Effect of Stress Build-up around Standalone Screens on the Screen Performance in SAGD Wells

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Abstract

Steam Assisted Gravity Drainage (SAGD) is the primary thermal recovery technology currently employed to extract heavy oil and high-viscosity bitumen from Alberta oil sands. In the near-wellbore region, the initial stresses are nearly zero, and as the SAGD chamber grows, the stresses tend to build up due to the thermal expansion of the formation. Also, melting of the bitumen and subsequent loss of the bonding between the grains leads to the collapse of the gap between the formation and sand control liner over time. The result will be effective stress buildup and gradual compaction of the oil sands around the liner.

Slotted liners have been extensively used as a sand control device in SAGD wells. Slotted liners must allow free flow through the slots with minimal plugging and acceptable amounts of sand production.

In our study, large-scale unconsolidated sand was packed over a multi-slot coupon of the slotted liner. The sand-pack was subjected to several stress conditions corresponding to the evolving stress conditions during the life cycle of a SAGD producer well. The testing program employed several multi-slot coupons to examine the flow performance under typical encountered stresses in SAGD wells. Cumulative produced sand was measured at the end of testing as an indicator of the sand control performance. The permeability evolution of the sand in the near-coupon zone was calculated by measurements of pressure differentials and considered as a measure of screen flow performance. Fines/clay concentration along the sand-pack was also quantified after the test to investigate the fines migration, a phenomenon which is considered to be the main reason for reduced wellbore productivity.

Experimental results show that the liner performance is significantly affected by the normal stress buildup on the liner. Experimental observations indicate sand-pack compaction due to the increase of effective stress around the liner leads to a lower porosity and permeability. The situation near the liner is further complicated by the fines accumulation that results in pore plugging and further permeability reduction. When it comes to sanding, however, higher stresses help stabilize the sand bridges behind the slots, leading to less sand production.

As for the design criteria, the lower and upper bounds of the slot size are governed by plugging and sand production, respectively. Considering the stress effect on plugging and sanding, testing data indicate that both the lower and upper bounds should be revised to larger slot aperture sizes.

Keywords: SAGD, Sand Retention Test, Slotted Liner, Sand Control

1. Introduction

1.1 The Basic SAGD Concept

In SAGD operations, a large volume of high-pressure steam is injected into the reservoir to mobilize the bitumen by reducing its viscosity. Considering the unconsolidated nature of the reservoir, the continuous injection of high-pressure, high-temperature steam into the formation results in a complex spatial alteration of the in-situ stress state and the geomechanical properties within the reservoir, which in turn impacts the reservoir permeability and porosity.

In SAGD, a horizontal well is drilled to introduce steam into the reservoir. Since gravity alone does not provide an adequate drive to move heated bitumen to a vertical well at an economic rate, another horizontal production well is drilled parallel to the injector well, as shown in Figure 1. By introducing the steam into the reservoir, a steam saturated zone, called steam chamber, is developed with the chamber temperature being close to that of the injected steam. When steam flows to the perimeter of the steam chamber and encounters the intact reservoir, it will transfer its heat to the oil sands by thermal conduction and mobilizes the oil by reducing its viscosity (Al-bahlani and Babadagli, 2008). Gravity causes the steam condensate and mobilized oil to flow to the production well located below the injector well (Butler et al., 1981). As the oil is produced, steam chamber expands both upwards and sideways creating two types of flow, one along the slopes and one at the ceiling of the steam chamber (Figure 1).

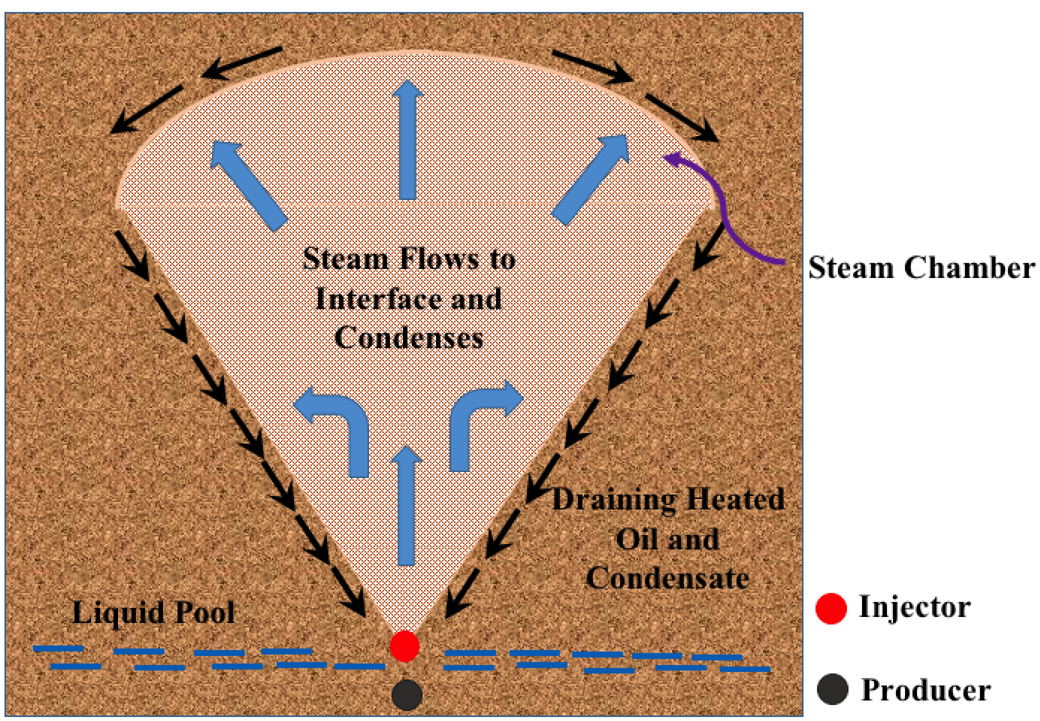


Figure 1: Schematic Concept of Steam Chamber in SAGD Operation

1.2 Slotted Liner Completions

Sand control completions support SAGD wells against collapse and typically employ installation of screens or liners. These completions should be designed in such a way to allow the flow of reservoir fluids and fine materials into the wellbore and prevent the pore space plugging behind the liner. They may also include flow control devices through which the flow of steam into the reservoir and the flow of oil into the production well can be controlled. Plugging of the sand control completions is a phenomenon that happens over time due to the gradual corrosion of the liner, buildup of scale and clay in the pore space around the liner, and buildup of scale and clay inside the liner slots, contributing to the so-called “skin” and lower wellbore productivity (Tiffin et al., 1998; Bennion et al., 2009).

Three major types of sand control completions in SAGD applications in order of popularity, are: slotted liners (SL), wire wrapped screen (WWS) and punched screen (PS) (Xie, 2015). Slotted liners are the most popular well completion technique in SAGD wells due to their desirable sand control performance in unconsolidated and high-permeable oil sands as well as their bearing tolerance of installation and thermal loads (Bennion et al., 2009). The application of slotted liners dates back to the early 1900’s in water wells (Kobbe, 1917; Alcorn and Teague, 1937; Dean, 1938; Chenault, 1938). Slotted liners’ low cost and low plugging tendency are the main reasons for their popularity in SAGD wells (Petrowiki, 2013). However, it should be noted that slotted liners are not as effective in formations with higher amounts of fines and reactive clays such as Smectite and Illite (Romanova et al., 2014). Based on the shapes of the slots, Bennion et al. (2009) summarized the three main configurations of slotted liners, as shown in Figure 2.

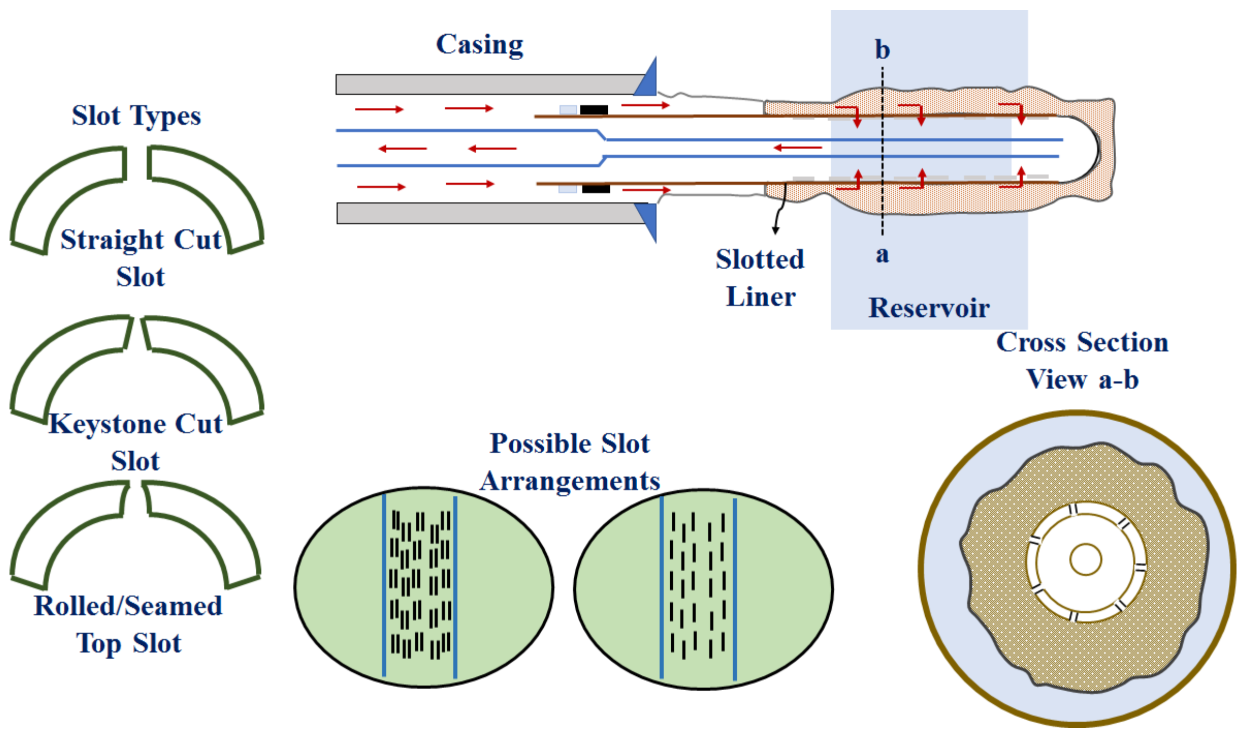


Figure 2: Configurations of Slotted Liners

The straight-cut slot is made by a single blade plunge into the liner. This type is the most conventional slotted liner. In the keystone slot, the aperture size at the top of the slot is smaller than that at the bottom. The advantages of this configuration are (1) the narrow inlet can keep finer sands from flowing into the wellbore; (2) the wider outlet makes the passage of the produced sand grains/fines easier and lowers the plugging potential inside the slot. The ratio of the aperture size at the top over that at the bottom is called "aspect ratio", which is an important parameter that can control the performance of the keystone-cut slotted liner. The seamed slot is a modified type of the keystone-cut slot. This slot type is made by applying concentric or longitudinal surface stresses on the surface of the slot. The applied stress plastically deforms and narrows the slot inlet by as much as 0.2 mm (0.08'') resulting in a higher aspect ratio compared to before the seaming operation.

