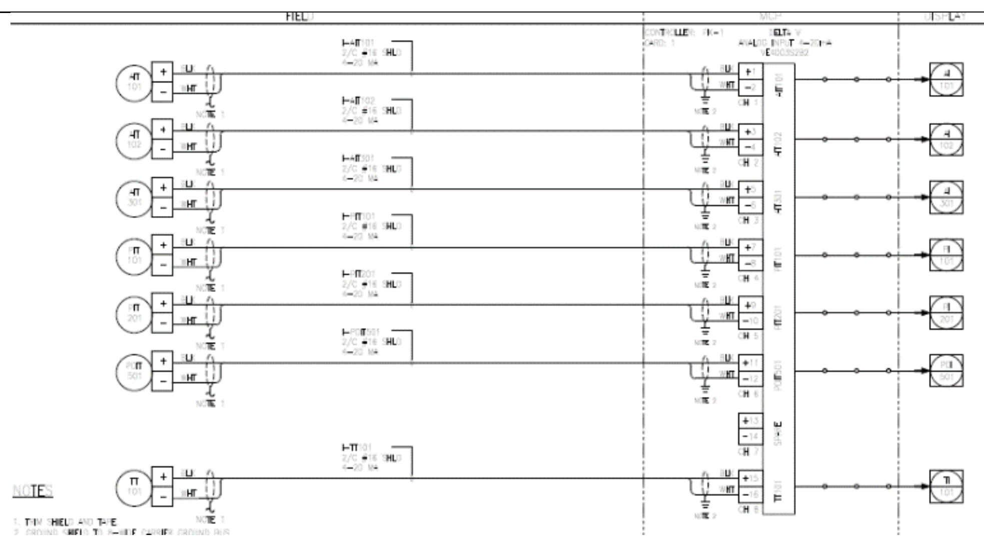


b. Control System Architecture

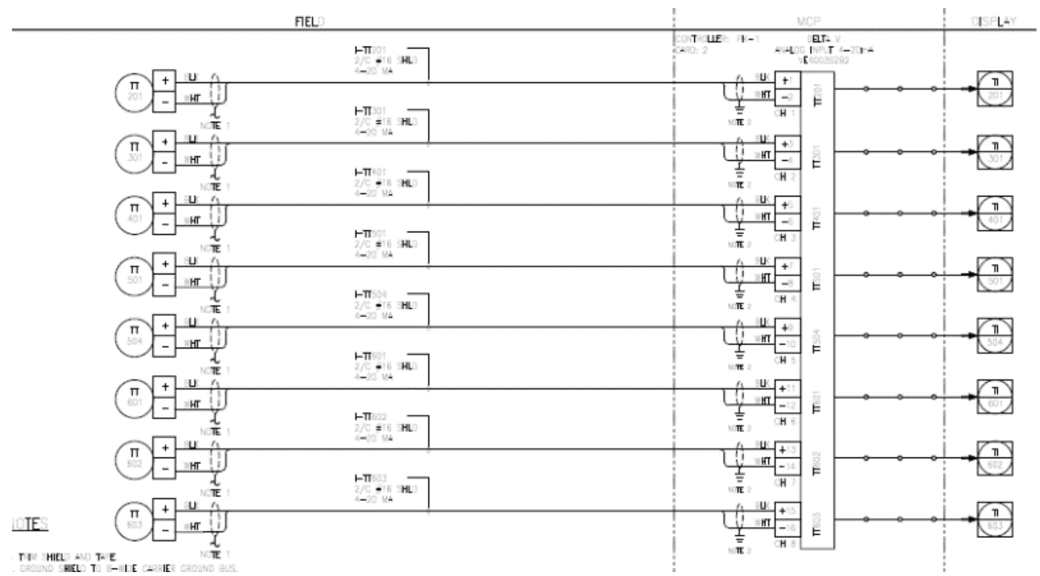


c. Power Distribution

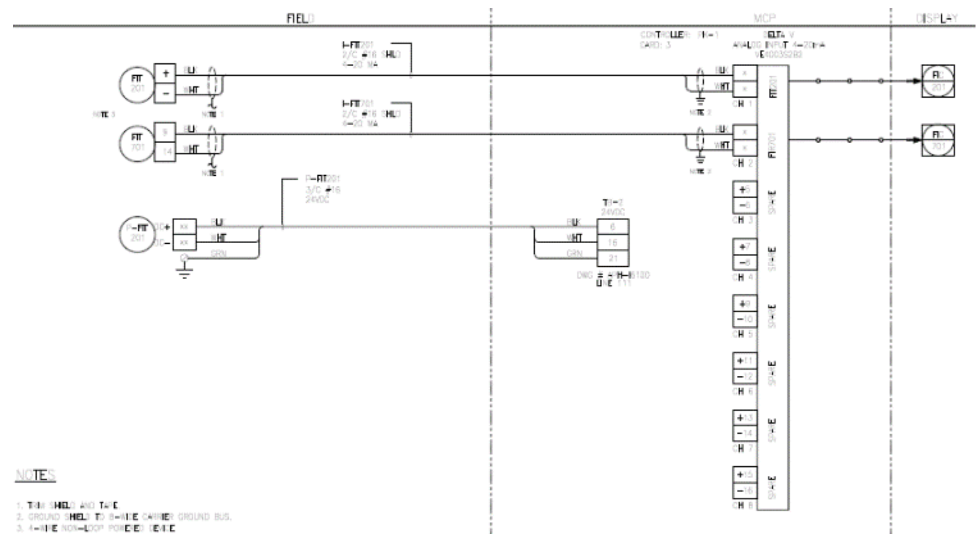
Exhibit 3.2.12 The Control System Design of APH



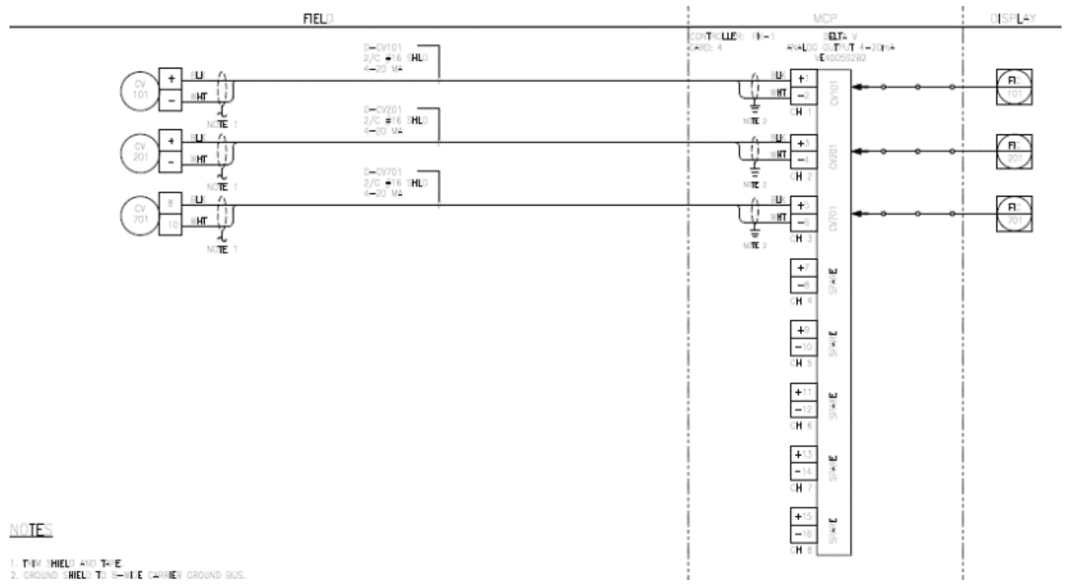
a. Analog Input – Card 01



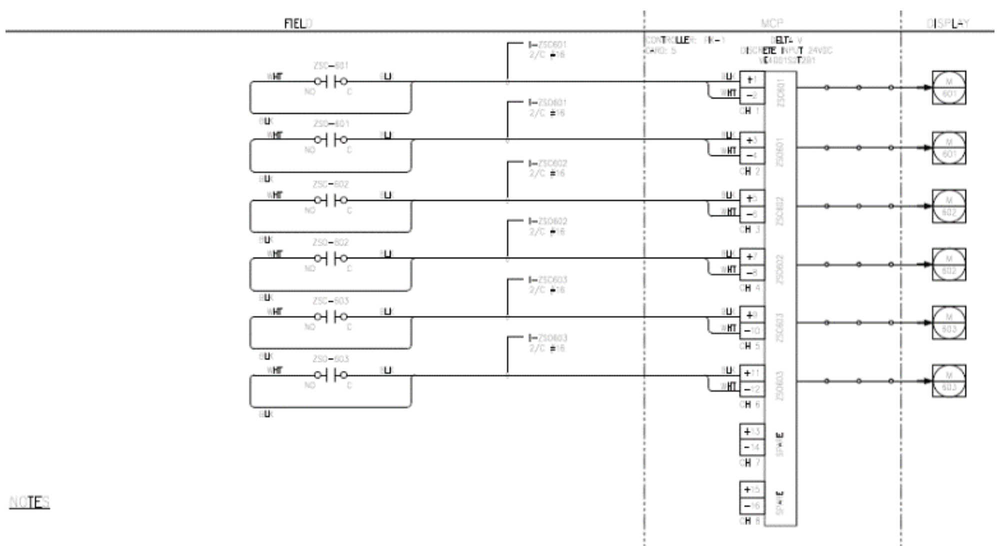
b. Analog Input – Card 02



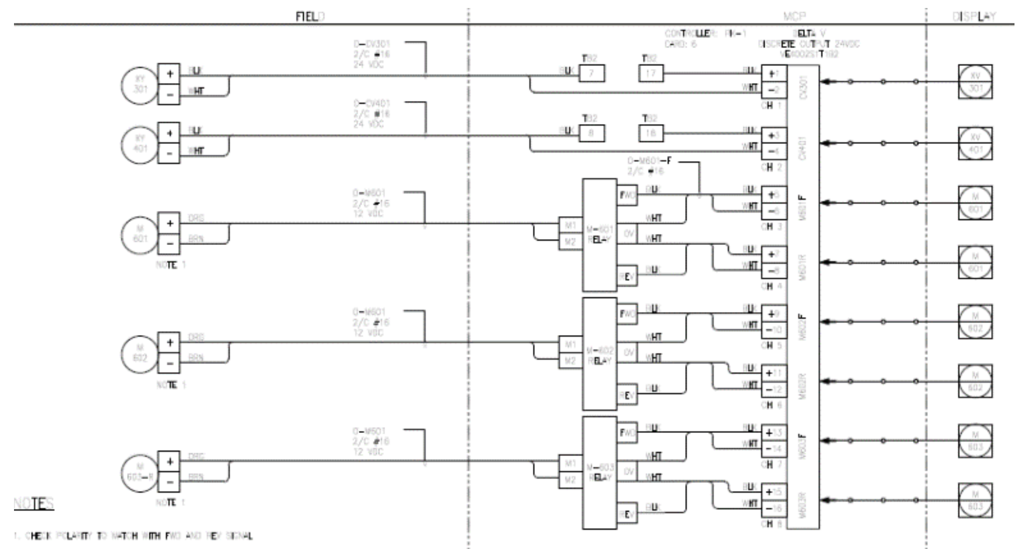
c. Analog Input – Card 03



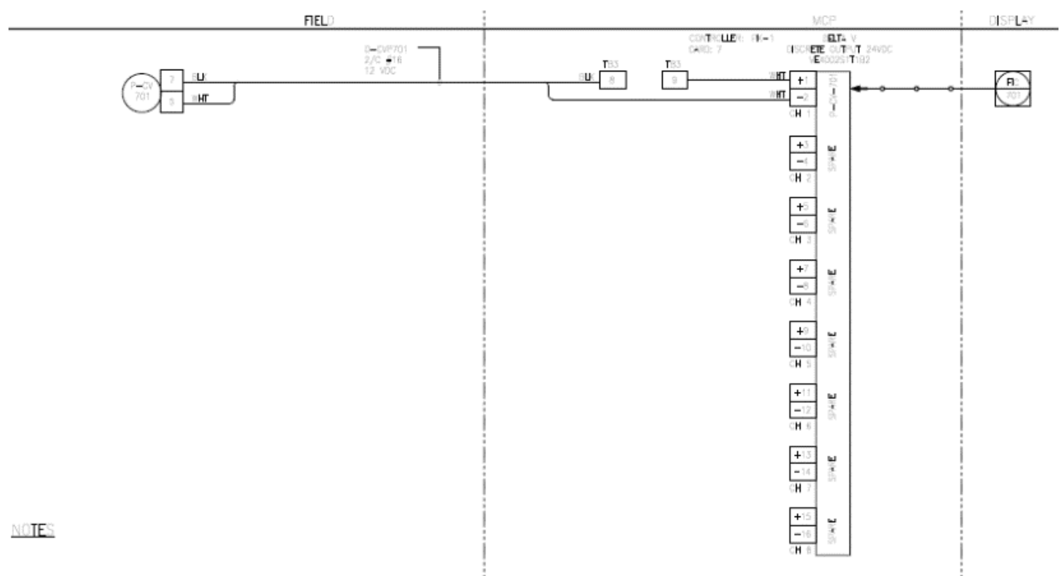
d. Analog Output – Card 04



e. Discrete Input – Card 05



f. Discrete Output – Card 06



g. Discrete Output – Card 07

Exhibit 3.2.13 Analog and Discrete I/O Cards

The definitions and locations of the instrument tags are shown in **Exhibit 3.2.14**. Details of each instrument are defined in the Instrument List as shown in **Exhibit 3.2.3**. Specifically, AI-101 and AI-102 are indicators of SO_2 concentration for flue gas flow rate measurement, with FIC-701 the mass flow controller to achieve precise SO_2 doping. TT-101, 201, 301, 401 are temperature transmitters for measurement at gas inlet, air inlet, gas outlet, and air outlet, respectively. PIT-101, 201 are pressure indicator transmitters for measurement at gas inlet and air inlet respectively. PDIT-501 is a differential pressure indicator transmitter for measurement across heating elements. FIT-201 is a flow indicator transmitter for measurement at air inlet. CV-101, 201 are flow control valves at gas inlet and air inlet respectively. XV-301, 401 are shut off valves at gas outlet, and air outlet respectively.

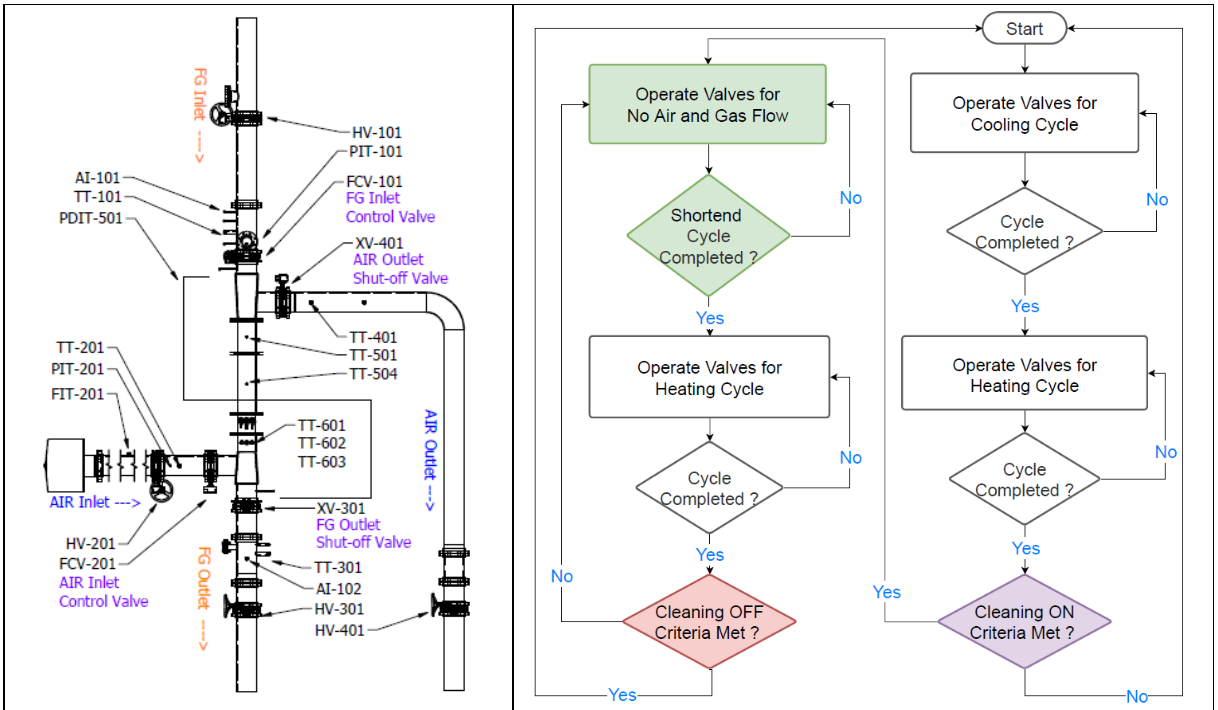


Exhibit 3.2.14. Instrument Tag Locations and Cleaning Control Logic Diagram.

3.3 Unit Installation

The three tie-ins were fabricated in house and installed on-site following the drawing in **Exhibit 3.2.11**, and shown in **Exhibit 3.3.1**. The four components of heating element housing were fabricated by GS Steel. Both the hot end and cold end type heating elements were fabricated by LJUNGSTRÖM, and were packed per their instruction into the housing, as shown in **Exhibit 3.3.2**. Steel bracing, unit installation, access platform (handrail, gratings, and ladder) installation, and insulation, are shown in **Exhibits 3.3.3** through **Exhibit 3.3.5**. The completed installation and wiring of instrumentation and control panel, computer and analyzer workstation panel with DeltaV HMI are shown in **Exhibit 3.3.6** and **Exhibit 3.3.7**. Control programming on DeltaV workstation was setup by the contractor BSI Engineering based on P&ID drawing as shown in **Exhibit 3.2.2** which includes mapping input/outputs signals, creating control module and classes, and HMI graphics. The gas and air alternating flow sequence was also built into the DeltaV DCS by controlling gas or air valves and hold for preset flow time for each cycle. DeltaV software was installed and configured on the Pro+ and Operator workstations.

Exhibit 3.3.1 Complete Installation of Three Tie-ins.

Exhibit 3.3.2 Hot End and Cold End Heating Element Sheet Packed into Housing.

