High-Temperature Multi-Process Sensor Development and Demonstration at a Full-scale PC Combustion System

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Abstract

Condition-Based Maintenance (CBM) is a maintenance philosophy that actively monitors the health of assets to predict and prevent failures and maximize power plant's availability and generating capacity at a reduced cost. The electric power industry is experiencing a push toward using big data to develop advanced control and smart maintenance management. CBM systems can provide the boiler condition data that the advanced control system can utilize for plant performance optimization, which is increasingly relevant as coal power plants shift from predominantly base-load operation to predominantly transient operation involving large load swings. A transient operation can create fluctuating local stoichiometries at tube surfaces in high-temperature regions, as well as reduced back-end temperatures creating acid dew-point corrosion concerns.

Reaction Engineering International developed a multi-process sensor that is capable of monitoring real-time boiler conditions including electrochemical noise-based metal attack/wastage as well as metal surface temperature, heat flux, and deposition under the US Department of Energy's Crosscutting Technology Research program (DE-FE0031680 and DE-FE0031682). This electrochemical noise-based technology had been put through various tests to ensure accuracy and repeatability for metal wastage measurements and has shown a possibility to be used in combustion tuning/optimization by simultaneous monitoring of other aspects of boiler performance including heat flux, metal surface temperature, and deposition with minor modifications. In these projects, REI re-designed and assembled new monitoring equipment, enhanced software by converting legacy code and implementing new process correlations, performed pilot-scale testing, and demonstrated the multi-process monitoring system in two full-scale PC-fired units with a range of fuels from lignite to bituminous coals. In this paper, REI will discuss the sensor development efforts and the full-scale demonstration results from the two demonstration sites.

Introduction

Condition-Based Maintenance (CBM) is a maintenance philosophy that actively monitors the health of assets to predict and prevent failures and, in the case of power plants, maximize availability and generating capacity at a reduced cost (Trout, 2019). The electric power industry is experiencing a push towards using big data to develop advanced automated control and smart maintenance management. Real-time CBM systems in conjunction with the artificial intelligence and machine learning model can be used to optimize the plant performance, which is increasingly relevant as coal power plants shift from predominantly base-load operation to predominantly transient operation involving large load swings. A transient operation can create fluctuating local stoichiometries at tube surfaces in high-temperature regions, as well as reduced back-end temperatures creating acid dew-point corrosion concerns.

Reaction Engineering International has developed a miniaturized multi-process monitoring system (mMPMS) to facilitate boiler condition management with the US DOE funding. This monitoring system is based on an electrochemical sensor that can provide a real-time indication of the risk of damage to key locations in the radiant or convective section of a coal-fired boiler such as metal loss rates, heat flux, metal surface temperature, and deposit thickness. These real-time indications can be utilized to optimize boiler performance as well as improve boiler availability under the corresponding operating conditions. This monitoring system was developed and tested in the high-temperature regions of coal-fired utility boilers, but can be applied to many other industries and applications as well.

Metal loss due to fire-side corrosion is responsible for approximately half of unscheduled outages in steam generation units according to EPRI. Formulating solutions to the fire-side corrosion problem can be complicated by the range of potential mechanisms, which can involve gas-phase sulfur and/or chlorine in addition to the direct deposition of unreacted solid fuel. The physics and chemistry controlling corrosion processes can be highly non-linear and brief periods of exposure to atypical conditions can dominate the overall material loss between inspections. Current tools available for retrospective monitoring of waterwall wastage are difficult to implement on a time frame shorter than between successive outages and it is highly preferable to have real-time online corrosion monitoring capability to provide timely corrective measures and reduce maintenance costs. The 2006 plant survey sponsored by EPRI showed that slagging and fouling are the main coal quality concerns at nearly all the plants participated in the survey (O'Connor & Harding, 2006). The pathway from coal particles to deposit formation is complex process and has been studied by many research groups (Barnes, 2009). Deposit is controlled or removed by soot blower and the real-time information on deposit formation can help the optimization of the soot blower operation.

