FOULING OF HEAT TRANSFER SURFACES IN A STEAM ASSISTED GRAVITY DRAINAGE (SAGD) IN SITU FACILITY FOR THE RECOVERY OF OIL SANDS BITUMEN

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ABSTRACT

Fouling of heat transfer surfaces presents an ongoing challenge to SAGD plants. SAGD produced water contains significant concentrations of dissolved solids as well as suspended clays, free oil, and dissolved organics. Under certain conditions of temperature, pressure and velocity, these compounds will cause fouling in heat exchanger and steam generator tubes. This leads to the need for complex water treatment in conjunction with frequent downtime for cleaning and maintenance. Hence fouling of these surfaces leads to additional operating costs and lost production for the SAGD sector. Field studies and laboratory work have been undertaken by Suncor and Statoil in order to mitigate the impact of fouling and to gain an improved understanding of fouling mechanisms in SAGD operations.

INTRODUCTION

The Athabasca oil sands of Northern Alberta, Canada are one of the largest oil deposits in the world. Proven reserves are nearly 170 billion barrels and oil sands operators produce about 1.6 million barrels of oil per day, or half of all Canadian crude oil production.

Bitumen is typically recovered from the oil sands by one of two methods: mining followed by extraction, or In Situ recovery using Steam Assisted Gravity Drainage (SAGD). In a SAGD operation, steam is injected underground into the oil sands deposit where it condenses and transfers heat to the bitumen. This mobilizes the bitumen, allowing it to flow by gravity, along with the now-condensed steam, to the producer well located below the steam injection well. The bitumen and produced water (PW) mixture is brought to the surface where the bitumen is separated and sent by pipeline to an upgrader, while the PW is recycled through multiple water treatment steps and re-injected into the steam generators to produce more steam.

The PW contains constituents in the form of Total Dissolved Solids or TDS (Ca, Na, Mg, *etc.*) suspended clays and silica, as well as free oil and dissolved organics. These components exhibit a propensity to foul heat exchanger surfaces and steam generator tubes when present in suitably high concentrations and under certain conditions of temperature, pressure and/or fluid velocity. This fouling necessitates the use of chemicals for cleaning-in-place during operation, requires scheduled shutdowns for cleaning and maintenance, or causes unscheduled shutdowns to address overheating and thinning of tubes. All of these outcomes have a cost in the form of either operational expenses or lost bitumen production, or both.

The present paper describes the fouling issues encountered in produced water coolers and steam generator tubes and the steps taken to mitigate the problems. The structure of the paper is as follows. First the problems are illustrated through the use of case studies taken from operating SAGD plants. Subsequently our current understanding of PW chemistry and the contribution to fouling of certain constituents in the PW will be presented.

FOULING IN PRODUCED WATER COOLERS

Figure 1 illustrates the PW cooling section of a SAGD plant. A bitumen-water emulsion enters the Free Water Knockout (FWKO) drum where the PW is separated from the oil by gravity. Emulsion breaking chemicals, and in some cases a light hydrocarbon diluent, are added upstream to effect the bitumen-water separation. The PW is then cooled prior to further processing. Figure 1 shows glycol used as the coolant; in most modern SAGD plants the PW exchanges heat with other process streams to achieve more efficient heat integration and glycol is used for trim cooling.
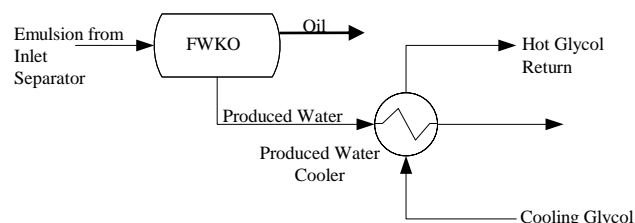

Fig. 1 – Schematic illustration of PW cooler system.

PW Cooler Designs

Two distinct types of heat exchangers are utilized in cooling PW in SAGD operations. These are traditional shell and tube exchangers and spiral exchangers. PW shell and tube exchangers are a conventional design, typically using

76.2 mm (¾") tube diameters. Produced water velocities range from 0.77 m/s to 1.70 m/s. Produced water flows on the tube side due to its fouling characteristics.

After significant produced water cooler fouling issues were experienced in the early SAGD facilities, several producers switched to spiral exchangers in later designs. Spiral exchangers use flat surfaces that are coiled to form two channels in a counter-flow arrangement. An opened spiral exchanger is depicted in Figure 2. Although one advantage of spiral exchangers over shell and tube exchangers is their smaller footprint, they have been employed in SAGD operations primarily for other reasons. One reason is the potential for 'self-cleaning'. The local velocity increases as the internal walls build up with foulant thereby helping to reduce additional build-up of material. Secondly, the fluid is believed to be fully turbulent at much lower velocities than in straight tube exchangers due to the spiral design. This may aid in keeping solids in suspension. Last, when cleaning is necessary the spiral exchangers have advantages over shell and tube designs due to the accessibility of the heat transfer surfaces (i.e. they are easier to clean).

