TOPICS IN ONCE THROUGH STEAM GENERATION AND PRODUCED WATER TREATMENT

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ABSTRACT

The steam assisted gravity drainage (SAGD) method produces oil at sites in Western Canada and other locations. The once-through steam generators (OTSG) are fed with produced water separated from the oil emulsion extracted from the reservoir. There are many challenges associated with generating high pressure steam with this produced water. Deposition of organic material on heat exchange surfaces is a major problem. One topic of this paper deals with the use of an antifouling agent to reduce deposition on produced water coolers, an essential component of the processing facilities. Fouling in these exchangers is assessed with differential pressure measurements and cleaning frequency data. Corrosion is another major issue and most corrosion mechanisms involve destabilization of the passive magnetite oxide layer on the surface of the boiler steel. The second topic in this paper presents iron corrosion product measurements obtained during the use of a metal passivating agent added to the boiler feedwater. Finally, the design of laboratory pilot test OTSGs and preliminary results from the units are presented. Thermocouple monitoring of the heat transfer surfaces in the test boilers has produced very encouraging results demonstrating that scale forms in the same locations as observed in field units and that the scale formation can be inhibited with chemical antiscalants.

INTRODUCTION

Thermal oil recovery operations such as steam assisted gravity drainage, SAGD, use water separated from the produced oil to generate steam that is injected into the oil formation. Once-through steam generators (OTSGs) are commonly used to generate the steam. OTSGs were first put to use in the 1980's to replace conventional drum boilers in order to produce high quality steam from poor quality water. By about 1992, OTSGs continued to evolve in their design and performance and were put to use in applications associated with Cyclic Steam Stimulation (CSS) and then SAGD. OTSGs were preferred because of the low capital cost per ton of steam produced, a short construction time and a relatively simple design which lent itself to a flexible and controllable steam output. Therefore, OTSGs are pervasive across the SAGD and CSS industry with a greater than 90% market penetration in Western Canada. The OTSG is a counter-flow heat exchanger where the liquid feed water enters one or more independent steam generating tubes often referred to as passes. The passes are arranged together in a bank called the convection section. Boiling generally begins at the end of the convection section at a location referred to as the shock tubes and then proceeds in the radiant section where the passes are arranged around a cylindrical furnace. A mixture of about 80% gaseous steam by weight and 20% liquid water in the form of a fine mist (80% quality steam) exits the OTSG. This design enables the units to tolerate poor quality feedwater at an elevated pH with high concentrations of dissolved solids, silica and total organic carbon. Refer to the schematic of the OTSG in Figure 1.
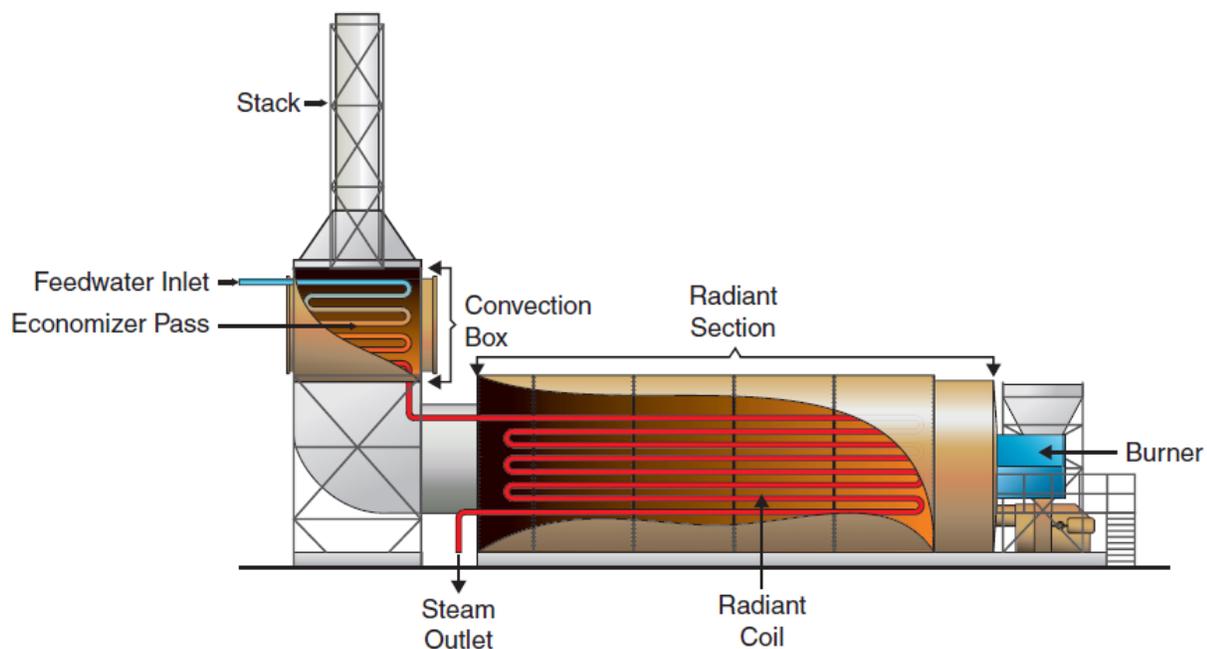
Figure 1. OTSG design. From the Nalco Guide To Boiler Failure Analysis, 2nd edition (McGraw Hill)

Two major challenges for the reuse of produced water to generate steam are deposition of organic material or inorganic scales on heat transfer surfaces and corrosion of the ferrous alloy materials of construction. Central processing facilities for the SAGD process are complex with unit processes for oil/water separation, produced water purification and steam generation. The facilities are thermally

integrated with a variety of heat transfer surfaces that are all critical to efficient plant operation and can all suffer deposition and corrosion issues.

Produced water must be treated prior to steam generation. Techniques like warm lime softening and weak acid cation exchange produce water that is suitable for use in OTSGs. However, the water must be cooled from its production temperature prior to these purification unit processes. Produced water coolers are critical plant components. Produced water coolers commonly suffer from loss of heat transfer efficiency due to deposition of organic materials on the heat transfer surface where the hot produced water prior to purification is cooled. The deposits may result from small amounts of emulsified oil still present in the water but the major fouling problem results from deposition of so-called water-soluble organics. The water-soluble organic materials, WSOs, are a complex mixture of thousands of individual molecules most of which become less soluble as temperature drops (Pernitsky et. al. 2012). The solubility reduction on cooling drives the deposition process and the deposits can be thick and highly insulating. Large pressure drops across the produced water coolers can develop that limit flow. Loss of heat transfer efficiency can limit the temperature drop that can be achieved with the coolers. Either flow restriction or limited cooling can create a plant bottleneck so most plants are designed with redundant banks of produced water coolers. Sometimes the performance deterioration can be reduced by a procedure known as a "bake out". Coolant to a specific exchanger is restricted so much hotter produced water is passed through that exchanger. The bake out may redissolve some of the organic material or drive water out of the deposit improving its thermal conductance. Obviously, other exchangers in the system must assume the thermal load during a bake out so that the overall produced water temperature at the exit of the coolers remains within a tolerated range. Individual coolers are also often taken out of service for off-line cleanings with high pH or solvent cleaning solutions that are effective at removing the deposits. Off-line cleanings carry a direct expense and the produced water cooler fouling problem can often result in an insurmountable bottleneck that limits oil production at the facility which can have an extreme financial impact. One topic of this paper presents the use of an antifoulant that can be added to the hot produced water to stop produced water cooler fouling. The additive has been quite successful at preventing the fouling without causing problems for downstream processes and carries a great benefit in terms of plant capacity, reliability and finances.

