IWC 17-14

Commissioning New Sample Panels and Online Analyzers for HRSG Plants

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KEYWORDS

HRSG, Combined Cycle, Boiler, Commissioning, Sample Panel, Online Monitors, Online Instruments, Troubleshooting, Cycle Chemistry

ABSTRACT

Sample conditioning, online analysis and immediate corrective actions are essential during startup for protection of critical steam and water components. This paper presents past experiences of events and actions taken during startup and commissioning of sample conditioning and online chemistry monitoring panels for new combined cycle HRSGs. Proper programming, calibration, panel maintenance and continuous surveillance are needed. Risks from unit trips, condenser leaks, polisher exhaustion and other upsets also are addressed.

INTRODUCTION

This paper developed out of experience with a collection of sample panel commissioning projects at primarily new combined cycle power plants over the last ten years. Tips on commissioning new sampling and monitoring systems are grouped in the following topics for discussion purposes. Following this overview, we present examples of some of the problems experienced during commissioning projects:

- Precommissioning Schedule
- Sampling System Design
- Preparations for Sample Panel Commissioning
- Chemistry monitoring during sample Introduction on Startup

PRECOMMISSIONING SCHEDULE

The pre-commissioning schedule for the sampling should comply with the following sequence:

- Commission makeup water pretreatment and demineralization system. Also, reevaluate the capacity of the system to see if additional temporary makeup capacity may be required to provide an uninterrupted flow of makeup water for high demand situations during commissioning such as steam blows, turbine bypass operations or having to drain and fill the evaporators several times due to contamination.
- Start commissioning of the entire sample panel and monitoring system before the steam blow.
- Complete sample panel commissioning either before steam blow or at least during the steam blow restoration outage.
- Then, commission the HRSG

SAMPLING SYSTEM DESIGN

Some of the problems experienced during commissioning have been partially due to the design of the sample collection, transport, conditioning and monitoring system design. As this paper is on commissioning, it is not the purpose of this document to provide guidance on design. The reader is referred to the references for that guidance (ASME, 1997) (ASTM, 2014) (ASME, 2006) (Banweg, 2016). However, we did want to highlight a few problems related to design that have been noted during or soon after commissioning a new unit.

Sample Points and Monitors

A few important coolers, sample points, and monitors are sometimes not included in the system design, which can cause unnecessary delays in attaining chemistry control and commissioning a system. Two of the most commonly missed types of monitoring are provided in the following list.

- Specific conductivity in condensate after chemical feed. Experience has found that automatic specific conductivity control of the ammonia feed is the best way to achieve stable pH control in the condensate, feedwater and steam. Some plants have not had this sample point, some have not had a secondary sample cooler with a chiller that provides sample temperatures of 25 °C and some have not had the specific conductivity monitor and have attempted online control using pH.
- Degassed cation conductivity monitor for steam and feedwater samples. On startup, the system will be saturated with air and carbon dioxide from the air. This will result in very high cation conductivities. Also, there often are residual preservatives from fabrication or residual organic solvents or corrosion inhibitors from the preoperational cleaning which will transport throughout the cycle and gradually decompose to carbon dioxide. This can cause high levels of cation conductivity and unnecessary delays during commissioning. There are different methods for degassing samples

such as nitrogen from an outside source, reboiler systems, vacuum systems with membranes or a nitrogen generator utilizing instrument air (Figure 1). In our experience the nitrogen generator systems have been fairly easy to commission and seem to be reliable.