Fig. 2 - An opened spiral produced water cooler at Statoil's Leismer SAGD facility near Fort McMurray AB.

Observed Rates of Fouling

There is a lack of data on the exact nature of foulants in PW coolers. However, the composition of foulants includes inorganics as well as both soluble and non-soluble organics. The observed rates of fouling vary between producing facilities. Typical service life between cleanings of PW coolers in SAGD applications may range from several weeks to as short as a few days. Some extreme fouling situations may limit run length to a matter of hours. Several factors are believed to influence the rate of fouling, as discussed below.

Design/operational aspects. Lower velocity in the cooler generally increases fouling rates. Rates of fouling between spiral coolers and shell and tube exchangers are difficult to compare with no clear consensus. As will be discussed later, Suncor installed spiral coolers at their Firebag SAGD facility with the expectation of increased PW velocity and hence reduced fouling, but this advantage has not materialized.

Diluent composition. Diluent is added to the inlet of separation vessels to assist with the transport of the highly viscous bitumen. There is some indication that diluent selection can impact cooler fouling.

Temperature profiles. Fouling is more pronounced as PW cools.

PW Chemistry. Variations in the composition of dissolved organics in the PW between sites may impact fouling rates. These variations are due to differences in the chemical composition of bitumen deposits throughout the region. Thus fouling tendencies can be reservoir-specific.

Chemical addition. Emulsion breaking (EB) and reverse emulsion breaking (REB) chemicals added in the upstream inlet separation process can have a significant impact on fouling rates and downstream PW quality.

Statoil's Leismer facility operates six spiral exchangers in parallel. A pressure control valve operates downstream of the exchangers. As the exchangers foul and pressure drop increases, the control valve opens. When the control valve is fully open, the exchanger must be cleaned as shown in Figure 3. Original baseline cleaning using a caustic wash was completed twice per week. This has been reduced to once per week with a modified chemical program.
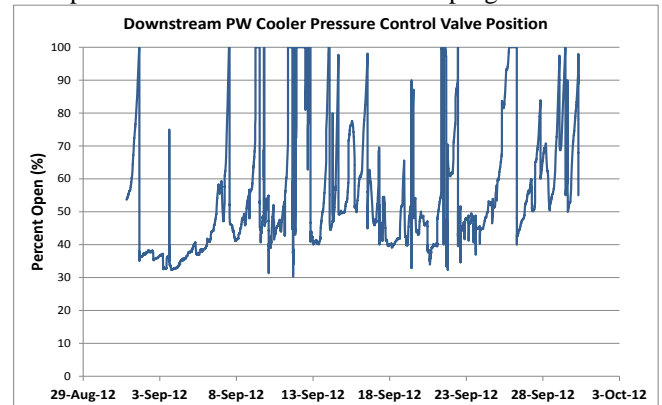

Fig. 3 - Control valve position downstream of one of Statoil Leismer's PW coolers, illustrating the frequency of cleaning required (when valve position reaches 100% open).

Suncor's Firebag facility operates multiple plants within the facility. Two plants employ shell and tube heat exchangers and one plant uses spiral coolers. The shell and tube exchangers in the first plant typically experience less fouling and average 17 days between cleanings. The second plant that utilizes shell and tube exchangers experiences run lengths of 5 to 11 days between cleanings. The spiral coolers in the third plant experienced severe fouling upon startup but after changing various process parameters, operate 3 to 5 days between cleanings. Other SAGD producers have experienced similar produced water cleaning cycle times.

Although the implementation of spiral coolers in the industry was expected to mitigate many of the challenges with produced water cooler fouling, a significant improvement has not materialized. Designs have attempted to maintain high velocities to decrease fouling rates but these designs have instead led to a low tolerance for fouling. This low tolerance has in turn led to more frequent cleaning requirements.

Cleaning and Mitigation Strategies

As the SAGD industry has developed, numerous approaches have been used to clean fouled exchangers as detailed below.

Mechanical Cleaning. Mechanical cleaning was the primary mechanism employed in the early stages of SAGD development. Exchangers are taken off-line, opened and cleaned with high pressure water. Mechanical cleaning is still often employed today although use of chemical cleaning methods, primarily caustic flushing, has greatly reduced the frequency of mechanical cleanings.

Caustic Cleaning. Caustic cleaning is generally considered the primary cleaning mechanism today. The exchanger is taken off-line and a caustic solution is circulated through the exchanger on the produced water (i.e. tube) side. Caustic is effective at dissolving organic material and to a lesser extent silica deposits in the foulant.