1.3 Laboratory Design of Slotted Liners

The majority of studies in liner performance evaluation and optimization are experimental. In this regard, two types of sand retention facilities are widely used in the industry: the slurry Sand Retention Test (SRT) (Markestad et al., 1996; Ballard et al., 1999; Chanpura et al., 2011) and the pre-pack SRT (Markestad et al., 1996; Ballard et al., 2006, 2012; Bennion et al., 2009).

The slurry sand retention test is designed to mimic the initial period of circulation/production stage in real-field cases. At that time, it is believed that there is still a gap between the initial formation face and the sand control liner. The gap is filled with a slurry consisting of condensed steam and a small amount of silt/sand particles. In a typical slurry SRT test, the slurry with a low silt and sand concentration (less than 1% by volume) is injected toward the screen coupon at a certain flow rate to build up a sand-pack behind the coupon. The sand-pack results in a pressure drop which is considered a measure of the plugging (Markestad et al., 1996; Gillespie et al., 2000; Williams et al., 2006). Also, the amount of solids that pass through the sand-pack and screen is weighed as a measure of the solid retention performance of the screen.

The pre-pack sand retention test is used to simulate the period after the initial stage when unconsolidated formation collapses around the liner and falls into the gap between the formation and sand control liner. At this state, the gap is filled with loose sand instead of sand slurry and a high-porosity zone is created. In other words, the liner contacts a high-permeability porous medium. The pre-pack SRT starts by packing a certain amount of sand (made of formation oil sand, outcrop sand, or synthetic sand-pack using commercial sands) over sand control screen and applying some axial stress to avoid channeling in the sand-pack. In the next step, the fluid with certain flow rate is injected through the sand-pack, toward the coupon. The measurements often include pressure drop across the screen and the sand-pack, the total produced sand and the produced fines (Ballard et al., 2006; Williams et al., 2006; Bennion et al., 2009; Romanova et al., 2014, 2015; Fattahpour et al., 2016).

In SAGD wells, the gap between the liner and the formation is believed to collapse at the initial stages of circulation or production due to the unconsolidated nature of the oil sand. This makes the stage which corresponds to slurry SRT very short. The pre-pack SRT seems to be more representative for simulating the actual field conditions in SAGD. Currently, slotted liner design practices are based on specifying a slot aperture window in relation to the formation particle size distribution (PSD). The proposed slot window includes a lower and an upper bound for the width based on PSD characteristics. For instance, Fermaniuk (2013) proposed the minimum slot width of two times the sieve size which retains the coarser 70% of the sand ($2D_{70}$) and the maximum slot width of $3.5D_{50}$. In the existing design recommendations, it is assumed that any slot width smaller than the specified minimum aperture leads to severe plugging. On the other hand, any slot width larger than the specified maximum is expected to result in severe sanding (Markestad et al., 1996). The issue that seems to need a thorough investigation is the stress build-up around the liner. During the circulation in SAGD, the gap between initial formation face and the slotted liner collapses due to the thermal expansion of the reservoir sands and the lost bitumen bonding between sand grains. These phenomena result in a gradual build-up of stresses and, consequently, compaction of oil sands near the liner. Compared with the initial stage, when the annular gap is open (slurry SRT), or shortly after the collapse, when the stresses are low (pre-pack SRT), the period of stress build-up is much longer and represents the majority of the life cycle of the well. Hence, the liner design should take the time-dependent effective stresses into consideration so that the designed liner can be in service for the whole life of the well.

Based on the abovementioned limitations, this study introduces a novel pre-pack SRT facility which unlike the current testing facilities, allows the use of multi-slot coupons. The use of multi-slot coupons allows fully capturing of the interaction between the slots. The setup can be used to conduct large-scale unconsolidated sand retention tests by applying different levels of axial and radial effective stresses, corresponding to the evolving stress conditions during the life cycle of a SAGD producer.

2. Experimental Facilities

To design an improved SRT apparatus, several different published designs of experimental set-ups for unconsolidated sand-pack samples were investigated. The experimental apparatus in this study was designed to accommodate a sand-pack sample placed on the top of a liner/screen coupon. The apparatus was named Scaled Completion Test (SCT) since (1) it is versatile in accommodating the coupon of any sand control completion, (2) it models the zone in the vicinity of the completion with a scaled geometry.

A conventional SRT facility was also used for sand control testing at near-zero stress condition. Both the SRT and SCT facilities can employ multi-slot coupons with different slot density and slot width, to provide more representative flow regimes and allow interaction between the slots. The SCT apparatus allows applying different levels of axial and lateral stresses to the sand-pack.

This section presents a detailed description of the experimental set-ups and procedures employed in the current research as well as preparation, packing, and saturation of the specimens.

2.1 SCT Set-up

Figure 3 is a schematic view of the SCT facility which includes: (1) fluid injection unit, (2) SCT cell and accessories, (3) confining stress unit, (4) data acquisition and monitoring unit, (5) produced sand and fines measurement unit, and (6) the backpressure/saturation unit.

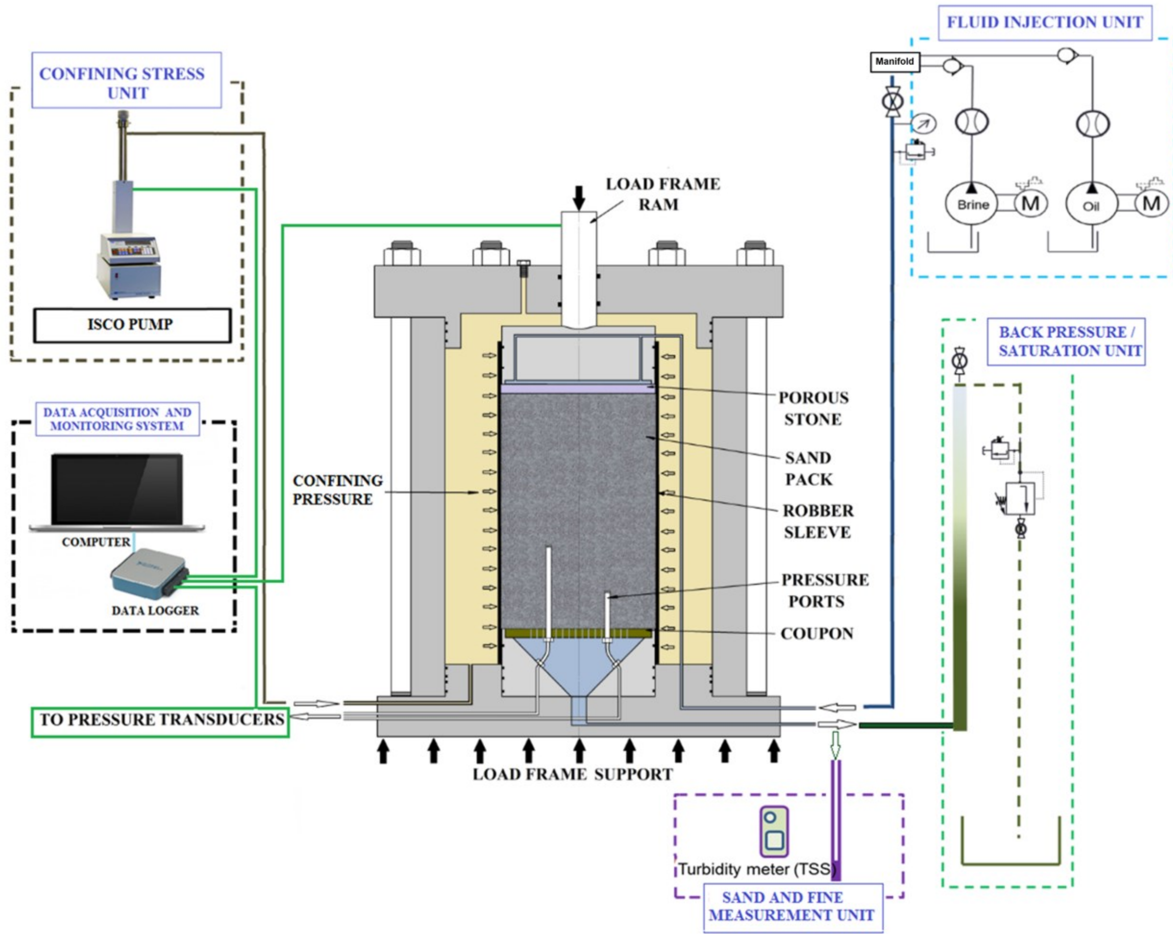


Figure 3: Schematic View of Different Units of the SCT Facility (after Fattahpour et al., 2016)

The fluid injection unit includes two diaphragm metering pumps for oil and brine injection. Each pump has a maximum flow rate of 22.7 L/hr at 2080 psi pressure. The pumps control the flow rate with a high ratio of 1:33 through manual stroke control and digital pulse control. A rotameter is installed at the outlet of the SCT cell to measure the flow rate every ten to fifteen minutes for verification purpose.

The SCT cell is a modified large-scale triaxial cell, which is capable of applying axial and lateral stresses onto the sand-pack. The sand-pack (7″ diameter and 8″ height) is enclosed by a membrane in the center of the SCT cell. There is an annular space around the sand-pack through which oil can be injected to apply confining stress. The confining stress unit consists of two syringe pumps with the capacity of 5000 psi.

The specially designed top platen and porous stone are installed on top of the sand-pack to provide a uniform fluid flow regime along the sand-pack. Beneath the sand-pack there is an interchangeable coupon disk underlain by a specially manufactured cone. The multi-slot coupons are installed with two pressure ports which allow the measurement of pressure differential along the sand-pack in the top 4 inches of the sand-pack, the 2 inches right above the multi-slot coupon and the remaining part of the sand-pack, in between these two regions.

The data acquisition and monitoring unit includes three 15-psi differential pressure transducers. They are connected to different locations along the specimen to measure the pressure drops alongside the sand-pack. The data acquisition device (National Instruments, Model USB-6210) was used to collect and record signals from pressure transducers through LabVIEW Signal Express software.

The sand and fines measurement unit consists of a specially designed sand trap to capture the produced sand and fines. Back pressure is applied to the sand trap by the backpressure unit. This unit which includes a column and an adjustable back pressure regulator valve allows the application of up to 200 psi backpressure. The same column is used for saturating the sand-pack prior the test.

The rate of produced sand is monitored by a camera which records the height of produced sand column in a graduated cylinder at the outlet. A 1/8'' tube is also installed exactly beneath one of the slots to collect a representative sample of the produced fines.

2.2 Pre-Pack SRT Facility

In addition to the SCT facility, the pre-pack SRT facility (Figure 4) was also employed to complete the test matrix. Since the only difference between pre-pack SRT and SCT is the absence of stresses, it can be assumed that SRT simulates near-zero effective stress situation. Further details about the pre-pack SRT facility and the testing procedure can be found in Mahmoudi et al. (2016).

