Effect of Stress Build-up around SAGD Wellbores on the Slotted Liner Performance

by

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Abstract

Steam Assisted Gravity Drainage (SAGD) is a thermal recovery technology currently employed to extract heavy oil and high viscosity bitumen from Alberta oil sands. Due to the unconsolidated nature of oil sands, SAGD wells are prone to producing sand, hence, requiring sand control devices to prevent sanding during oil production. Slotted liners are a prominent sand control technique, which have been extensively used in Alberta's SAGD wells to avoid sand production problems. The design of the slots must allow free flow of fines and clays through the slots and the porous medium around the well, with minimal plugging.

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 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. In addition, melting of the bitumen and subsequent loss of the bonding between the grains leads to the collapse of the gap between the oil sand and sand control liner over time. The result will be buildup of effective stresses and gradual compaction of the oil sands around the liner.

The focus of this study is to improve the understanding of the effect of near-liner effective stress on the sanding and flow performance of the slotted liner over the life cycle of the well through physical model testing. Another aim is to study how the design criteria for slotted liners in SAGD are affected by the liner stress.

Large-scale unconsolidated sand is packed on a multi-slot coupon and is subjected to several stress conditions corresponding to the evolving stress conditions during the life cycle of a SAGD producer. Cumulative produced sand is measured at the end of testing as an indicator for the sand control performance. Retained permeability is calculated by pressure differentials across the close-to-coupon zone and considered as a measure of screen flow performance. Fines/clay concentration along the sand pack is also measured after the test to investigate the fines migration, a phenomenon which is the main reason for reduced wellbore productivity.

Experimental results show that the liner performance is significantly affected by the normal stress loaded on the liner. Experimental observations indicate sand pack compaction by the increase of effective stress around the liner leading 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.

In addition to investigating the effect of stresses, the current study employs multi-slot coupons to examine the role of slot width and slot density on the liner performance as well. According to the experimental observations, increasing slot width generally reduces the possibility of pore plugging caused by fines migration. However, there is a limit for slot aperture beyond which the plugging is not reduced any further and only higher level of sanding occurs.

As for the design criteria, the lower and upper bounds of the slot are governed by plugging and sand production, respectively. Considering the stress effect on plugging and sanding, testing data indicates that both the lower and upper bounds should shift to larger slot apertures. Test measurements also indicate that beside the slot width, the slot density also influences the level of plugging and sand production and must be included in the design criteria.

Dedication

This dissertation is dedicated to my dearest parents, Mrs. Doingfang Wang and Mr. Baisuo Guo.

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Nomenclature

BC	Bottom Centre Portion of the Sample
BL	Bottom Left Portion of the Sample
BR	Bottom Right Portion of the Sample
Δc	Absolute Uncertainty of Fines Concentration
DC-I	Class I Oil Sand for Devon Pike I
DC-II	Class II Oil Sand for Devon Pike I
DC-III	Class III Oil Sand for Devon Pike I
DC-IV	Class IV 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_{40}	Sieve opening size that retains 40% 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
D_{90}	Sieve opening size that retains 90% of the particles in a sample
D_{95}	Sieve opening size that retains 95% of the particles in a sample
F_D	Drag Force
J_l	Joint Length
k	Permeability
k_b	Permeability of the Bottom Section
k_m	Permeability of the Middle Section
k_t	Permeability of the Top Section

$k_{retained}$	Retained Permeability
$\Delta k_{retained}$	Absolute Uncertainty of Retained Permeability
L	Horizontal Length
MC	Middle Centre Portion of the Sample
ML	Middle Left Portion of the Sample
MR	Middle Right Portion of the Sample
Max SW	Maximum Slot Width
Min SW	Minimum Slot Width
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
SD_{opt}	Optimum Slot Density
S_1	Slotted Portion per Joint
TC	Top Centre Portion of the Sample
TL	Top Left Portion of the Sample
TR	Top Right Portion of the Sample
V	Volumetric Flow Rate per Slot

w	Slot Width
ΔW	Absolute Uncertainty of Produced Sand
Δw	Absolute Uncertainty of Measurement form Lab Balance