The design concept of the mMPMS is to use the gap in the membrane for sensor insertion and embed the sensor in the sensor body with a heat management module so that it doesn't require active air cooling. Our legacy systems were relatively large and expensive and unsuitable for quick and permanent installation for simultaneous monitoring of a large number of locations. Also, we want to reduce the power requirement for potential future development such as a self-powering sensing system. The newly developed system was demonstrated at two full-scale power plants, PacifiCorp's Hunter Unit #3 and Basin Electric's Leland Olds Station Unit #1 (LOS1). In this paper, the mMPMS development and the key results from the demonstration are discussed focusing on tube wastage and deposition.

Development of mMPMS

The mMPMS is made of three parts: 1) Sensor Assembly, 2) Sensor Body, and 3) Data Processing Unit (DPU) as shown in Figure 1. The mMPMS leverages the existing electrochemical noise-based monitoring system Reaction Engineering International (REI) and its partner, Corrosion Management Ltd. (C-M) have previously utilized for monitoring metal loss during several successful joint projects ranging from a lab- to full-scale. The probes and equipment used in those projects were relatively large and expensive and unsuitable for quick and permanent installation for simultaneous monitoring of a large number of locations. The sensor assembly is designed and machined to be installed through the webbing of the waterwalls without the need for long shut-downs to bend tubes and includes new ceramics to improve performance. The sensor body was designed for the waterwall geometry specific to the demonstration sites and to self-regulate to the tube surface temperature. The DPU houses the signal conditioning module and the hardened data acquisition electronics with cloud-capable software, a scalable system to support multiple sensors, and processing power to enable future support for machine learning and artificial intelligence. The signal conditioning module was updated with a simplified electronic design and increased resolution to allow the detection of localized attacks. Also, the full digital signal conditioning and data communication features were implemented.

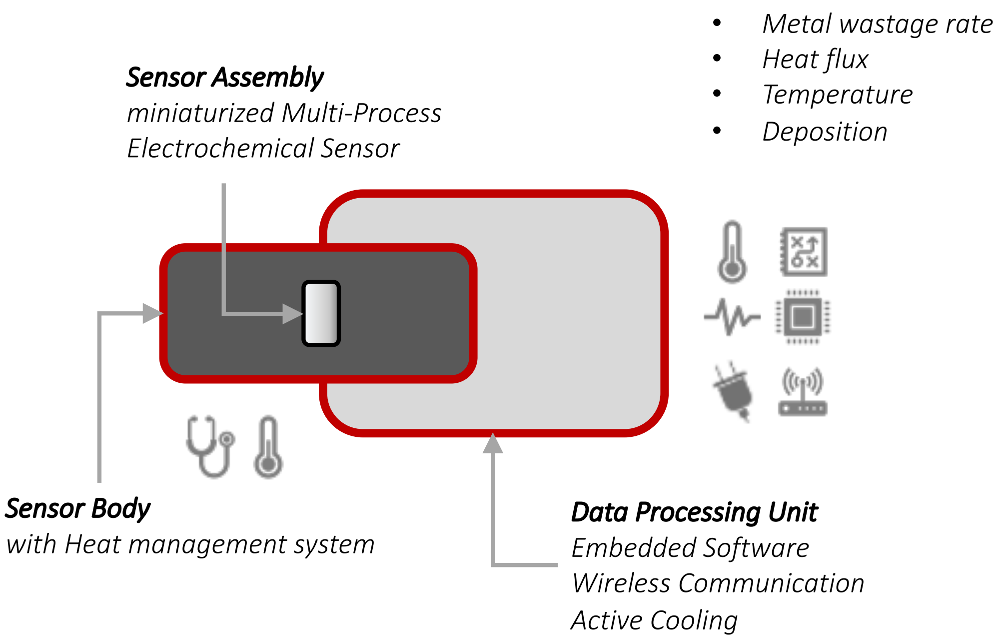


Figure 1. Schematic of the miniaturized Multi-Process Monitoring System (mMPMS).