Although the warm lime softening, and weak acid cation exchange purification processes provide water that is suitable for high pressure steam generation in OTSGs the units still suffer from a complex variety of interrelated deposition and corrosion issues. The most damaging corrosion mechanisms all involve destabilization of the passive magnetite oxide film on the surface of the boiler steel (Godfrey et. al. 2014) (Desch. 2010) These corrosion mechanisms tend to generate iron corrosion products that leave the site of corrosion and can be measured quantitatively in the water downstream (Godfrey and Chen 1994) (LaRocque et. al. 2015). The soluble iron corrosion products are unfortunately not innocent and can increase the formation rate of a particularly troublesome mineral scale, $NaFeSi_2O_6$ aegirine. The most troublesome aspect of aegirine is that it is quite hard and has been associated with dislodging from its formation site and supplying the abrasive force for the damaging erosion-corrosion mechanism which in turn generates more iron corrosion products so that a vicious spiral can develop that links corrosion and scale formation mechanisms. Passivating agents such as carbohydrazide are known to slow the rate of many corrosion mechanisms that involve destabilization of the protective oxide film on steel. The second topic of the paper deals with the use of carbohydrazide in OTSGs.

The final topic of the paper deals with laboratory simulations of OTSGs. Pilot scale laboratory simulation devices for drum boilers have been in use for decades. These test boilers have been used with great success for the development of antiscalants, oxygen scavengers and condensate treatments (Ralph et. al. 2012). Specialized simulators have also been used to study the boiling process and flow dynamics in boiler systems. While good simulators for drum boilers are relatively easy to design capturing the

special characteristics of once-through steam generators is more challenging. OTSGs have a variety of boiling mechanisms and flow conditions that must be reproduced for a simulation boiler to provide relevant results. Preliminary testing has yielded very promising results using an OTSG lab pilot test rig design originally developed by ConocoPhillips, Bartlesville, OK. The Southern Alberta Institute of Technology, SAIT, upgraded the original unit that was transferred to their laboratory in Calgary, Canada. Based on lessons learned from the first test boiler a second refined test rig with identical operating characteristics was constructed. The two lab pilot test boilers develop mineral scale deposits in the same zone as field OTSGs and the mineral scale formation responds to the use of antiscalant chemistries in the expected manner. The pilot OTSGs are extremely useful for study of scale and fouling processes in OTSGs and elucidation of methods and treatments to reduce the effects of those chronic problems.

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TOPIC 1: PRODUCED WATER COOLER ANTIFOULANT

EXPERIMENTAL

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Certain antifoulants have found success in other applications in the SAGD industry such as fouling inhibition in produced water evaporators (Godfrey et. al. 2018) and off-line cleaning applications. Since these chemistries had shown strong interactions with similar organic materials at heat transfer surfaces we wanted to determine if they could be effective at inhibiting deposition on produced water coolers.

We trialed the antifoulant formulation at a plant that had a chronic experience of relatively rapid produced water cooler fouling. The plant is designed with three banks of produced water coolers. Two individual heat exchangers were present in each bank for a total of six exchangers. The normal operating practice is to run two banks of exchangers simultaneously while keeping one bank in reserve. The two banks of exchangers in service suffered relatively rapid fouling and loss of efficiency and they would eventually require an out of service chemical clean. The different banks were rotated in operation. When the two operational banks required chemical cleaning the reserve bank would be brought into service and one dirty bank would be taken out of service, cleaned, and then returned to service. Then the second dirty bank could be taken out of service, cleaned and then held in reserve. Efficiency could be partially recovered by using a bake out procedure as described in the introduction. The bake outs were quite frequent with only a few days between the procedures and they did not restore full heat transfer efficiency to the exchangers. Therefore, balancing heat load in the system required nearly constant attention on the part of the operations staff. Careful attention also had to be paid to scheduling chemical cleanings. In a typical year there were 5 heat exchanger chemical cleaning outages with 9 banks of exchangers being cleaned in those 5 outages. The direct cleaning cost was about $45,000 per bank but the great redundancy in the plant design and diligent attention by the operations staff meant that the produced water coolers never resulted in a plant bottleneck that limited oil production.

The antifoulant formulation was fed at a single injection point in a common line upstream from all the produced water coolers. The product was started at a minimal dosage since it is known to clean up old deposits from any pipe surface and rapid release of a large amount of that material can potentially cause temporary problems downstream if the full dosage is immediately introduced to the system. The dosage was gradually ramped up to about 2 ppm over a period of a few days. To best gauge the effect of the treatment the system was operated with two banks of heat exchangers that were put into service in a clean state.