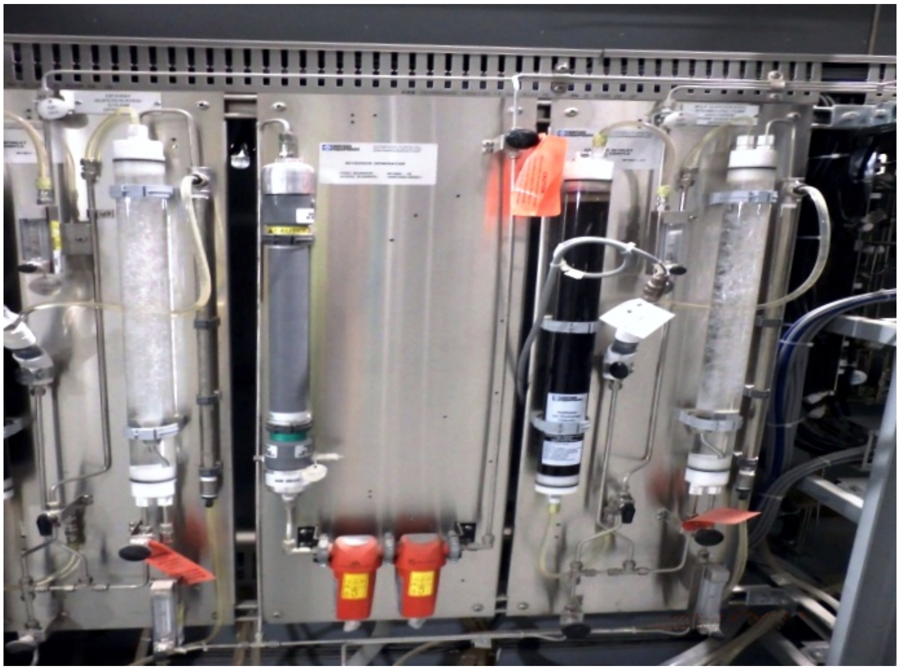

Figure 1: Nitrogen Generator Degassed Conductivity Sparging Setup

Isokinetic Steam Sampling

While less common today, there have been some combined cycle facilities that have just installed steam sample taps off of low points in steam lines – which is inconsistent with recommended guidelines and can give false indications of steam purity – especially during operational transients. Steam samples should be collected by isokinetic sample nozzles preferably installed in vertical steam lines and located 35 pipe diameters downstream of any fittings and 4 diameters upstream of any fittings (ASTM, 2014). More commonly on plant startups in the last ten years, someone has installed an isokinetic steam sample nozzle, but the details of the sample nozzle size(s) and isokinetic sample flow rate required are sometimes difficult to locate by the commissioning team. When commissioning a sampling system, one needs to be able to know and set the correct sample flow rates. Another area where industry practices do not always follow the recommended guidelines in ASTM is primary sample cooling. The recommended approach for superheated steam samples is to have the primary sample cooler located within about 10-20 feet of the point of extraction (i.e., out in the field). Quite a few facilities have been installed with no local coolers for superheated steam samples. Information on designing steam sampling systems is presented in the references (ASTM, 2014) (ASME, 1997) (Banweg, 2016) (ASME, 2006). Incidentally, the ASTM standard advises to install a sample cooler near the source for both saturated steam and superheated steam samples whereas the ASME performance test code provides detailed guidance how saturated steam sample lines can be effectively designed without a local sample cooler (ASME, 1997).

Sample Room/Building Design

Items that are commonly missed for the sample room design include:

- Blow-off/blowdown manifold for each sample point located outside before entering the sampling building. This enables high flow purging of the lines to a safe location (usually a concrete sump or pad) where the steam can be released and the debris and corrosion products are flushed to the wastewater system. Also, these can be useful for ensuring isolation of the sample room from the unit during maintenance.
- Demineralized water supply to sampling room for flushing and advance calibration of analyzers. This enables commissioning the sample panel well in advance of the actual unit commissioning. This should be at least a 0.5 inch nominal diameter stainless steel pipe.
- High purity water supply for laboratory uses. While the demineralized water provided to the unit should be sufficient for the online analyzers and most needs, a local purification unit is suggested to further polish the demineralized water used for dilution or preparation of reagents (required for some silica analyzers), sample blanks, etc.
- Laboratory bench top and sink for basic laboratory equipment
- Cabinets for storage of
    - Standards
    - Buffers
    - Reagents
    - Spare probes
    - Spare sample filters
    - Cation resin or columns
    - Portable instruments (conductivity, pH, dissolved oxygen). When commissioning a new system, the condition, accuracy and reliability of everything is suspect and a handheld pH and specific conductivity meter is invaluable for a rough check when initially flushing out samples, initially setting up online meters, checking samples without online meters, rinsing cation columns, etc.
- Hazardous reagent storage cabinet (sodium analyzer reagent is hazardous)
- Safety shower and eye wash station
- Telephone and computer terminal for communication with control room and monitoring CT and HRSG startup.
- Book case or cabinet for storage of sample panel and analyzer manufacturer process and instrument drawings (P&IDs), installation manuals, instrument operating

manuals, commissioning chemistry limits and procedures, safety data sheets, standard reference texts (ASTM, etc.).