Abbreviations

ASW	Average Slot Width
CRD	Collaborative Research and Development
DAQ	Data acquisition
ERCB	Energy Resources Conservation Board
HT/HP	High Temperature/High Pressure
LL	Lower Limit
Max SW	Maximum Slot Width
Min SW	Minimum Slot Width
NSERC	Natural Sciences and Engineering Research Council of Canada
OFA	Open to Flow Area
PPE	Personal Protective Equipment
PSD	Particle Size Distribution
PVC	Polyvinyl Chloride
RP	Retained Permeability
SAGD	Steam Assisted Gravity Drainage
SC	Sorting Coefficient
SCT	Scaled Completion Test
SOP	Standard Operating Procedure
SPC	Slot Per Column (number of slot in one column of 7” liner)
SRT	Sand Retention Test
TLS	Traffic Light System
UC	Uniformity Coefficient

UTF	Underground Test Facility

Chapter 1: General Introduction

1.1. Overview and Background

The development of heavy oil and unconventional resources has become a major priority worldwide in response to the increasing global energy demands as well as the continuous depletion of conventional oil resources. Canada is reported as one of the largest heavy oil producers with an estimated 176.8 billion barrels proven oil reserves (World Energy Council 2010). The hypothetical resources are estimated to add another 126 billion barrels. In Canada, Alberta is the largest oil-producing province. The heavy oil is mostly located near the Alberta and Saskatchewan border and the oil sand is mainly situated in three specific regions: the Athabasca, Peace River, and Cold Lake in Alberta. Figure 1.1 presents a plan view of Alberta, indicating the location of its heavy oil reservoirs. Most Alberta reservoirs are situated in high-porosity, poorly consolidated or unconsolidated formations. According to Chalaturnyk et al. (1992), these heavy oil deposits can be classified as: 1) reservoirs which require enhanced oil recovery after 2 to 3 years of primary production, 2) reservoirs which require enhanced oil recovery from the onset of production. An unfavorable and seemingly unavoidable consequence of oil production in these reservoirs is sand production.

Steam Assisted Gravity Drainage (SAGD) has been the most widely used method for heavy oil in-situ recovery in western Canada (Ito et al. 2004, Gates et al. 2007, Keshavarz et al. 2016). Approximately half of the bitumen produced in Alberta is obtained by SAGD operation (ERCB 2011). In SAGD, two parallel horizontal wells are drilled with an inter-well offset of around 4-6 meters (Figure 1.2). The upper wellbore is called the injector, and the lower wellbore is called the producer. Initially, after the installation of the two wellbores, high-temperature and high-pressure steam is circulated through both wells to warm up the formation. Next, steam is injected through the injection well to penetrate the reservoir and form the 'steam chamber'. As the steam transfers its latent heat to the formation and is converted to hot water, the viscosity of heated bitumen reduces to the extent that it can be mobilized by gravity towards the production well. SAGD solves the immobility challenge in in-situ bitumen recovery by taking the advantage of the strong temperature dependency of bitumen viscosity.

Figure 1.1: Location of the Athabasca, Cold Lake and Peace River Oil Sands in Alberta (Alberta Geological Survey, 2011)