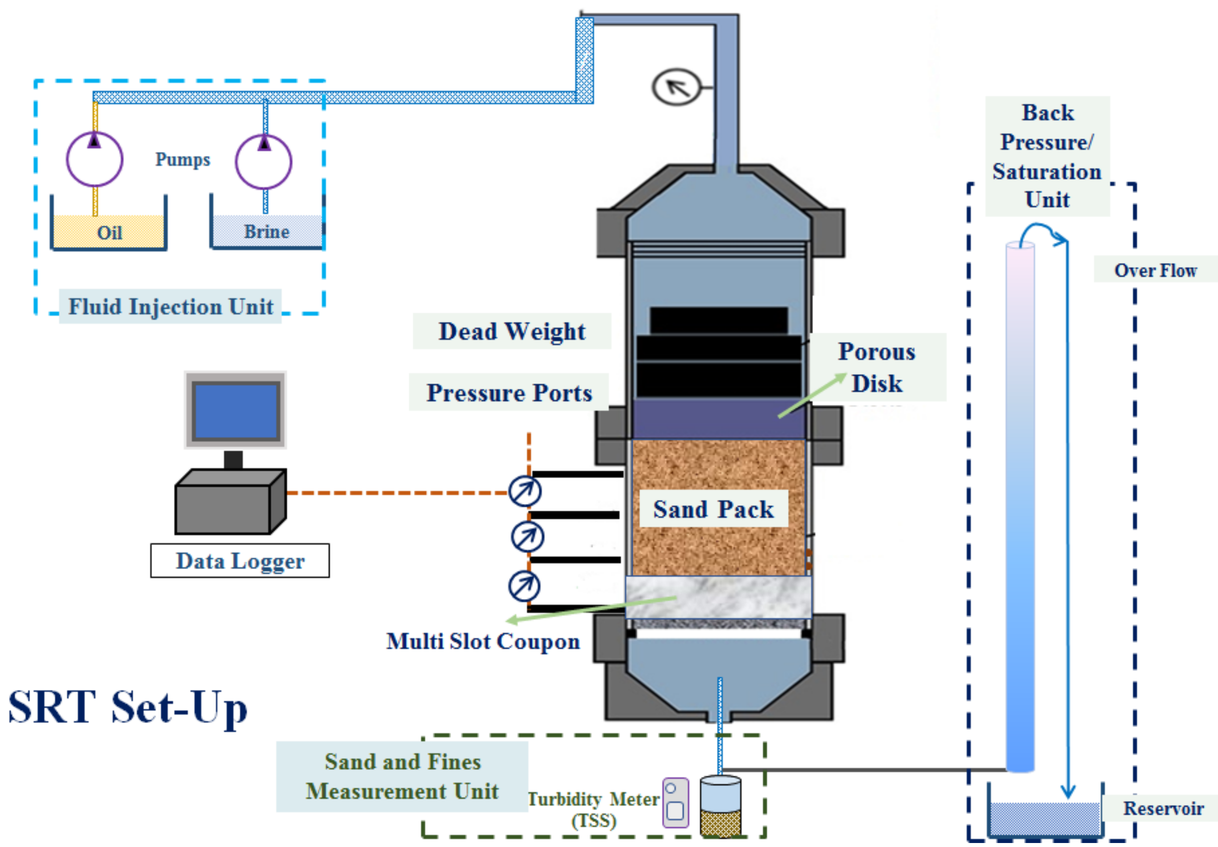


Figure 4: Schematic View of Different Units of the SRT Facility (after Fattahpour et al., 2016)

3. Testing Material

Test materials consist of the sand-pack materials including the sands, silts, and clays as well as the slotted liner coupons and brine as the flowing fluid.

3.1 Sand, Silt, and Clay

Sand-pack was prepared using commercial sands, silts, and clays with certain proportions to duplicate PSD of Class II Devon Pike 1, as proposed by Abram and Cain (2014). According to Mahmoudi et al. (2015), natural oil sands and commercial sands yield equivalent mechanical properties if they have similar PSD, mineralogy, and shape factors (sphericity, angularity, and aspect ratio). Figure 5 shows the comparison between the PSD of Class II and the PSD of duplicated mixture used in the testing.

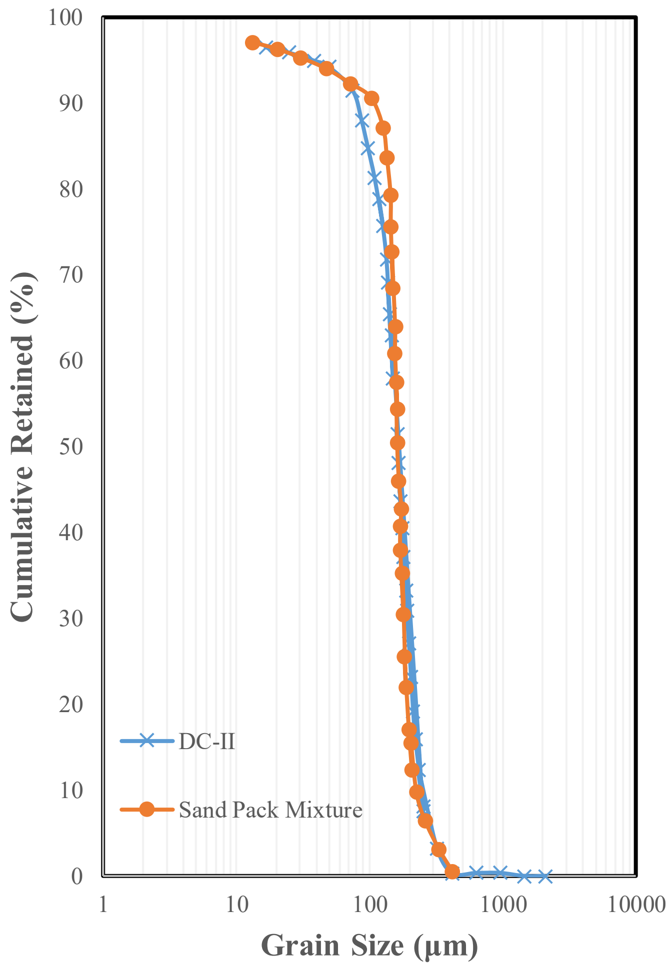


Figure 5: PSD of the Tested Sand-Pack Mixture and Class II Devon Pike 1 Project Categorized by Abram and Cain (2014)

3.2 Slotted Liner Coupons

The test coupons used in the testing are like disk-shaped samples cut out from the actual slotted liner pipe (Figure 6). The coupons were multi-slotted, rather than single-slot coupons used in past testing. The use of multi-slot coupons allows to capture inter-slot interactions and, consequently, incorporate the effect of slot density on the testing results. The coupons were manufactured with a seamed slot opening and provided by the slotted liner manufacturer, RGL.

Slot density in the multi-slot coupons is represented by the number of Slot per Column (SPC) in the corresponding slotted liner with 7-inch diameter. It should be noted that there typically are four columns of slots per foot of slotted liners. Therefore, SPC 54, for example, is equivalent to 216 Slots per Foot (SPF). In this study, coupons with slot width of 0.014″ to 0.022″ (SPC: 54), 0.018″ to 0.026″ (SPC: 42), 0.026″ to 0.034″ (SPC: 30) and 0.014″ to 0.022″ (SPC:30) were tested. Figure 7 shows the slot patterns for the three employed slot densities.

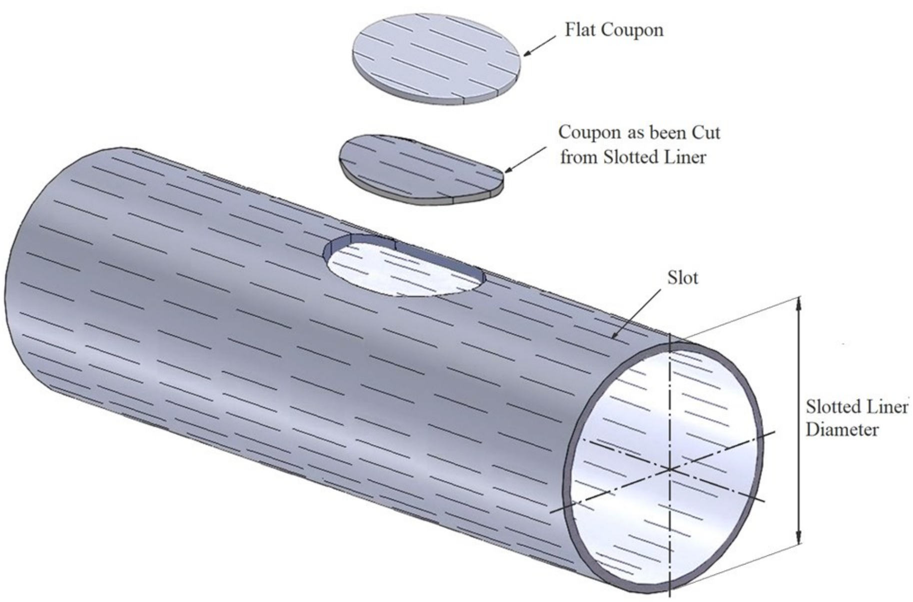
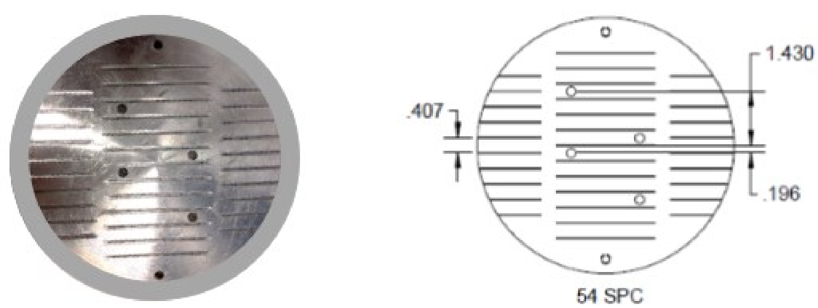
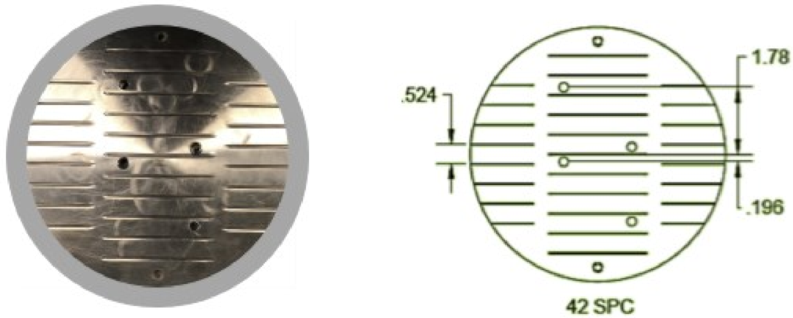


Figure 6: Schematic View of Multi-Slot Coupon as a Section of a 7-Inch Slotted Liner



(a)



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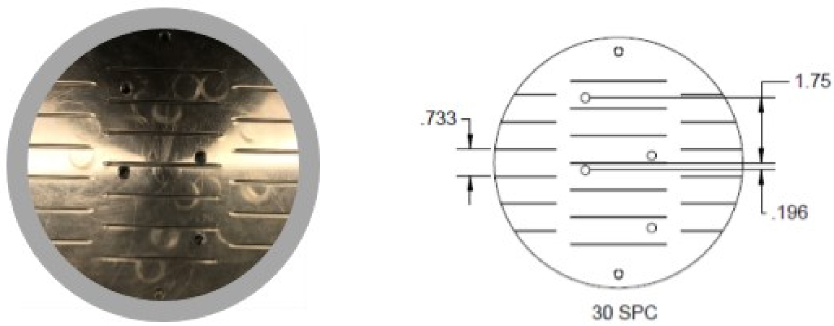


(c)

Figure 7: Image and schematics of Seamed Coupons: (a) SPC: 54, (b) SPC: 42, (c) SPC: 30

3.3 Flowing Fluid

Brine was used as the saturation and flowing fluid in the tests. The brine was designed to match the pH and salinity characteristics of typical brines in SAGD environments. Fluid pH and salinity in SAGD environment are highly variable due to steam injection as well as invasion of underground water and the formation acidic gases. Many researchers have attempted to investigate the effect of salinity and pH on fines migration (Tang and Morrow, 1999; McGuire et al., 2005; Sheng, 2014). The clay in the formation sand is generally susceptible to electrochemical forces and, hence, is highly sensitive to the pH of the flowing fluid (Bennion et al., 2009).