- Area to locate and secure (keep from falling over) a high pressure nitrogen cylinder for blowing out blocked sample lines and panel components. The trailer also should have a fresh air exhaust and intake ventilation system and two or three doors on the sample room to enable rapid exit from the trailer should a problem with the nitrogen cylinder develop (or if there is a failure of a primary cooler or other component carrying steam or high temperature hot water).

PREPARATIONS FOR SAMPLE PANEL COMMISSIONING

It is desirable to have a plan for sample panel commissioning. A methodical plan for sample panel commissioning would include the following activities. Personnel involved in the sample panel commissioning will need to be knowledgeable in sample flow P&ID's, wiring diagrams, calibration of instruments, 4-20 mA or digital outputs and steam/water cycle chemistry.

- Stock the laboratory. As indicated in the prior section on sample room and building design, there are a number of materials that need to be specified, ordered, received, and organized in the sample room prior to starting a commissioning process.
- Install probes. Normally the sample panel manufacturer will ship the panel with analyzers mounted but sufficient time should be allotted for installation and flushing of all probes.
- Select calibration solutions and procedures. Some meters can use different calibration standards and procedures and these are preferably planned and documented.
- Program Analyzer, Transmitter and Sample Sequencer (if provided). Proper programming would need to include all of the following:
    - Entering the correct conductivity cell constants into the transmitters
    - The correct units of measure and ranges for each sample parameter
    - Solution and temperature correction factors
    - Barometric pressure for dissolved oxygen
    - Alarm set points in analyzers and control room.
    - Sample sequencer communication of sample source with control room.
- Select and Set Ranges for 4-20 mA Signals to Control System. Before commissioning the HRSG, one also has to properly set and verify the 4-20 mA outputs from the analyzers, transmitters or sequencers to match the plant's Distributive Control System (DCS) inputs and proper readings are displayed in the control room. If the 4-20 mA is not properly set up to the DCS, the actual values can be an order of magnitude or more different than the reading displayed to control room operators. Since chemistry during initial commissioning can be much worse than during normal operation, the analyzer ranges may need to be temporarily expanded during initial startup.

- Review HRSG and turbine manufacturer chemistry limits.
- Develop a comprehensive chemistry and response guide, which is agreed by all parties prior to startup. The guide should detail the parameters limits for each phase of startup from water cleanup with turbine bypass to condenser, turbine startup, and normal operating conditions.

CHEMISTRY MONITORING DURING SAMPLE INDRODUCTION ON STARTUP

Chemistry excursions are anticipated during initial startup of a unit. However, close monitoring and proper response to out of limit conditions is essential to verify and maintain the long term health of the unit. Prompt response to serious conditions such as a low pH excursion or a condenser leak is critical in preventing serious damage to equipment.

Communication between the startup group, control room operators and chemistry personnel or consultant is essential during startup to distinguish between minor, temporary chemistry upsets due to operational changes such as placing a feedwater heater in service, switching boiler feed pumps or condensate pumps, steam flow path changes etc., and severe upsets such as a condenser leak. The following recommendations will help ensure a successful startup from first fire to commercial operation.

- Ensure 24 hour chemistry monitoring is available at the sample panel
- Utilize high/low pressure sample blowdown for as long as possible before introducing the samples to the analyzers.
- Plan for frequent maintenance. Due to initial contamination, frequent maintenance may be required such as blowing back restricted or blocked sample lines or panel components, changing filters or membranes and performing additional calibrations.
- Enforce HRSG and turbine manufacturer's quality control limits for water and steam to prevent damage to the unit.
- Use multiple analyzer/probe sample points or portable process analyzers for verification of out-of-specification parameter values.
- Post and distribute the comprehensive chemistry and response guide described in the prior section to the commissioning team.