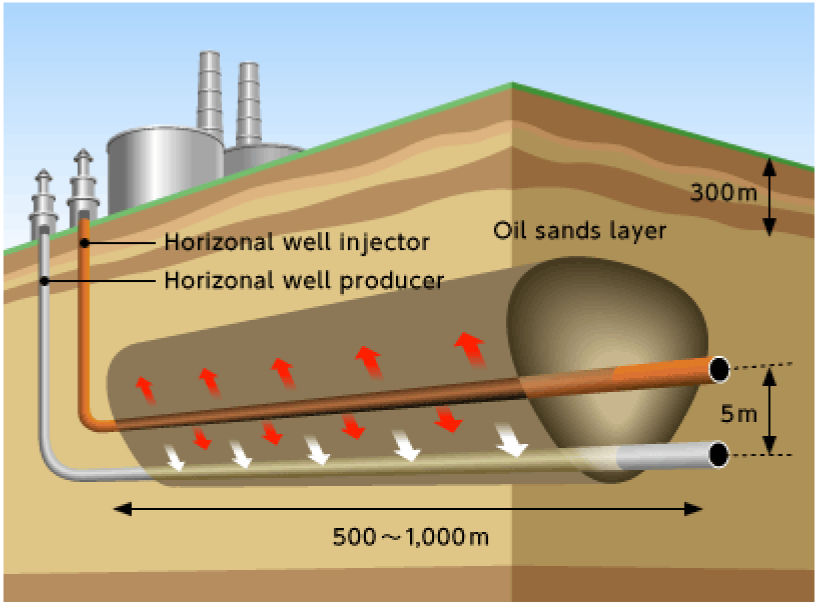


Figure 1.2: SAGD Setup to Extract Bitumen from Oil Sand Deposit (Japan Petroleum Exploration Co., Ltd.)

Sand control completions, which support SAGD wells against collapse, 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 (FCDs) 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, which impedes the reservoir flow, 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” (Markestad et al. 1996).

Three major types of sand control completions in SAGD applications in order of popularity, are: Slotted Liners (SL), Wire Wrapped Screen (WWS) and Precise Punched Screen (PPS). Figure 1.2 shows images of slotted liners that are the most popular well completion technique in SAGD wells. Slotted liners exhibit desirable sand control performance in unconsolidated and high-permeable oil sands and provide a suitable mechanical integrity against installation and thermal loads Figure 1.3. The application of slotted liners dates back to 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 in formations with higher amounts of fines and reactive clays such as smectite and illite, slotted liners are not as effective (Romanova et al., 2014).

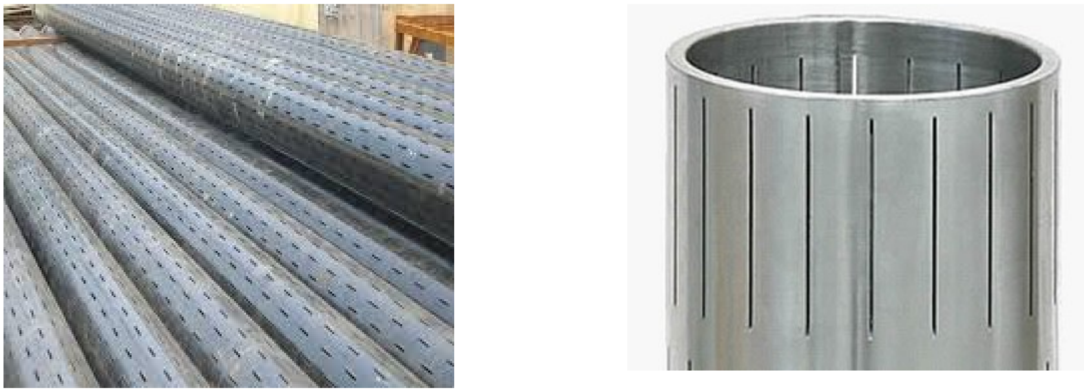


Figure 1.3: Slotted Liner

Extensive research has been performed to optimize the design of slotted liners. Performance assessment of slotted liners is based on their ability to prevent sand production and to allow the passage of reservoir flow. Historically, design guidelines have been proposed in relation to the particle size and slot width (Coberly, 1937; Suman, 1985; Markestad et al., 1996; Ballard et al., 1999; Gillespie et al., 2000; Chanpura et al., 2011). The central phenomena considered in the slotted liner design are the inflow performance and sand control. Considering these two factors, the current design criteria are proposed in terms of slot aperture window in relation to one or more attributes of the formation sand Particle Size Distribution (PSD) (Coberly, 1937; Suman, 1985; Markestad et al., 1996; Ballard et al., 1999; Gillespie et al., 2000; Bennion et al., 2008; Chanpura et al., 2011). The Open to Flow Area (OFA), which is defined as the ratio of the open area exposed to the reservoir over the total area, is another important parameter which can influence the flow performance (Kaiser et al., 2000).