The dominant ions that are present in SAGD effluent are sodium and chloride (Mahmoudi et al., 2015. Hence, sodium chloride brine, with a salinity of 0.7% (7000 ppm) was used in the testing. Using NaCl results in a strong tendency for fines migration, hence plugging (Khilar and Fogler et al., 1984). Therefore, NaCl is a good substitute to simulate the worst-case scenario in SAGD as far as the salinity is concerned (Khilar and Fogler et al., 1984). The pH was kept at 7.9 since high-pH environment represents the worst-case scenario in a SAGD operation (Mahmoudi et al., 2015). Such an environment tends to disperse and mobilize fines and, consequently, increase plugging (Khilar and Fogler et al., 1984). The sodium chloride brine was prepared by dissolving NaCl into deionized water, and the pH of brine was adjusted using a pH booster (sodium bisulfate $NaHSO_4$) right before testing. All tests were conducted at a constant fluid salinity and pH value.

4. Testing Procedure

A testing procedure was designed and strictly followed for all tests. Figure 8 shows the SCT testing procedure for a test with the effective stress of 700 psi. The sand-pack was de-aired under 25 psi confining stress during a 1-hour saturation phase. The applied confining stress was increased to a target value by the load frame and syringe pump. When the target was reached, fluid was injected into the cell for long enough for the conditions to reach the steady state.

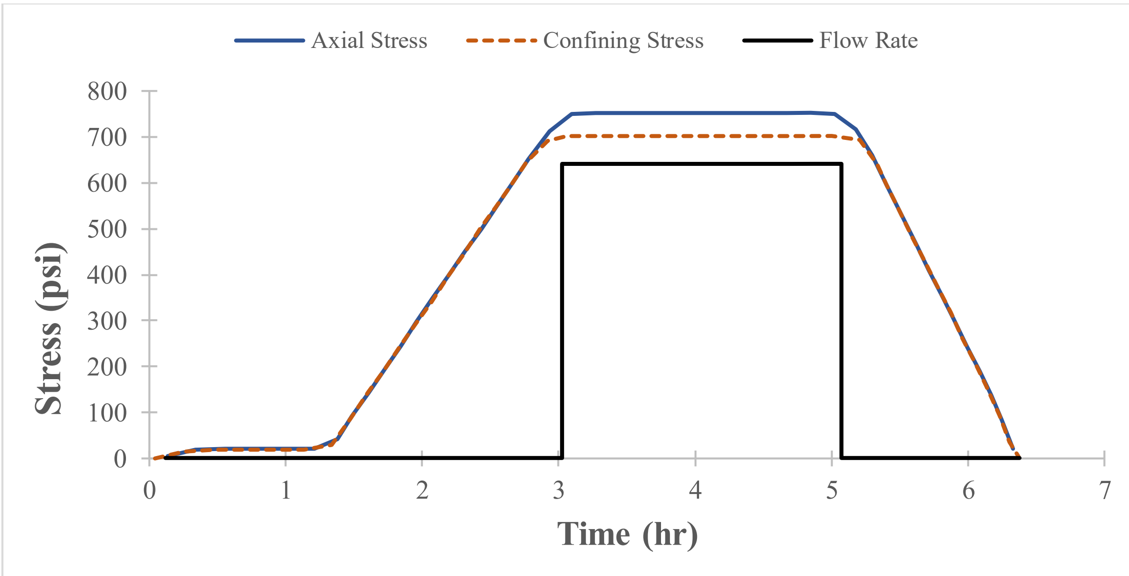
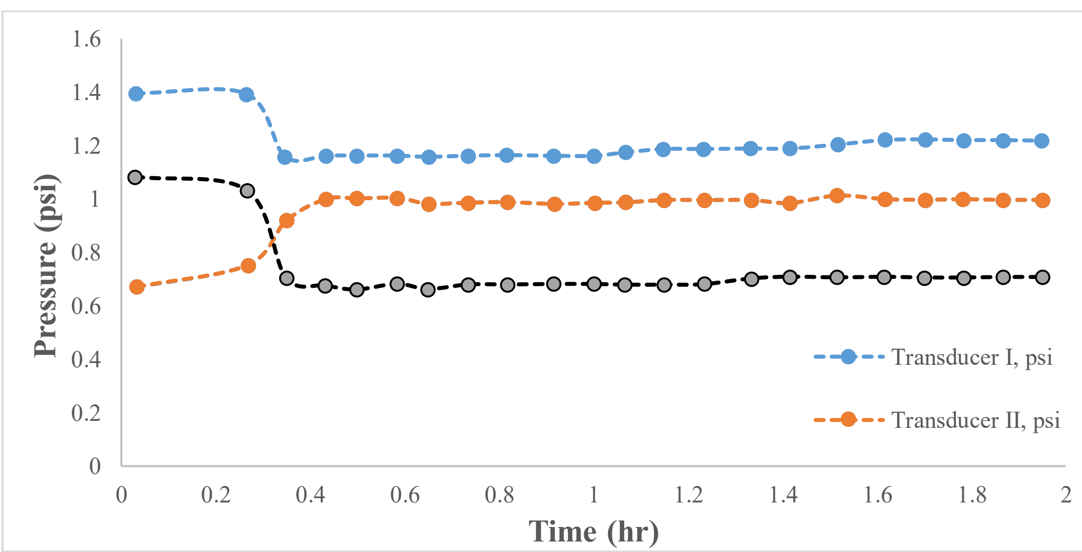
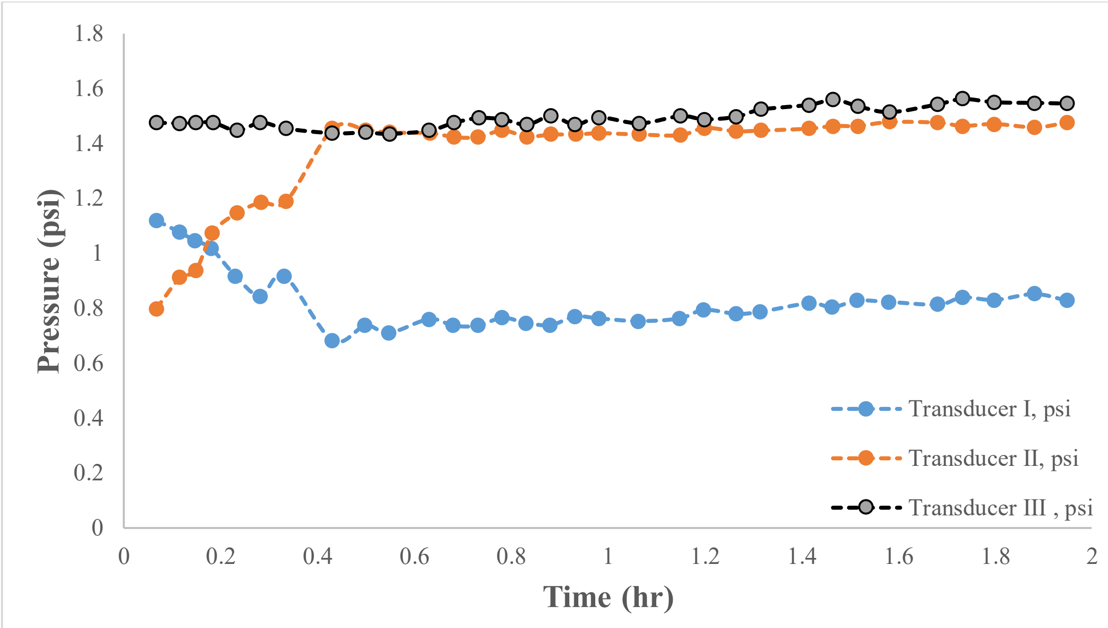


Figure 8: Example of Effective Stress (700 psi) and Flow Rate Application During SCT Test

The fluid injection period should be long enough to ensure the pressure readings of transducers are stabilized and the fines migration phenomenon is fully captured. In Figure 9, transducer I to III represent the three pressure differentials along the sand-pack. According to Figure 8, one-hour injection was enough for the pressure data to get steady for the sand sample used in this research. A flow duration of two hours was used to ensure steady-state conditions were reached in all tests.



(a)



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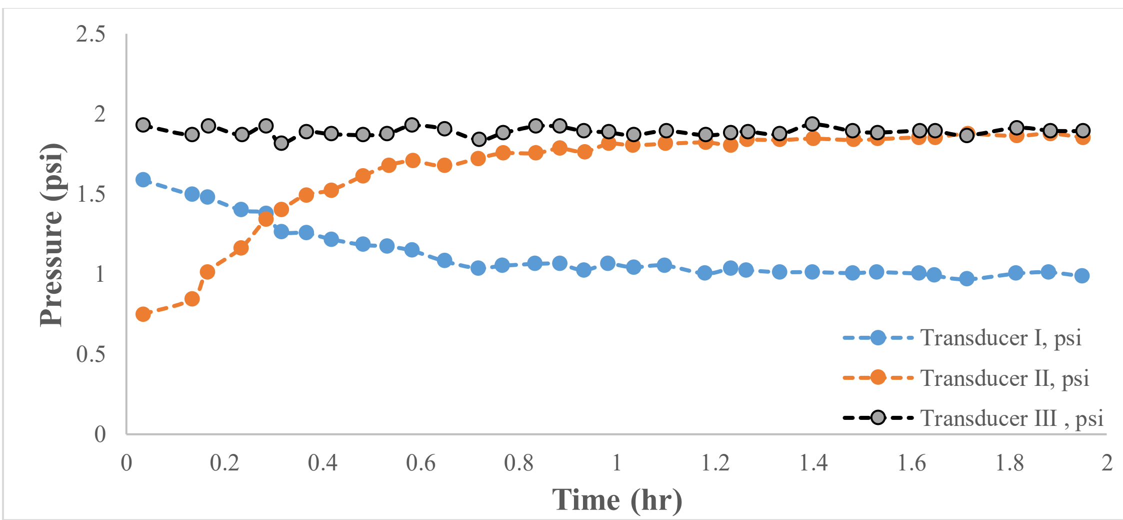


(c)

Figure 9: Pressure Differentials During Injection, Stress Levels of (a) 300 psi; (b) 500 psi; (c) 700 psi

4.1 Sand-pack Preparation

The sand-pack preparation starts with mixing dry commercial sands and fines based on the procedure presented by Mahmoudi et al. (2015) to replicate the PSD of the formation sand. The clay part of the sample comprises 80% Kaolinite and 20% Illite. These two clay types are the dominant clays in the McMurray oil sand formation (Bennion et al., 2009). The sand-pack sample for each test was approximately 8 inches in height with a diameter of 7 inches and constant porosity of 30.5%. Unlike other published apparatus (Markestad et al., 1996; Ballard et al., 2006, 2012; Bennion et al., 2009), in which the small sand sample is not large enough to allow the investigation of fines transportation or aggregation in the sample, this amount of sand volume offers a more realistic slot performance under a larger scale sample geometry.