CASE STUDIES AND EXAMPLES OF PROBLEMS EXPERIENCED DURING SAMPLE PANEL COMMISSIONING

Even where one has followed best practices, there will be problems that will need to be identified and corrected. A successful commissioning requires a lot of equipment from different suppliers to work and communicate and work with equipment from other suppliers and under conditions that may not exactly match the manufacturer's assumed conditions. There can be various types of electrical interference that will need to be field adjusted to provide an adequate correlation between local meter readings and the signal received and stored in the control room data management system. Commissioning is a rather severe service condition. Sample lines will plug and some probes and other equipment will either not work or will break during commissioning. Expect that you will need to perform some troubleshooting to find and fix problems. Some examples of problems encountered during sample panel commissioning of several units are discussed and then a list of additional common problems are provided. This list is not exhaustive, but is provided to demonstrate the types of problems which can be encountered and corrected.

SCHEDULING PROBLEM - TRYING TO START BEFORE YOU ARE READY

For one project, we received a call from an equipment and procurement contractor (EPC) regarding a two on one combined cycle plant with a combustion turbine (CT) and two heat recovery steam generators (HRSG) that were being commissioned. They needed some help with the sample panel. The project schedule called for preliminary firing of the combustion turbine (CT) in a day or two. There was no hot gas bypass damper so starting the CT meant steam generation from the HRSG. Fortunately, the steam turbine could be bypassed during initial firing of the HRSG. For the preceding steam blows the unit was on just all volatile treatment using an ammonia/ethanolamine blend. While the Owner specified a phosphate feed system for the HP evaporators, the phosphate feed systems were not yet operational.

We walked into the sample panel room the day before they wanted to start firing the CT for commissioning and a lot of the instruments were dry (had never seen water). As shown in Figure 2, the reference electrode reservoirs for the pH electrodes still had the packing tape and had not been filled, while some cation columns were in use, some of the cation columns were still dry. The sodium analyzers had not seen water.

Figure 2: Sample Panel Day before Starting HRSG Commissioning

The sampling system consisted essentially of a trailer with the sample panel fully contained in the trailer. There was no laboratory bench, no chemical storage for reagents or standards, no bench top instruments, no cabinets, no telephone or computer system to communicate with the control room, no sink or separate demineralized water supply, no sample blowdown system outside of the trailer. There was a portable metal frame book case that had a collection of spare parts, manuals, pH buffers, conductivity standards, reference electrode filling solution, and an incomplete inventory of reagents.

The Owner had an operator testing grab samples flowing out of some of the sample taps and they had squeezed in a three feet long portable table between the wall and the sample sink with a bench pH/conductivity meter and spectrophotometer for silica testing. The Owner had what they needed for bench top tests (apparently used for the steam blows). However, the chemistry requirements for commissioning can be greater than for steam blows.

Fortunately there was a demineralized water sample to the sample panel. This was temporarily run with plastic tubing to key analyzers (cation conductivity and sodium in condensate, feedwater, steam and boiler water) to get them operational and calibrated. This quickly revealed that there was too much contamination to proceed with startup and the startup was ceased, the entire steam/water cycle was cooled, drained, rinsed and flushed before proceeding. This resulted in a 3-5 days delay in commissioning the unit. A lot of the problems in this example and commissioning projects in general can be avoided by having experienced chemistry personnel involved in the planning process.

WIRING ISSUES

On more than one occasion, after the dissolved oxygen probes had been properly prepared and installed, several probes were displaying highly irregular readings, such as ppm level concentrations even when pulling vacuum on the condenser. The usual checks were performed: such as looking for loose fittings on the panel, swapping probes with one that was reading correctly, or rebuilding the probe with a new membrane (this was an electrode type not the luminescent type), and changing the reference solution, but no problems were found. However, an inspection of the wiring diagrams revealed that the wiring for the anode and cathode on the dissolved oxygen probes were reversed and the shield wires were not individually landed on the proper terminal points on the board in the transmitter. After correcting the issue, the probes responded correctly.