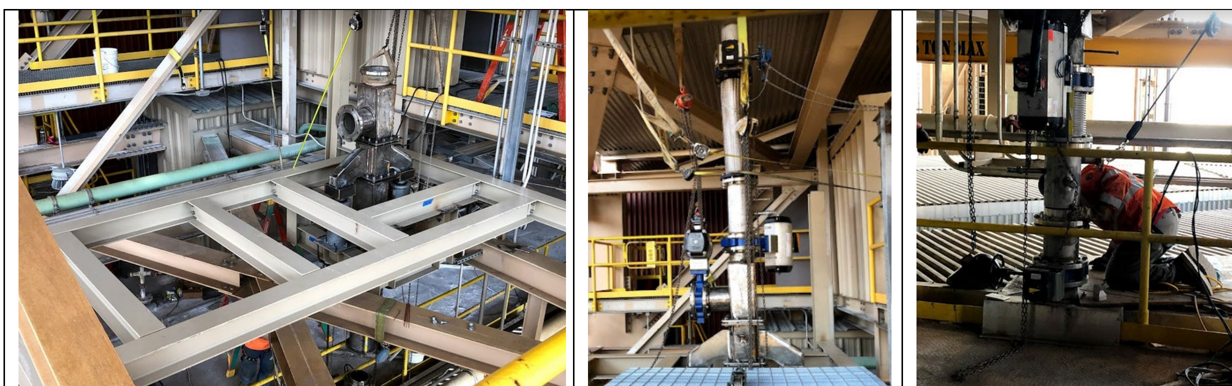


Exhibit 3.3.3. Steel Braces, APH Unit Set, Flue Gas Inlet and Outlet Lines Installed.

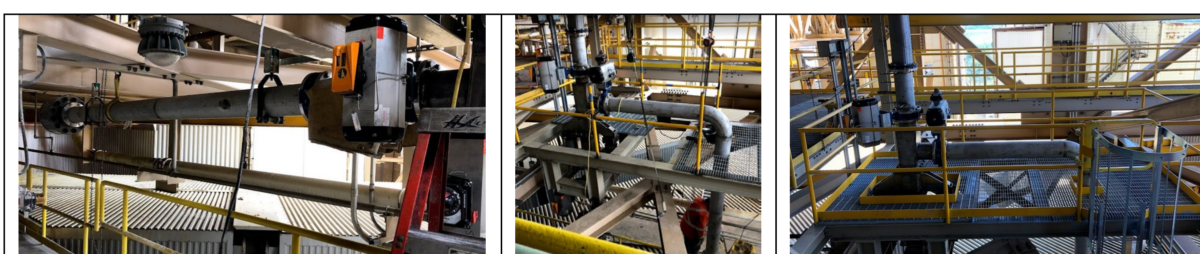


Exhibit 3.3.4. Air Inlet, Outlet Lines, Platform Grating, Handrail, and Ladder Installed.

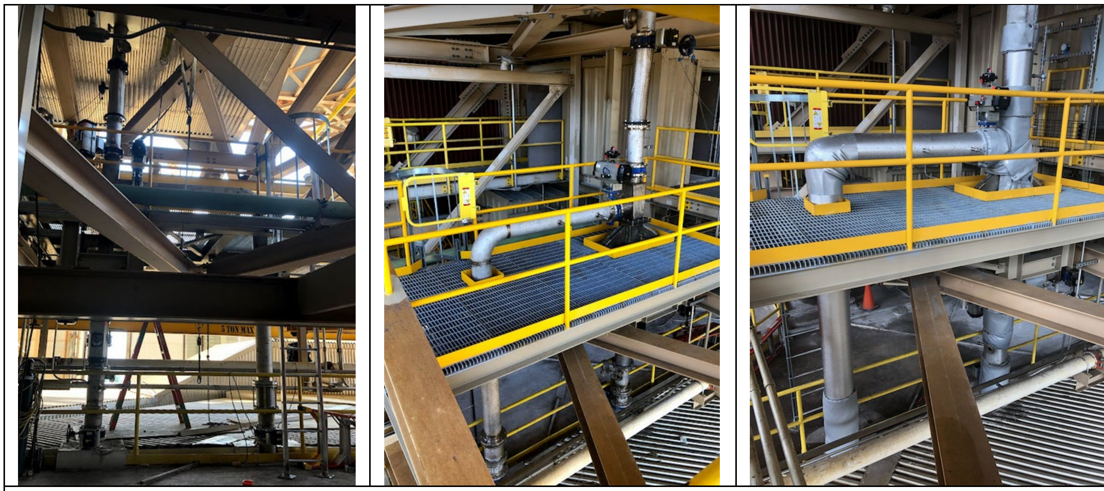
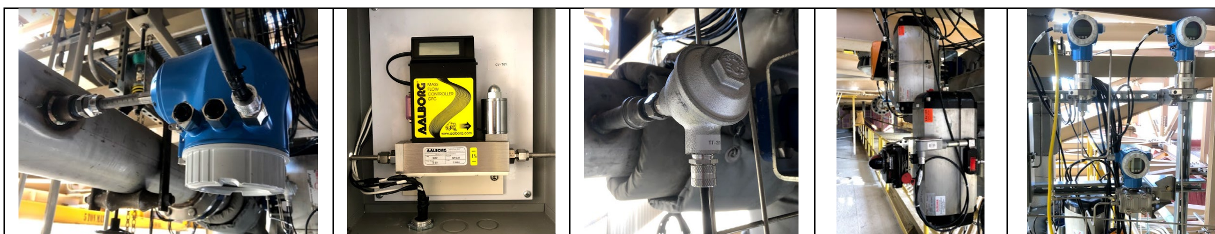


Exhibit 3.3.5. Front and Back View of Completed APH Installation, and with Insulation.



Air Inlet Flow Meter | SO_2 MFC | Thermocouples | Flow Control and Shutoff Valves | Pressure and Differential Pressure Transmitters

Exhibit 3.3.6. Instrumentation Installed, Wired and Tubing Connected.

Exhibit 3.3.7. Wired Control Panel, Computer Workstation Setup and DeltaV HMI

4) OPERATIONS

With the completion of commissioning, two groups of experiments were conducted – a parametric investigation and long-term continuous verification studies. Starting January of 2022, from best practice, the parametric campaign initiated by adjusting valve opening period to achieve various exiting temperatures. APH gas exiting temperature as 250 °F was operated as baseline condition for 7 days. The baseline performance data was collected and namely as the low temperature data detailed below. Both high exiting temperature and low exiting temperature operations were intentionally tested. Specifically, in the parametric investigation, flue gas exhaust temperature was set from high (300 ~350 °F) to low (<250 °F) by adjusting the air and gas flow ratio in addition to varied plant load. Additional variables were investigated in this parametric study whenever they were available during the loading cyclic operation, including flue gas inlet temperature, and flue gas/air flowrate determined by duct vacuum pressure. The friction factor and load-independent ash indicator were proposed to evaluate ash accumulation at various temperature set points and the effectiveness of UKy self-cleaning technique. High system temperature allowed smooth unit operation without observation of ash fouling, while low temperature led to significant ash fouling as expected and ended up with a full clog when the UKy technology was not in service. Upon completion of the parametric study, a long-term (1 year) campaign was conducted to investigate the effectiveness of the UKy in-situ self-cleaning technology on air preheater operation whenever the host unit was in service during the year. Testing operation with cleaning sequence was started in June of 2022. Temperature based cleaning operation parameters were adjusted to achieve a balance of cleaning performance and its frequency while the overall air preheater performance was maintained. Tuned temperature criteria (e.g. temperature entering cleaning sequence and temperature exiting cleaning) with reasonable cleaning frequency were then applied to operation at low temperature for long term campaign. Fixed number of cleanings control was also implemented while maintaining the cleaning performance.

The system operation follows safety protocols guided by OSHA and our host site company, PPL. All operating personnel have been trained with safety protocol from PPL quarterly. The pilot-scale APH supporting platform has been collaboratively designed with PPL civil engineering to align with safety codes. Cage ladders are built in for extra safety to access the elevated floor. All operating personnel are equipped with required PPE when they were on the platform, including hard hats, safety glasses, working gloves, ear buds, N95 particulate masks, steel toed boots, portable SO_2 alarms. Lanyards and harness are used for fall protection when work is performed 4 feet above the standing level. All operating personnel have been trained for unit operation based on standard operating procedures (SOP) established for this project specifically. The SOP containing system's response to emergency shutdowns and appropriate sequence for startup operation is attached in Appendix I.

Along with the operation, functionality tests of power, compressed air supply, and rotational check on all control valves and emergency shutdown were conducted during every startup. Rotational check on manual valves were also conducted every startup and shutdown. The system auto shutdown is performed whenever gas inlet temperature to pilot APH goes below 500 °F. The functionality test of available heat tracing was conducted regularly during site visits. The functionality tests of safety shower/eyewash stations were performed regularly by PPL's contracted service. The system leak check was conducted regularly and the SOP of pressure and pressure difference measurement leak check is attached in Appendix II.

4.1 Gas Flow Rate and Validation

There is no flow meter installed for measuring direct flue gas flow rate due to the concern of high solid content in the flue gas. Alternatively, a heat balance and SO_2 doping are used to determine the flue gas mass flow rate by assuming that heat loss and leakage are negligible, as described below,

$$\dot{m}_a\left(c_{pa,out}T_{a,out} - c_{pa,in}T_{a,in}\right) = \dot{m}_g\left(c_{pg,in}T_{g,in} - c_{pg,out}T_{g,out}\right)$$

where c_p is the specific heat capacity, the value of which is related to the air or gas species and local temperature. The present study used the following values: $c_{pa,in} = 1.004\frac{kJ}{kgK}$ at 60 °F, $c_{pa,out} = 1.028\frac{kJ}{kgK}$ at 430 °F, $c_{pg,in} = 1.12\frac{kJ}{kgK}$ at 580 °F, and $c_{pg,out} = 1.08\frac{kJ}{kgK}$ at 260 °F.

Exhibit 4.1.1. Gas Conditioner and Gas Analyzer.

The test unit further utilizes the SO_2 doping method to indirectly measure the flue gas flow rate in order to validate the aforementioned heat balance calculation on the gas flow rate. Specifically, the SO_2 concentration is measured by analyzer (HORIBA Model VA-5111G, shown in **Exhibit 4.1.1**) for the input flue gas from sample port 1 (tag AI-101, as shown in **Exhibit 3.2.14**) located in the gas inlet, as well as the flue gas after doping a given amount of SO_2 from sample port 2 (tag AI-102) located in the gas outlet. The gas sampling and calibration line setup is illustrated in **Exhibit 4.1.2**. Two streams of gas sampling from the sample ports AI-101 and AI-102 were connected to two separate sensors in the analyzer. The gas flow rate is calculated by using the following equation,

$$Q_g = \frac{Q_{SO_2}}{X_2 - X_1}$$

Where Q_g is the calculated flue gas volume flow rate, Q_{SO_2} is the preset SO_2 volume flow rate for doping that is controlled by a mass flow controller, X_1 and X_2 are the measured SO_2 concentration before and after the doping. Note that the above equation assumes that SO_2 is well mixed with flue gas after injection and that the doping amount is small enough to not affect the overall gas flow rate. In the test unit, the sampling port after doping is kept a sufficient distance from the doping point to ensure that the mixing assumption is justified. Such calculated flue gas flow rate is termed indirect measured gas flow rate to differentiate from the calculated gas flow rate from forementioned heat balance. Both stream SO_2 sensors were calibrated by zero and span before the measurement, same

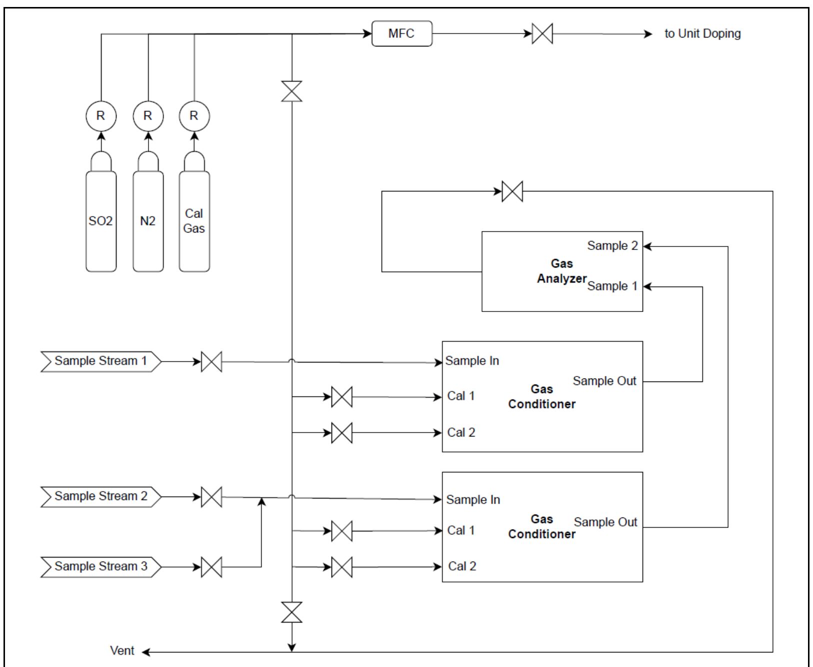


Exhibit 4.1.2. Gas Sampling and Calibration Line.

readings were obtained after calibration as shown in **Exhibit 4.1.3** between 16:00 and 16:30 when only the flue gas from the two ports were sampled without SO_2 doping.

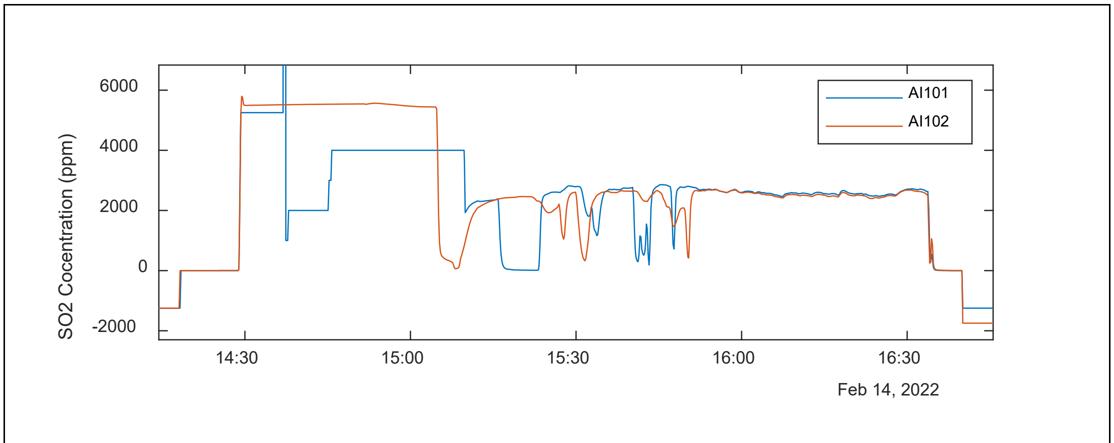
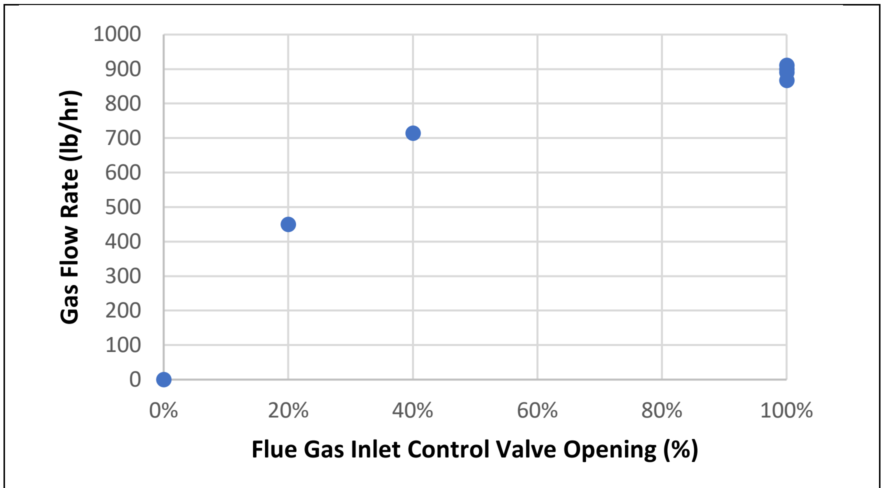


Exhibit 4.1.3. Analyzer Calibration of SO_2 in Flue Gas.

With various SO_2 doping amount (Q_{SO_2} from 12~23 slpm) and flue gas valve openings (20%~100%), measurements of SO_2 concentration from both ports were obtained March 10 of 2022 and the indirectly measured gas flow rates are plotted against the flue gas inlet valve opening, as shown in **Exhibit 4.1.4**. Note that such indirect measurement can be conducted during flue gas flow only in the pilot unit. As the operation data shown in **Exhibit 4.1.5**, the calculated flue gas flow rate from heat balance is 963 lb/hr at 15:30 on Mar 10. The flue gas flow rate indirectly measured by SO_2 doping at 16:00 to 16:30 on Mar 10 was 900 lb/hr, as shown in first row of **Exhibit 4.1.4**. Considering the plant load was slightly decreasing during this period of time (yellow line in **Exhibit 4.1.5**), the calculated flue gas flow rate shows good agreement with the indirectly measured gas flow rate via SO_2 doping method. The calculated gas flow rate will be used to show the result hereafter.