Other Techniques. Other approaches to reduce fouling in PW coolers include reversing flow direction of the produced water, stopping flow of the produced water to increase temperature ("bake-out") and intermittent and continuous high velocities through the tube side by increasing the flow of produced water.

Chemical Trials. More recently, attempts have been made to add aromatic solvents, anti-foulants and coagulants upstream of the produced water coolers. Recent trials at Statoil Leismer involved injecting three different chemicals upstream of the PW coolers: a coagulant typically used in the downstream water treatment process, a more conventional water clarifier coagulant, and an antifoulant additive. The antifoulant and the first coagulant showed little to no improvement. The water clarifier coagulant reduced cleanings from twice per week to once per week however, it reduced the quality of downstream water requiring additional chemical additives at that point in order to prevent upsets from reaching the water treatment and steam generation plants.

Recent chemical trials at Suncor's Firebag facility have shown more significant potential. The addition of a coagulant upstream of the shell-and-tube exchangers along with testing of alternative emulsion breaking chemicals added to the inlet separation vessels were trialed. Run length between cleaning for the shell-and-tube exchangers was extended significantly, as shown in Figure 4.

In the Firebag plant with spiral exchangers, run length was increased from 3 days to 78 days during the trials. However, this coagulant addition and change in emulsion breaker again had a significant impact on the downstream water treatment facility. Trials are still on-going, however, it appears run lengths of over 6 days are possible without upsetting the downstream process units.

Evidence gleaned from these chemical trials suggests that the coagulant polymer injected upstream of the produced water coolers acts as an anti-foulant agent in conjunction with the new emulsion breaker. Fouling returns when the coagulant dosage is reduced or eliminated. Coagulant spikes (60+ ppm) were shown to recover overall

heat transfer rate. Performance is sensitive to the combination of coagulant and emulsion breaker and the ratio of the concentration of the two.
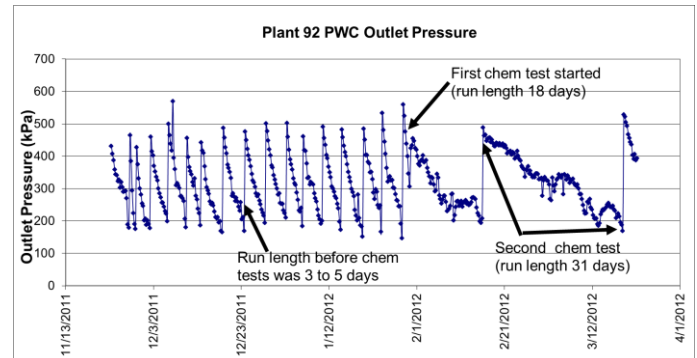

Fig. 4 – Results of chemical addition on run length (time between cleaning) on PW shell-and-tube exchangers at Suncor's Firebag facility.

Analysis of PW Cooler Deposits

Figure 2 shows an opened produced water heat exchanger at Statoil's Leismer facility, and Figure 5 shows deposits in the same heat exchanger. For this case, deposits were found across the whole spiral, but it seemed to be more in the outer rings where the water was coldest. (Water inlet is in the central part, and the outlet is at the outer rim.)

Fig. 5 - Close-up of Figure 2; heat exchanger with deposits.

In Figure 6 typical compositional analytical results on the deposits in Figure 5 are shown. The organic part of the dry sample made up 94 %. In spite of it being mostly organic, only 10-20 % was soluble in organic solvents at 20 °C (toluene, chloroform, methanol, dichloromethane). The best of the tested solvents was an aqueous solution of NaOH (about 5 %). At 70 °C about 75 % of the sample was dissolved. (This is the way the deposits are removed from the heat exchangers in the industrial scale; cleaning with 5 % NaOH at 70 °C). The O:C mole ratio was relatively high, 0.21. An H/C ratio of 1.15 on mole basis is considered as quite low. Saturates, aromatics and resins (by Iatroscan) made up about 21 % of the dry sample. The four most abundant elements in the inorganic part were S, Fe, Al, and Si.

Several possible components have been suggested as the most significant part of the foulant, but none is identified, yet. Naphthenic acids, production chemicals, mellite, and precipitation of dissolved silica are suggestions for important parts of the deposits. Acid/toluene wash didn't indicate any significant