On one startup, there were problems trying to calibrate high purity pH probes. The probes would not respond when placed in different buffers. Again, after rebuilding the probe with a new membrane and applying new reference solution many would assume that the probe was bad. Further investigation found that there was a missing jumper wire on the board needed for the solution ground. After making new jumpers and installing them, the high purity pH probes calibrated correctly.

On another startup, the general purpose pH probes installed for the drum waters would not calibrate. It was found that all the pH transmitters were wired for the high purity pH probes which uses different terminal points and includes a jumper for the solution ground. After correcting the general purpose probe wiring and performing a calibration the drum water pH probes were reading correctly.

Troubleshooting of a polisher vessel cation conductivity reading indicated the local readout was 0.112 µS/cm but the DCS was reading 0.7 µS/cm. It was discovered that the DCS was seeing the temperature output of the cation conductivity analyzer rather than the conductivity output of the analyzer.

In another example the wiring was actually transposed on the drawings and it routed from the output of an ammonia analyzer to the inputs for the calibration and alarm signals on the sequencer. Fortunately, this was found and corrected before the start of the actual unit commissioning. The wiring was corrected and the drawings were updated.

PIPING ISSUES

On one startup there was a high pressure (HP) separator sample in a subcritical once through HRSG that was shutting off due to high sample temperature tripping the thermal safety shut off valve. The first check we performed was to run demineralized water through the sample coil in the cooler to make sure it was not restricted. Then, we used instrument air to blow out the water. We put the sample back in service and reduced the total sample flow to the minimum needed for conductivity and pH probes.

We then noted that cooling water was piped wrong from the sample panel manufacturer. There are two Ports on the top of the cooler, one marked cooling water IN and the other cooling water OUT. The outlet piping was connected to the cooling water inlet port and the outlet port was capped off – so the cooler was at best pressurized with cooling water, but it certainly had no cooling water flow. Once the piping was corrected, we had cooling water flow and we were then able to open the sample flow fully and not trip the thermal switch.

During this startup, it also was speculated that a sample cooler may have a leak. To evaluate, we capped off one side of the coil and used a hand-held pump to pressurize the sample coil to 500 psi and then watched for any pressure loss which would indicate an internal coil leak. There was no loss in pressure. Instrumentation departments will sometimes have these manual pumps for testing pressure gauges. We found that they can be quite handy in the evaluation of a sample cooler leak.

SAMPLE SYSTEM PLUGGING AND FOULING PROBLEMS DURING STARTUP

One of the most time consuming activities when commissioning a sample panel is keeping sufficient sample flow to all of the probes and analyzers. Ideally each sample point would have a high pressure blowdown line to an outside drain and each sample would have sample inlet filters of 90 to 150 microns ahead of any sample components. Sample filters can plug up fairly quickly. Figure 3 presents an example of a plugged inline filter removed during a commissioning. Changing the filters can be done fairly quickly – depending on the tag and lock requirements for isolating and opening up pressurized lines in the sampling system.

Figure 3: Example of Plugged Inline Sample Filter

On a recent sample panel commissioning there was a low pressure evaporator blowdown sample, with no inlet filters. The unfiltered sample passed through the sample cooler and then through a pressure reducing valve (called a VREL). This led to plugging of the valve due to the length of the valve and tiny threads used to reduce pressure. Once the samples were placed in service within a short period of time the dissolved oxygen, PH and specific conductivity probes needed to be removed and cleaned due to fouling. Figures 4 and 5 present examples of fouled probes removed during a commissioning.