RESULTS

Dramatic performance improvements were immediately noted after the antifoulant feed was initiated. The same two banks of exchangers were operated for about 5 ½ months after the antifoulant was introduced into the system. Almost no degradation in heat transfer efficiency was noted. Differential pressure over the two banks gradually crept up during this phase of the trial but no bake outs were performed for 90 days. After the initial 5 ½ months one bank was rotated and bake outs continued to be performed at the 90 day interval. Figure 2 shows the differential pressure over the banks of produced water coolers and the produced water flow over the trial period. Differential pressure from the two operational banks are nearly superimposed indicating that both banks of coolers operate almost identically. The blue line for the A/B bank is pictured much wider than the other banks so that each data set is apparent. The data from September to March are most easily interpreted since produced water flow and thusly heat load is nearly constant. Note the rapid increase in differential pressure and the frequent dips due to bake outs during the pre-trial period when the system was operated without the antifoulant treatment. Contrast that period to the first 90 days of operation with antifoulant treatment. Note the much more gradual increase in differential pressure. Examination of the best fit slopes for periods between bakeouts before and after treatment indicate a reduction in fouling rate by a factor of about 7-fold. After 7 months of operation no out-of-service chemical cleanings have been needed.
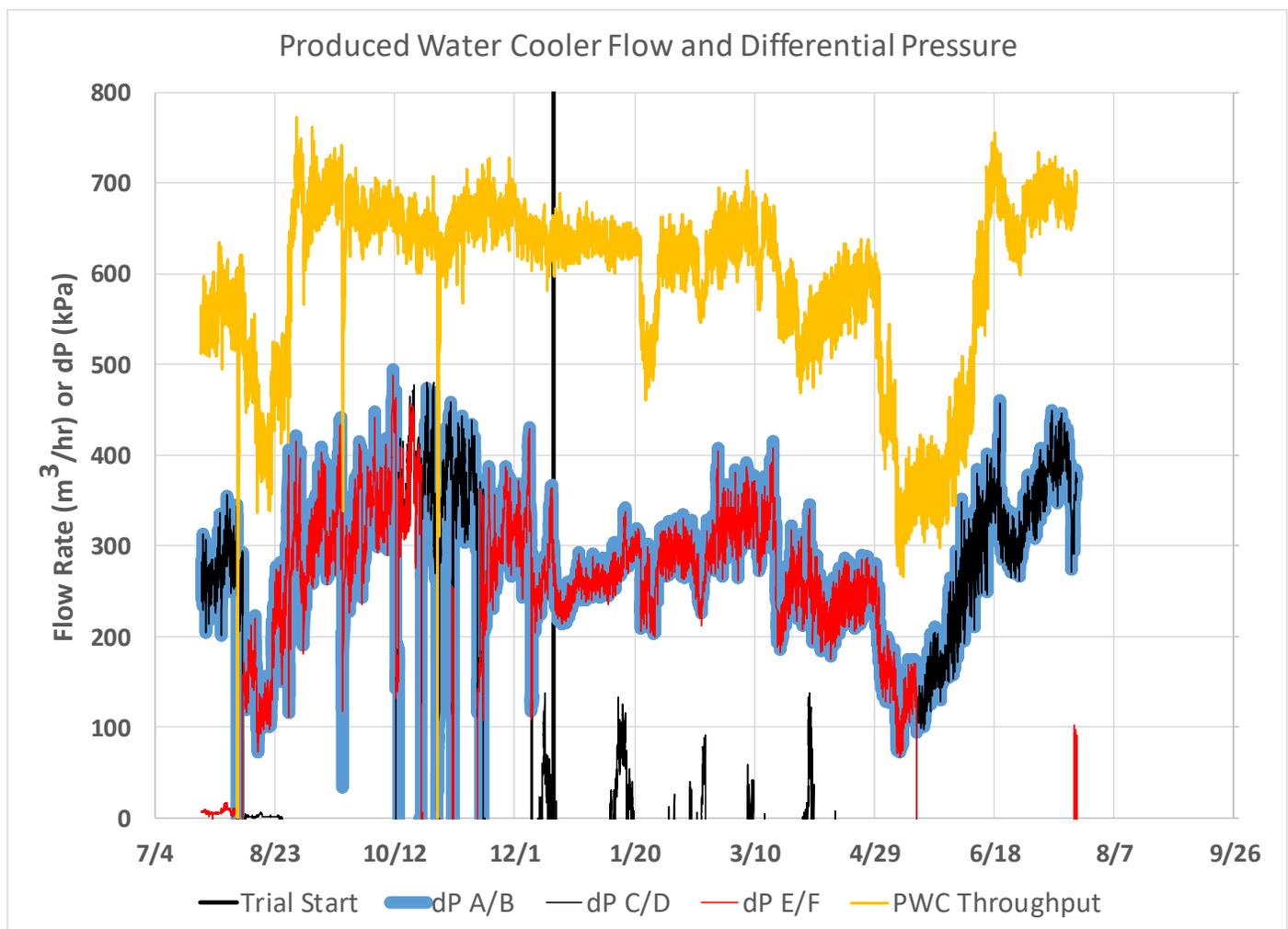
Figure 2. Differential pressures and total flow rate of water across produced water coolers.

TOPIC 2: USE OF A METAL PASSIVATOR IN OTSGs

EXPERIMENTAL

Passivating agents have been used for many years in industrial boilers (Slovinsky 1981) (Cuisia et. al. 1983). These reductants are primarily oxygen scavengers applied to power boilers after the feedwater has been mechanically deaerated, but they supply a major benefit of promoting the formation of a stable, dense, adherent and protective oxide film on the surface of the boiler steel. Magnetite is normally the oxide that forms and this process is referred to as passivation since it limits further corrosion of the boiler steel. As mentioned in the introduction, most of the corrosion mechanisms in OTSGs involve destabilization of the protective magnetite film so any chemistry that will increase the rate of formation of the magnetite film or improve its stability should shift the equilibrium between passivation and the corrosion reaction thus slowing the rate of corrosion damage.

In these experiments a widely available formulation of carbohydrazide was used. In most power boiler systems that use highly purified water a residual of about 1 ppm of this product over the dosage needed to scavenge oxygen is maintained for the purpose of promoting passivation. In the system tested here demand for oxygen scavenging is low with the boiler feedwater averaging about 3-5 ppb dissolved oxygen as measured with an on-line luminescence oxygen probe. The boiler feedwater was produced by warm lime softening and weak acid cation exchange of water separated from the oil emulsion produced by the SAGD process. The boiler feedwater is thus quite saline and has a far higher intrinsic corrosivity towards mild steel than the highly purified water used to feed power boilers. Due to the high corrosivity of the boiler feedwater and the desire to produce discernable changes in corrosion rate in a reasonable experimental time frame a dosage of 5 ppm of the product was chosen for the initial experiments with the passivating agent being fed downstream of the purification unit processes but upstream of a bank of OTSGs. In a subsequent set of experiment the dosage of product was increased from 5 ppm to 10 ppm in a single step to determine if higher dosages could produce further changes in the corrosion rate present in the OTSGs.

Corrosion in the OTSGs was monitored by testing the steam pass exit samples with a colorimetric test for iron based on the ferrozine ligand. This testing method was described in detail in a previous paper (LaRocque et. al. 2015). The method involves sampling the steam pass exit samples of an OTSG. These samples use a separation device to isolate a continuously flowing water sample from the mist of liquid water present in the gaseous steam at the exit of an OTSG generating pass. The sample stream is collected into a vial containing a buffer and the ferrozine ligand. Soluble iron in the ferrous oxidation state, Fe(II), reacts immediately with the ferrozine ligand to form a stable, highly colored complex. Addition of a digestion reagent solubilizes any iron particulates and reduces any iron in the ferric oxidation state to Fe(II) thus providing a measure of total iron concentration. Subtraction of the total iron value from the Fe(II) value yields a measurement of the amount of iron particulates in the system. The Fe(II) value has been shown to correlate with active corrosion in boiler systems that generates soluble corrosion products and the particulate iron concentration has been shown to be associated with erosion-corrosion in OTSGs where an abrasive force can scour small magnetite particles off the surface of boiler steel at areas of flow impingement (LaRocque 2015). It was hoped that the addition of the passivating agent would reduce the production of corrosion products in the OTSGs which would be revealed by a reduction in the iron concentrations measured at the steam pass exits. One OTSG in the plant was selected for testing and this unit was operated in the steadiest manner possible keeping total steam output and steam quality constant while using the other OTSGs to respond to changes in steam

demand or water flow rates. During the tests described above the boiler feedwater and each of the six steam pass exit samples of a single OTSG were monitored for Fe(II) and Total Iron once per day.