Full-scale Demonstration

PacifiCorp's Hunter plant is located near Castle Dale, Utah, and has three units with a total generating capacity of 1,320MW. As California solar power ramps up, the unit has cycled aggressively down to less than 20% of full loading daily. Figure 2 shows the load swings at Hunter #3 during the demonstration. The plant cycles from 500 MW to less than 100 MW and cycles back up to 500 MW daily. The load is maintained high overnight and low during the daytime. Potential tube wastage from cycling is a concern at the plant and the key results related to the tube wastage are discussed in this paper.

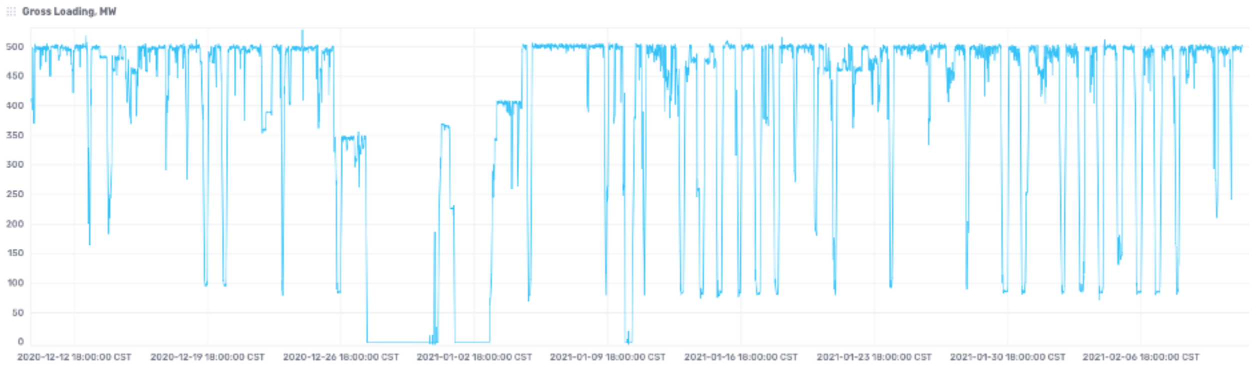


Figure 2. Load swings at Hunter Unit #3 in January 2021.

The Hunter #3 is an opposed wall-fired unit with 40 low NOx burners on the front and the rear walls. The four mills control those 40 burner's fuel flow rates and are operated to meet specific loading requirements. The mill operation variation that goes with the loading change can affect the near-wall conditions significantly, which is important in understanding tube wastage behavior. We performed CFD simulations to evaluate the impacts of loading and the associated air flow rate changes. Figure 3 shows the CO and O2 profiles under different loadings from Baseline (500MWe) to 60MWe with the top row showing the front/right side wall view and the bottom row showing the rear/left side wall view. The drastic changes in the near-wall CO profiles are shown from high to low loadings. The unit is operated fuel-rich in the lower furnace at full loading for NOx control. The high CO region represents a reducing zone and the low CO (typically O2 rich then) oxidizing zone. As the loading is reduced, the stoichiometry increases, and more O2 is available as shown in the O2 profiles. At 380MW, some regions of the right side wall start to having a less CO-rich zone and turn to oxidizing conditions. At less than 100MW loadings, low or no CO can be found near the wall and most areas become oxidizing zones. Daily occurrence of these drastic changes can limit the formation of the protective oxide scale, repeat the formation and shedding of the oxide scales, exposes the bare tube metal surface to the corrosive species in the furnace, and accelerate tube metal wastage. This behavior was identified in the demonstration as well.