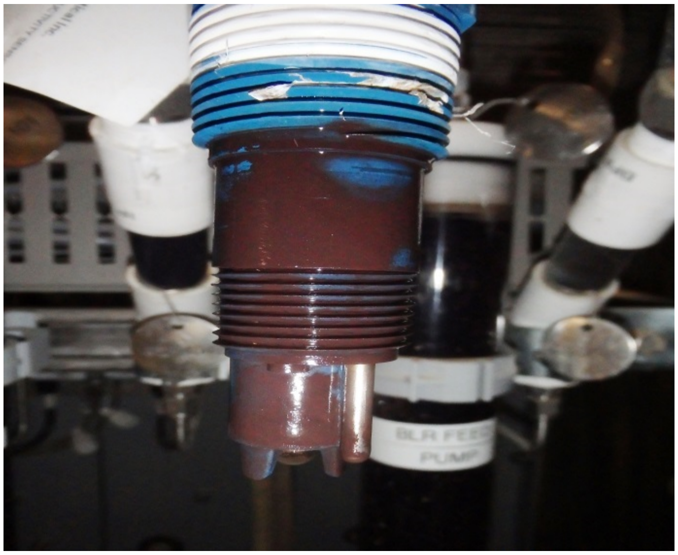

Figure 4: Example of Fouled pH Probe

Figure 5: Example of Fouled Dissolved Oxygen Probe

The probe fouling was due to iron oxides and was removed by following the manufacturers' procedure of first cleaning the pH and conductivity probes with a non- abrasive detergent to remove any oil residue, then removing any scale deposits by soaking the probes for one to five minutes in a 5% hydrochloric acid solution. The dissolved oxygen probes were cleaned by removing the old membrane, cleaning the sensor tip with a mild detergent solution and installing a new membrane.

When high pressure blow off valves and filters are not provided, sample lines need to be blown back frequently to root valves using high pressure nitrogen during water cleanup and startup, particularly for evaporator blowdown samples. For safety reasons the high pressure blowback of samples lines should preferably be done when the unit is offline so you are not blowing back against sample pressure. After closing the sample inlet line at the panel, the blow back connection for the nitrogen should be connected on the outlet side of the primary cooler. Open the nitrogen flow at the desired delivery pressure, and then open the sample inlet valve to blow the line out through the cooler and back through the open root valve. Figure 6 provides an example of a single bottle nitrogen setup for blowing out sample lines. It is suggested to provide a six or twelve pack rack of nitrogen cylinders to ensure enough volume of high pressure nitrogen can be provided for flushing out sample taps throughout the startup period.

Figure 6: Example of a Nitrogen Purging System for Sampling Systems

If provided, demineralizer flush water or instrument air can be used to flush clogged or restricted sample components such as flow switches, thermal shutoff valves, flowmeters, and sequencer solenoid valves. Sample filters for the steam samples can be removed after the unit is operating normally for a period of time.

LOW PURITY MAKE UP WATER

During commissioning, makeup can be provided through a combination of a designed makeup system and temporary treatment equipment. On some commissioning projects, the sample panel analyzers have detected that low purity makeup water was entering the cycle. In one case, we experienced demineralizer polishing truck breakthrough on silica but not cation conductivity which resulted in silica contamination of the demineralized water storage tank. While there should be alarms set in the control room for a high value, during commissioning they may not be active yet or are assumed by the operators to be false readings and ignored. This is also true of units with kidney loop or full flow polishers. Silica breakthrough has occurred on several startups which led to delays while the evaporators were blown down to get the silica levels back in compliance or the demineralized water storage tanks had to be dumped and refilled with acceptable water quality.

Another issue that may be encountered is when the plant is running grab sample that do not agree with the online analyzers. On one commissioning the grab sample silica readings were 1-2 ppb while the calibrated online makeup water silica analyzer was reading 22-24 ppb. After a thorough investigation utilizing the grab sample feature of the online analyzer it was determined that the plant was using the demineralized water from the outlet of the mixed bed, assuming it was of good quality, in their blank analysis for grab sampling which led to very low readings after blanking out 20 ppb of silica. Grab sample readings were verified when they began using distilled water for the blanks.

OTHER SAMPLE PANEL COMMISSIONING PROBLEMS

The following is a list of other problems experienced during other sample panel commissioning projects.