contribution from naphthenic acids or naphthenates in the deposits. Based on the amount of Fe and other naphthenic acid binding metals, the amount of oxygen is far too high to come from naphthenates. Other sources for the oxygen therefore must be found. H^1NMR of the NaOH soluble fraction reveals a significant fraction of aromatic hydrogen compared to aliphatic. Peaks are in general broad, indicating either a very complex mixture or possibly fewer but larger molecules eg. polymers. IR reveals similarities with oxygen containing polymers (epoxy polymers).
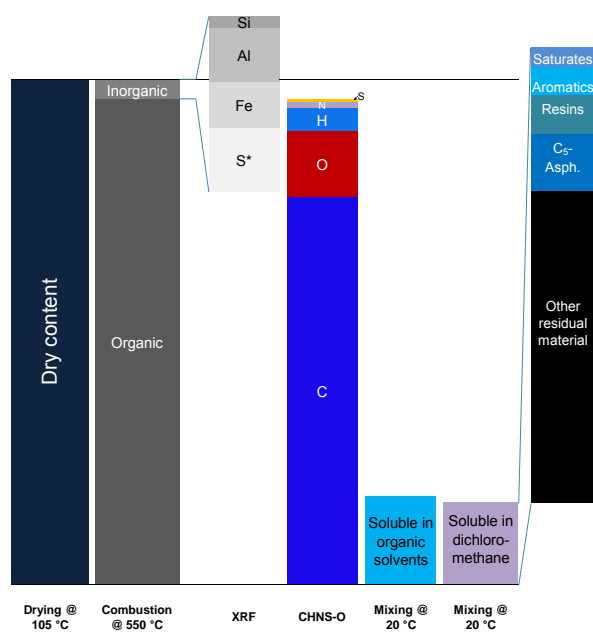

Fig. 6 - Analytical results of deposits from Figure 5. The asterisk (*) attached to the S means that there also can be some organic S included in this amount. 'Organic solvents' are toluene, methanol and trichloromethane. The deposit had almost the same solubility in all three solvents.

It is clear that fouling in PW coolers is a complex combination of competing factors including, exchanger design and operation, water chemistry, and fouling chemistry and kinetics. There is a need to establish a more fundamental understanding of fouling in PW coolers in the SAGD industry that can then be applied to establish an optimum design and operating strategy.

ONCE-THROUGH STEAM GENERATOR (OTSG) FOULING

Steam generation forms the heart of SAGD operation; without steam, there can be no in situ recovery of bitumen in a SAGD plant. The treated PW from the water treatment plant forms the boiler feed water (BFW) for the steam generator. Various steam generation technologies exist, but historically once-through steam generators or OTSGs have been used in SAGD plants. All of these technologies have in common the presence of tubes into which the BFW is fed. On the outside of the tubes, natural gas or fuel gas is combusted and the heat from the burning gas is transferred

through the tube walls to the BFW, causing it to boil and produce steam.

One of the key operating parameters of steam generators is steam quality, defined as the mass fraction of steam in the steam-liquid mixture inside the tubes. OTSGs used in SAGD applications are designed to operate at low steam quality (typically 75 to 80 wt%). Operation in this manner ensures that the tube walls are covered with a liquid film so that any impurities in the BFW do not deposit on the tube surfaces, but instead are transported through with the liquid phase. At the exit of the steam generator, the steam is separated from the liquid and sent to the well pads for injection into the reservoir. The separated liquid, known as blowdown, is characterized by high concentrations of dissolved solids and organics. A portion of the blowdown is recycled back to the plant for heat exchange and re-injection into the water treatment facilities while the remainder is either injected into disposal wells or trucked away.

OTSGs have been traditionally favored over drum boilers in SAGD applications for three main reasons (Gwak and Bae, 2010):

1. TDS and silica in the BFW can be tolerated up to the solubility limit at operating temperature and pressure, i.e. these solids stay in the liquid phase of the 80% quality steam as the two phase mixture flows through the boiler tubes;
2. Heat flux is lower in OTSGs than in drum boilers, making OTSGs more tolerant to overheating caused by foulant deposition on tubes;
3. OTSGs are relatively less complex than drum boilers due to the absence of liquid circulation and drum level controllers.

A typical OTSG configuration is schematically illustrated in Figure 7. OTSGs are divided into the radiant and convective sections. In the radiant section, the boiler tubes "see" the burner flame and the controlling heat transfer mechanism is radiation. In the transition between the radiant and convection sections, both convection and radiation contribute to the overall heat transfer from the hot gases to the BFW flowing inside the tubes. In the convection section, the gases are relatively cooler and the controlling mechanism is convection heat transfer.

The BFW first enters the convection section at the top of the OTSG (also known as the economizer section) and flows downward to the top of the radiant section. At the bottom of the radiant section, multiple tube passes merge into a single line that exits the steam generator.