SO_2 Doping	Measured SO_2 Concentration -Port 1	Measured SO_2 Concentration -Port 2	Gas Inlet Valve Opening	Gas Flow rate (Indirectly Measured)
slpm	ppm	ppm	%	lbs/hr
23	2759	6576	100%	900
15	2742	5358	100%	911
23	2799	6748	100%	890
15	2725	5543	100%	867
15	2869	6176	40%	714
12	2721	6755	20%	450
			0%	0

Exhibit 4.1.4. Indirectly Measured Flue Gas Flow Rate from Measurement of SO_2 Concentration and Doping

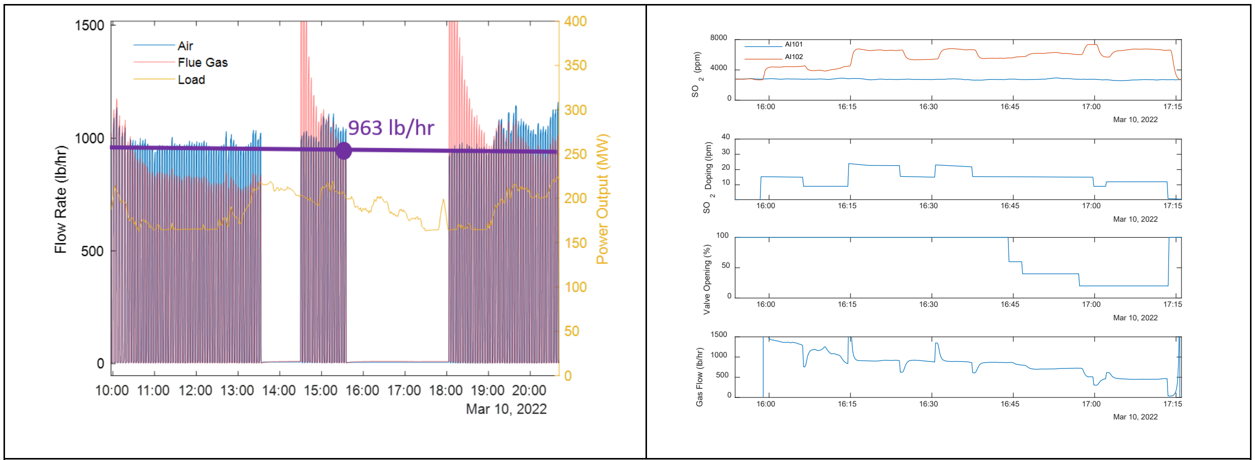


Exhibit 4.1.5. Operational Data with Calculated Gas Flow Rate.

4.2 Definition of Terms used in this report

There are a few variables that are calculated from measurement which are defined in this section.

4.2.1. Capacity Ratio (X-ratio)

The typical way to measure the amount of air relative to flue gas that flows into the air preheater is to use the capacity ratio, or X-ratio, as defined below (Mallikarjuna, et al, 2014),

$$X_{ratio} = \frac{\dot{m}_a c_{p,a}}{\dot{m}_g c_{p,g}}$$

The X-ratio of 0.88 corresponds to a gas to air flow ratio of 1.05, by inserting the average specific heat capacity values within the operating temperature range, respectively. During steady state operation, assuming neglectable heat loss and temperature effect on specific heat capacity, the heat transfer from the gas side to the air side is balanced as,

$$\dot{m}_a c_{pa} \Delta T_a = \dot{m}_g c_{pg} \Delta T_g$$

where $\Delta T_g = T_{g,in} - T_{g,out}$, $\Delta T_a = T_{a,out} - T_{a,in}$. This leads to the expression of the X-ratio to be directly estimated from temperature data, as below,

$$X_{ratio} = \frac{\Delta T_g}{\Delta T_a}$$

4.2.2. Efficiency of Gas Side and Air Side

The air preheater efficiency including gas side and air side efficiency are commonly used to assess the heat transfer. The definitions are as follows (Mallikarjuna, et al, 2014),

$$\eta_g = \frac{Q_g}{Q_{g,max}} = \frac{\Delta T_g}{\Delta T_{max}}$$

$$\eta_a = \frac{Q_a}{Q_{a,max}} = \frac{\Delta T_a}{\Delta T_{max}}$$

Where $\Delta T_{max} = T_{g,in} - T_{a,in}$, $\Delta T_g = T_{g,in} - T_{g,out}$, $\Delta T_a = T_{a,out} - T_{a,in}$.

4.2.3. Heat Transfer Coefficient and Heat Flux

The overall heat transfer coefficient is estimated by the equation below,

$$Q = Q_g = Q_g = U \cdot A \cdot LMTD$$

Where A is total heat transfer area (15.3m^2) of all heating elements installed in pilot unit, and LMTD is the log mean temperature difference, which is defined as,

$$LMTD = \frac{\Delta T_A - \Delta T_B}{\ln\left(\frac{\Delta T_A}{\Delta T_B}\right)} = \frac{\Delta T_A - \Delta T_B}{\ln \Delta T_A - \ln \Delta T_B}$$

Where $\Delta T_A = T_{g,in} - T_{a,out}$, $\Delta T_B = T_{a,in} - T_{g,out}$. The heat flux is defined as,

$$q = \frac{Q}{\mathrm{A}}$$

4.2.4. Ash Indicator and Friction Factor of Heating Elements

The pressure drop across the heating elements is affected by the host plant load change. In addition to the varying suction from ID fan operation, the density and velocity of gas and air flow is also affected by the temperature variation. Friction factor is thus induced based on the Darcy–Weisbach equation, as shown below, to identify the pressure drop variation according to ash build up,

$$\frac{\Delta p}{L} = f_{D,HE} \frac{\rho}{2} \frac{u^2}{D}$$

Here L and D are the depth and hydraulic diameter of heating elements section, respectively, $f_{D,HE}$ is induced from Darcy friction factor and here defined as the friction factor for heating elements, ρ is the fluid density, and u is the fluid mean velocity. The gas or air density is estimated by ideal gas law ($\frac{p}{\rho} = R_g T$, where p is local pressure, R_g is gas constant, and T is local temperature). The above equation is reformed as below,

$$f_{D,HE} = 2 \frac{\Delta p D}{\rho u^2 L}$$

The friction factor for heating element flow is mainly a function of the flow condition and can also be related to surface roughness for large Re number in turbulent regime. The Re number for APH unit are estimated typically between 1500 to 3000, where the flow regime is in laminar and transition regime, so the friction factor as function of Re number is proposed in a formula below,

$$f_{D,HE,cl} = f(Re) = aRe^{-b}$$

The coefficient a and b is to be determined by the data from smooth parametrical operation of the unit. An ash indicator, AI, is proposed as the ratio between the friction factor and the friction factor of clean heating element, as shown below to predict the ash build up level during the operation,

$$AI = \frac{f_{D,HE}}{f_{D,HE,cl}} = \frac{1}{a} f_{D,HE} Re^b$$

AI is a dimensionless indicator to describe the friction of the flow through the heating element by eliminating the inertia and viscous effect in the laminar flow regime. The absolute value of AI is used here as a dimensionless index to identify the significance of the ash fouling level. A value that is close to 1 means the friction simply generated by the cleaned heating element surface, while a value of greater than 1 is indicating of a level of ash build up. The higher value of AI, the more significant the ash fouling level.

4.3 Parametric Campaign

The pilot unit initiated with temperature parametric operation after commissioning. Unit was operated at various higher exiting temperature (gas outlet temperature >245 °F) for >900 accrual hours smoothly. As anticipated, when unit operated at lower exiting temperature (gas outlet temperature <210 °F), severe ash accumulated quickly to lead to a clog in 120 hours. A summary of temperature parametric operations and operating parameters are listed in **Exhibit 4.3.1.** In this parametric study, varied air to flue gas flow ratio, or the capacity ratio (X-ratio) is tuned to simulate high or low temperature condition for the pilot unit. To adjust the X-ratio, the flow time in the cycle of either flue gas and air, and the opening percentage of air inlet valve are used as operating parameters, as shown in **Exhibit 4.3.1.** Note that varying the flow time of each cycle is solely for simulating different temperature conditions during the parametric campaign. The flow time is fixed at 120s (flue gas) and 90s (air) in the long-term campaign. The values are determined based on estimated flow time in industrial regenerative air preheater. Also, given around 5% O_2 and 13% of CO_2 content in the flue gas in coal-fired power plants, the mass flow rate ratio between flue gas and air is estimated close to 1.05 at normal full-load operation, or X-ratio = 0.88 correspondingly. Adjusting the flow ratio or X-ratio for the pilot unit is mainly for the purpose of simulating operation with different heating element surface temperatures so that ash free operation at high temperature and accelerated clogging behavior at low temperature could be verified.

Exhibits 4.3.1. Summary of Operating Parameters

Flue Gas Heating Time(s)	Air Cooling Time(s)	Air Inlet Valve Opening (%)	Gas Inlet Valve Opening (%)	Average Gas Outlet Temperature (°F)	System Operating Temperature
120	30	20%	100%	440	High
120	60	20%	100%	332	High
180	90	20%	100%	345	High
180	90	20%	100%	270	High
120	90	20%	100%	245	High
90	90	20%	100%	195	Low
120	90	20%	100%	205	Low
180	90	15%	100%	335	High
180	90	15%	100%	337	High

4.3.1. High Exiting Flue Gas Temperature Operation

Sampled operation data in February of 2022 under high temperature conditions is shown in **Exhibits 4.3.2 to Exhibits 4.3.5.** The operation parameter refers to 180s flue gas heating time, 90s air cooling time, and 20% air inlet valve opening, shown in **Exhibit 4.3.1**. The operation was smooth and ash fouling free, and the air preheater was well functioning. The gas outlet temperature is mainly greater than 300 °F. The cold end temperature ranges from 260 °F to 500 °F. Given the load variations from the host power plant, gas inlet temperature varies from 590 °F and higher. The gas outlet temperature, pressure drop, and flow rate vary correspondingly. The friction factor for air and gas flow are stable at 0.65 and 0.3, respectively, regardless of the load variation. The stable value of friction factor indicates negligible ash accumulation on heating element surface.

It can be seen that air flow rate is close to 1000 lb/hr, where gas flow rate is around 1300 lb/hr, which gave the X-ratio between 0.62 to 0.7, and even lower to 0.54 when host plant load ramped up. The efficiency on air side is 75~80%, while much lower at 45%~52% on gas side. This is not surprising when more gas relative to air flows to the air preheater (lower X-ratio).

For this high temperature condition, the heat transfer coefficient is estimated around 20 kJ/kg-K with LMTD about 200 °F, and heat flux 2 kW/m^2. The air velocity is estimated at 3m/s (Reynolds number = 1600), and the flue gas velocity is estimated at 5.2 m/s (Reynolds number = 1900).

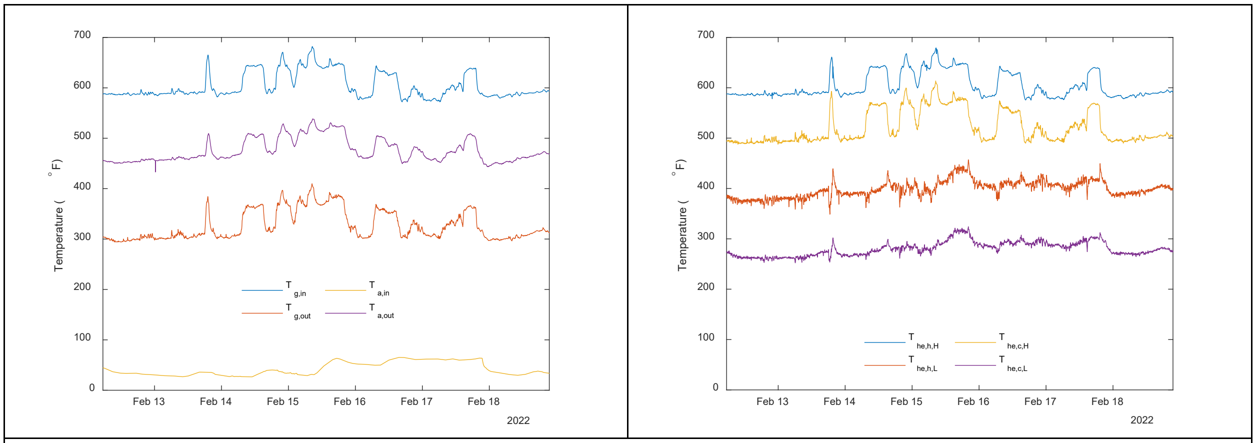


Exhibit 4.3.2. Operation Data – System and Heating Element Temperatures.

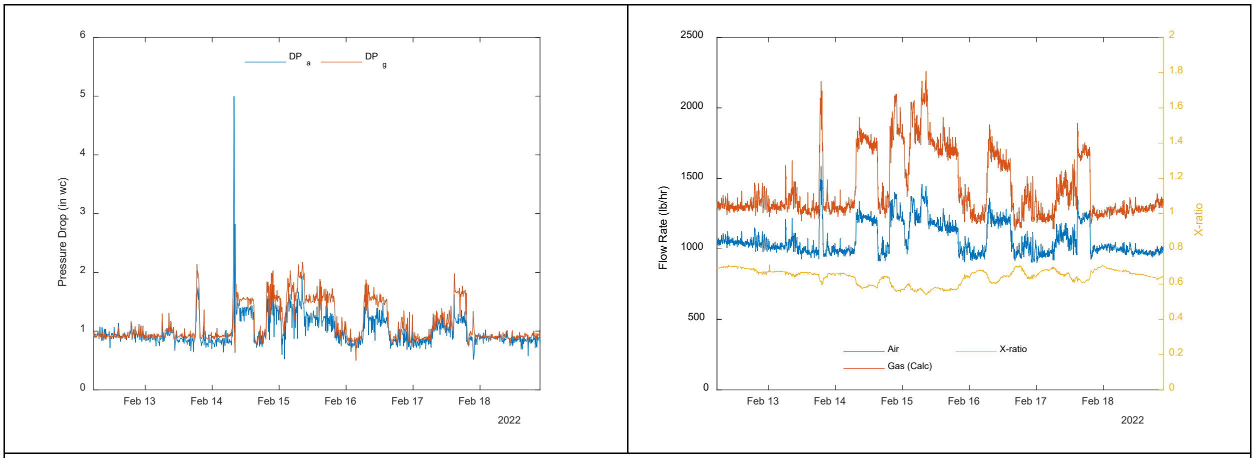


Exhibit 4.3.3. Operation Data – Pressure Drops and Flow Rate of Air and Flue Gas, and X-ratio.

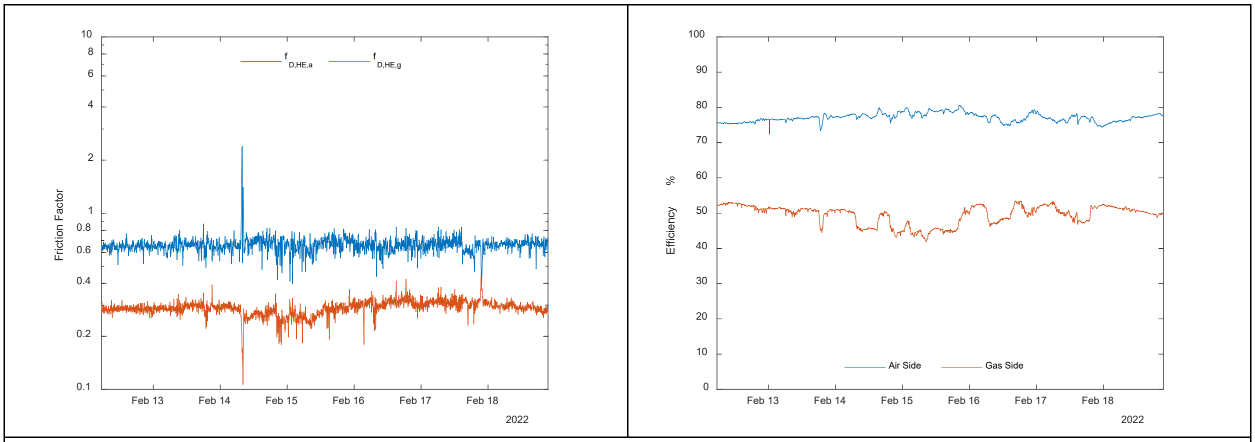


Exhibit 4.3.4. Friction Factor and Efficiency on Air and Gas Side.

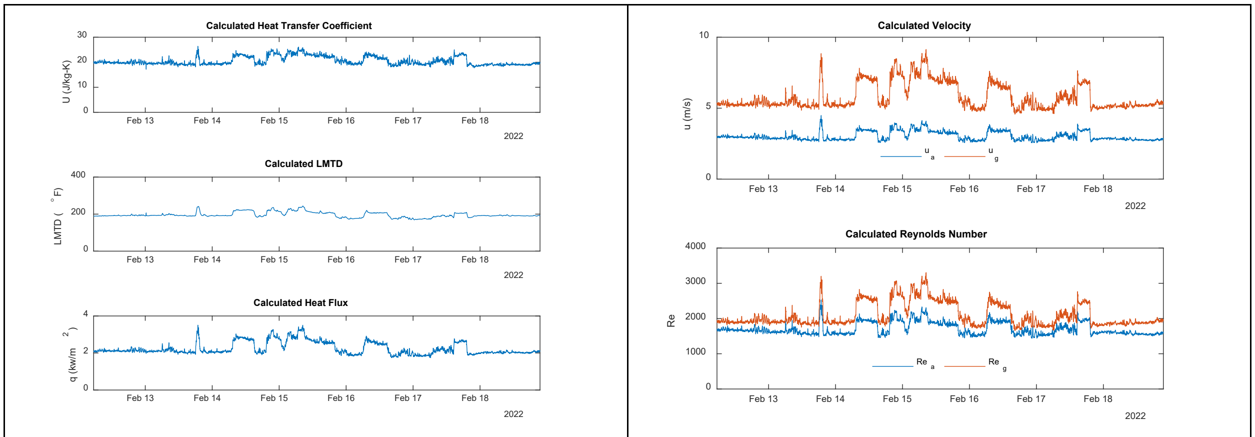


Exhibit 4.3.5. Calculated Heat Transfer Coefficient, LMTD, Heat Flux, Velocity, and Reynolds Number.

4.3.2. Low Exiting Temperature Operation

Sampled operation data in March of 2022 where the operation parameter refers to 120s (3/1/2022 – 3/10/2022) and 90s (3/10/2022 – 3/11/2022) flue gas heating time, 90s air cooling time, and 20% air inlet valve opening, shown in **Exhibit 4.3.1** under low temperature conditions. The condition change is detailed in **Exhibit 4.3.6.** The operation was smooth and ash free for the initial 10 days, but experienced clogging shortly after condition changed.