- Air Leaks. Loose fittings on panel tubing connections. This causes elevated dissolved oxygen and can increase cation conductivity and decrease pH values.
- Faulty Switch Settings. On several silica analyzers it was found that the sequencers were not advancing to the next sample, even though the sequencer was programmed for batch sampling mode. It was found that the dual in-line package (DIP) switches were in the wrong position for batch mode sampling when using a sample sequencer. They are located on the control motherboard inside the analyzer. Once placed in the correct position the diagnostic menu allows you to enable the End Of Measure setting which signals the sequencer to advance to the next sample.
- No Sample Flow. Steam sample lines not connected to sample building manifold. (Someone should trace each sample line as part of the pre-commissioning activities).
- Poor Sample Flow. Steam sampling system undersized for sufficient flow and pressure to the panel. When the sampling system pressure drop is too great to get the flow needed, then one may have insufficient fluid velocities in the sampling system (condensed steam fluid velocities should be 5-6 ft/s to avoid settling of suspended matter in lines) and sub-isokinetic sample flows resulting in overestimation of steam contamination. See the references for guidance on sample system design.
- Diluted Samples. Leaking solenoid valves on sequencers diluting samples.
- Resin Leaks. Polisher resin leakage into condensate, feedwater and evaporators. Decomposition of polisher resin will raise cation conductivities in evaporators and sometimes the steam. It usually will cause evaporator pH to decrease. It can also plug up sample lines.
- Temperature Control Problems. Chillers not being able to reduce sample temperatures to 25°C. In addition to the dead-headed pipe example noted earlier, there have been systems in which the cooling water was piped backwards through a cooler. Some combined cycle plants have been built without a dedicated sample chiller and the plant chill water system could not achieve 25°C. Sample systems should have dedicated chillers. There also have been plants that have had problems with the chiller control system resulting in the chiller tripping out-of-service.
- Programming Errors. Initial programming of analyzers from the manufacturer may be incorrect for the application. When setting up an analyzer, one often has to make

choices to tailor the instrument to the particular application. See the earlier discussion of Preparations for Sample Panel Commissioning.

OTHER CONSIDERATIONS

When commissioning a sample panel it is important to understand some factors that have contributed to rather bizarre readings. If you are performing the initial conditioning of the sample panel simultaneously with commissioning of a combined cycle plant, bizarre readings can be easily misinterpreted as being due to problems with the online analyzers rather than the actual chemistry upsets that they represent.

- Residual Layup Solution. A combined cycle unit was going to be out of service for an extended period between the preoperational cleaning (which used organic solvents) and the HRSG commissioning. A sodium nitrite passivation/layup solution was apparently applied to the entire steam/water cycle and just drained (no rinsing) to inhibit out-of-service corrosion. This was not initially related to personnel in charge of chemistry for commissioning and sodium levels appeared to be impossibly high throughout the steam system during initial operation. While sodium nitrite may be satisfactory for out-of-service layup, a system treated in this manner should be thoroughly rinsed just before startup. This unit fortunately had a steam turbine bypass so the contamination did not reach the steam turbine. However, it was necessary to cool, drain the entire system, refill to hydrostatic test volumes of everything and drain before it could be filled and startup could resume.
- Lack of Polisher. On a number of startups, residual preservatives and other contaminants washed off steam path components (often not part of a preoperational cleaning) seem to persist and decompose to organic acids resulting in high cation conductivities and degassed cation conductivities. In response to these findings, the startup team had to scramble and find a means of installing temporary condensate polishing systems. This requires connection points on the condensate system. Where the system was not designed to enable full flow condensate polishing, a side stream (kidney type) system has been used, which generally is less effective than a full flow system.

CLOSING

Not having a well-developed plan for sample panel commissioning can contribute to delays during Unit commissioning. The sample collection, conditioning and monitoring system should be commissioned before the HRSG and steam turbine are commissioned. Failing to follow these recommended practices could lead to damage to these components. New condensers and other components can fail during commissioning and one should not underestimate the importance of having an operational sample panel and steam/water cycle monitoring system before starting commissioning.

REFERENCES

ASME. (1997). *Performance Test Code 19.11*. New York, NY: ASME International.

ASME. (2006). *7. Consensus on Operating Practices for the Sampling and Monitoring of Feedwater and Boiler Water Chemistry in Modern Industrial Boilers, CRTD-Vol. 81*. NY: ASME.

ASTM. (2014). *D1066, Standard Practice for Sampling Steam.* Philadelphia, PA: American Society for Testing and Materials.

Banweg, A. a. (2016). Monitoring Industrial Steam Purity: Why Wait?, IWC-16-38. *International Water Conference.* Pittsburgh, PA: Engineers Society of Western Pennsylvania.