Different types of dry sands and fines were weighted and mixed in a large box for at least 20 min to ensure homogeneous samples were obtained. Brine was added into the mixed dry sand to reach a certain water content. Dry sands and fines were carefully mixed with brine to ensure the uniformity of the sample. The sand was packed in layers using the moist tamping method to gain a uniform porosity and permeability (Ladd, 1978).

4.2 Sand-pack Saturation

The initial water saturation of the samples was estimated to be around 75%. To fully saturate the sample, after de-airing the cell, 25-psi confining stress was applied to the sand-pack. Meanwhile, the sand-pack was saturated slowly by establishing 60 cc/min of upward brine flow rate. The pressure used for sand-pack saturation was the hydrostatic pressure of brine in the backpressure column (approximately 1.9 psi). This small backpressure was intentionally chosen to prevent the injected brine from channeling through the sand. Since the samples had a high permeability value, it was assumed that full saturation could be obtained without vacuuming the sample. In the next step, the pressure transducers and related tubes were connected.

4.3 Effective Stress Application

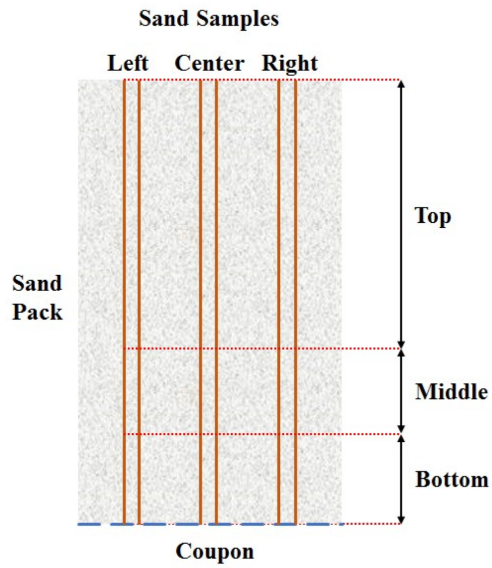
Confining stress was increased gradually to reach the required stress level. The injection rate of the syringe pump was carefully monitored to avoid any leakage inside of the SCT cell. At the same time, the axial stress controlled by the load frame was increased to reach the target stress. Fluid injection started after the target confining, and axial stress levels were reached.

4.4 Brine Injection

Brine was injected downward through the sand-pack and toward the multi-slot coupon. The duration of flow injection was two hours. A flow rate of 40 cc/min (0.36 bbl/day), which is in line with a typical SAGD production flow-rate, was applied. During flow injection, the pressure differences across the sand-pack were recorded by three pressure transducers so that permeability change and consequently, the fines transportation that was occurring inside the porous media could be monitored. The produced fluid was sampled during brine injection to measure its fines concentration. The total accumulated sand was collected at the end of the injection phase and was considered as the cumulative produced sand.

4.5 Post-Mortem Analysis

After disassembling the cell, several samples were collected to investigate the fines concentration across the sand-pack. The total produced sand was collected and weighed at the end of each test and reported in terms of pounds per square foot of the screen to indicate the sand control performance of the liner. The fines concentration was considered as a direct indicator of fines migration. The after-test samples were taken from different parts of the sand-pack by a 0.5-inch PVC tubing (Figure 10). The samples were dried at room temperature and then crushed. Then, the crushed powders were wet-sieved, and the particles larger than 44 micrometers were separated and weighed. The fines portion was collected, and its PSD was determined by a laser particle analyzer to investigate the severity of the fines migration and the size range of the migrated fines.



(a) (b)

Figure 10: Sample Obtaining

4.6 Test Matrix

Slotted liner coupons with three different specifications were tested under different effective stresses. Design criteria used by the slotted liner manufacturer, RGL Reservoir Management Inc., were used to design the coupons used in the testing for the PSD of Devon Pike 1 (DC-II) in the McMurray Formation. The slot width window for this PSD ranges from 0.010″ ($2.00D_{70}$) to 0.023″ ($3.50D_{50}$), with a seamed profile. For each coupon, the testing program was conducted at different lateral effective stresses of 300, 500 and 700 psi. SRT experiments with the same testing materials and procedure were also performed at minimal effective stress conditions. One test was also conducted at 100 psi lateral effective stress for coupon 0.026″ to 0.034″, SPC 30 to track the variations of sand production and plugging tendency between 0 psi to 300 psi. The axial effective stress, which was parallel to the sand-pack cylindrical axis, was always kept 50 psi higher than the lateral effective stress. These effective stress levels were chosen based on the range of stress conditions for a typical SAGD reservoir. Table 1 summarizes the testing matrix which consists of three coupons and different stress levels.

Table 1: Testing Matrix to Study the Effect of Stress Build-Up on Liner Performance

Slot Width (1/1000 inch)	SPC	Effective Stresses (psi)
0.014″ - 0.022″	54	0, 300, 500, 700
0.018″ - 0.026″	42	0, 300, 500,700
0.026″ - 0.034″	30	0, 100, 300, 500, 700

4.7 Test Measurement and Uncertainty Analysis

The test measurements include cumulative sand production, retained permeability, fines concentration at the near-coupon zone, PSD of fines along the sand-pack and the median size of produced fines. An uncertainty analysis is also performed for each measurement. The produced sand is obtained by a balance in grams and is converted to lb/sq ft by multiplying by a constant (c) based on area of the coupon. The corresponding uncertainty can be calculated by Eq. (1). ΔW is the absolute uncertainty of cumulative produced sand and Δw is the uncertainty of measurements read from the lab balance (± 0.001g).

$$\Delta W = c * \Delta w \tag{1}$$

The retained permeability is a function of flow rate and corresponding pressure drop. Hence, the uncertainty of retained permeability is caused by a combination of these two uncertainties, which can be calculated by using Eq. (2). $\Delta k_{retained}$ is the absolute uncertainty of retained permeability. P and q are pressure drop and the flow rate, ΔP and Δq are the absolute uncertainties of pressure drop and flow rate, respectively.

$$\Delta k_{retained} = \sqrt{\left(\frac{\partial k_{retained}}{\partial P}\right)^2 (\Delta P)^2 + \left(\frac{\partial k_{retained}}{\partial q}\right)^2 (\Delta q)^2} \tag{2}$$

The uncertainties of the fines concentration along the sand-pack can be obtained by Eq. (3) in which Δc is the absolute uncertainty of fines concentration. m_{fine} is the mass of fines and m_{total} is the mass of both sand and fines. Δm_{fine} and Δm_{total} are the uncertainties of the mass of fines and total mass.

$$\Delta c = \left|\frac{m_{fine}}{m_{total}}\right| \sqrt{\left(\frac{\Delta m_{fine}}{m_{fine}}\right)^2 + \left(\frac{\Delta m_{total}}{m_{total}}\right)^2} \tag{3}$$

The PSD of the fines and the median size of the produced fines are obtained based on the uncertainties of the devices. The confidence intervals are also plotted for each measurement in all related figures in the next sections.

4.8 Test Assumptions and Limitations

The simplifying assumptions of the SCT test include:

(1) A typical SAGD well produces two-phase oil and water at a steam-oil-ratio of 1.5-4 bbl water/bbl oil. There is also a potential for steam breakthrough, hence an additional gas phase in the produced fluids. However, the research presented in this thesis simulates liquid production only by employing a single-phase brine flow. The fines and clays tend to disperse and mobilize in the wetting phase, brine in this case, which increases the plugging potential compared to a two-phase oil-brine flow condition. The multi-phase SCT tests are part of the future work of this research.

(2) In the experiments, Sodium Chloride was used to prepare the brine and adjust the salinity since Sodium and Chloride ions are observed to be the dominant ions in produced water in SAGD operations. Further, the fines and clays are more prone to migrating in brine containing monovalent cations. Other ions were not used for brine preparation.

(3) The production well in SAGD operation has a temperature ranging from 220°C-260°C during the steam chamber growth. Since the effect of temperature on the viscosity of brine is small, the single-phase SCT tests were conducted at room temperature.

(4) The sand specimens for all the SCT tests were synthesized sand-packs made of commercial sand. The duplicated sand specimens have the same characteristics in terms of PSD, shape factors and mechanical properties as the formation sand. Since over 10 kg of sand is needed for each test, it was impractical to use real formation sand. Also, it is difficult to separate bitumen from the sand without changing the characteristics of the sand particles (e.g. wettability, absorbency).

(5) The tested multi-slot coupons are made of stainless steel, extracted from 7-inch slotted liners. However, the slotted liners used in real SAGD operation are made of carbon steel, which are prone to erosion and corrosion.

(6) As the high-temperature and high-pressure steam is injected into the formation, the steam chambers grow over time and the stress distribution around the liner also change. However, the stress conditions in all the SCT tests were nearly isotropic. Anisotropic conditions should be investigated in a future study.

5 Results and Discussions

The test results are analyzed to investigate the effect of stress build up around the liner on liner performance in terms of sanding resistance and flow efficiency.

5.1 Cumulative Produced Sand

The testing results indicate that the sand resistance performance of the liner is significantly affected by the effective stresses around the liner. Figure 11 shows the cumulative produced sand at the end of testing versus effective stress. The existing acceptable limits of the produced sand at 0.12 to 0.15 lb/sq ft are also annotated in the graph. The figure indicates a reducing sanding trend for higher effective stresses. The physical reason is the mobilization of friction angle at higher normal effective stresses (Jafarpour et al., 2012), which results in more stable sand bridges above each slot and less produced sand.

Figure 11 shows that the sanding for the slot width of 0.026″ (larger than the upper bound provided by slot window) is higher than the upper limit for sanding (0.12 lb/sq ft) under zero-effective stress condition. This result agrees well with the existing design criteria form RGL. All tests show acceptable sanding under higher effective stress conditions. Based on the results, one can expect that the maximum sanding occurs early in the life of SAGD well when effective stresses around the liner are low.

It should be noted that the test matrix consisted of several slot sizes and slot densities while keeping the open-to-flow area (OFA) constant (about 3%). The OFA is defined as the ratio of the total slot area over the total coupon surface area. Two coupons with different slot widths and densities but same OFA result in the same flow velocity and pressure gradient at the slots. The idea was to remove the effect of flow velocity on screen’s flow performance and pressure drops across the sand pack. Therefore, the slot density was not necessarily the same for all the tested coupons. According to Figure 11, since the produced sand is affected by both slot size and density, a clear trend for the amount of this parameter cannot be observed. This is consistent with the previous investigation performed by Mahmoudi (2017).