Boiler tube fouling predominantly occurs at or near the end of the economizer section. This is likely related to the fact that heat flux is highest in this region (convection plus radiation heat transfer contribute here) and flow is developing as significant amounts of steam are first generated in this region of the OTSG.
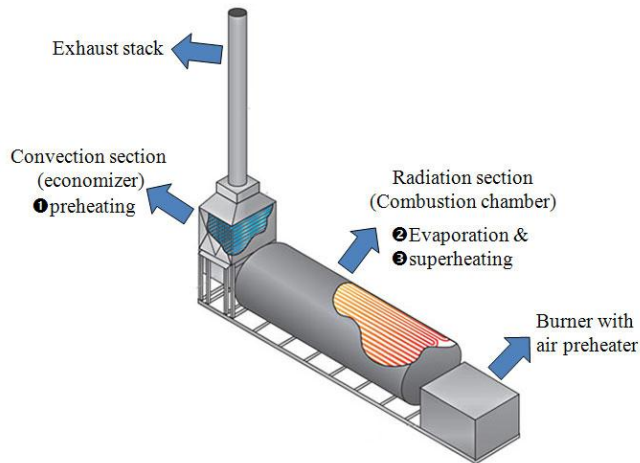
Fig. 7 – Schematic illustration of an OTSG (Gwak and Bae, 2010).

The image of Figure 8 is of stainless steel fouling coupons following a simple experiment in which BFW was boiled in a beaker. The coupons were lying on the bottom of the beaker. Similar experiments with coupons suspended vertically in the beaker showed no such deposits. The black nature of the deposit would seem to be consistent with dissolved organics in the BFW. In a follow-up experiment, the BFW was treated in the lab with coagulant and flocculant and the boiling tests repeated. The resulting coupons (not shown here) were much lighter, probably due to the absence of dissolved organic materials that had been settled and then filtered from the BFW following chemical addition.

In another set of tests, both stainless steel coupons and carbon steel pipe were tested in an autoclave environment with the raw BFW. Both showed fouling tendencies, but the foulant on the coupons was easily removed while on the carbon steel pipe the foulant was much more strongly adhered. This may indicate that in addition to the BFW composition, the materials in contact with the water also play a role in fouling.

Fig. 8 – Image of fouled coupons following a boil-off test of SAGD BFW. Coupons were laid horizontally on the bottom of the beaker.

When there is an upset in the water treatment section of a SAGD facility, BFW will usually go off-spec. In response, steam quality is reduced below the typical 75 to 80% range until BFW specifications are re-established. Repeated cuts

in steam quality leads to millions of dollars in losses due to reduced thermal efficiency in the boiler and less dry steam to the bitumen reservoir and hence reduced oil production.

To better understand the role of steam quality in boiler deposition, especially in regards to oil-in-water deposition, a wet steam sampling station was installed directly at the outlet of one Suncor's OTSGs and was used to conduct a transport study. In the transport study, feed and outlet contaminant concentrations were measured to quantify deposition rates in the boilers. The relationship used to define transport is as follows:

$$\% \, Transport = (Conc_{outlet} \, / \, Conc_{inlet}) x \, 100$$

Transport of 100% equates to no deposition of foulants, while transport results lower than 100% indicate deposition.

The wet steam directly at the OTSG outlet was measured using an isokinetic sampling nozzle, specifically designed for sampling two-phase flow. While this sampling station design has been used extensively in the utility industry for monitoring particulate silica concentrations in superheated steam, it appears that use of isokinetic sampling in SAGD is a novel application.

While other approaches to transport studies are currently used in the SAGD industry, isokinetic sampling can capture the vapor and liquid fractions of the boiler outlet into one sample, allowing measurement of any contaminants in the vapor phase as well as the liquid phase. This was felt to be especially valuable when studying the complex mixture of organic compounds in produced water.

In order to determine if the wet steam isokinetic sampling system could collect representative samples, sodium was measured in the OTSG feed and in the wet steam. Sodium is added to the BFW during water softening steps upstream of the OTSG. At these sodium concentrations, all sodium in the BFW will report to the outlet of the boiler. Therefore, regardless of steam quality, the sample is representative if the sodium transport is 100%. As Figure 9 illustrates, when the average sample flowrate over the course of collecting a composite steam sample fell in the range of 1250 to 1400 mL/min (corresponding to isokinetic sampling velocity at the nozzle tip), mass balance closure on sodium was within -15/+5%. This confirmed the accuracy of this sampling technique over the target sample flow range. Note that the error bars in the figure correspond to the variation in the sample flow rate during the period of sample collection.