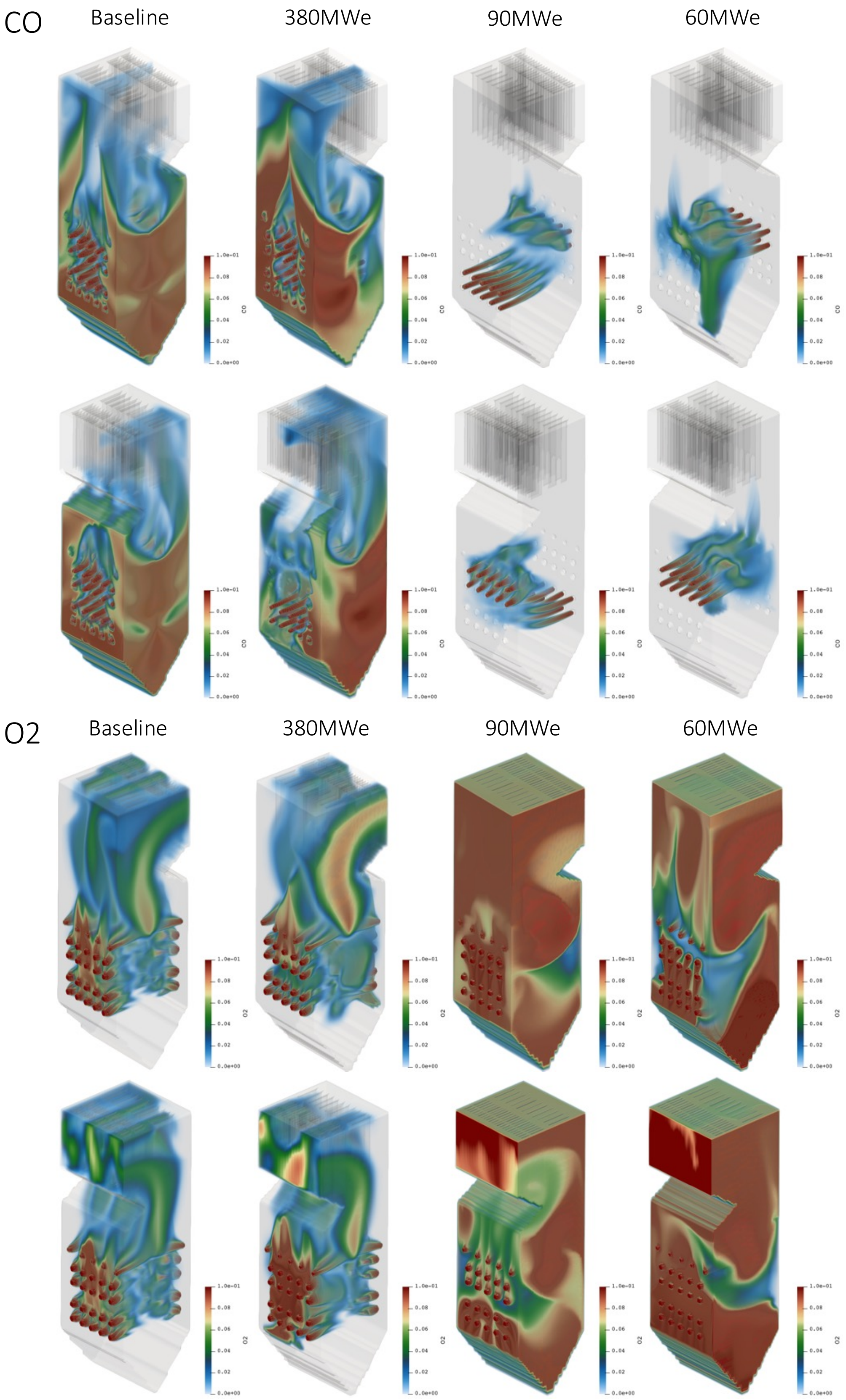
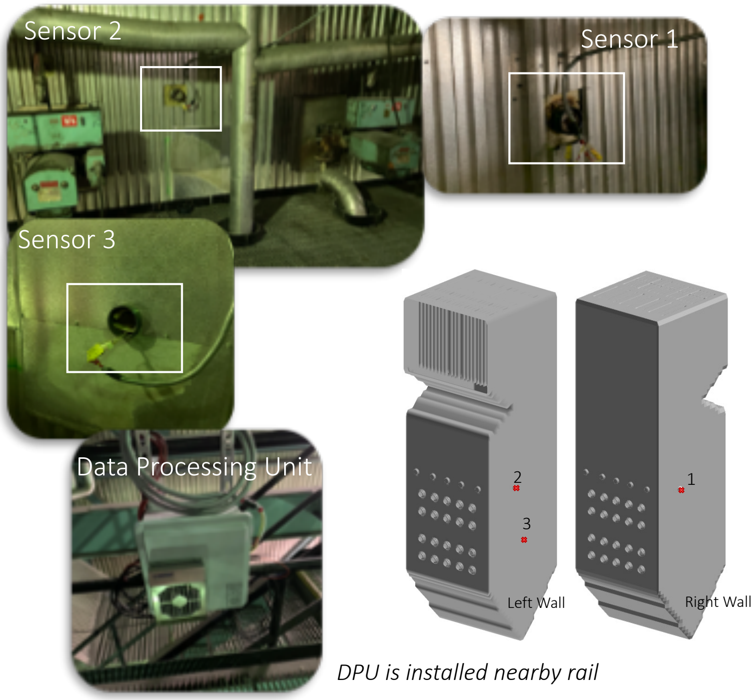