It should be noted that the iron concentration in the boiler feedwater at the OTSG inlet is not zero. The iron present in the feedwater concentrates in the water during the steam generation process and is detected in the steam pass exit samples. Therefore, not all the iron measured at the steam pass exit is a corrosion product generated in the OTSGs. No attempt was made to account for this feedwater iron in the steam pass exit data presented here. This is largely due to the great difference in sample matrix between the feedwater and the concentrated water at the steam pass exit samples. This creates difficulties with the optical blanking procedure and introduces uncertainty and variability into the measurement if an attempt is made to subtract the feedwater iron from the iron measured at the steam pass exit. The subtraction of feedwater iron also requires a knowledge of the concentration factor between the boiler feedwater and the steam pass exit water that results from evaporation of about 80% of the water to form steam. We found that when attempting to detect changes in the iron concentrations at the steam pass exits it was best to use the raw data without introducing additional variability to the measurements by attempting to convert that data to just iron generated in the OTSG. Iron in the boiler feedwater was measured as a check and could easily be associated with some changes seen in the OTSG pass exit samples but in most instances the feedwater iron remained constant enough that it did not cloud the interpretation of the steam pass exit results.

RESULTS

Three instances were monitored closely for changes in iron concentrations at the steam pass exits. The first was when the passivating agent was initially introduced to the system. The second was when a freshly pigged (mechanically cleaned) OTSG was brought into service using feedwater containing the passivating agent and the third was when the feed rate of the passivating agent product was increased from 5 ppm to 10 ppm in a single step.

Initial injection of the passivating agent is shown in Figures 3 and 4. Figure 3 shows the Fe(II) results. One observation that we have made repeatedly is immediately evident in the data; not every pass in a single OTSG behaves identically. Pass A is clearly and outlier in this group but has similar directional behavior to the other passes that are all more closely grouped. The individual passes are, in effect, different boilers although they are all grouped together in a single furnace. We often see one or two passes with much higher iron values than the rest and the outlier pass often changes over time. We theorize this may be due to the recent history of that pass. Perhaps a deposit release event has thrown solid material down the pass, abrading the surface, disturbing the passive oxide film and temporarily increasing its corrosion rate. When performing weekly tests on a single OTSG we have noticed that the passes that are outliers change from week to week possibly indicating repassivation in that time frame. All the passes in this experiment seem to show some decrease in iron corrosion product generation when the passivating agent was introduced but the outlier pass with higher iron concentration seems to respond most dramatically. Perhaps this pass had recently suffered from an event that disrupted the magnetite oxide film, so the passivating agent had the greatest effect on surfaces that were most disturbed. Figure 4 shows Total Iron and Fe(II) data averaged over all the passes for each time. It is evident from the averaged graph that there is very little difference between the Total Iron concentration and the Fe(II) concentration indicating that there is only a small amount of iron in particulate form present in this system. The small amount of particulate iron is consistent with the experience of very little erosion-corrosion damage to U bends or other points of flow impingement in this boiler system.
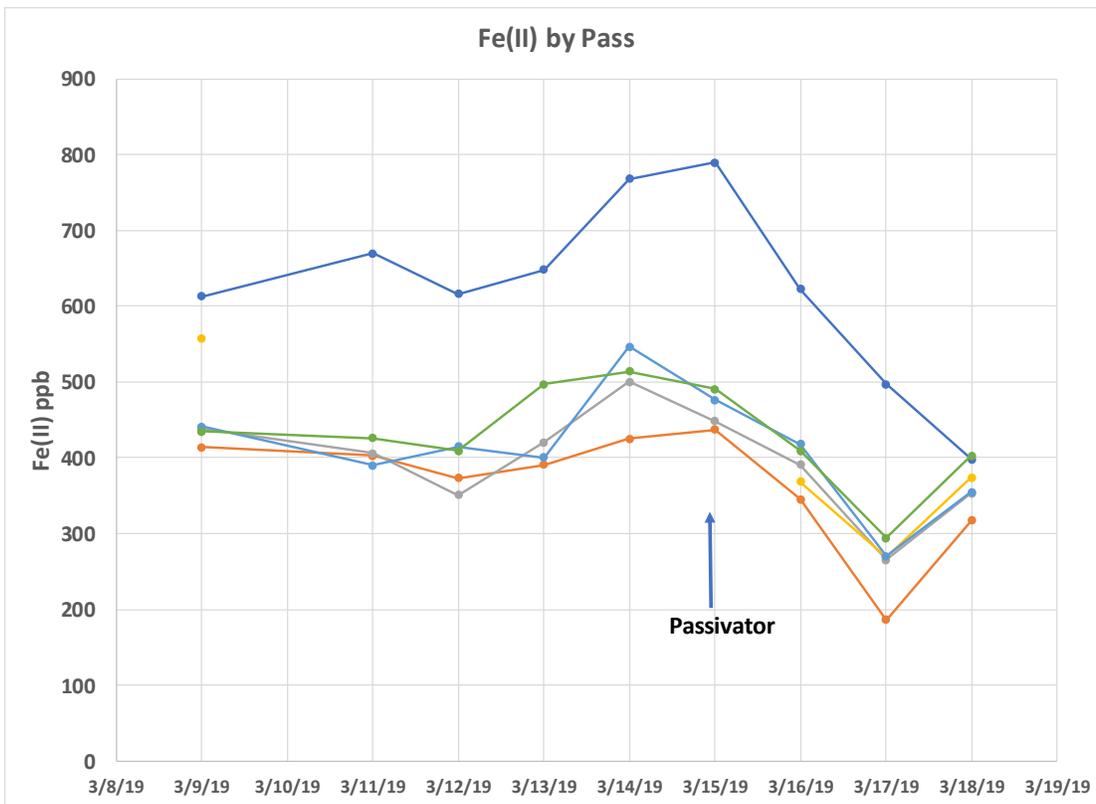
Figure 3. Fe(II) concentration immediately before and after start of passivating agent feed.
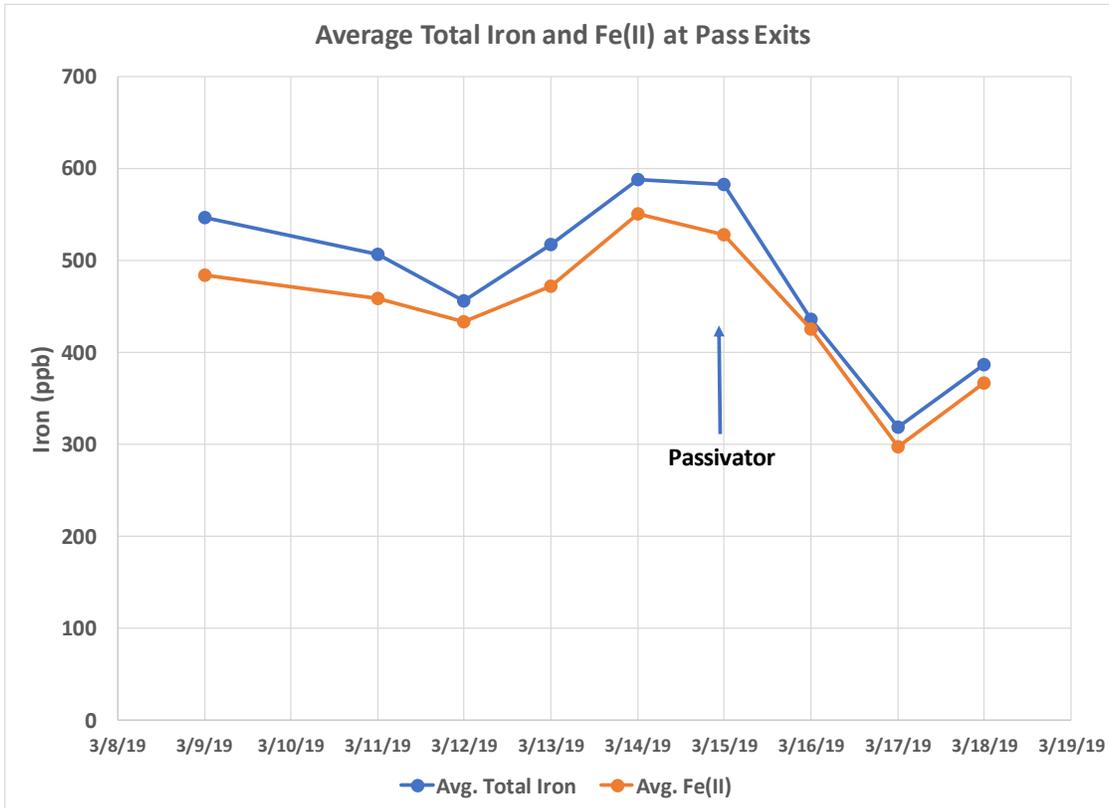
Figure 4. Iron concentration data averaged over all passes at start of passivator feed.