Exhibit 4.3.6. Operating Parameters

	Before March 10, 10:22 AM	**After March 10, 10:22 AM**
Flue gas inlet valve opening	100%	100%
Air inlet valve opening	20%	20%
Flue gas cycle time	120 s	90 s
Air cycle time	90 s	90 s

The operation data is shown in **Exhibits 4.3.7 to 4.3.10.**

Along the operation before condition changed, the gas outlet temperature is mainly close to 250 °F. The cold end temperature ranged from 240 °F to 400 °F. Gradual increase of the friction factor was observed from 0.7 to 0.9 for air side, and from 0.6 to 0.7 for gas side. Pressure drop on air side shows a slight increase. Both indicate a gradual ash build up, but overall speaking air/gas flow rate and system temperature are quite stable before condition changed. Both air and gas flow rate are close to 1000 lb/hr, which gave the X-ratio between 0.8 to 0.9. The efficiency is 72% on air side, and 62% on gas side. For this low temperature condition, the heat transfer coefficient is estimated around 20 kJ/kg-K with LMTD about 190 °F, and heat flux 2 kW/m^2. The air velocity is estimated at 3m/s (Reynolds number = 1700), and the flue gas velocity is estimated at 4 m/s (Reynolds number = 1600).

When conditions changed to even lower temperature on 3/11/2022, the friction factor spiked extremely, and all other variables such as system temperature, pressure drop, flow rate changed dramatically, indicating significant increase of flow friction from ash build up. The pilot unit was found clogged shortly after.

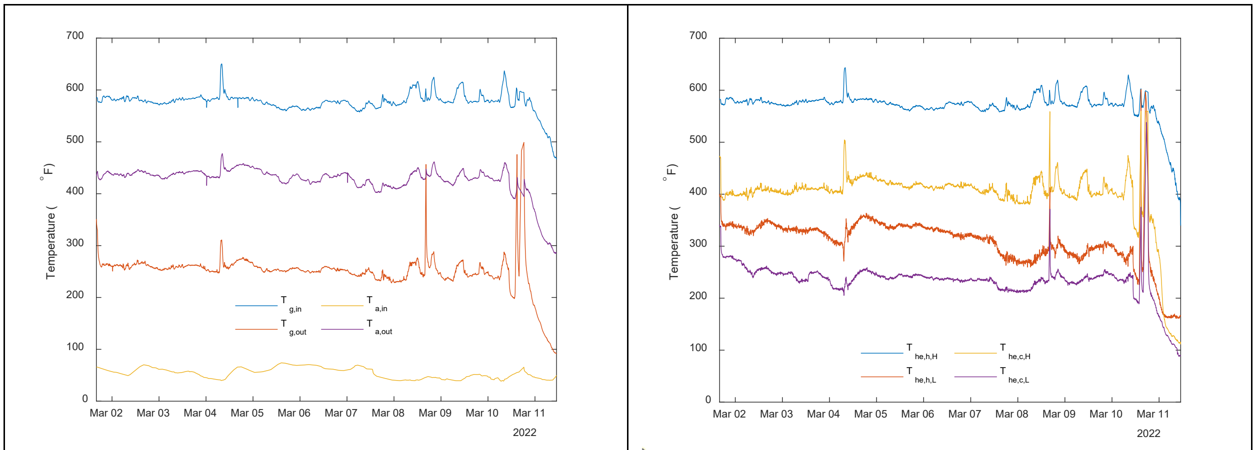


Exhibit 4.3.7. Operation Data – System and Heating Element Temperatures.

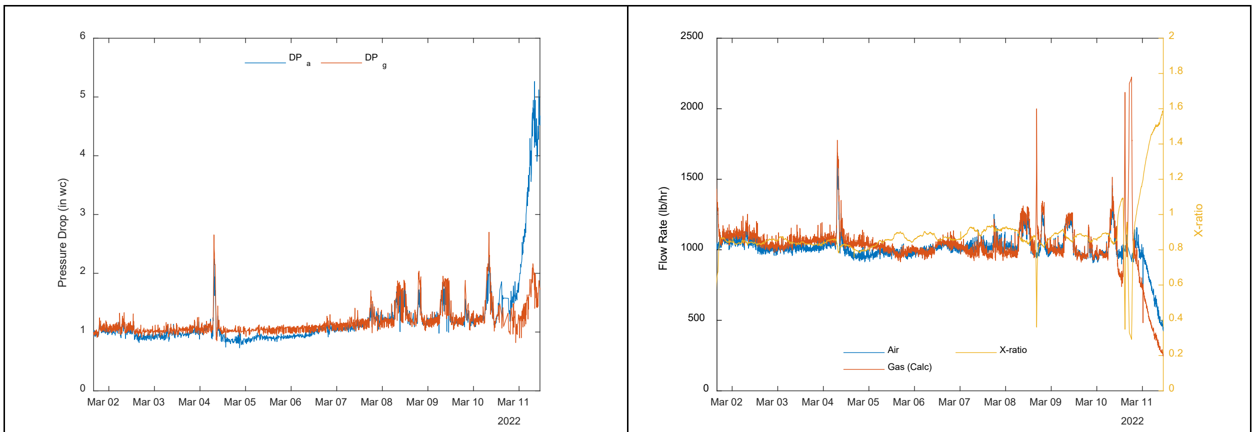


Exhibit 4.3.8. Operation Data – Pressure Drops and Flow Rate of Air and Flue Gas, and X-ratio.

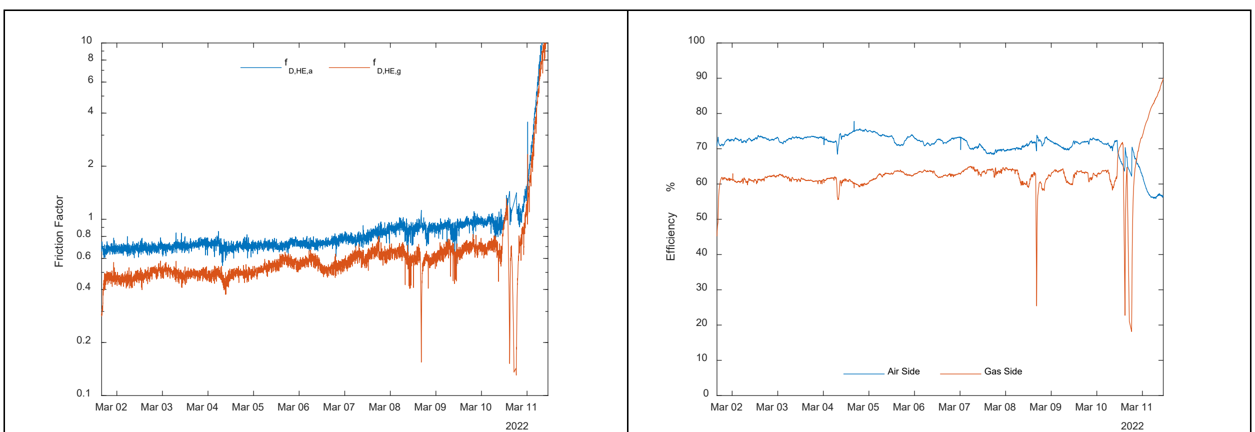


Exhibit 4.3.9. Friction Factor and Efficiency on Air and Gas Side.

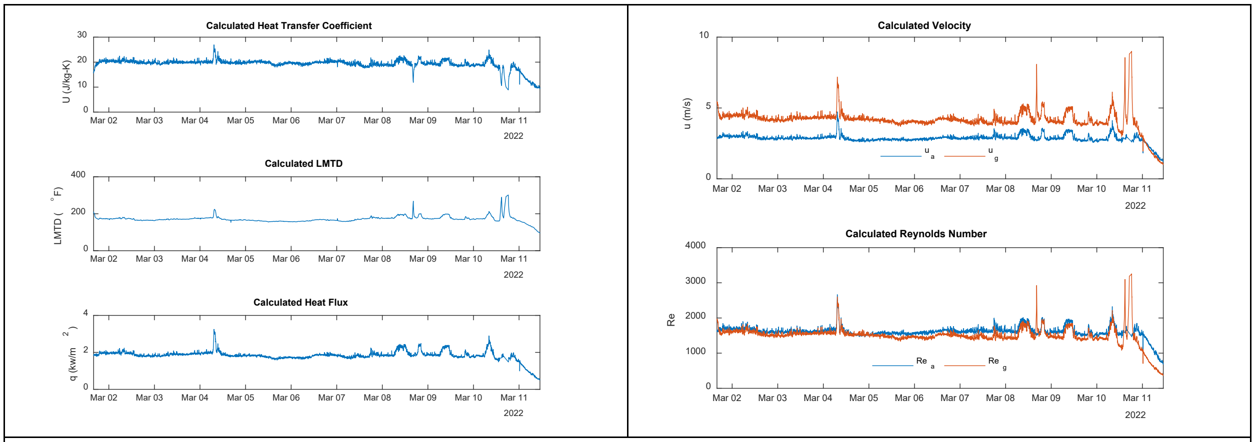


Exhibit 4.3.10. Heat Transfer Coefficient, LMTD, Heat Flux, and Velocity.

4.3.3 Parametric Study Analysis

Over the course of the parametric study on temperature, the unit was found to be operated smoothly when cold end average temperature is above 310 °F but can have significant ash build-up and clogging when cold end operating temperature falls below 280 °F, as shown in **Exhibit 4.3.11.** As solids were building up in the heating element, the pressure drop increased, the gas and air flow decreased, and the system temperature decreased. The variation of operation temperature was achieved by differentiating air to flue gas capacity ratio, X-ratio, as shown in **Exhibit 4.3.11**. The parametric study proves that the APH unit can be well functioning at higher operating temperature but is susceptible to clogging at conventional lower temperature. The results from various operating temperatures show the pilot unit is representative of the commercial air preheater. Ultimately the parametric operations show that clogging of the heating elements can be avoided when a high metal surface temperature is maintained and that clogging does occur when cold end operating temperature drops to below 280 ºF (or gas outlet temperature 240 °F), which is exactly the principle that the UKy air preheater design is based on.

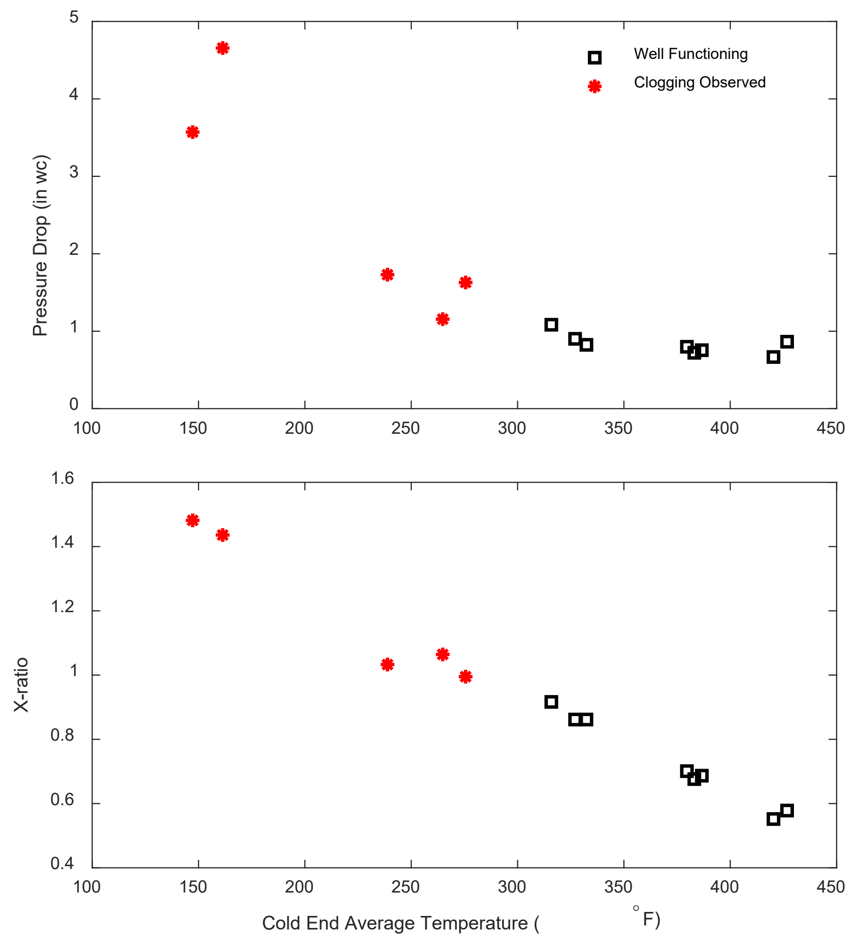


Exhibit 4.3.11. Various Operating Temperatures at Different Air to Gas Capacity Ratios.

The friction factor of clean heating elements was calculated based on the equation in **Section 4.2.4** with differential pressure and flow rate data from the parametric study at various temperature and flow conditions, under which the unit was operating smoothly. **Exhibit 4.3.12** shows the calculated friction factor of clean heating elements of all parametric data points plotted against the Reynolds number. The coefficients of the power equation, $f_{D,HE,cl} = aRe^{-b}$, are obtained from a least square method as $a = 900.1$ and $b = 0.981$. **Exhibit 4.3.13** further correlates data points considering data density and obtained that as $a = 900.1$ and $b = 1$. By calculating ash indicator, detailed in **Section 4.2.4**, over the 1000 accrual hours of parametric study operation, the **Exhibit 4.3.14** shows clearly when clogging happened twice when AI reached 20 and 100.

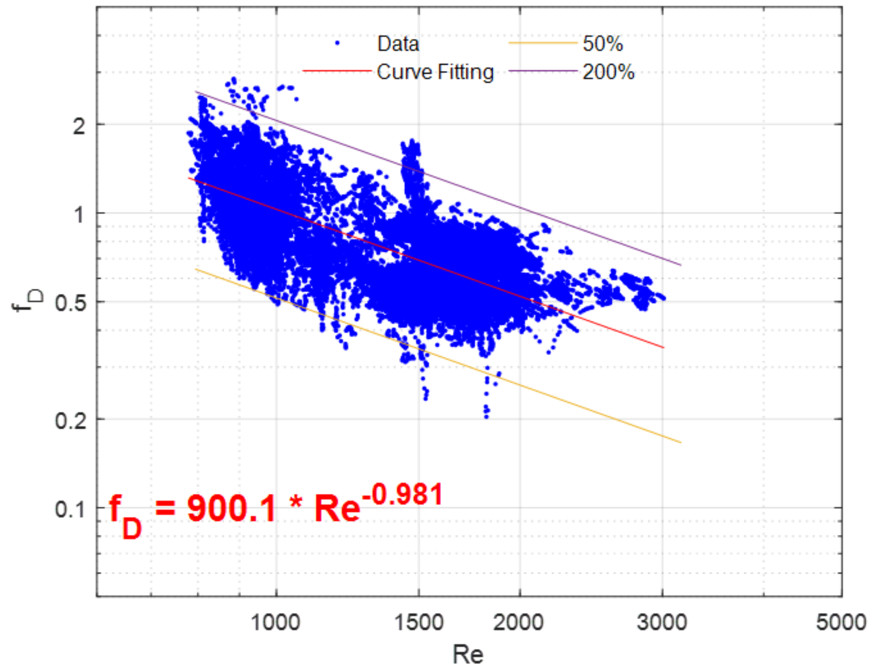


Exhibit 4.3.12. Friction Factor of Clean Heating Elements vs Reynolds Number.

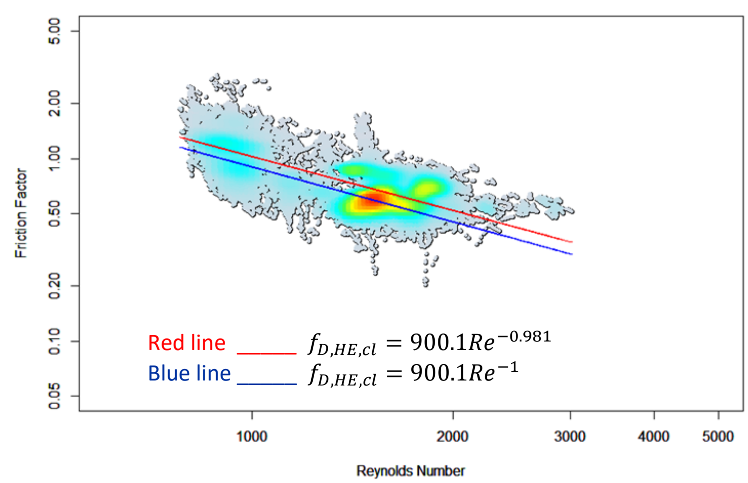


Exhibit 4.3.13. Friction Factor of Clean Heating Elements vs Reynolds Number with Colored Data Density.

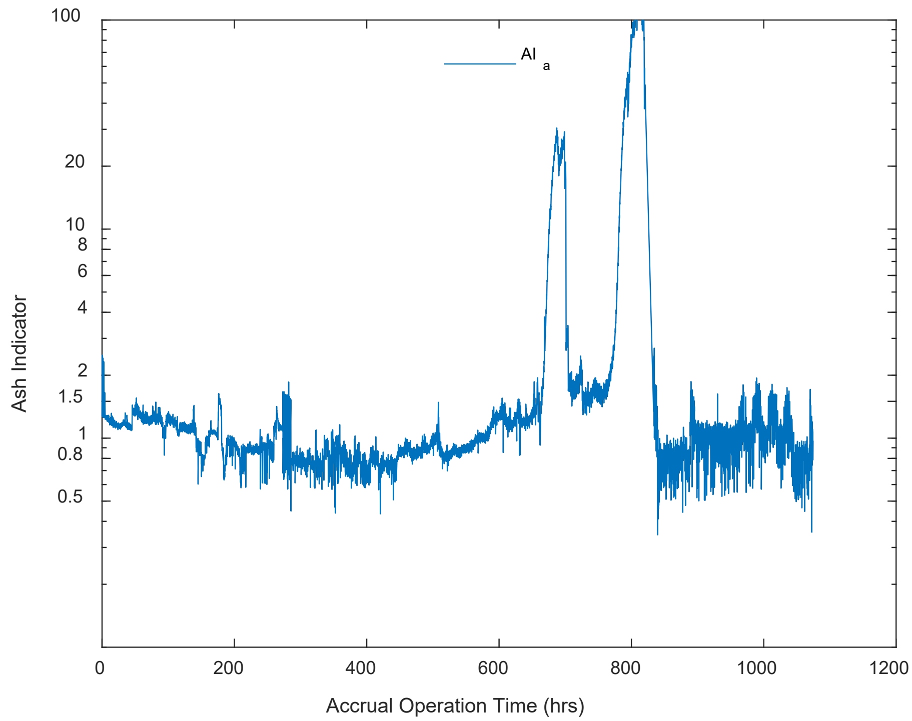


Exhibit 4.3.14. Ash Indicator of Over 1000 Accrual Hours of Parametric Study before Self-Cleaning Implemented.