Figure 3. CO and O2 distributions for Baseline, 380MWe, 90 MWe, and 60MWe cases.

Three mMPMS were installed at Hunter #3 as shown in Figure 4. The sensor locations were determined based on the plant observations and CFD modeling. Two sensors were placed just below OFA on either side wall and one sensor in the center of the left wall burner belt.



DPU is installed nearby rail

Figure 4. Three mMPMS installations at the Hunter #3.

Figure 5 shows loading, excess O2, and mill fuel flow rates from plant and corrosion rate data from our sensors for January 17 and 18. The vertical dotted white line in the middle shows the date change. On January 17, loading started decreasing in the morning down to 80 MW and, after 5 hours, the load was ramped up to 500 MW. Under the reduced loading, the plant ran at higher excess O2 as shown in the figure. Also, the mill fuel flow rates of all four mills changed accordingly. To reduce the loading, Mill 3 was turned off first followed by Mill 4 and 2. When the unit was ramped up, Mill 2 was on first, followed by Mill 4 and 3. The bottom figure shows corrosion rates. When the loading was high and cycling down, all sensors showed relatively low corrosion rates. But when the unit was ramped up, sensor 3 showed high corrosion rates and sensor 2 low to moderate rates. Before midnight, there was some load reduction by shutting down the flow from Mill 2, but not many corrosion activities were shown. Early on the following day, there was some load decrease and increase with Mill 3 off and on, but only during the load increase, the sensor 3 showed moderate corrosion rates. Then, the load was reduced to 80 MW, as on the previous day, and there were some corrosion activities in sensors 1 and 2. When the unit was ramped up, sensor 3 showed moderate to high rates. The corrosion seems to be more active during cycling especially during ramping up, and this behavior could be found on other days as well. This is consistent with the load swing concern discussed early.