Having established the sampling technique and confirming acceptable closure on sodium transport, steam samples were then collected to determine the transport of oil through the OTSG and to determine if reductions in steam quality from 78% to 65% (i.e. the typical response when BFW goes off-spec) had any effect. Sample analysis was done using a hexane extraction followed by gas chromatography in the C10 – C60 range. This method is known as total extractable hydrocarbons (TEH).These results are depicted in Figure 10. While a slight increase in oil transport may be discernible from the Figure, statistical

analysis concluded that this difference would only be significant at high confidence intervals. Given the inherent variability in the sample flow rates as well as normal fluctuations in the process itself, high confidence intervals are unlikely for this version of the sampling nozzle. Hence for the conditions studied here, in which boiler feed water was always on-spec, reducing steam quality did not have a significant effect on oil transport.
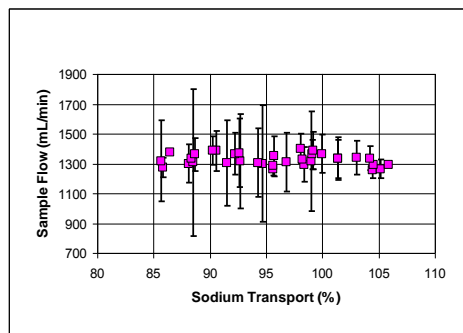

Fig. 9 - Sodium transport closure at sample flow rates between 1250 and 1400 mL/min.
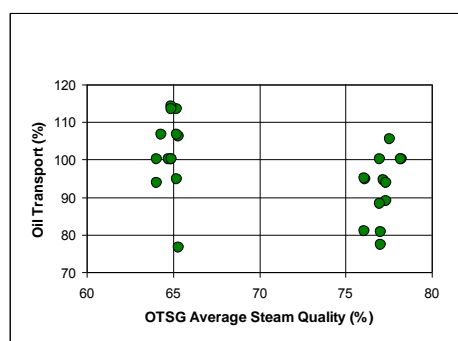

Fig. 10 - Oil transport as a function of OTSG steam quality.

Considering that an isokinetic sampling nozzle had never before been implemented in the low-quality, high TDS and oil environment (compared with the relatively pristine BFW used in the electrical utility sector) of a SAGD OTSG, this testing campaign was highly successful. Challenges were encountered in accurately controlling the sample flow rate and this needs to be overcome; however in spite of this, as operational experience on the sampling system was gained, accurate sodium transport closure data was obtained. During the course of our measurement campaign, BFW oil content was never out of spec and so reductions in steam quality showed no significant effect on oil transport. We believe that isokinetic sampling could be an excellent way to connect plant data and operating protocols with fundamental fouling studies in the laboratory.

LINKING WATER CHEMISTRY TO FOULING

SAGD produced water varies with reservoir location and recovery technique, but can typically be characterized as having low to moderate salinity, high alkalinity, high total organic carbon (TOC), high silica, and low hardness, as shown in Table 1. The amount of free and emulsified oil and grease present in the produced water depends on where in the treatment process the fluid is sampled. Downstream of the primary oil/water separation step (the fluid passing through the produced water cooler), free and emulsified oil and grease is typically less than 100 mg/L, with excursions to a few thousand mg/L. In the boiler feed water, however, oil and grease is typically less than 0.5 mg/L.

Table 1 - Typical SAGD PW composition.

Parameter	Units	
pH		7-8
Alkalinity (as $CaCO_3$)	mg/L	75-200
TDS	mg/L	1000-4000
TSS	mg/L	<30
Reactive Silica	mg/L	100-400
Calcium (as Ca)	mg/L	5-25
Magnesium (as Mg)	mg/L	1-5
Sulfate	mg/L	10-60
TOC	mg/L	200-500

The dissolved organics matter (DOM) present in SAGD produced water is heterogeneous and complex. It represents the water-soluble compounds originally present in the bitumen. The SARA classification scheme (Masliyah et al., 2011) is often used to generally describe the organics associated with the bitumen phase, and compounds from these classes can be found in the produced water. The SARA fractions typically found in Athabasca bitumen are shown in Table 2. Each fraction consists of hundreds of individual compounds. Of all the SARA classifications, asphaltenes are the most frequently discussed in SAGD applications, as they can precipitate under certain conditions when diluent is added to reduce the viscosity and density of the bitumen. The asphaltene classification is based solely on solubility in an n-alkane solvent, and therefore this class of compounds contains individual compounds with many different functionalities (acid, base, neutral), polarities, masses, and surface activities.

Table 2. Typical composition of SARA fractions in Athabasca bitumen.

Fraction	Concentration (wt%)	Molar Mass (g/mol)
Saturates	15-21	<500
Aromatics	18-19	<1000
Resins	44-48	1000-2000
Asphaltenes	14-20	400-1500+