4.4 Long Term Campaign

The year-long campaign was initiated in June of 2022 after some tuning of cleaning parameters to achieve reasonable cleaning frequency. The host plant could go offline depending on utility demand and grid dispatch. The pilot unit was maintained in operation whenever the host plant was online. Up to July of 2024, the pilot unit had accumulated over 8000 hours of operation, as shown in **Exhibit 4.4.1**.

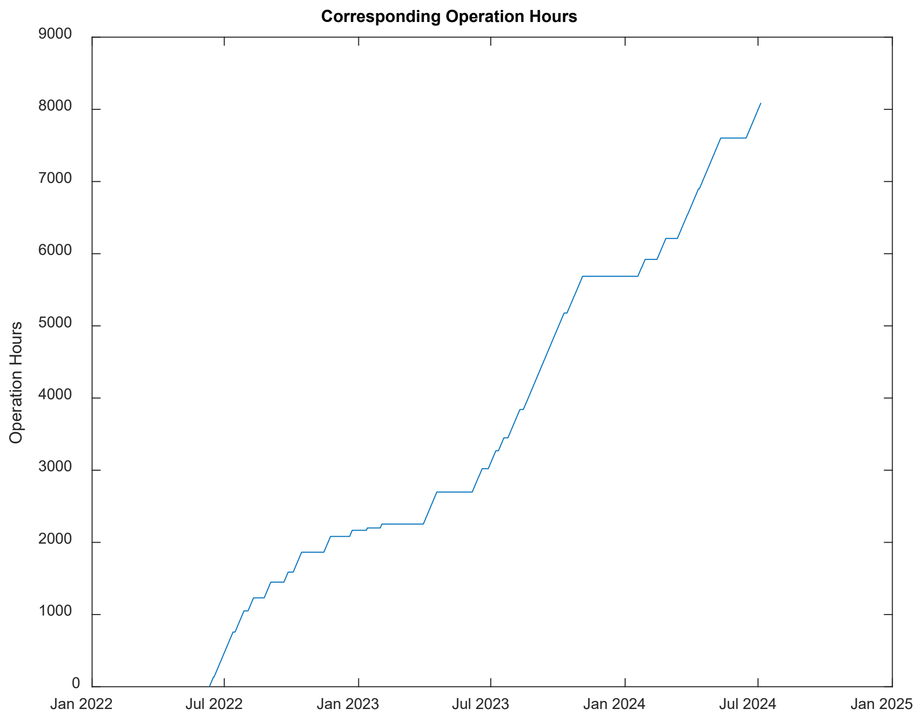


Exhibit 4.4.1. Over 8000 Accrual Operation Hours along Year-long Operation Campaign.

4.4.1 Operation with Self-Cleaning

In-situ self-cleaning was implemented by extending the heating cycle but limiting the cooling cycle either via flow rate or flow time. In other words, when the system entered cleaning mode, the air flow was restricted. Only flue gas was allowed to flow through. Cleaning mode helped to quickly recover heating element temperature. The temperature criteria to enter and exit cleaning mode was adjusted and refined to achieve reasonable cleaning frequency and cleaning time in addition to cleaning performance. The control logic is shown in **Exhibit 4.4.2.**

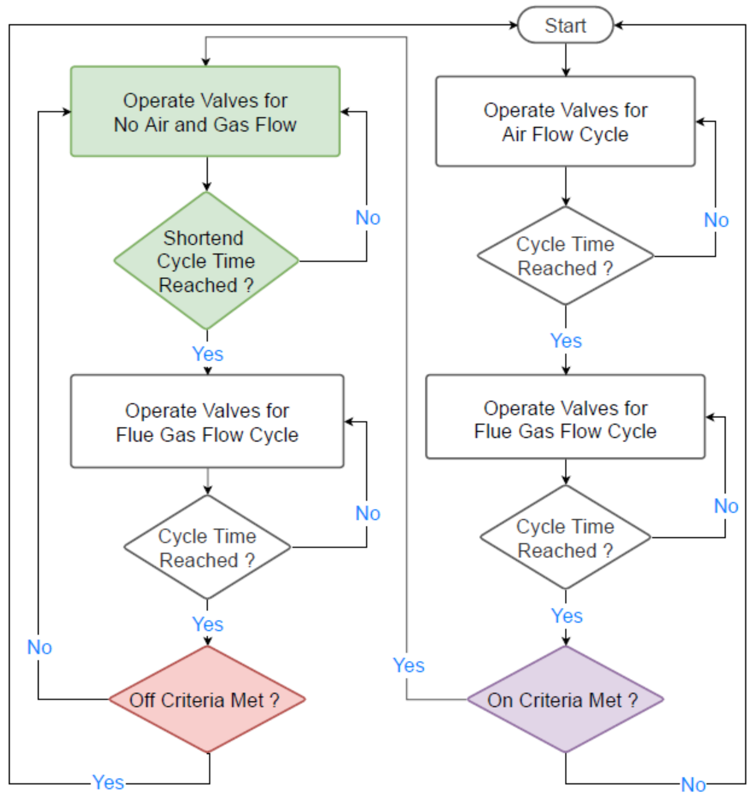


Exhibit 4.4.2. Cleaning Control Logic

The system monitors gas exhaust temperature and cold end temperature to control the operation of cleaning. Specifically, the criteria to enter the cleaning mode is set as when gas exhaust temperature is lower than 225 ^{o}F and cold end temperature is lower than 380 ^{o}F after every flue gas flow cycle. The criteria to exit the cleaning mode is set as when gas exhaust temperature is higher than 415 ^{o}F or cold end temperature is higher than 520 ^{o}F after every flue gas flow cycle. When system operation enters cleaning mode, the time for flue gas flow cycle is extended from 120 s to 180 s and the air inlet/outlet valves are closed for the air flow cycle. This allows more heat transfer to occur and remain in the heating element and essentially raise up metal temperature. When gas exhaust temperature or cold end temperature reach the critical temperature, the system operation exits cleaning mode and returns to normal operation. A sample operation data of typical operation with in-situ self-cleaning is shown in **Exhibit 4.4.3**. Data show that operation temperatures quickly rise when cleaning mode was entered and until criteria were met for exiting the cleaning mode. During cleaning mode, heating elements are mainly heated up with flue gas with limited cooling as expected.

A centered moving average is further used to smooth out data fluctuations, as given below

$$MA_i = \begin{cases} \frac{1}{k} \sum_{i-\frac{k-1}{2}}^{i+\frac{k-1}{2}} DATA_i\,, & k \text{ is odd} \\ \frac{1}{k} \sum_{i-\frac{k}{2}}^{i+\frac{k}{2}-1} DATA_i\,, & k \text{ is even} \end{cases},$$

where k=360, accounts for 1 hour period of data (sampling frequency $0.1s^{-1}$). A sample operation data of typical operation with in-situ self-cleaning using a 1-hour centered moving average is shown in **Exhibit 4.4.4**. When in-situ cleaning mode was entered, the gas efficiency temporarily dipped down. The efficiency restored back to the normal value immediately when in-situ cleaning mode was exited and normal operation resumed.

Exhibit 4.4.3. Sample Data of Operation with Self-Cleaning Mode.

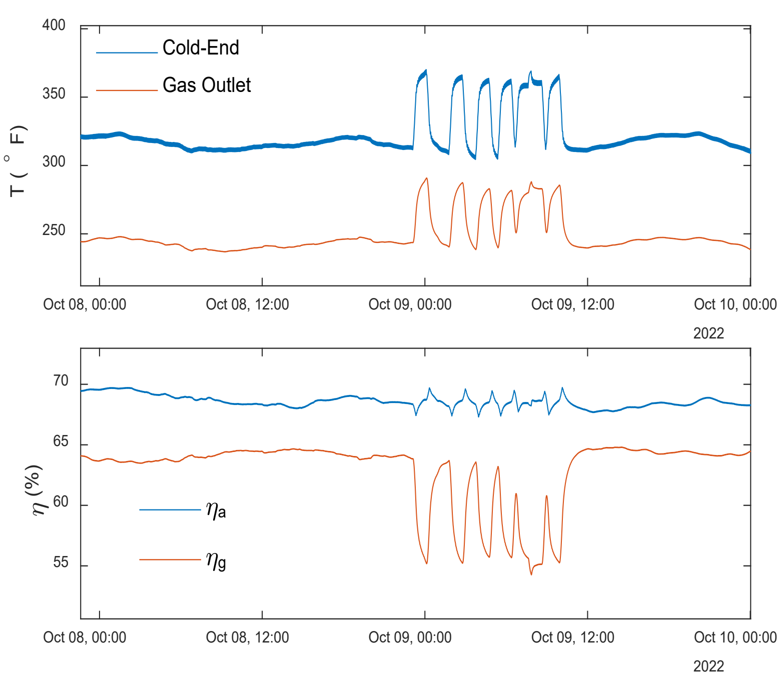


Exhibit 4.4.4. Temperature and Efficiency of Operation with Self-Cleaning.

Since the cleaning control is based on monitoring system temperature, the ambient temperature tends to affect the cleaning frequency in different seasons given more heat loss during the low ambient temperature conditions, such as winter. The number of cleanings per day is tentatively plotted with the ambient temperature as shown in **Exhibit 4.4.5**. It is seen that the applied temperature criteria can lead to a higher cleaning frequency when ambient temperature drops below 35 °F.

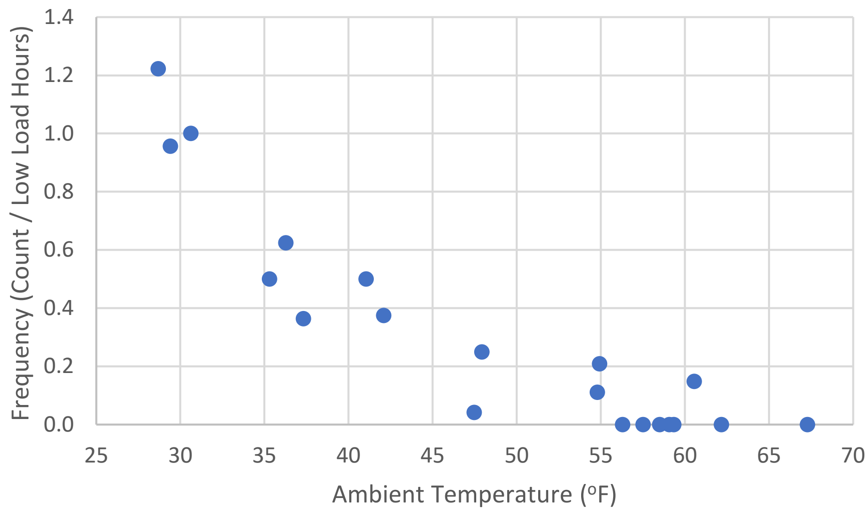
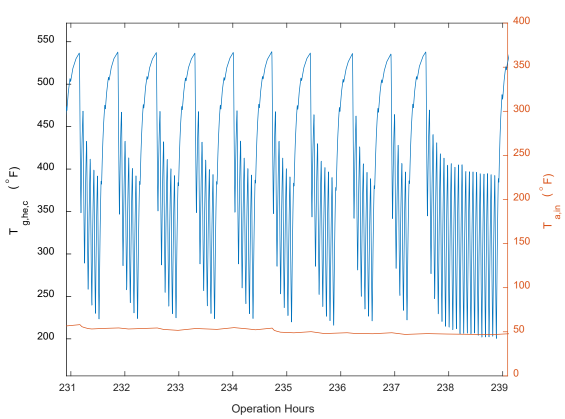
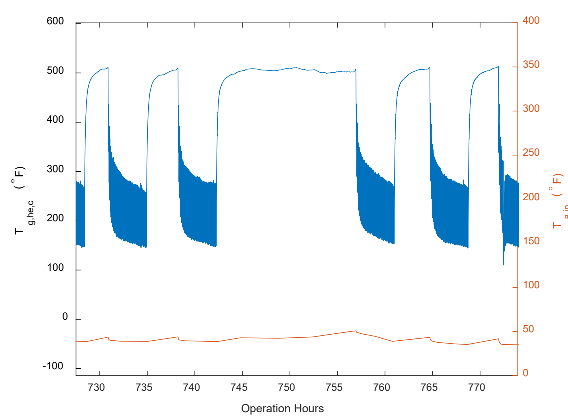


Exhibit 4.4.5. Cleaning frequency with respect to ambient temperature.

Fixed number of cleanings control is also introduced to allow the operation to enter a predetermined number of cleanings per day at same interval between each. **Exhibit 4.4.6** shows examples of cleaning operation based on temperature (Left) as well as fixed number of cleanings (Right). For temperature based cleaning control, the cleaning frequency can vary by adjusting the temperature criteria to enter the cleaning sequence. Specifically, higher enter-cleaning temperature criteria will lead to more frequent cleaning. The cleaning frequency may also be relatively higher during winter season with heat loss affecting the system temperature, as shown in **Exhibit 4.4.5**. The duration of cleaning is determined by the temperature criteria to exit the cleaning sequence. Specifically, higher exit-cleaning temperature criteria requires longer time of cleaning. For fixed number of cleanings control, the cleaning frequency remains constant, and the cleaning duration is determined by the temperature criteria to exit the cleaning. For both types of control, the duration of cleaning can vary by adjusting the temperature criteria to exit the cleaning sequence.



Temperature based Control
Cleaning in service when:



Time-based Control
Cleaning in service when:
Count every 5-6 hours;

TI301<=225 °F OR TI504<=380 °F after flue gas cycle; Cleaning off service when: **TI301>=415 °F OR TI504>=520 °F after flue gas cycle.**	Cleaning off service when: **TI301>=415 °F OR TI504>=520 °F after flue gas cycle.**

Exhibit 4.4.6. Operational Data of Temperature and Fixed Number of Cleanings Control

4.4.2 Year-long Operation with Self-Cleaning

Operation data of the year-long operation campaign with in-situ self-cleaning service standby from June of 2022 to July of 2024 with >8000 accrual hours are shown in **Exhibits 4.4.7 to Exhibits 4.4.10.** The year-long operation went smoothly for >6000 hours with temperature based in-situ cleaning in service when needed. Under fixed number of cleanings control when cleaning frequency was initially set as 5 times per day, unit operation temperature gradually decreased over time towards a new balance of flow and pressure drop (or ash buildup level). The winter season with much lower ambient temperature had brought the unit temperature further lower that broke the balance and led the unit towards a quite higher ash level. A manual water wash cleaning was performed to continued operation under fixed number of cleanings control with cleaning frequency of 10 and 7 times per day for over another 2000 hours of stable operation. As shown in **Exhibit 4.4.11**, ash indicator is maintained close to 1 along the operation with temperature based cleaning control, meaning that the ash level is quite low and well maintained. For fixed 5 cleanings per day operation, the ash indicator gradually increased to 10~20 and could go higher if continuing such cleaning frequency. Ash indicator was able to be maintained at 4~6 for operation with fixed 10 and 7 times per day, showing a new balance of ash level was being achieved. **Exhibit 4.4.12** shows the cleaning frequency observed along the year-long operation. Cleaning frequency could be varied for temperature based cleaning control, with most of the time in the range of 5~20 times per day.

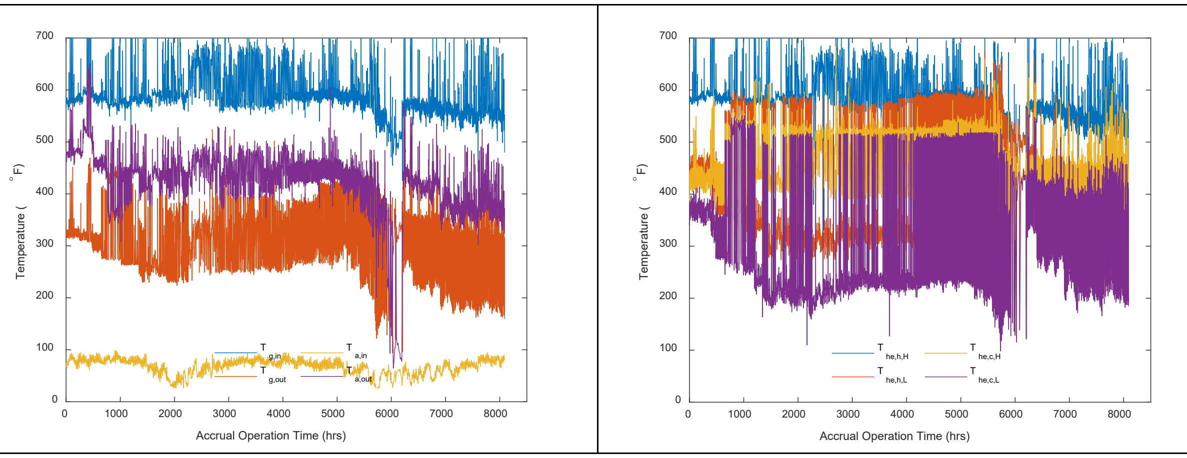


Exhibit 4.4.7. Operation Data – System and Heating Element Temperatures.

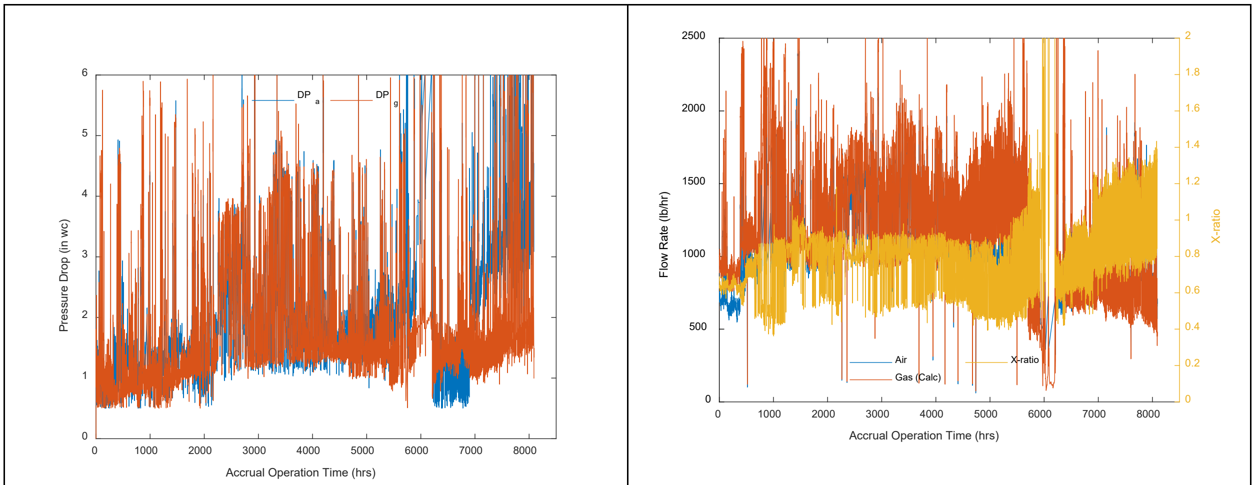


Exhibit 4.4.8. Operation Data – Pressure Drops and Flow Rate of Air and Flue Gas, and X-ratio.