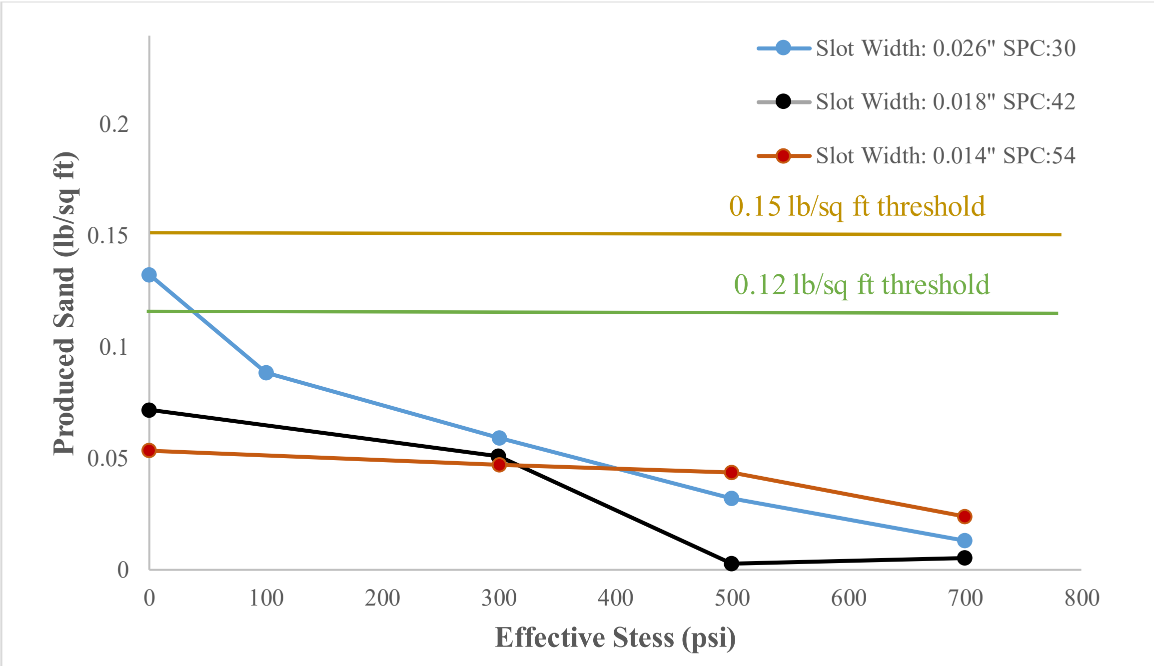


Figure 11: Cumulative Produced Sand vs. Effective Stress; Solid Lines are the Upper Limits of Acceptable Produced Sand of 0.12 lb/sq ft and 0.15 lb/sq ft

5.2 Fines Migration

Fine particles are defined as particles smaller than 44 (API Bulletin 13C). According to Bennion et al. (2009), fines mobilization and migration are part of SAGD reservoir flow due to the significant amount of wetting phase (water) flow. The fines would accumulate around the liner and result in severe plugging in the porous medium. The migrated clays would also generate a microfilm at the surface of the slots and gradually infill around the sand grains to partially or fully plug the slots (Romanova et al., 2015). The combination of these two types of plugging causes a reduction in retained permeability. In this study, no severe plugging was observed inside the slots for any of the tests. Pressure measurements also indicated negligible pressure drops across the coupon. Hence, the investigation mainly focuses on the plugging in the sand-pack. To capture the fines migration, the fines content along the sand-pack was measured after the test completion.

Figure 12 shows the changes in fines concentration along the sand-pack for different effective stress conditions. It is evident that the fines concentration for the top segment (top 4″ of the sand-pack) is lower than the initial level as this zone is losing the fines. On the contrary, the fines are accumulating in the vicinity of the coupon (bottom 2″ of the sand-pack). Hence, fines concentration is higher than the initial values. Figure 12 also shows a stronger fines migration for higher effective stresses as evidenced by a larger loss of fines from the sample top and a higher fines accumulation in the near-coupon zone. The higher fines migration can be attributed to the stress-induced compaction which results in a lower porosity and, consequently, a higher real flow velocity. In sand-packs with lower porosity (higher compaction under higher confining stress), pore throats are smaller and pore flow velocities are higher for same flow rates resulting in stronger drag forces. Further, pressure induced seepage forces are higher for lower permeabilities due to higher pressure gradients along the sand-pack.

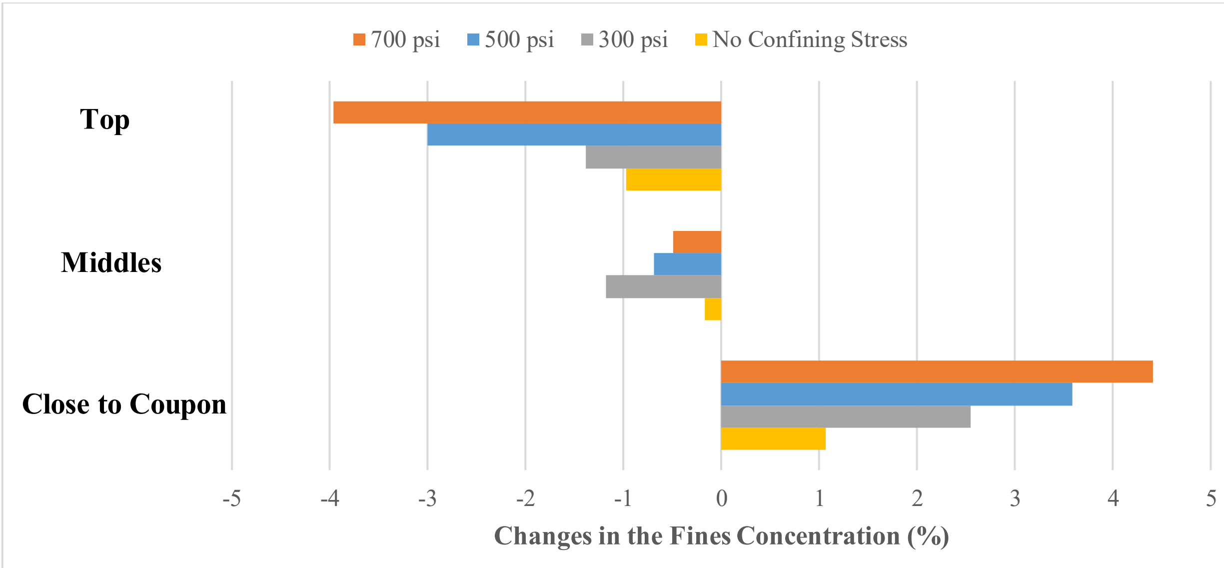


Figure 12: Changes in Fines Concentration along the Sand-Pack under Different Effective Stresses, for Coupon: 0.014″-0.022″ SPC: 54

5.3 PSD of Fines

In the study of fines migration, it is instructive to investigate the PSD of the fines along the sand-pack at the end of the testing. Figure 13 shows the fines PSD curves at the top, middle, and bottom of the sand-pack as determined by a laser particle size analyzer. Several measurements were performed for each part of the sand pack to ensure accuracy. Test results indicate that coarser fines at the top segment and finer fines at the bottom of the sand-pack. This can be attributed to the mobilization of small fines particles with the flow from the sample top to bottom.

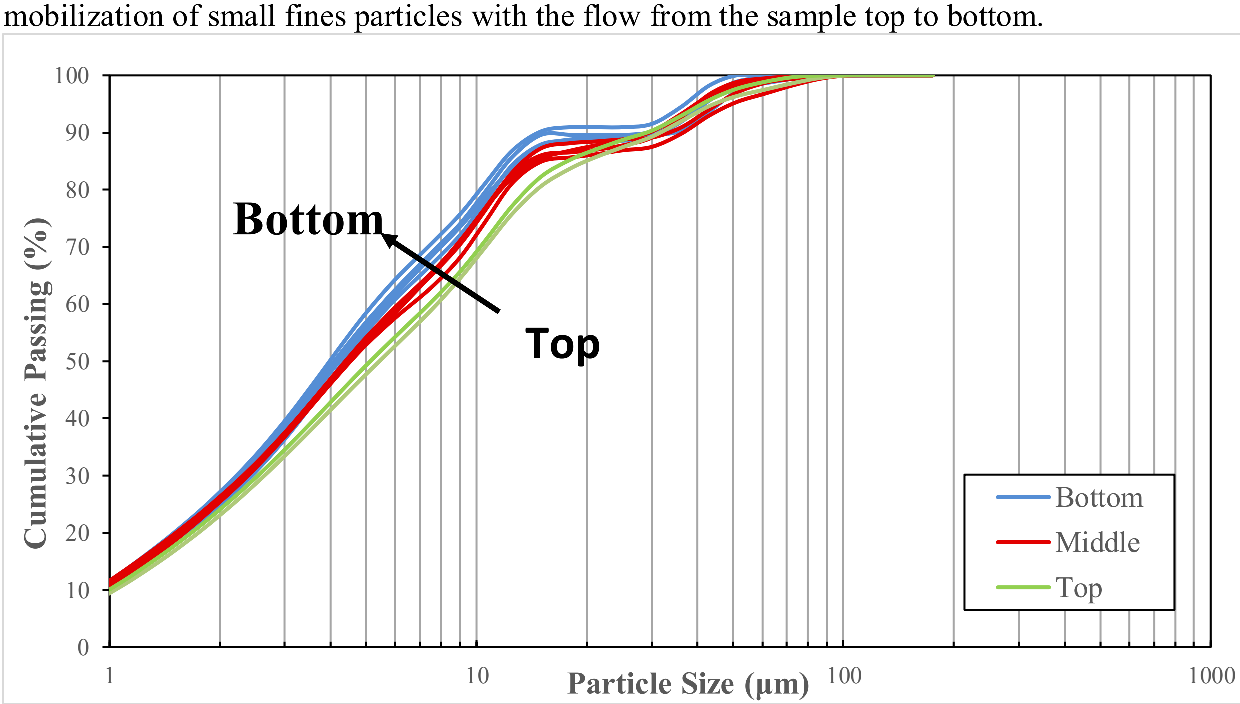


Figure 13: PSD of Fines across the Sand-Pack for Single Flow Rate Test

5.4 PSD of Fines at High Flow Rates

Higher flow rates than typical values were used in one test to simulate extreme cases where factors such as plugging of some slots or non-uniform SAGD production along the production well may result in higher flow rates behind open slots. The total flow rate in this test was increased in steps from 40 cc/min (typical SAGD production rate per slot) to 120 cc/min and, then, 200 cc/min. Each flow step was kept constant for one hour. Figure 14 presents the PSD of fines along the sand-pack for this test. Results indicate that the fines migration is highly sensitive to the flow rate, where larger fines quantity and larger fines sizes can migrate at higher flow rates. Higher flow rates lead to stronger drag forces which can mobilize larger fines particles as well as larger amount of fines along the sand-pack.