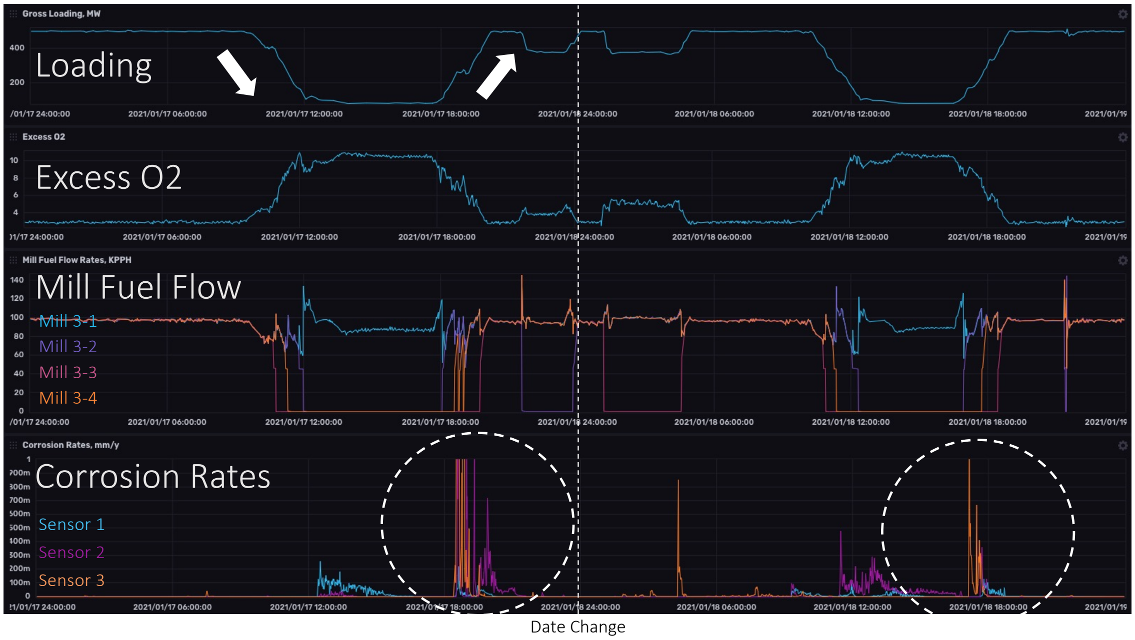


Figure 5. Loading, excess O2, mill fuel rates, and corrosion rates for January 17-18, 2021.

At Basin Electric's Leland Olds Station Unit 1, five mMPMS were installed based on the plant experience and CFD modeling. Three sensors were installed on the sidewall where the high deposition was observed. Then the two additional sensors were placed on the front wall. For this demonstration, the key results related to deposition are discussed in this paper.

Figure 6. Five mMPMS installations at Basin Electric's Leland Olds Station Unit 1.

Figure 7 shows deposit thickness from 9 AM to 3 PM on March 3, 2021. After the sensor is inserted, the deposit increased first and decreased at about 10 AM due to soot blower operation. Then, the deposit thickness started increasing again until a slight decrease at 11 AM and 12 PM due to some impacts from the remote soot blower operations. At 1 PM, the sensor was retracted, and the reported deposit thickness was about 8 mm at the time of retraction. The deposit formed on the sensor was broken into two parts during the retraction. One part stayed on the sensor surface and the other part was left at the membrane hole. The combined thickness of the deposit was bout 8 – 9 mm, consistent with the reported value of 8 mm. The sensor was re-inserted, and the soot blower operation was intentionally stopped for 2 hours until 3 PM, the deposit kept growing during this time. Then the soot blowers were back in operation and the deposit was removed.