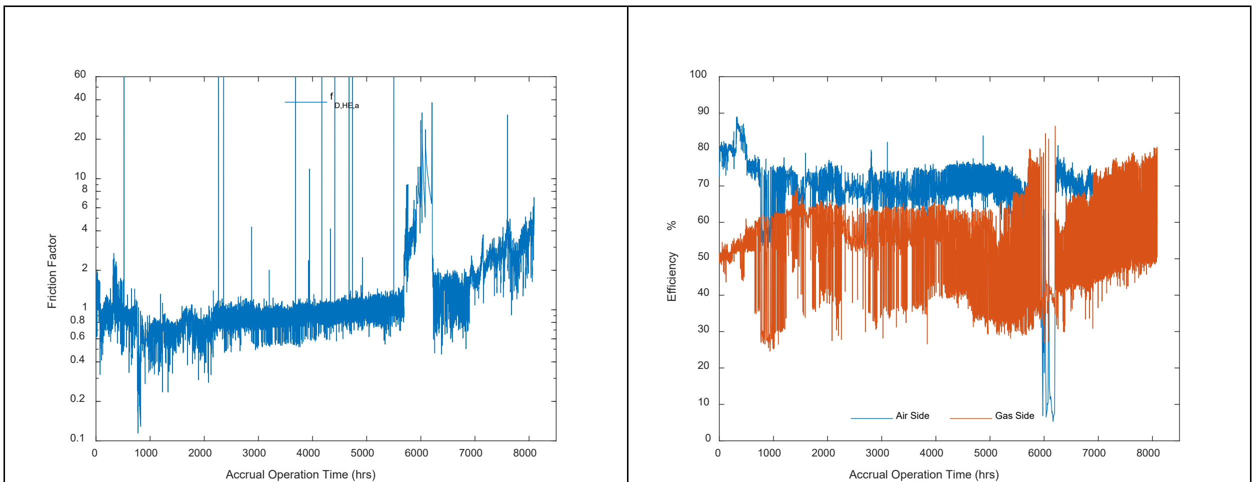


Exhibit 4.4.9. Friction Factor and Efficiency on Air and Gas Side.

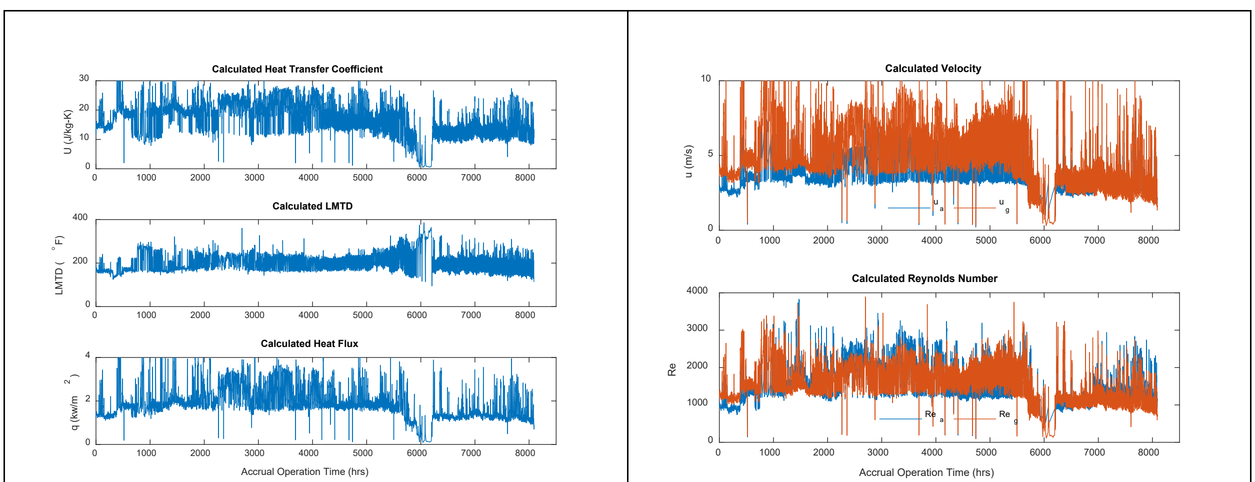


Exhibit 4.4.10. Heat Transfer Coefficient, LMTD, Heat Flux, and Velocity.

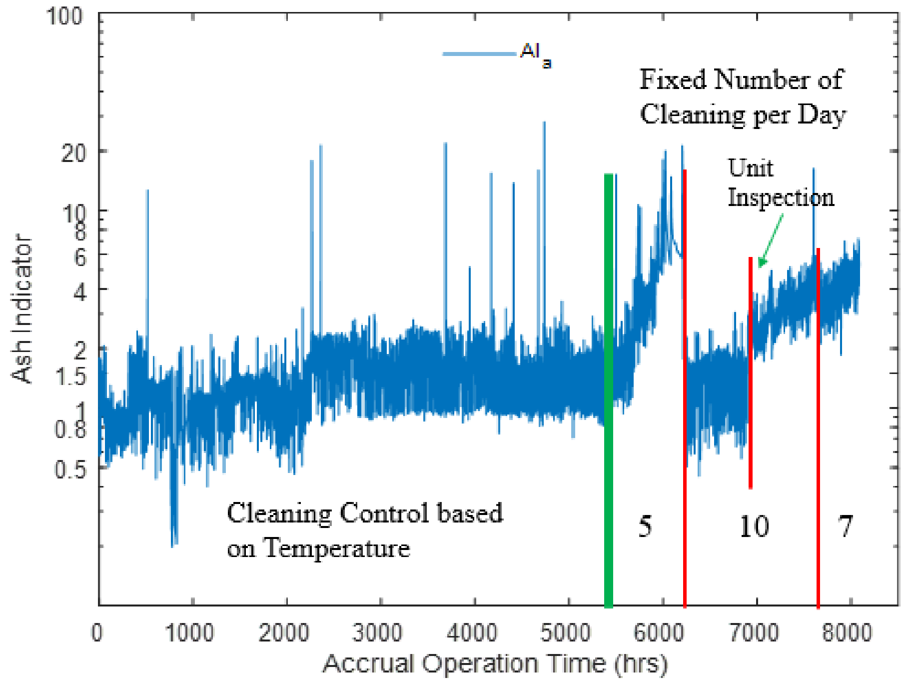


Exhibit 4.4.11. Ash Indicator over Long Term Operation Campaign.

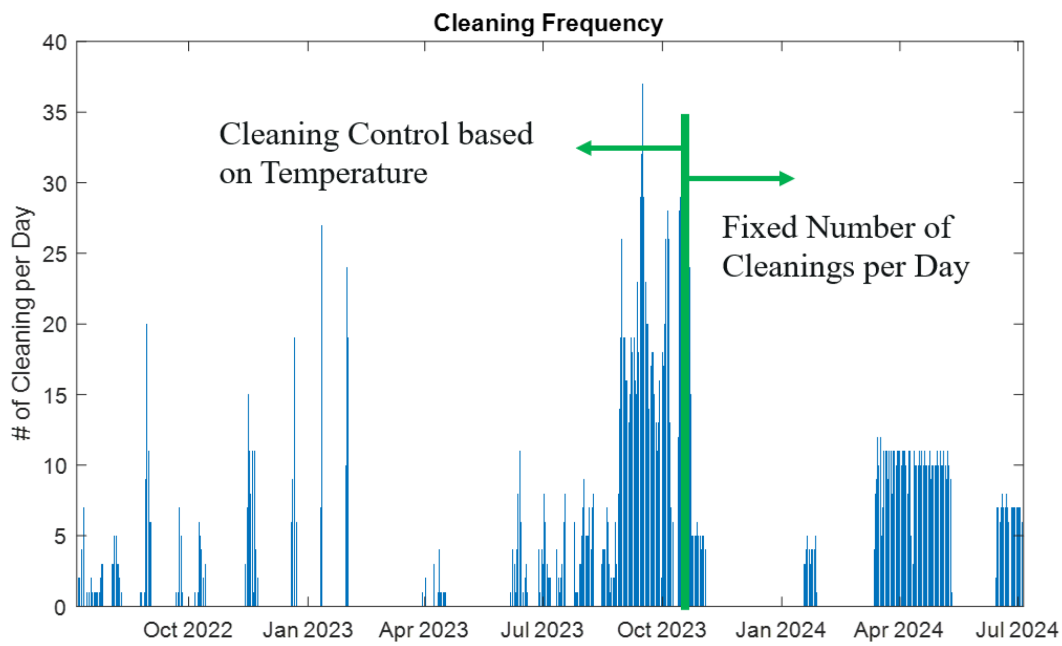


Exhibit 4.4.12. Number of Cleanings per Day from July 2022 to July 2024

4.4.3 Corrosion Analysis from Coupon

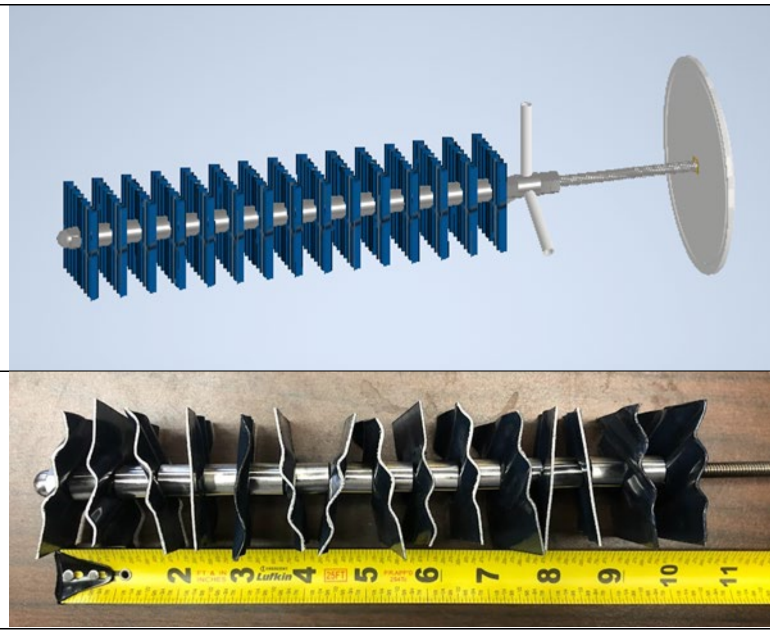


Exhibit 4.4.12. Design and Fabrication of Corrosion Coupon Set

A corrosion coupon set was designed, fabricated and installed in the pilot unit to monitor and analyze potential pitting corrosion that can be caused from condensed sulfuric acid at 250 °F. As shown in **Exhibit 4.4.12**, a coupon set, made of same material as cold end heating element, was designed and fabricated. The coupon set consists of 15 precut square-shaped coupons, with each size of 2”x2”. Spacers of ½” length are placed between each pair of coupons to separate and allow sufficient gas flow around the coupon. A threaded rod is inserted into each coupon, and nuts are threaded at both ends to tighten all coupons in fixed and aligned position. The coupon set is inserted into the 4” port right below the cold end heating element, as shown in **Exhibit 4.4.13**. The 3-leg at the end of the coupon set, is to support weight of coupons once installed. The coupon set was placed in unit for service on 6/5/2023.

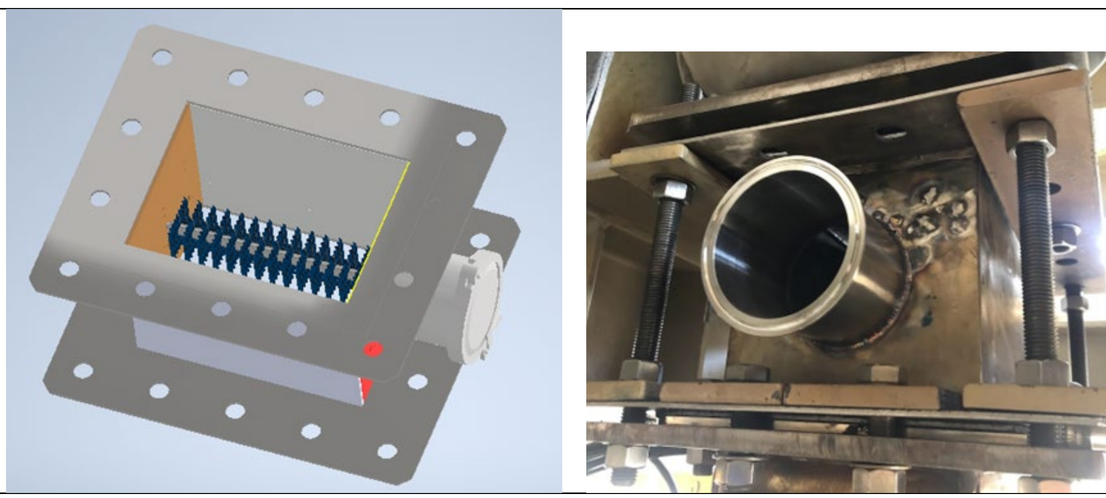


Exhibit 4.4.13. Location of Coupon Set Installation under Cold End Heating Elements

One coupon at a time was planned to be collected after every 250 accrued operating hours. This time interval was extended when minimum pitting corrosion was observed. Standard operating procedures were developed after collecting each coupon before optical microscope analysis. Specifically, immediately after collection, the ash attached to the surface of the coupon is first vacuumed. The coupon is then gently cleaned with a soft brush and flushed with DI water. The coupon is then dried with compressed air, then wrapped with paper towel and stored in sealed bag together with a handful of dry rite and then placed in a vacuumed desiccator before microscope analysis. A physical look at the coupon after each step is shown in **Exhibit 4.4.14**.

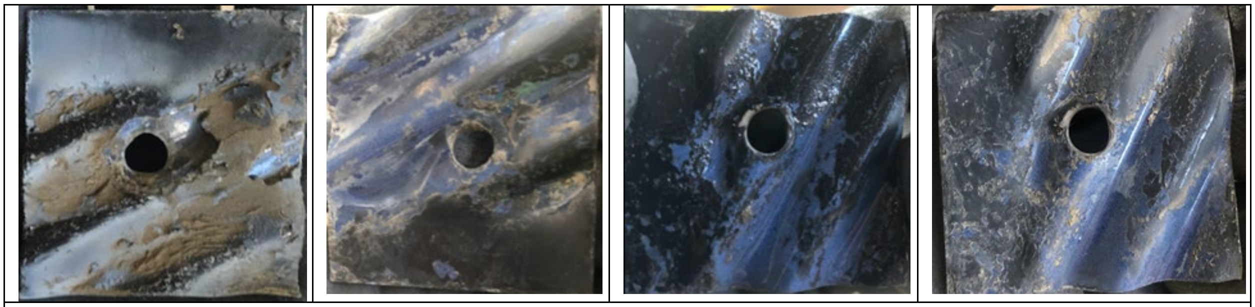


Exhibit 4.4.14. Photos of Coupon after Steps of Vacuumed, Brushed, DI Water Flushed, and Compress Air Dried Before Microscope Analysis.

The coupon is placed under an optical microscope at 5x, 20x, and 50x for analysis. Given the uneven corrugated structure of heating element coupon, the flat surface, convex surface, and concave surface are defined and shown in **Exhibit 4.4.15**. The optical microscope is capable of obtaining focused images on convex and flat surfaces, but not concave surfaces because the relatively large sized lens can not reach close enough to the valley of the coupon. Considering the contact point of packing of heating elements are mainly convex surface, the corrosion is expected more likely happening at the convex surface, if any, than other surfaces. A coupon prior to service is also placed under an optical microscope for comparison. The actual image at 20x and 50x as well as a schematic drawing are shown in **Exhibit 4.4.16**. The bubble-like appearance indicates the coating on top of the metal surface of the heating element.