Petersen and Grade (2011) and Kawaguchi et al. (2012) conducted detailed analyses of produced water samples and identified a wide variety of organic constituents, including significant amounts of polar compounds with carboxylic and phenolic functional groups. Because of the large number of individual compounds present in SAGD waters, and because the importance of each individual compound in the fouling process is unknown, alternate analysis schemes have been

developed to classify SAGD DOM according to their general chemical properties. A resin fractionation technique adopted from the study of aquatic natural organic matter was used to separate the DOM into hydrophobic and hydrophilic fractions of acid, base and neutral compounds (Thakurta et al. 2013). The percentages of different organic matter as a percentage of total organic carbon (TOC) present in the SAGD boiler blowdown are presented in Figure 11. Hydrophobic acids (HPoA), hydrophilic neutrals (HPiN), and hydrophobic neutrals (HPoN) represent the largest classes of compounds.
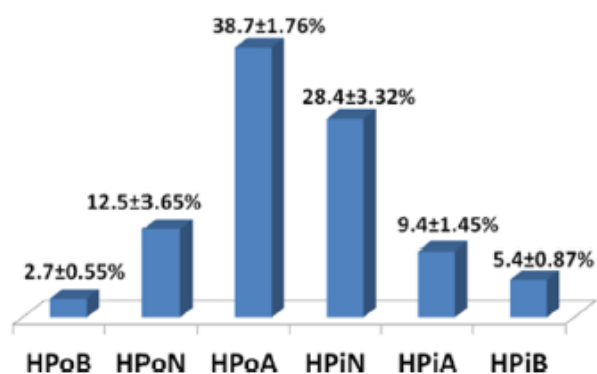

Fig 11 - Percentage distribution of different organic fractions in SAGD steam generator blowdown (Thakurta et al., 2013).

The roles of various water quality constituents and the physical and chemical mechanisms of fouling are not yet understood. It is expected that produced water cooler fouling is caused by interactions of suspended solids, inorganics (Si, Ca, Mg), dissolved organics, and high molecular weight bitumen constituents. Only limited data has been reported on the composition of foulant solids found in the field. As discussed earlier, analyses on foulants from PW coolers at Statoil's Leismer facility show predominantly organic matter, but no indication of significant concentrations of organics acids and organic acid salts. On the other hand, Jennings et al. (2007) examined the chemical characteristics of SAGD heat exchanger deposits, and determined that in the PW coolers the deposits were predominantly organic in nature, with significant concentrations of organic acids and organic acid salts. Further analysis of the organic acids isolated from these deposits, using a high-resolution mass spectroscopy technique, identified several thousands of individual organic acids with broad distributions of molecular weight, heteroatom content, aromaticity, and carbon number (Schaub et al., 2007).

Because OTSG BFW has been treated to remove suspended solids, Ca, Mg, Si and oil and grease, boiler tube fouling is thought to occur due to water quality excursions leading to higher than normal concentrations of Ca, Mg, and Si due to process upsets in the softening and ion exchange processes, or higher than normal concentrations of oil and grease due to process upsets of the de-oiling steps. The presence of high concentrations of dissolved organics,

which are not removed in the water treatment process, may also be involved.

In one detailed study, analysis of fouled OTSG tubes found that tube sections that experienced localized overheating had deposit layers that generally consisted of non-crystalline deposits with over 40% wt. carbon content (Desch, 2010). Other SAGD operators have found similar carbon content in OTSG tube deposits; particularly in the convective section of the boiler (Suncor unpublished data). These carbon-based deposits are suspected to be due to oil contamination in the boiler feed water and/or the precipitation of DOM or DOM-Si-metal compounds. Related work in the area of membrane filtration fouling has found that a Si-DOM precipitate can form and lead to fouling in SAGD ultrafiltration applications (Maiti et al., 2012). Similar mechanisms may be responsible for boiler tube fouling.

DISCUSSION

According to estimates of Müller-Steinhagen et al. (2011), heat exchanger fouling costs in the order of 0.25% of the (GDP) of industrialized countries and it is further responsible for 2.5% of the total equivalent anthropogenic emissions of carbon dioxide. The technical challenges and costs of fouling in the SAGD industry described above are clearly a microcosm of the challenges faced by other industry sectors. As a result, significant effort is being spent on both lab work and field trials aimed at better understanding the fundamental aspects of fouling.

Because organic compounds appear to be associated with fouling deposits in both cooler and boiler fouling, a major focus of the SAGD industry's R&D program is to identify the TOC fractions that may be responsible for this fouling. One of the most promising approaches is to use the resin fractionation technique described earlier to investigate the fouling propensity of the various groups of dissolved organics. Once the fractions and the physical and chemical conditions most responsible for fouling are identified, the resin fractionation technique can also be used to evaluate the effectiveness of water treatment processes for removal of the responsible fraction. This work is currently underway.

While various field-based studies are ongoing, these bring with them inherent challenges. As noted above, field chemical trials created unforeseen disruptions of downstream water processes. Also, experimental plans can be thrown into disarray when units to be tested have their operating conditions changed to meet production targets or must be unexpectedly shutdown. To overcome these and other challenges associated with field trials, an unprecedented industry collaborative effort known as the Water Technology Development Centre (WTDC) was recently announced by Canada's Oil Sands Innovation Alliance or COSIA (2013). This initiative will provide hot coupling of process streams to the Centre's facilities at Suncor's Firebag site. Under controlled conditions, various technologies will be evaluated and fundamental, continuous flow fouling studies will be undertaken. The WTDC will provide an innovative means of bridging fundamental lab

and pilot fouling R&D to implementation in a commercial facility.