The OTSG chosen for the initial observations after the passivator feed was started unfortunately suffered an outage due to a mechanical issue but observations were shifted to another unit. Data from that unit starts one week after the passivator feed was initiated. Data from that period of the experiment is shown in Figures 5 and 6. Figure 5 shows the Fe(II) data and Figure 6 shows the Total Iron data and the Fe(II) data averaged over all the steam passes. Again, we note one pass that is an outlier at a higher corrosion rate, but it rapidly joins the band where the other passes reside. A gradual decline is noted over this period which may be due to improved passivation and a lower corrosion rate in the system. The amount of particulate iron also decreased somewhat during the period which could also indicate improved stability of the passive magnetite film.
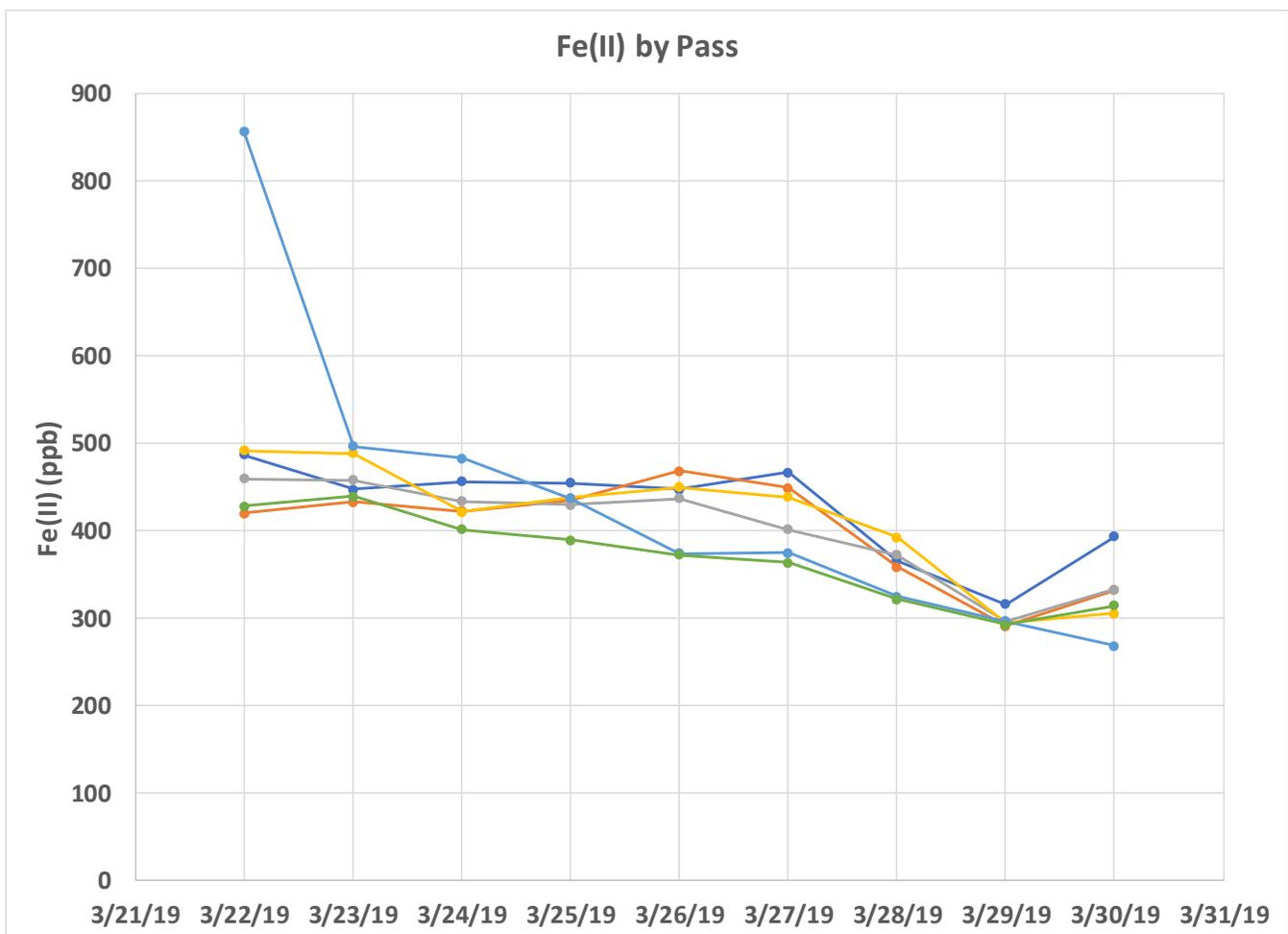
Figure 5. Fe(II) concentrations beginning 7 days after passivator feed was initiated