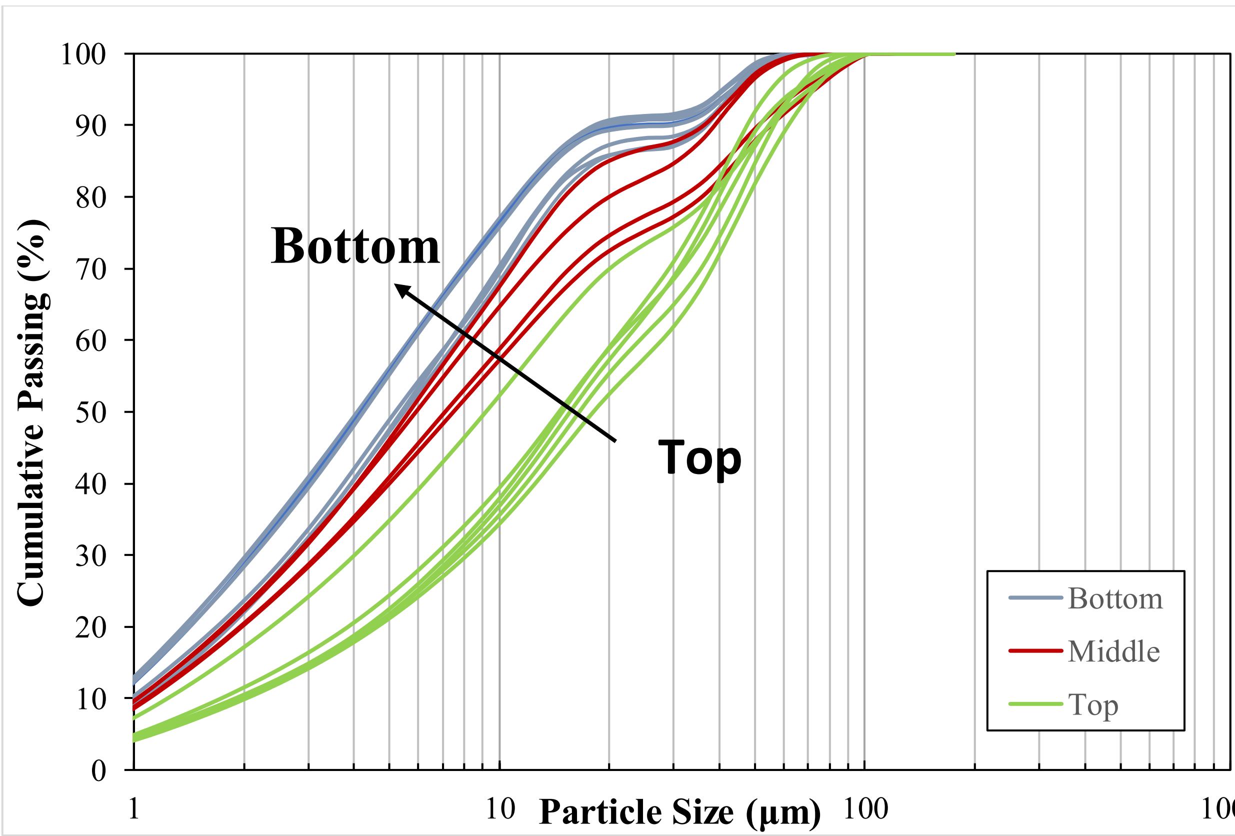


Figure 14: PSD of Fines across the Sand-Pack for Multi-Flowrate Test

5.5 Near-Coupon Fines Concentration

Figure 15 shows the fines concentration in the near-coupon zone at the end of experiments versus effective stress. The figure shows higher near-coupon fines concentrations for higher effective stresses. Higher near-coupon fines concentrations lead to more plugging potentials, hence, lower flow efficiencies for the well. From the slopes of the curves in Figure 15, it appears that the effective stress has a stronger effect on plugging for narrower slots, which indicates the benefits of using wider slots for lower plugging over the life cycle of the well.

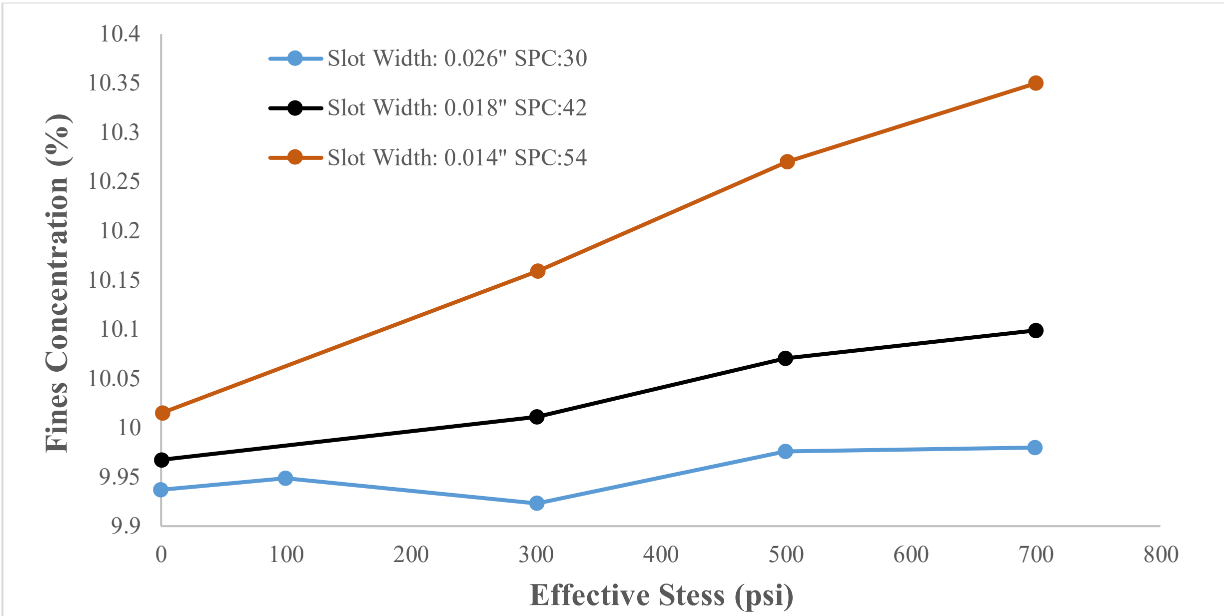


Figure 15: Fines Concentration at the Near-Coupon Zone vs. Effective Stress

5.6 Retained Permeability

Retained permeability is a measure of the plugging caused by such phenomena as fines migration. Retained permeability is defined as the ratio of near-screen permeability to the initial formation permeability (Figure 16). Here, 2 inches of the sand-pack immediately above the coupon is considered as the near-screen zone.

$$k_{retained} = \frac{k_b}{k_{original}} \tag{4}$$

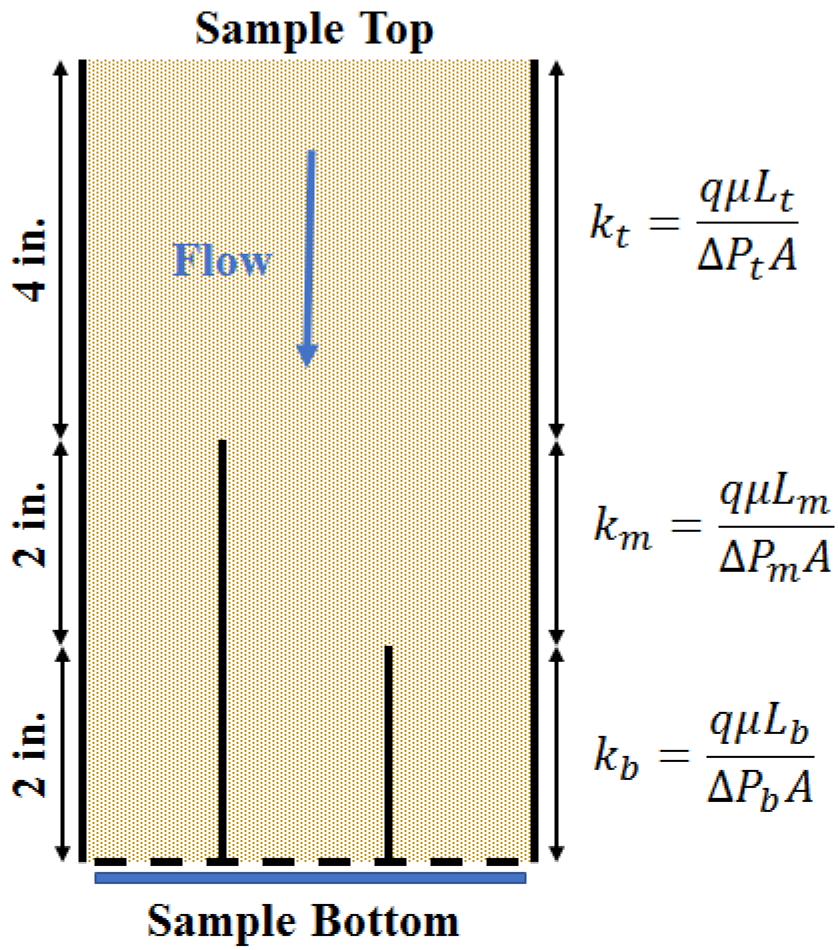


Figure 16: Retained Permeability Definition

Figure 17 shows the retained permeability under different effective stresses. It is evident that the effective stress reduces the retained permeability for all three coupons. The physical reason for this is believed to be the sand compaction at higher effective stresses, resulting in a lower porosity and permeability for the sand-pack, hence, narrower pore throats for the flowing fluid to pass through. The narrower pore throats lead to higher real flow velocities, hence, higher pressure differentials across the particles, which facilitates fines mobilization (Fattahpour et al., 2016). The mobilized fines accumulate around the liner resulting in an increased plugging potential and a lower retained permeability.

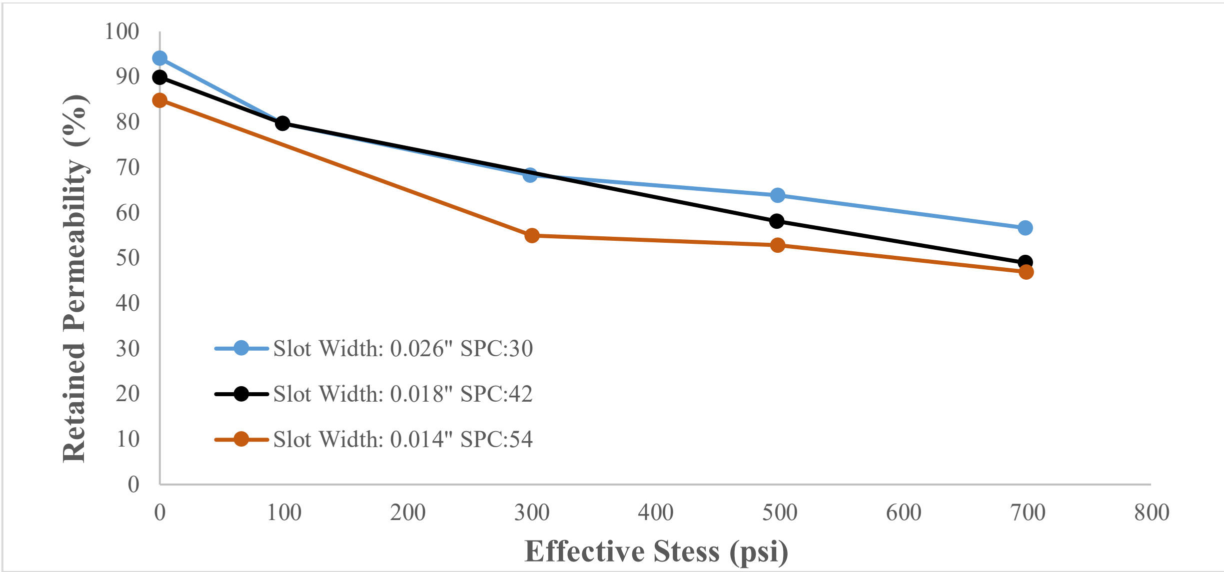


Figure 17: Retained Permeability at the Near-Coupon Zone vs. Effective Stress

5.7 Median Size of Produced Fines

Figure 18 shows the median size of produced fines (D_{50}) versus the effective stress. Fines transport is related to the characteristics of porous media, distribution of fines in the pores structure as well as the hydrodynamic conditions. In this study, the stress-induced compaction contributes to lower porosity and narrower pore throat, which makes the porous media more prone to producing finer particles and trapping the coarser ones. Figure 18 also indicates a more significant impact of the effective stress at lower stresses on the D_{50} reduction. This is mainly due to a greater compaction level at lower effective stresses.