CONCLUSIONS

Fouling of produced water (PW) coolers is presently one of the most significant operational challenges facing SAGD operators. Movement from the traditional shell and tube exchanger design to spiral coolers, while anticipated to mitigate the fouling challenges through design, has mostly exacerbated the situation. To extend run lengths between cleanings, chemicals are added upstream of the PW coolers; however these chemicals can upset the downstream water treatment and steam generation processes. An ideal outcome would be an effective PW cooler design that gives much longer run times without the need for excessive chemical treatment.

Much of the fundamental R&D in the industry related to fouling focuses on the relationship with water chemistry. It is currently felt that dissolved organics that enter the water phase from the bitumen product as it is brought to surface and processed, are the main cause of fouling. However, these dissolved organics are complex and made up of many individual constituents. A novel resin fractionation technique is being used to identify those constituents with a particular propensity to foul surfaces. Armed with this knowledge, more effective exchanger designs and/or optimized chemical treatments may be developed.

Fouling of tubes in Once-Through Steam Generators (OTSGs) is an ongoing concern. Fouling normally occurs at the end of the economizer section where steam is first being generated and fluid mechanics are complex. Examination of tubes during shutdowns suggests that deposition on the tubes occurs during upsets in BFW composition. Therefore, when there is upset, operational protocols dictate a reduction in steam quality to offset increased organics and/or TDS or silica in the BFW. In order to assess the usefulness of this approach, an isokinetic sampling nozzle was inserted into the main steam production header and steam samples collected and analyzed for total extractable hydrocarbons. The sampling system worked very well and could be a valuable means of measuring deposition in tubes during BFW upsets.

REFERENCES

COSIA, "Dedicated Water Technology Development Centre to Improve Water Treatment" http://www.cosia.ca/projects/water/dedicated-water-technology-development-centre-to-improve-water-treatment, accessed May 2013.

Desch, P.B. Characterization of Deposition and Metallurgical Degradation in OTSG Overheating Failures. International Water Conference IWC-10-51 (2010).

Jennings, D.W.; Shaikh, A. Heat-Exchanger Deposition in an Inverted Steam-Assisted Gravity Drainage Operation. Part 1. Inorganic and Organic Analyses of Deposit Samples. Energy & Fuels, 21, 176–184 (2007).

Gwak, K.-W. and W. Bae, "A Review of Steam Generation for In-Situ Oil Sands Projects", Geosystem Engineering 13(3), 111-118 (2010).

Kawaguchi, H., Zhengguo, L., Masuda, Y., Sato, K., and Nakagawa, H. (2012). Dissolved organic compounds in reused process water for steam-assisted gravity drainage oil sands extraction. Water Research, 46: 5566-5574.

Masliyah, J.H., Czarnecki, J., and Xu, Z. "Handbook on Theory and Practice of Bitumen Recovery from Athabasca Oilsands, volume 1: Theoretical Basis". Kingsley Knowledge Publishing. (2011).

Maiti, A., Sadrezadeh, M., Thakurta, S.G., Pernitsky, D.J., and Bhattacharjee, S. (2012). Characterization of Boiler Blowdown Water from Steam-Assisted Gravity Drainage and Silica−Organic Coprecipitation during Acidification and Ultrafiltration. Energy Fuels 26: 5604-5612.

Müller-Steinhagen, H., Malayeri, R. M., and Watkinson, A. P. (2011) Heat Exchanger Fouling: Mitigation and Cleaning Strategies. Heat Transfer Engineering 32: 189-196.

Petersen, M. A.; Grade, H. Analysis of Steam Assisted Gravity Drainage Produced Water Using Two-Dimensional Gas Chromatography with Time-of-Flight Mass Spectrometry. Industrial & Engineering Chemistry Research, 50, 12217–12224 (2011).

Schaub, T. M.; Jennings, D. W.; Kim, S.; Rodgers, R. P.; Marshall, A. G. Heat-Exchanger Deposits in an Inverted Steam-Assisted Gravity Drainage Operation. Part 2. Organic Acid Analysis by Electrospray Ionization Fourier Transform Ion Cyclotron Resonance Mass Spectrometry. Energy & Fuels, 21, 185–194 (2007).

Thakurta, S.G., Maiti, A., Pernitsky, D.J., and Bhattacharjee, S. (2013). Dissolved Organic Matter in Steam Assisted Gravity Drainage Boiler Blow-Down Water. Energy Fuels 27: 3883-3890.

ACKNOWLEDGEMENTS