Average Total Iron and Fe(II) at Steam Pass Exits
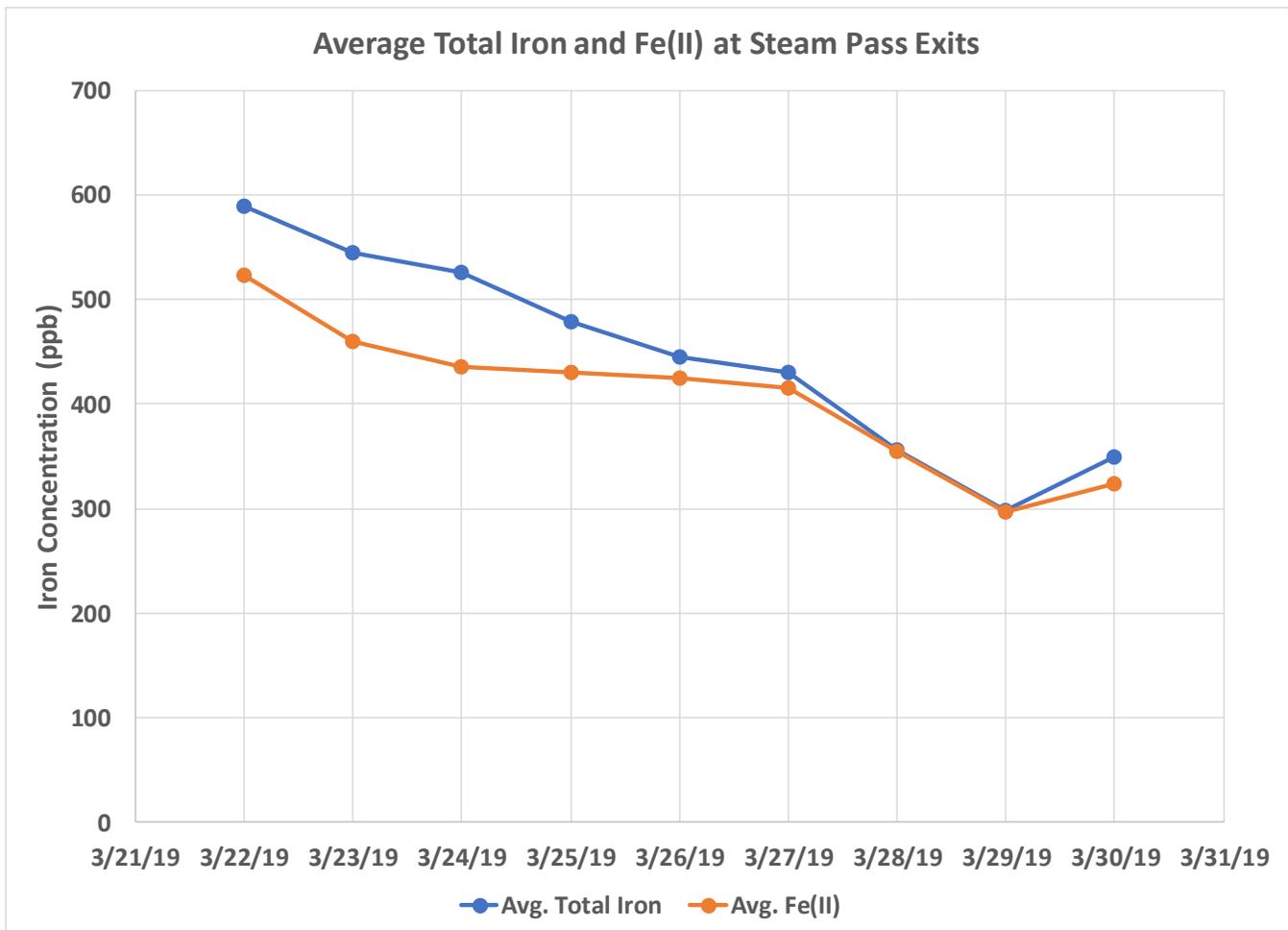
Figure 6. Iron concentration data averaged over all passes starting 7 days after start of passivator feed.

Another experiment was performed when a freshly pigged OTSG was brought into service with feedwater containing the passivating agent. Pigging is an out-of-service mechanical cleaning process where a hard polyurethane foam plug called a pig is pushed through the boiler tubes with pressurized water to mechanically dislodge deposits. Appendages such as stainless steel bolt head screws are added to the pig on subsequent insertions so the tubes are generally cleaned down to bare metal. When the boiler is brought online after such a cleaning the entire surface must form the passive magnetite oxide film. The passivation process observed by iron testing in the absence of a passivating agent generally requires a period of 2-8 weeks to come to a steady state condition of corrosion product generation. Figure 7 shows what we observed in the presence of the passivating agent product at a dose of 5 ppm. As in the previous examples the data from all passes at a given time are averaged in this graph. First note that there is essential zero particulate iron in this example. This is highly consistent with the theory of the origin of particulate iron in OTSGs that we have proposed previously. We believe that the particulate iron is the result of tiny particles of the magnetite passive film being dislodged by an abrasive force such as could be provided by the release of solid deposit at a location upstream from the site of corrosion. If there is no oxide layer there is simply no oxide present to be abraded off as tiny particles. Since the boiler is clean there is also no deposit to be released to provide the abrasive force for removing the passive oxide layer.

Passivation, as evidenced by the reduction in the concentration of Fe(II) generated in the system, is quite rapid in this case reaching a steady state equilibrium concentration in roughly one week. The rapid

passivation may be good evidence of the action of the passivating agent on the bare metal of the freshly cleaned boiler.