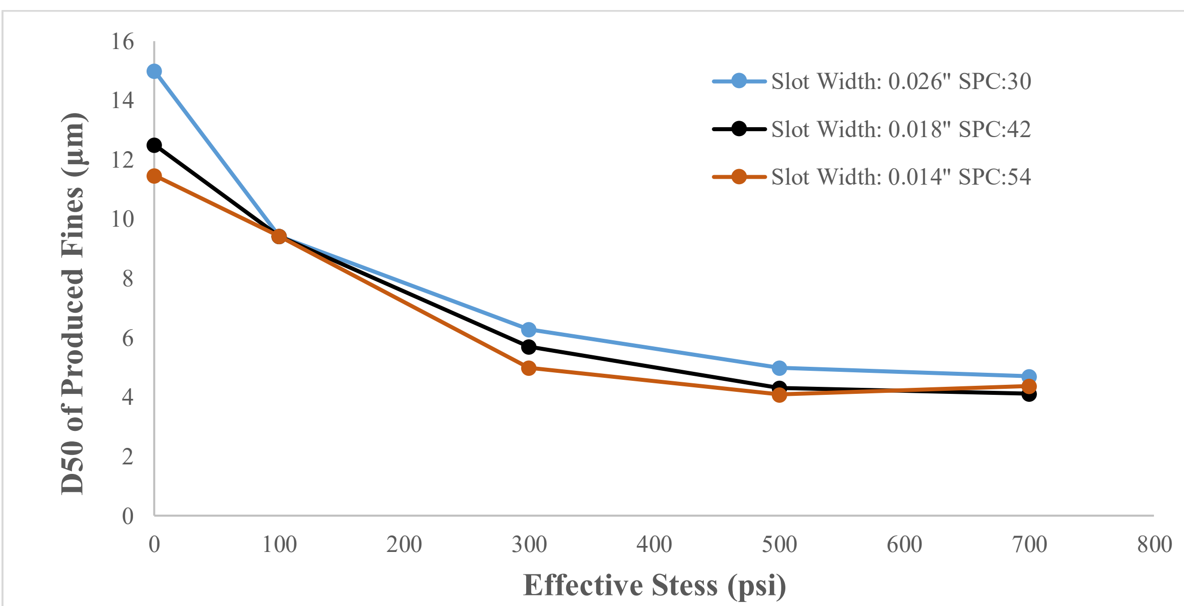


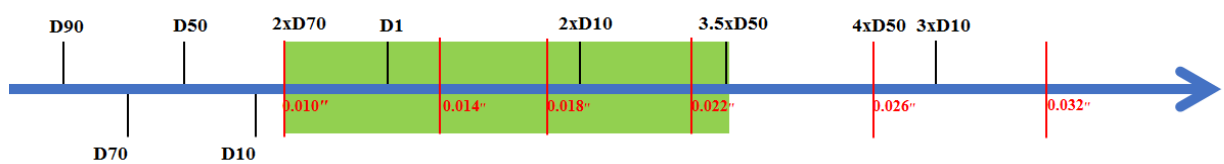
Figure 18: D_{50} of Produced Fines vs. Effective Stress

5.8 Acceptable Slot Window

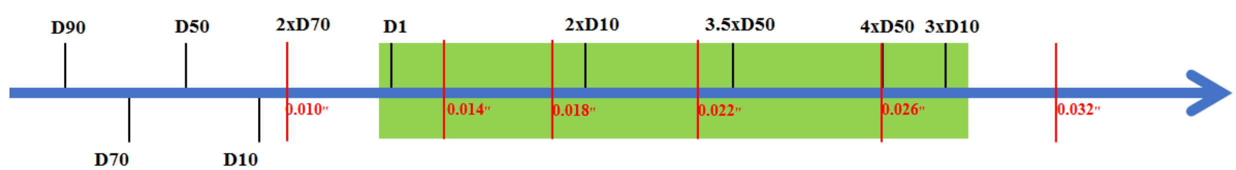
Past design criteria have been based on specifying a safe slot range for acceptable sanding and flow efficiency. The testing program in this paper uses cumulative sanding and retained permeability as indicators for the evaluation of sand production and flow performances, respectively. Mahmoudi (2017) proposed a set of new design criteria that present the criteria graphically based on a traffic-light system approach. These criteria were presented for different PSD categories, slot densities, and operational conditions, and were based on an extensive SRT testing program at near-zero stress condition.

Based on the SCT results in this work, it can be concluded that the plugging tendency increases while the sand production decreases at higher effective stress levels. This indicates that under increasing stress conditions, one should use wider slots to avoid severe plugging. This means the lower bound of the safe slot window should be revised higher. Since less sanding is observed under evolving effective stresses, wider slots can be used as long as the sanding level remains acceptable. Therefore, at higher effective stress, a larger upper bound can be employed.

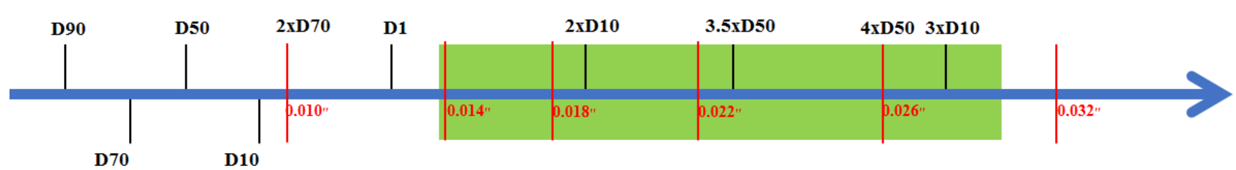
The testing results provide a general idea of how the design criteria are affected by the stress build-up around the liner. Figures 19a to 19d show the acceptable slot windows under higher effective stress conditions. In the figures, the DC- II PSD is represented by a linear axis and is annotated by the D values (e.g., D_{50}).



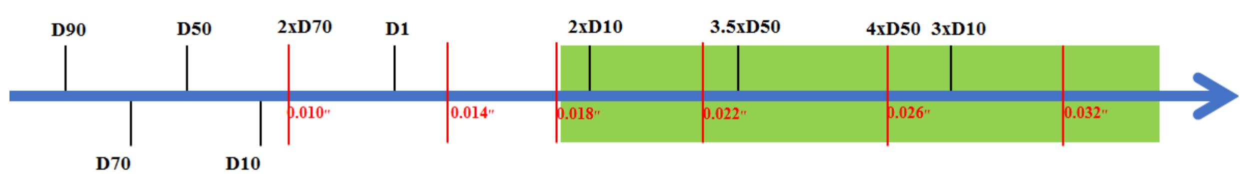
(a)



(b)



(c)



(d)

Figure 19: Slot Windows for DC- II under (a) ~0 psi (Mahmoudi, 2017), (b) 300 psi, (c) 500 psi, (d) 700 psi.

6. Conclusion

This paper presents the experimental results of a novel pre-pack sand retention testing facility, named SCT. The possibility of parametric testing with the new apparatus allows studying the effects of liner design and operating conditions, which in turn provides the development of more efficient design criteria for sand control for different types of sand media.

The optimization of slotted liner performance and liner design in sand control screens have been the subject of many studies over the past decades. This research was mainly focused on improving the current slotted liner design criteria by investigating the effects of stress build-up on liner performance. The test results are analyzed based on three performance indicators to gauge the liner performance:

1) Mass of produced sand: the cumulative produced sand at the end of testing is measured as a direct indicator of sand production resistance.

2) Flow performance of the screen: the retained permeability is calculated by measuring pressure drops in the near-coupon zone of the sand-pack and is considered as the indicator of screen flow performance.

3) Fines concentration along the sand-pack is also measured after the test to examine the fines migration phenomenon, which is considered as the main contributing factor in pore plugging and reduced retained permeability.

These performance indicators are assessed experimentally for one PSD of the McMurray formation under different effective stresses ranging from almost 0 psi to 700 psi. Three multi-slot coupons with seamed slots of 0.014″, 0.018″ and 0.026″ and slot densities of 30, 42 and 54 slots per column (SPC) were used to conduct the SCT tests. The slot width of the multi-slot coupons is chosen based on the common design criteria in the industry regarding the PSD of typical oil sands.

The testing results indicate that effective stress plays a critical role in both sand production and retained permeability values. As the effective stress increases, the sand production decreases. Higher effective stress is expected to increase the mobilized friction between the grains, enhance sand bridge stability, and reduce sanding. The relatively wider slot, which proved to be unacceptable at zero effective stress due to excessive sanding, showed an acceptable level of sanding under higher effective stress conditions.

The results also indicate lower retained permeabilities at higher effective stresses. Higher effective stresses are expected to compact the sand around the liner, reduce the sand porosity, and, therefore, increase the real flow velocity. Thus, the higher interstitial flow velocity triggers an increased level of fines mobilization due to extra drag exerted on the fines which can lead to a higher skin build-up and lower retained permeability.

Post-mortem analysis indicates a more severe fines migration at higher effective stresses, which is the main reason for the retained permeability reduction. Results show a higher fines concentration in the vicinity of the coupon for higher effective stresses. The PSD of fines along the sand-pack indicates coarser fines particles at the top and finer fines at the bottom, which is due to the migration of finer fines in the flow direction. Results also show a strong relationship between the fines migration and flow velocity. Higher flow velocities mobilize more fines and increase the average particle size of the mobilized fines. The median size (D_{50}) of produced fines is also affected by effective stress: Higher effective stress results in a smaller D_{50} for the produced fines.

Based on the experimental investigation, this paper also evaluates the existing design criteria under several effective stress conditions and inspects how the existing industrial design criteria are affected by the stress build-up. Conventionally, design criteria for slotted liners specify two limits for the slot aperture. The upper bound for the slot aperture is specified to limit the produced sand, and the lower bound is specified to keep the plugging within an acceptable level.

It is evident that an increase in the effective stress leads to an increase in both the lower and upper bounds of the safe slot window. According to the experimental results, higher effective stresses lead to less sanding. Hence, larger aperture sizes can be used without exceeding the sanding limits at higher effective stress conditions. At the same time, higher effective stresses also result in higher plugging potential and lower retained permeability, which needs wider slot to reduce the flow resistance. Consequently, one can expect that higher effective stress leads to lower retained permeability and less sand production. Therefore, wider apertures than those in existing design criteria should be used to avoid excessive plugging. Based on the above rationale, the design criteria for slot aperture should shift towards wider aperture sizes than those proposed by the existing design criteria that have been developed based on SRT testing at near-zero stress conditions.

7. Acknowledgment

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8. Nomenclature

Δc	Absolute Uncertainty of Fines Concentration
DC-II	Class II Oil Sand for Devon Pike I
D	Diameter of Particle Size
D_{10}	Sieve opening size that retains 10% of the particles in a sample
D_{50}	Sieve opening size that retains 50% of the particles in a sample (Median size on the PSD curve)
D_{70}	Sieve opening size that retains 70% of the particles in a sample
K	Permeability
k_b	Bottom Part Permeability
k_m	Middle Part Permeability
k_t	Top Part Permeability
$k_{retained}$	Retained Permeability
$\Delta k_{retained}$	Absolute Uncertainty of Retained Permeability
L	Horizontal Length

m_{fine}	Mass of Fines
m_{total}	Total Mass of Sand and Fines
Δm_{fine}	Absolute Uncertainty of Mass of Fines
Δm_{total}	Absolute Uncertainty of Total Mass of Sand and Fines
P	Pressure Drop
ΔP	Absolute Uncertainty of Pressure Drop
Q	Production Rate
Q	Flow Rate
Δq	Absolute Uncertainty of Flow Rate
w	Slot Width
ΔW	Absolute Uncertainty of Produced Sand
Δw	Absolute Uncertainty of Measurement form Lab Balance

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