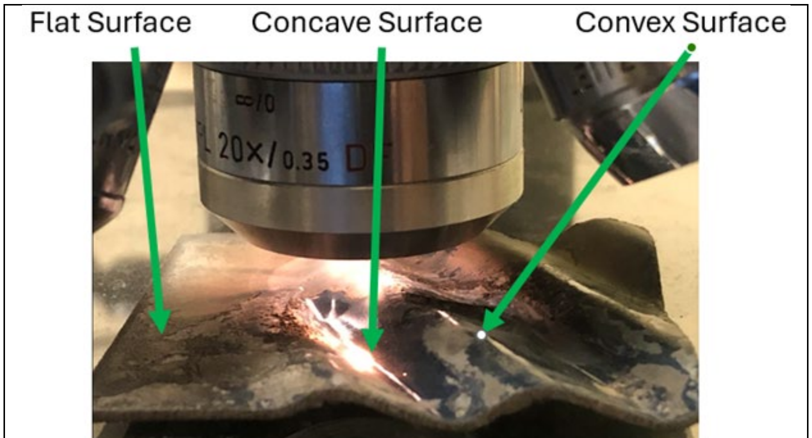


Exhibit 4.4.15. Definition of Coupon Surfaces for Optical Microscope Analysis

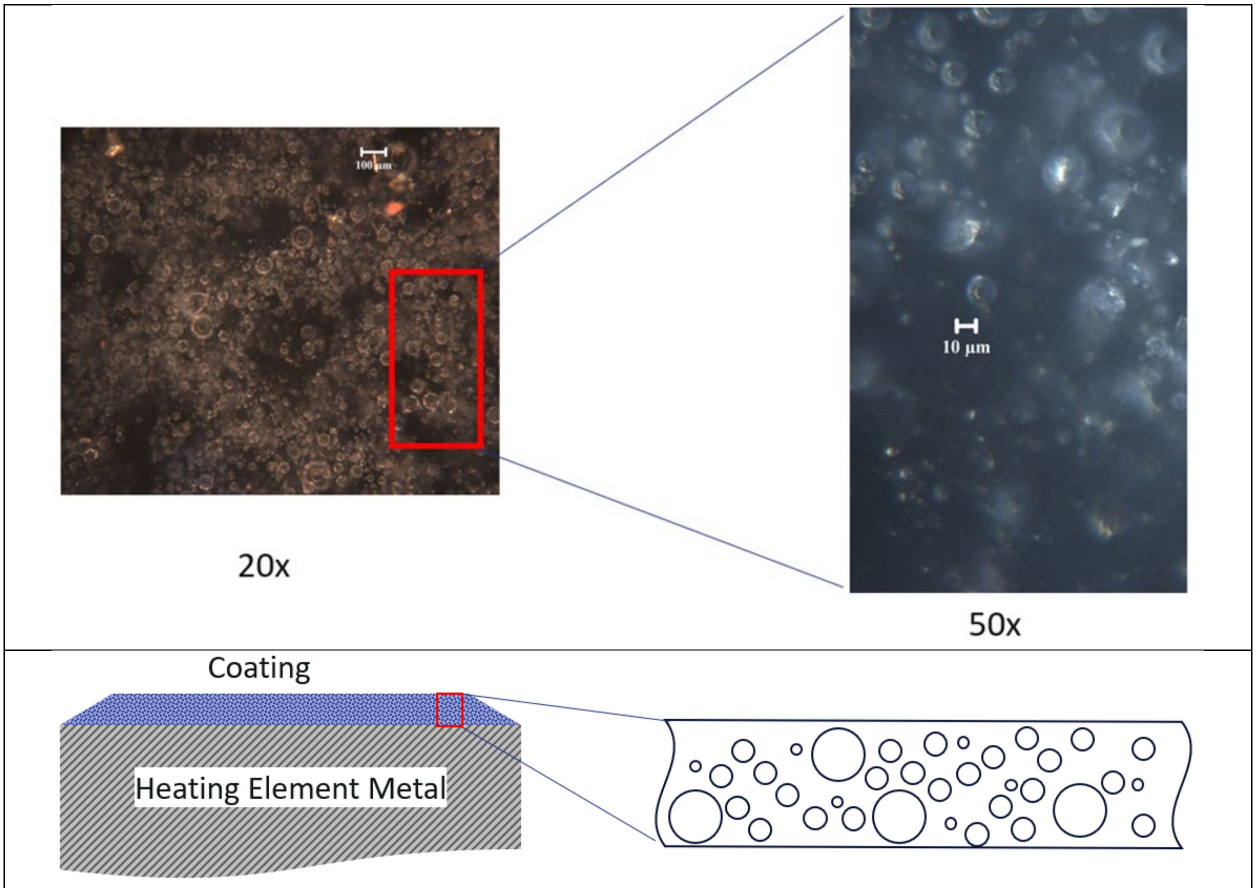
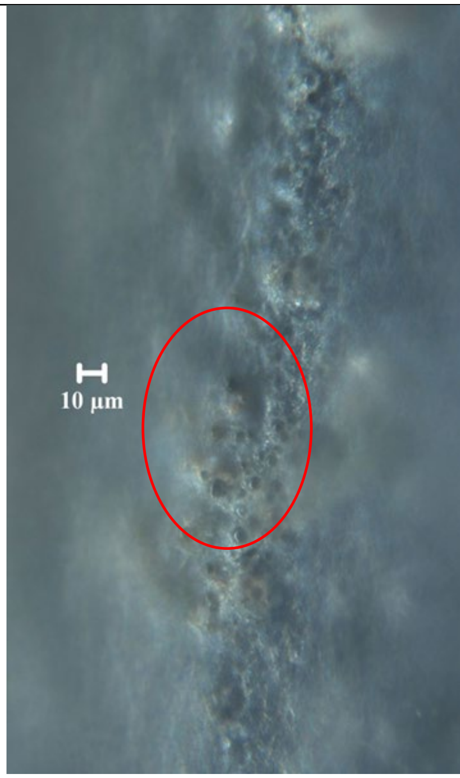
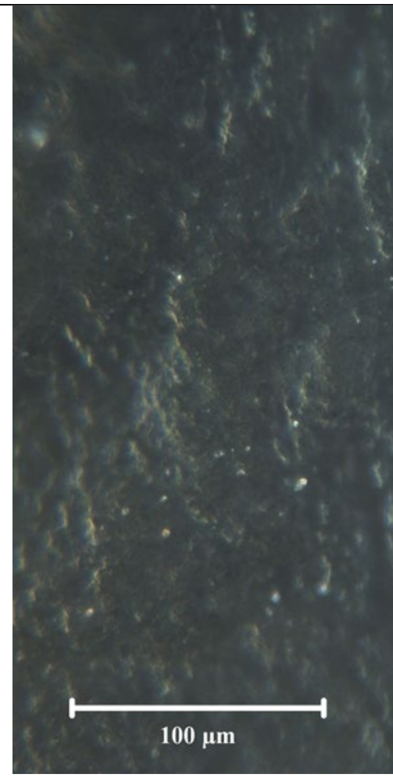


Exhibit 4.4.16. Optical Microscope Image of Heating Element Coupon Prior to Service

In one coupon after 2200 accrued hours of service, the onset of a few possible pitting corrosion spots was observed. These potential pitting corrosions were not uniform but happened only on certain convex surfaces. Optical microscope images at 50x of both convex and flat surfaces are shown in **Exhibit 4.4.17**. The depth of such pitting spots is unknown. The size at the surface is less than a few microns. By comparison, a typical moderator heat exchanger pit depth is 0.2~1 mm over 8~28 weeks (Tapping, et al., 1986). No corrosion was observed for another two coupons collected subsequently after 3000 and 3500 accrued hours of service, respectively. The images show exposed metal surface with deposited ash, as shown in **Exhibit 4.4.18**. This indicates minimum pitting corrosion happened within 3500 accrual operation hours, if any. Images that were taken at various locations of a coupon are summarized in **Exhibit 4.4.19**.

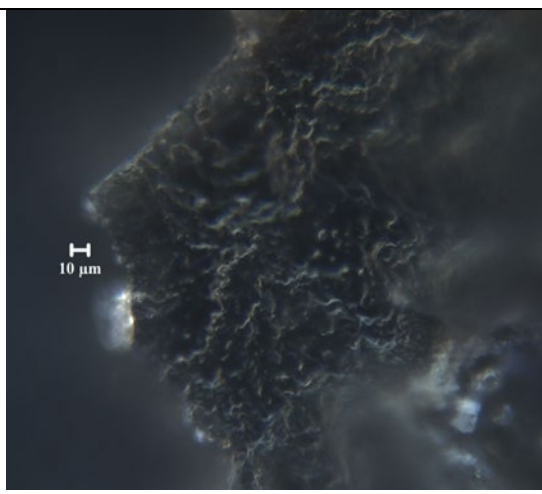


Convex Surface

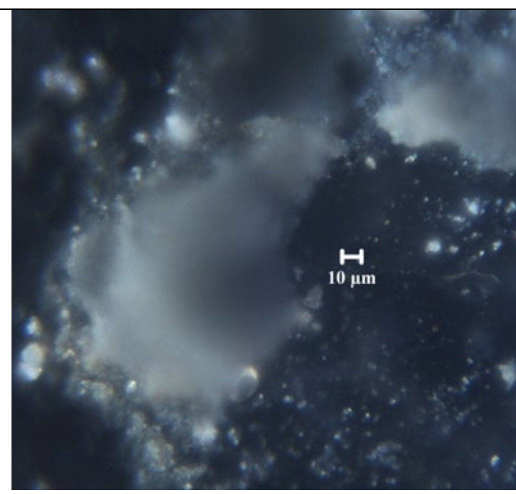


Flat Surface

Exhibit 4.4.17. Optical Microscope Image (50x) of Possible Pitting Corrosion Observed only at Convex Surfaces (Left) at Coupon Serviced after 2200 Accrued Hours



3000 Hours



3500 Hours

Exhibit 4.4.18. Optical Microscope Image (50x) of Metal Surfaces and Deposited Ash at Coupon Serviced after 3000 (Left) and 3500 (Right) Accrued Hours

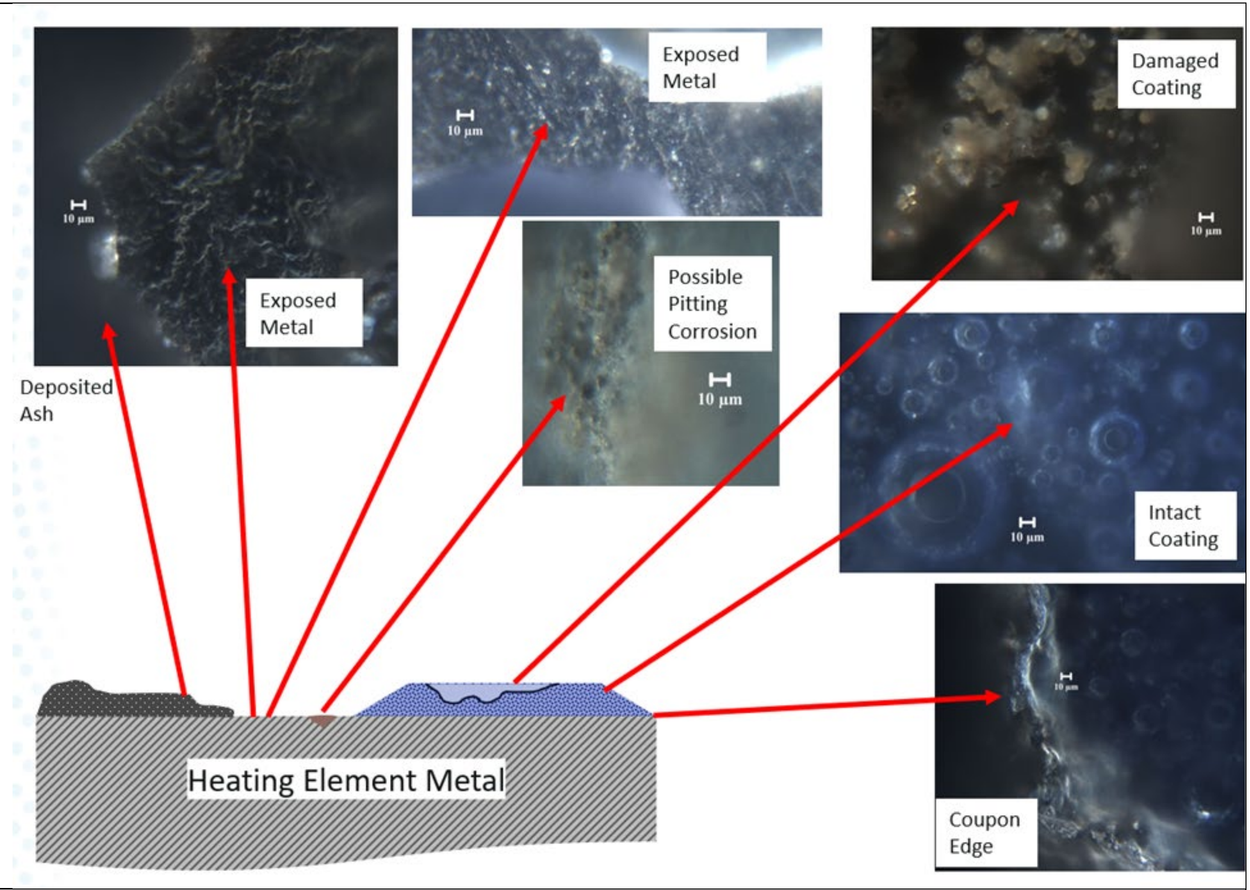


Exhibit 4.4.18. Summary of Optical Microscope Images of a Coupon at Various Locations.

5) MAIN FINDINGS/ACHIEVEMENT

UKy will carry forward five key findings from this project.

1) This project demonstrated that temporary and periodic high temperature of heating elements (450 ~ 500 °F) can prevent ash accumulation and maintain air preheater free of clogging. This significant finding proves UKy's low-cost ash fouling free technology can be implemented to avert the need for operating the entire air preheater at constant high temperature.
2) The ash samples analysis and unit operation provide solid evidence of ABS formed during low load with SCR ammonia slip being the major cause of ash accumulation, and air preheater clogging can be prevented by raising the heating element temperature up to 450 °F~ 500 °F at which ABS is decomposed.
3) In-situ self-cleaning can be controlled by monitoring temperature and/or presetting fixed number of cleanings per day. Both approaches in pilot testing show positive results for maintaining an ash free state for the air preheater.
4) Temperature criteria (cold end or gas outlet temperature) for entering self-cleaning service is critical to balance the number of cleaning cycles with maintaining the ash level .
5) Temperature criteria (cold end or gas outlet temperature) for exiting self-cleaning service is critical to balance the duration of the cleaning cycles with maintaining the ash level.

6) TECHNOLOGY BENEFITS AND SHORTCOMINGS

Benefits of the technology that have been incorporated into plans for demonstration at larger scales are the self-cleaning control sequences based either on temperature or a fixed number of cleanings. Both control sequences can be applied at low load conditions to enhance in-situ ash removal without increasing pressure drop for the air and flue gas, leading directly to capital and operating cost reduction.

The in-situ self-cleaning technology is designed to tackle severe clogging issues at the air preheater caused by ABS, which occurred during low load and deep cyclic operation. The autocleaning will occur only when the unit is operated during the low load and deep cyclic operation, where the air flow can be restricted by the blinder-typed vanes without the impact on the boiler output. The number of blinder-typed vanes to be operated at the same time are determined by operation load.

7) FUTURE DEVELOPMENT

With pilot scale demonstration complete, the UKy-IDEA in-situ self-cleaning transformational technology will be further advanced to scale-up for retrofit and validation at the commercial scale in a coal fired power plant. This will allow 1) ash free air preheater to better handle low load and deep cyclic conditions, 2) broader operating temperature range of boiler and SCR under low load conditions, 3) reduced down time due to ash buildup and/or clogging in air preheater.

The UKy 250 kW_{th} pilot unit has been in test operation at E.W. Brown Generating Station in Harrodsburg, KY since 2022, and continued long term campaign until 7/10/2024 for technology validation. This technology can be readily transferred to larger regenerative air preheater with a simple retrofit at air inlet by adding a number of pneumatically controlled blinder-type vanes. The cleaning control sequence developed in DeltaV can also be readily transferred to commercial DeltaV or other DCS.

UKy is also actively collaborating with coal fired power plant on planning a commercial demonstration and operation, which may provide additional improvement on operation and retrofit for future deployment of this technology.

8) REFERENCES

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2. H. Chen, et al., “Corrosion and Viscous Ash Deposition of a Rotary Air Preheater in a Coal-Fired Power Plant”. 2017.
3. F. Nie, “A Study of the Prediction of Ammonium Bisulfate Formation Temperature by Artificial Intelligence”. 2017
4. J. Menasha, D. Dunn-Rankin, L. Muzio, J. Stallings, “Ammonium bisulfate formation temperature in a bench-scale single-channel air preheater”, Fuel, Volume 90, Issue 7, July 2011, Pages 2445-2453.
5. W. Counterman, R. Afonso, and S. Tavoulareas, “Assessment of Air Preheater Fouling due to Utilization of SNCR and SCR Systems”, EPRI GC-111797, December 1998.
6. Mallikarjuna V, Jashuva N, Reddy BRB. Improving Boiler Efficiency By Using Air Preheater. International Journal of Advanced Research in Engineering and Applied Sciences 2014;3:11–24.
7. Tapping, R L, Lavoie, P A, and Disney, D J. 1986. "Corrosion of heat exchanger materials under heat transfer conditions." Nuclear Journal of Canada.

9) LIST OF ACRONYMS AND ABBREVIATIONS

ABS – Ammonium Bisulfate
APH – Air Preheater
BET – Brunaeur-Emmett-Teller
BP – Budget Period
CAD – Computer Aid Design
DCS – Distributed Control System
EDS – Energy Dispersive X-ray Spectroscopy
HAZOP – Hazard and Operability
HMI – Human Machine Interface
HWRC – Hot Water Recirculating System
IC – Ion Chromatography
I/O – Input/Output
IUPAC – International Union of Pure and Applied Chemistry
IDEA – Institute for Decarbonization and Energy Advancement
NPS – Nominal Pipe Size
OEM – Original Equipment Manufacturer
PFD – Process Flow Diagram
P&ID – Piping and Instrumentation Diagram
SCR – Selective Catalytical Reactor
SEM – Scanning Electron Microscopy
SOW – Scope of Work
TGA – Thermogravimetric Analysis
UKy – University of Kentucky
USG – US Standard Gauge for Stainless Steel
VDC – Volts Direct Current
XPS – X-ray photoelectron spectroscopy
X-ratio – Capacity Ratio
XRD – X-ray Diffraction
XRF – X-ray Fluorescence

Appendix I, SOP - APH OPERATION

Procedure Description
This SOP outlines most of the procedures associated with the APH Unit including full start-up, daily start-up, calibration, daily shut down, full shut down, and preventative maintenance tasks.
In case one person is on site only for short period of time, lone operation SOP needs to be followed.

Safety Precautions

- PPEs including safety glasses, hard hat, safety vest and steel toe boots are required working in E.W. Brown station.
- N95 respirator is required when performing dealing with ash and open up the unit.
- Ear plugs are encouraged when host plant is online.
- Pay close attention to existing I-beams at the height of 5 feet when walking towards the unit. Prepare to bend and walk through.
- Follow ladder safety standard when climbing up and down ladders.
- Carry along the SO_2 and NO_x monitors all the time during on site operation. If the battery is dead in either, it must be replaced before opening any gas cylinders.
- Maintain house keeping by organizing tools, removal trash, clean up to dust/ash, keep walkway clear, and regularly replace filter bag in vacuum, etc.

Tools, Parts, Materials, Test Equipment
Materials
1. SO_2, N_2 and Calibration gases (5000 ppm SO_2 mixed with N_2)

Tools
1. Toolbox on site
2. Vacuum on site

Test Equipment
1. APH Unit
2. Gas analyzer and gas conditioners

Miscellaneous
2. SO_2 and NO_x monitor
3. Calibration checklist & clipboard

Hazardous Material
The SO_2 gas is corrosive. The calibration gases, as well as the sample flue gases contain SO_2. Consult SDS for handling procedures and safety requirement. Precautions should be taken to ensure the safety of the operators. When unit is in operation, no gas should be leaking out due to negative pressure inside.