Average Total Iron and Fe(II) During Initial Passivation After Pigging
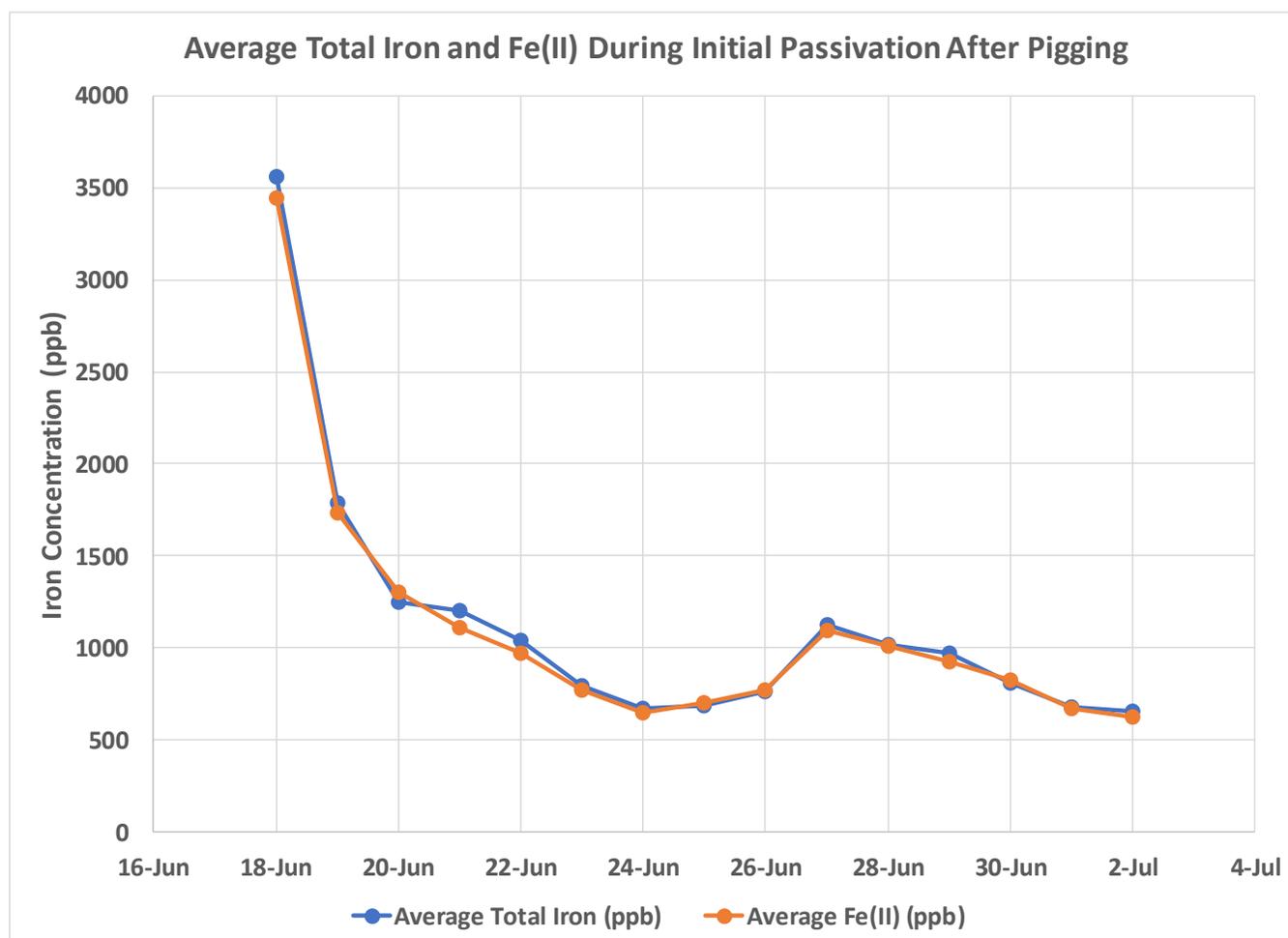
Figure 7. Passivation of a freshly pigged boiler. Total Iron and Fe(II) averaged over each pass.

Another experiment was performed after the passivating agent had been in use for several months. In this experiment the concentration of the passivating agent in the boiler feedwater was doubled by increasing the product dosage from 5 ppm to 10 ppm in a single step. Iron data was taken on the steam pass exits each day for one week prior to the dosage step change and one week after the step change. A very gradual reduction in corrosion product generation was noted. One might expect that any new equilibrium state would be achieved in roughly the same time frame as was observed for the initial passivation of the freshly cleaned boiler or about one week. When the averaged data for all the passes at the end of the one week at 10 ppm passivator product dosage was compared with the averaged data from the entire one week of the 5 ppm dosage baseline a 30% reduction in Total Iron and a 24% reduction in Fe(II) was observed. This indicates that higher dosages of the passivating agent can drive further reductions in the corrosion rate in OTSGs.

TOPIC 3: OTSG LABORATORY PILOT TEST RIGS

EXPERIMENTAL

As topics 1 and 2 demonstrate it is possible to perform useful experiments in operational plants, but the data presented are also a good illustration of the difficulties of field experimentation. Plant operations always take precedence over any experiment that may be in progress. Output swings and system upsets are common and unexpected failures and outages are always a possibility. Most significantly, experimentation is strictly limited to conditions that pose little risk to plant operations or equipment. Intentionally creating conditions that would cause adverse scale or deposit formation or create a corrosive condition in an OTSG are out of the question so the breadth of experimentation and the ability to perform blank experiments is limited. Laboratory pilot test OTSGs immediately solve all these problems since they are operated for the sole purpose of experimentation and they allow for safe operation under conditions that would have unacceptably adverse consequences for field units.