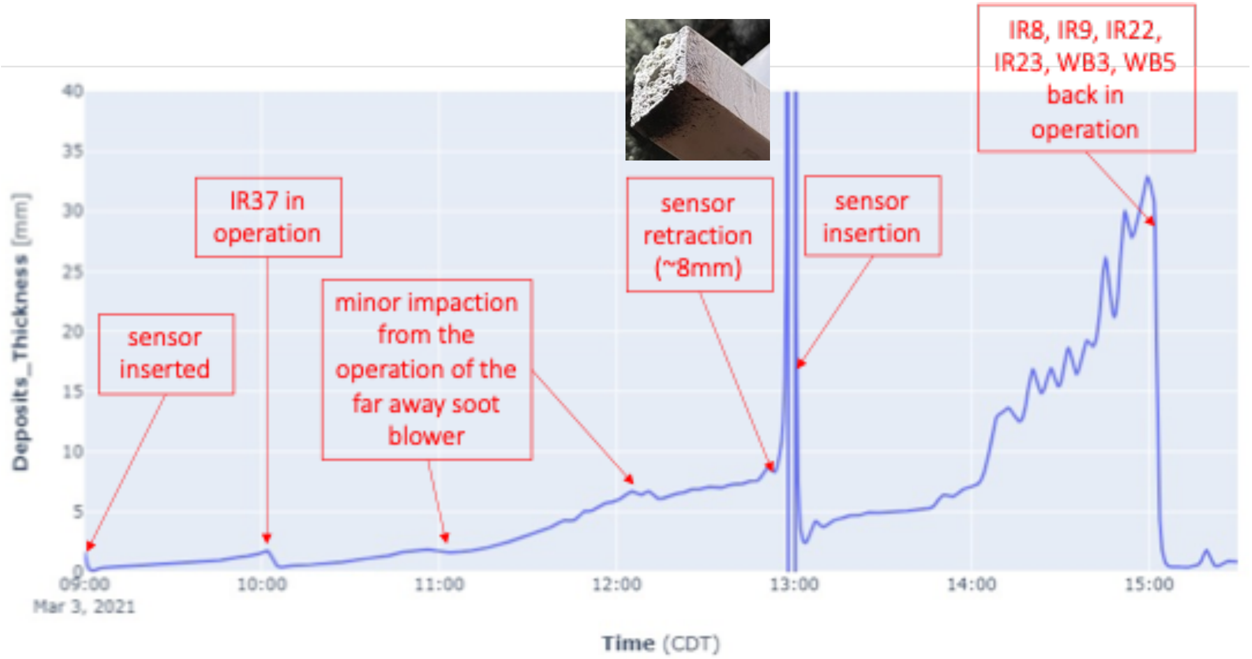


Figure 7. Measured deposit thickness at Sensor 1 on March 3, 2021.

Figure 7 shows the deposit thickness from sensors #4 and #5 and the loading changes between February 27 and March 1, 2021. During this time frame, the loading cycled from the full load to low and back to full load. Sensor #4 initially did not show deposit formation and did not need soot blower operation, but the soot blower was operated as indicated by the abrupt peaks (water lance). Then during low loading, it formed some deposits, the soot blower was operated, and the sensor data showed a decrease in the deposit thickness. When the loading was back to full loading, the deposit did not form and didn't need a soot blower and there were no soot blower operations. However, later at 6 AM, the soot blower started operating even though it was not needed. Each plant operator can operate the soot blower differently and it was confirmed that there was a shift at 6 AM. The operator before the 6 AM shift did not operate the soot blower and the sensor measurements showed there were no needs. However, the operator after the 6 AM shift did run the soot blower even if it was not needed. Sensor #5 showed the soot blower was operating more properly, meaning that they were operated when they were needed, and were not when they were not needed. This illustrates that the sensor could be used to optimize the soot blower operation so that it's operated only when it's needed.

Figure 8. Deposit thickness changes between February 27 and March 1, 2021, including impacts of soot blowing.

Conclusions

The new sensor system, mMPMS (miniaturized Multi-Process Monitoring System) was successfully developed including miniaturization and modification of the sensors accommodating membrane installation and passive cooling, new signal conditioning module with improved data communication and resolution, replacement of legacy data acquisition hardware with easily maintainable and scalable electronics, more than 50% of size reduction with updated electronics and smaller form factor, and development of new big data platform for collection and analysis. Three (3) mMPMS and five (5) mMPMS were successfully installed through the membrane walls in Hunter Unit 3 and LOS Unit 1, respectively. Hunter 3 demonstration showed that the sensor data were sensitive to the near-wall environment changes, the corrosion activities increased during the transition, especially when the unit was ramping up. LOS1 tests have also confirmed that the sensors are very sensitive to the surroundings including the operation of soot blowers and water lances (i.e. deposit growth). Tests demonstrated that the mMPMS deposition measurements were qualitatively and quantitatively reliable. The mMPMS has achieved 4000+ hrs of continuous operation. The real-time data obtained from the sensor could be used to optimize the boiler operation (e.g. soot blower operation) and could be utilized for advanced process optimization.

Acknowledgment

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References

Barnes, I. (2009). *Slagging and fouling in coal-fired boilers.* IEA Clean Coal Centre.

O'Connor, D., & Harding, N. (2006). Survey of US utility concerns with coal quality. *Ash Deposition Conference.* Snowbird, Utah, USA.

Trout, J. (2019, July). *Condition-based Maintenance: A Complete Guide*. Retrieved from ReliablePlant: https://www.reliableplant.com/condition-based-maintenance-31823