Full Start-Up
1. Start-up check list (start from a fully shut-down status):
   a. Following list is to ensure system fully shut down, before performing a full startup.
   b. Ensure all 4 hand valves and 4 auto control valves are at closed position.
   c. Ensure main instrument air valve (located at a separate platform 15 feet away behind control panel, can be accessed through plant ladders) is open and all downstream ¼" hand valves are closed except one that controls purge flow to control panel. Check and ensure pressure gauge at the side on control panel is positive pressure.
   d. Ensure all ¼" hand valves for gas/solid sampling are closed.

   e. Ensure all ¼” hand valves connected to pressure gauges are closed.
   f. Ensure main instrument air valve is closed.
   g. Ensure power switches are off in control panel.
   h. Ensure the solid sampling pump is unplugged.
   i. Ensure both computer workstations, gas conditioners, and gas analyzer are powered down.
2. Following list is to perform full startup when host plant is online.
3. **Remove ash that accumulated above HV-101 (the chain valve) and CV-101 (the gas inlet auto-valve)**. **This is the most important step to prevent unwanted heating element clogging from accumulated ash right above these two valves.**
   a. Ensure CV-101 is closed, Open HV-101, (chain valve at flue gas inlet).
   b. Open up the 4” blind flange that is right above CV-101. Clean up accessible ash by vacuum as much as possible. When host plant is online, upper duct is in sort of vacuum (about -5 in wc) which will likely remove majority ash.
   c. Close up and bolt up the 4” blind flange with new gasket.
   d. Close up HV-101.
4. Power on both extension power cords located in the small room (can be accessed by plant ladders) behind the APH unit control panel.
5. Turn on main power breaker in control panel (1^{st} breaker on top left). Turn on 24VDC and 12VDC power supply breaker (2^{nd} and 4^{th} breaker on top left).
   a. 24 VDC and 12 VDC power supply indicator light should be on.
   b. Controller and i/o cards power indicator light should be on.
   c. Motor relay power indicator light should be on. (Motors are not in use starting April 2023)
   d. Check if fuses are at good condition in each fuse terminal in case any indicator not lit.
6. Turn on both Pro+ and Operator computer workstation in the cabinet. Log in computer with username and password. Log in controller with password.
   a. Pro+ Workstation: Username: **Emerson**, Password: **xxxx**;
   b. Op Workstation: Username **Emerson**, Password: **xxxx;**
   c. Controller: Username: **Emerson**, Password: **xxxx**.
   d. Ensure physical connection (2 blue ethernet cables) between computer workstations and controller.
   e. Load DeltaV Operate HMI in both Pro+ and Operator workstations. Log in DeltaV with password. (**Username and Password are same as computer login for that specific computer workstation**)
   f. Load APH operation main page.
   g. Check readings of temperature, pressure, and flow.
   h. Check auto control valve states.
7. In Windows or DeltaV Desktop, open DeltaV Operation application. Open APH page. APH HMI should show up with current pressure, temperature, valve, and flow readings.
8. Open ¼” hand valves on instrument air pipeline for all 4 auto control valves.
   a. Test open and close auto control valve in Manual mode. Interlocks may need to be disabled.
   b. Test open and close motor-controlled vanes in Manual mode.
9. On HMI, Enable sequence mode. Test sequence operation by performing the following: click “Start”, then type “0” and confirm.
   a. Ensure Interlocks are enabled.
   b. All 4 hand valves should be closed during the sequence test.
   c. Start sequence and ensure that valve/vane operations are consistent with sequence.
10. If valves/vanes operated well, stop the sequence in HMI by performing the following: Click “Stop”, then type “1” and confirm. And click “Reset”, then type “5” and confirm.

11. Heat up unit before auto sequence cycling
    a. Open flue gas inlet and outlet valves (**both auto valves and hand valves**) and keep air flow inlet and outlet valves closed.
    b. Monitor temperature profile at flue gas inlet, heating element and flue gas outlet (TI 101, TI 501, TI 504, TI 301) and pressure drop (PDI 501).
    c. Move to next step (auto sequence) when system heated up and maintain constant temperature profile, which typically takes 2 hours.
12. Starts heat transfer cycle. On HMI, Enable sequence mode.
    a. Open all 4 hand valves.
    b. Ensure Interlocks are enabled.
    c. Start sequence by 1) clicking the button "Start" and 2) typing 0 in the pop-up window and 3) hitting "Enter" to confirm.
    d. Ensure that valve/vane operations are consistent with sequence.

Emergency Stop:

1. Click the "Stop" button and type 1 in the pop-up window. All valves will stay at current position. Sequence can be resumed by click the "Start" button again and type 0 in the pop-up window and hit "Enter" to confirm.
2. Click the "Reset" button and type 5 in the pop-up window. All valves will be closed off. Sequence can be resumed by click the "Start" button again and type 0 in the pop-up window and hit "Enter" to confirm.

Daily Start-Up

1. No daily start-up is needed. In case of startup when host power plant is back online after a temporary shutdown, follow the steps of full startup. Some steps might be skipped, **but Step 3, 11 and 12 must be followed during each startup**.
2. Check DeltaV HMI for in-situ readings.
3. Check unit, control panel and instruments. Look for connections that might have loosened overnight.
4. Calibrate analyzer, if needed by following the procedure outlined in this document.

Daily Shutdown

1. No daily shutdown is needed.
2. In case of power station planned shutdown, shut down the unit by following the "Full Shutdown" procedure 1 to 4 in this document.
3. In case of power plant unplanned shutdown, APH test unit can shut down automatically when plant duct cools down. Chain valve (HV-101) need to be closed manually.

Full Shutdown

1. Stop and Reset sequence then Disable sequence.
2. Close all 4 hand valves.
3. Turn off gas sampling and flush analyzer with N_2 for 5-10 minutes.
    a. Turn off sampling pumps.
    b. Turn off analyzer and gas conditioners.
    c. Turn off all ¼" valves on sampling streams.
4. Turn off solid sampling.
    a. Turn off sampling pumps.
    b. Turn off all ¼" valves on sampling streams
    c. Collect samples in filters.

   d. Open compressed air purge valves to clean up sampling line for 1 min. Leave valves slightly open to prevent sampling line plug.
5. Turn off both computer workstations.
6. Power off control panel breakers.
7. Power off power strip located in the room behind the control panel.

Routing Checklist:

1. Check if 4 auto valves operating sound can be heard repetitively.
2. Check if rain/water falls into analyzer and computer cabinets.
3. Check temperature profile (in DeltaV HMI located inside cabinet) to determine if unit is operating as expected:
   a. TI 101: ~ 600 F
   b. TI 501, 504: cycling ~300 F to ~500 F
      i. Zoom in to see if cycling is steady
   c. TI 601, 602, 603: cycling ~ 50 F to ~400 F
      i. Zoom in to see if cycling is steady
   d. TI 301: ~300 F
   e. TI 201: ~60 F
   f. TI 401: ~400 F
4. Check pressure profile
   a. PI 101: ~ - 5 in wc
   b. PI 201: ~ 0 in wc
   c. PDI501: cycling ~-2 to ~2 in wc
      i. Zoom in to see if cycling is steady
5. Check valve opening percentage and time is consistent with the value used in "Sequence" box in DeltaV HMI.
6. Check Coupon Insert, inspect bottom of heating element, and collect the very end coupon every 200~250 hours by following the **Coupon Collection and Heating Element Inspection Procedure**.
7. Log every activity and time in One Notes in preset table.
8. Download operation data and save in IDEA shared drive .
   a. Go to the "Operator" workstation.
   b. Go to D drive and the folder "APHDataExport", then go to "10 SEC".
   c. Open the latest data file (MS Excel spread sheet).
   d. Save as a copy and follow the same file name pattern with new date, e.g. "DATA - APH - 2022-2-22- 10 sec".
   e. Change the "Start" and "End" date located at the 1st column in the data file.
      i. Note that only include one day's data in one file, e.g. Start: 2/22/2022 12:00:00 AM, End: 2/22/2022 11:59:59 PM
   f. Follow the step c and d to save all operation data until current. Only the data file with the dates that APH unit is operating are needed.
   g. Use USB drive to download the new data files and copy to IDEA shared drive.

Coupon Collection and Heating Element Inspection Procedure

1. Remove part of insulation that covers the 4" port, right below the heating element section.
2. Hand loose clamp and carefully pull out 4" cap/coupon insert. Ash usually accumulated in the port, so have vacuum ready before pulling out the coupon insert.
3. Take pictures of entire coupon insert from various perspective.
4. Carefully Remove and collect the very end coupon, and ensure the remaining coupons stay the same position and direction. Tightened the remaining coupon.
5. Take a few pictures of collected coupon from various perspective.

6. Carefully pack the removed coupon with packing paper and save it in Ziplock bag.
7. Mark dates, coupon #, name of employee on the bag. And save the bag with all other bags with collected coupons.
8. Use borescope to inspect the bottom of heating elements through the 4" port. Take videos from various perspectives via borescope video function. For a great view, a straight pipe/stick needed to tie with borescope cable to support the weight of camera head. Pull out borescope once completed.
9. Reinstall the remaining coupons back to the 4" port at the same direction (as marked on the cap).
10. Retighten clamp and replace insulation.
11. Save videos/pictures in IDEA shared drive with clearly date named folders.

Gas Sampling Procedure (for flue gas flow rate measurement in gas flow mode only)

1. Turn on gas analyzer and both gas conditioners by pressing the on/off switches in the back. Allow 60 minutes to warm up before continuing.
    a. Ensure gas analyzer and gas conditioners are isolated from the unit. Check valves on sampling line (upstream of analyzer) and vent line (downstream of analyzer) are closed.
    b. Ensure needle valves for flow meter at the front of both gas conditioners are closed.
2. Open vent valve. Open ¼" valves on stream 1 or 3 and 2.
3. Power on both sampling pumps, and gradually open the needle valve to allow desired amount of flow of sampling gas (0.5 mL). Analyzer should have readings for SO_2, O_2 and CO_2.
    a. Ensure knob at the front panel of gas conditioners pointed to "Sampling gas".
4. Click "Power on" button for FIC-701, to turn on the MFC for SO_2 flow.
5. Set SO_2 flow rate at 30 slpm. The reading of flue gas flow rate (FIC- 101) shows calculated flue gas flow rate.

Gas Sampling Frequency

- Gas sampling needed for the first time to check and verify flue gas flow rate.
- When sampling, N_2 and calibration gas and SO_2 cylinders need to be capped at the end of the day when calibration or SO_2 doping performed.

Gas Sampling Stop Procedure

1. Power off both sampling pumps, and gradually open the needle valve to allow desired amount of flow of sampling gas (0.5 mL).
2. Close ¼" valves on stream 1 or 3 and 2.
3. Flush analyzer with N_2 for 5 minutes.
4. Close N_2 and vent valve. Close needle valves at the front of both gas conditioners.
5. Turn off gas analyzer and both gas conditioners by pressing the on/off switches in the back.

Analyzer Calibration Procedure

1. Turn on gas analyzer and both gas conditioners by pressing the on/off switches in the back. Allow 60 minutes to warm up before continuing.
    a. Ensure gas analyzer and gas conditioners are isolated from the unit. Check valves on sampling line (upstream of analyzer) and vent line (downstream of analyzer) are closed.
    b. Ensure needle valves for flow meter at the front of both gas conditioners are closed.
2. Select Calibration Mode at analyzer panel.
3. Open vent valve.
4. Open valves for N_2 flow and valves on stream "CAL 1".
5. Power on both sampling pumps, and gradually open the needle valve to allow desired amount of flow of sampling gas (0.5 mL).

   a. Ensure knob at the front panel of gas conditioners pointed to “CAL 1”.
   b. Analyzer should have readings for SO_2, O_2 and CO_2.
6. Select desired gas and set “Zero”.
7. Power off both sampling pumps, and gradually close the needle valve.
8. Close valves for N_2 flow and valves on stream “CAL 1”.
9. Open valves for Calibration gas flow and valves on stream “CAL 2”.
   a. For O_2 calibration, open the valve that connected to air.
10. Power on both sampling pumps, and gradually open the needle valve to allow desired amount of flow of sampling gas (0.5 mL).
    a. Ensure knob at the front panel of gas conditioners pointed to “CAL 2”.
    b. Analyzer should have readings for SO_2, O_2 and CO_2.
11. Select desired gas and set “Span”. Span value is set 5000 ppm for SO_2 (same as the SO_2 concentration in calibration gas.) Span value is set 20.95% for O_2 (same as the O_2 concentration in the air at atmosphere.)
12. Detailed calibration can be found on Analyzer manual.

Analyzer Calibration Frequency

- Full calibration needs to be performed prior to each analyzer operation. Need to complete calibration check attached to clipboard.
- N_2 and calibration gas and SO_2 cylinders need to be capped at the end of the day when calibration or SO_2 doping performed.

Solid Sampling Procedure

1. Open ¼” valves on solid sampling stream. Close valves on compressed air stream.
2. Turn on sampling pump.
3. Adjust the flow to 2.5 L/min.
4. Check filter element the 1^{st} 24 hrs to inspect collected samples.
5. Continue sample collection for 7 continuous days and inspect collected samples.

Stop Solid Sampling Procedure

1. Turn off sampling pump.
2. Close needle valve on flow meter by adjusting the flow to 0 L/min.
3. Close ¼” valves on solid sampling stream. Slightly open valves on compressed air stream to prevent sampling pipe plugged.
4. Collect solid samples from filter.

Appendix II, SOP - DP MEASUREMENT LEAK CHECK

Air Preheater DP Measurement System Leak Check Standard Operating Procedure

University of Kentucky
Institute for Decarbonization and Energy Advancement
1 Quality St, Lexington, KY

Building: E.W. Brown Station (PPL Facility) Room: ________________
Group: IDEA PI: Kunlei Liu Co-I: Heather Nikolic

1. Type (check one)
■ Process ☐ Equipment ☐ Hazardous Chemical ☐ Hazard Class

2. Description
This SOP describes the procedure for checking leakage in the Air Preheater DP Measurement System.

When the UK pilot air preheater (APH) unit restarts after experiencing ash build up each time or on the bi-month basis whichever may occur first, both legs of DP measurement system (DPI-501) need to be opened and cleaned out. A leak test is required for each disassemble and reassemble.

3. Potential Hazards
Fly ash particles (generally 10~100 µm); System high pressure during pressurization process.

4. Personal Protective Equipment
Safety glasses, long pants, general purpose gloves, N95 (or other type recommended from respirator fit testing result) and safety toe shoes/boots are required at all times. Lab coat or apron are recommended. Safety blue vest is required for any PPL contractors with less than 5 years of experience at any PPL facility.

5. Engineering Controls
Wearing particle filtration mask before opening and cleaning any ports. Release pressure by opening the outlet valves and closing compressed air valve before opening any ports.
6. Special Handling and Storage Procedures
There are not special handling and storage procedures for this procedure.

7. Spill and Accident Procedures
There are not spill and accident procedures for this procedure.

8. Decontamination Procedures
There are not decontamination procedures for this procedure.
9. Waste Disposal Procedures
There are not waste disposal procedures for this procedure.

10. SDS Location
There are not SDS for this procedure.

11. Procedure

DPI-501 Service to Ensure Functionality

1. Open both high leg and low leg of DPI 501 at the ports that are closest to main unit body.
    a. Use 1/8" wire brush to clean out both ports.
    b. Use compressed air to blow through both ports to ensure ash is free from ports.
2. Open both high leg and low leg at the ports that are closest to the instrument DPI 501, regardless if ash build-up is observed at the two ports closes to main unit body.
    a. Use compressed air to blow through both legs (tube portion only) to ensure that no ash within either tube legs. Ensure all valves along these two legs are open.
    b. This step is required to protect the instrument from damage during the next step of pressurization if pressure is unbalanced due to possible ash in one or both tube legs.
3. After ensuring that both tube legs are completely free from ash, connect both the high leg and low leg with the original connections. Specifically, the high leg connects back to the DPI 501 high end port and gas inlet port, and the low leg connects back to the DPI 501 low end port and gas outlet port.

Leak Test of APH Unit

4. The leak test is performed by following steps:
    a. Close autocontrol valves CV 101, CV 401,and CV 301.
    b. Close hand valve HV 201. Leave hand valves HV 101 closed. Leave HV 401and HV 301 open for potential pressure release.
    c. Open autocontrol valve CV 201.
    d. Disconnect PI 201 from air inlet pipe and connect its port to compressed air with valve and pressure gauge.
    e. Slowly open the valve on the compressed air line to gradually pressurize the system. Closely monitor the reading of DPI 501 and system pressure reading during the pressurization process, from both instrument onsite display and the DeltaV human-machine interface (HMI). With well-practiced cleanings completed in **Step 2**, DPI 501 should read 0 all the time.
    f. If the DP1 501 reads more than 3 (or lower than -3) inch WC, stop and immediately open one of autocontrol valves (CV 401 or CV 301) and close the compressed air valve to depressurize the system. This is to prevent the DPI 501 from being damaged during the pressurization. Do not open CV 101 in case accumulated ash above CV 101 has not been removed. Opening CV 101 without completely removing accumulated ash above, could potentially result in a significant amount of ash falling onto the top surface of heating elements, which can cause the system to be nonoperable and require additional thorough cleaning. Repeat **Steps 1 to 3** to further clean both DPI 501 ports and tube legs, then restart from **Step 4a**.
    g. If DPI 501 reads zero, use snoop spray on each fitting connection along the two legs of DPI 501, from main unit body end to instrument end.
    h. Closely monitor if any bubbles appear and enlarge which indicates a local leakage. Pay attention to hissing sound to identify major leaks. Tighten fittings correspondingly to eliminate leakage. If replacement of a fitting is needed, follow **Step f** to depressurize the system before replacing. After replacement, start from **Step e** to identify any further leakage.

i. Repeat **Steps g to h** until no leakage is found. Ensure DPI 501 reads constantly as zero during the entire leak check process.
j. Close compressed air valve, and open one of autocontrol valves (CV 401 or CV 301) to depressurize the unit. Remove compressed air line. Connect back PI 201. Open hand valve HV 201. Close autocontrol valves (CV 201, CV 401, and CV 301). CV 101 should remain closed all the time.

5. Leak check on DP measurement system is completed.