The design goal for the laboratory pilot OTSGs was to replicate all the major components and operating conditions of field OTSGs in hopes that their behavior in terms of inorganic mineral scale formation, organic deposit formation and corrosion mechanisms would closely simulate the real units. The experimental goal was to be able to study all those tendencies independently or in combination under the range of operating conditions experienced at SAGD facilities in Western Canada. The units were constructed at roughly 1/1000th scale of a commercial OTSG. Figure 8 compares commercial field units and the test rig design.
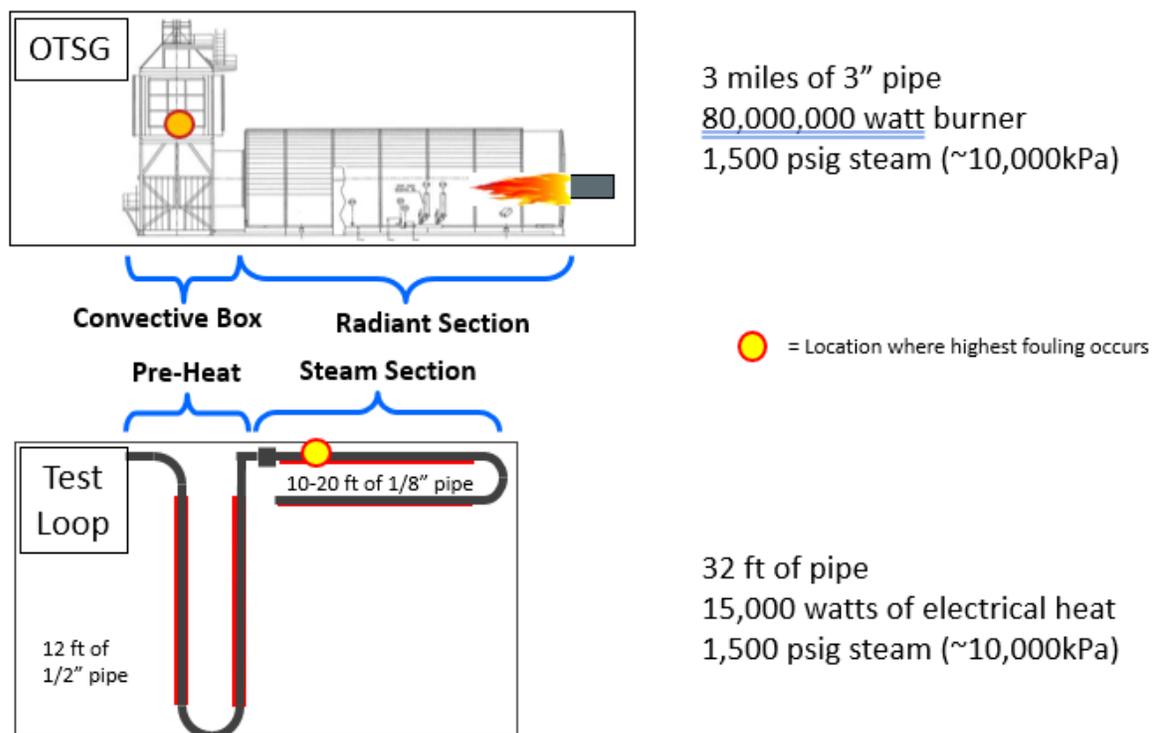
Figure 8. Schematic of commercial and laboratory pilot test OTSGs.

Specific design criteria for the test rigs are as follows:

Scaled down replica laboratory pilot test rig to simulate full commercial OTSG operation
- Same temperature, pressure, dissolved O_2 concentration and boiler feed water quality
- Simulates both convection and radiant sections
- Generates steam   (representing a true boiler)
- Default mode is once-through, not recycle

Practical
- 1 cubic meter of water per test run
- Test rig, pump, tanks, instruments, and unit operations must operate within a laboratory setting
- No fired burner

Control of Key Parameters
- Steady-state operation (same feedstock for entire test, minimal shutdowns)
- Know exactly where nucleate boiling occurs and where the start of net steam generation occurs
- Control the heat flux

Destructive Analysis Each Run
- Cut up all steam pipes to find out where and what fouled in order to understand mechanism
- Key areas of study are end of pre-heat, start of steam section, end of steam section and tubes in between
- The tube sections are to be disassembled after each test run and replaced/reassembled with a new set of tubes.

Simulate Fouling Mechanism
- Duplicate OTSG heat flux
- Be reasonably close to OTSG residence time
- Use select antifoulants

Heat is supplied with electric resistance heaters and thermocouples are attached to the tubes as the main sensor for scale or deposit formation. If insulative scale or deposits form on the heat transfer surface there is an increase in the tube wall temperature detected by the thermocouples. The arrangement of the heaters and thermocouples is shown in Figure 9. The entire lab pilot test rig system with feedwater tanks and other auxiliary equipment is shown in Figure 10.
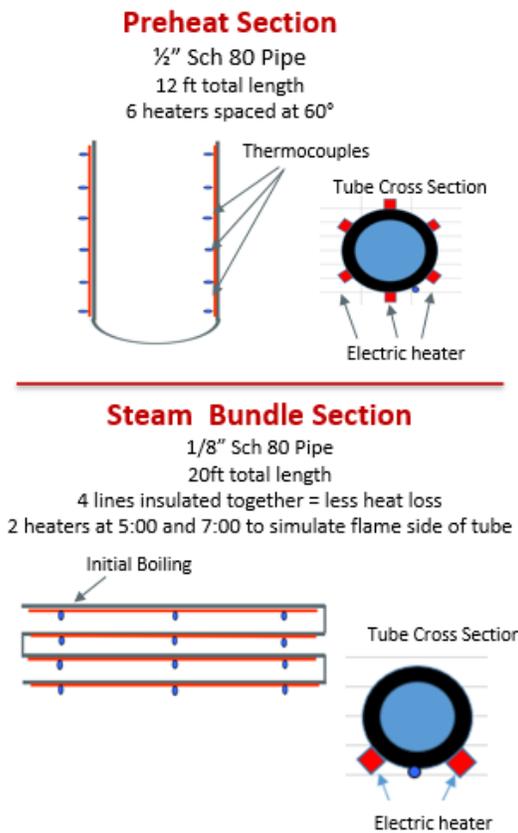
Figure 9. Arrangement of electric heaters and thermocouple in the two sections of the test rigs.

Figure 10. SAIT Laboratory OTSG Pilot Test Rig.

RESULTS

Preliminary experiments are very encouraging at this point. Reproducible baseline and scaling conditions can be obtained. Thermocouple readings indicate that mineral scale forms at the same general location as the heaviest deposits observed in commercial OTSGs which is at points near the onset of boiling. The use of a commercial boiler antiscalant polymer that has been used successfully in field OTSGs is seen to inhibit scale formation in the test rigs.

CONCLUSIONS

Three topics of interest to the SAGD industry and OTSG operators were presented in this paper. The first topic was a field study showing that an antifoulant chemistry can vastly improve the operational characteristics of produced water coolers. The system studied went from a condition of performing frequent bake outs and chemically cleaning 9 banks of coolers in 5 outages per year to a situation where bake outs are performed every 90 days and no cleanings have been performed for a period of 7 months with an estimated savings of $250,000/yr. Analysis of differential pressure data suggests that the treatment reduced the fouling rate by a factor of about 7. The second topic investigated the use of a passivating agent for OTSGs. Introduction of the passivating agent reduced iron corrosion product generation significantly and greatly increased the rate of passivation for OTSGs after mechanical cleaning. Increasing the dose of the passivator further decreased iron corrosion product generation. Passivator chemistries have great potential for reducing corrosion damage in OTSG systems. The third topic introduces new equipment installed at the Southern Alberta Institute of Technology for the laboratory simulation of OTSGs. The two lab OTSG pilot test rigs show great promise for improving experimentation in the area of OTSG treatment chemistry and corrosion. The two field studies presented in the first topics of the paper give evidence of the difficulty of performing experiments in operational plants and the very real limitations on the precision of data that can be obtained. These laboratory simulation test rigs are expected to resolve pragmatic problems associated with field experimentation. Preliminary results indicate that the pilot test rigs form mineral scale primarily in the same site as observed in field units in the nucleate boiling zone. The scale formation also responds to treatment by antiscalant polymers commonly used with success in field units.

ACKNOWLEDGEMENTS

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