Conventionally, the upper bound of the slot aperture is the aperture that keeps sanding at an acceptable level, while the lower bound is specified based on conditions that limit the plugging tendency (Markestad et al., 1996; Hodge et al., 2002; Constien and Skidmore, 2006; Adams et al., 2009; Fermaniuk, 2013; Mahmoudi, 2016). Retained Permeability (RP) is a widely used parameter to measure the slotted liner plugging tendency and is defined as the ratio of near-screen permeability over the original formation permeability. A retained permeability of 50% is also proposed as the limit for the inflow resistance (Hodge et al., 2002). As for the sand production, the maximum thresholds of 0.12 lb/sq ft (Constien and Skidmore, 2006) and 0.15 lb/sq ft (Adams et al., 2009) have been used to measure the sanding performance. Thus the safe slot window is obtained based on the retained permeability and the sand production.

1.2. Problem Statement

Most of studies in liner performance evaluation and optimization are experimental. In this regard, two types of Sand Retention Test (SRT) facilities are widely used in the industry: the slurry 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 SRT simulates the initial stage after the liner installation, when the gap between the liner and formation is filled by a slurry with low sand concentration. The pre-pack SRT simulates a rapid collapse of the borehole onto the liner, during which normal stresses on the liner are low and the porosity of the porous media right around the liner is high.

Currently, slotted liner design practices are based on specifying a slot aperture window. Furthermore, the formation PSD is the main factor in determining the slot aperture. The proposed slot window includes a minimum and a maximum value for the width based on PSD characteristics, e.g. two times the D_{50} (Fermaniuk, 2013). In the existing design recommendations, it is assumed that any slot width smaller than the specified minimum aperture leads to severe plugging. Any slot width larger than the specified maximum is expected to result in severe sanding (Markestad et al., 1996). These simple design approaches do not consider the effect of many important screen characteristics such as slot density and width. In addition, in developing these design criteria, only single slot coupons have been employed in laboratory testing (Bennion et al., 2009), which neglects the interaction between the slots.

The second issue that seems to need a thorough investigation is the stress build-up around the liner. Thermal expansion of the reservoir in SAGD results 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 pre-pack SRT facility which unlike the current testing facilities, allows the use of multi-slot coupons to investigate the role of slot size and slot density on the liner performance. The new testing facility can fully capture the interaction between the slots and 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.

1.3. Research Objectives

Mechanisms of sanding and plugging in sand control screens have been the subject of many studies over the past decades. This research is mainly focused on improving the current slotted liner design criteria by investigating the effects of slot width and density on the liner performance. The effect of stress build-up on liner performance is also evaluated experimentally. The proposed criteria are based on two 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.

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 a select PSD using different slot widths and densities. Another objective is to evaluate the existing design criteria under several effective stress conditions, and examine how the existing industrial design criteria are affected by the stress build-up.

1.4. Research Hypothesis

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.

The increase in effective stress is anticipated to elevate both the lower bound and the upper bound of the design criteria. Higher effective stress is expected to increase the mobilized friction between the grains, enhance sand bridge stability, and reduce 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 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 fines which can lead to a higher skin build-up and lower retained permeability. Consequently, it can be expected 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 design criteria. Clearly, as the slot aperture is increasing, the mass of produced sand is increasing as well, leading to the enhancement of retained permeability. However, the effect of the variation of slot width and density on fines migration, sanding and slot plugging is less evident. If slot density is to be kept constant, having larger slot aperture (and therefore higher OFA), leads to a reduction in fine migration and pore plugging due to the fact that the flow velocity behind the slot will be reduced.

1.5. Research Methodology

This research is an attempt to increase the existing understanding of the fines migration, sand production and plugging tendency for slotted liners by using a large-scale SRT facility. A triaxial cell assembly was used to load sand packs with specified and controlled grain size distribution, shape and mineralogy, on multi-slot sand control coupons. Different stress levels were applied parallel and perpendicular to the multi-slot coupons while brine was injected from the top of the sand pack towards the coupon. Liner coupons with different slot widths and densities were utilized. At each stress level, the mass of produced sand was measured and the pressure drops along the sand pack and coupon were recorded. Fines migration was also investigated by measuring fines/clay concentration along the sand pack.

The following steps were taken to accomplish the study objectives:

1) A novel large-scale SRT facility, called Scaled Completion Test (SCT) (Fattahpour et al., 2016), was utilized, which allows to produce different stress conditions around the liner coupon.

2) A standard operating procedure for SCT testing was determined. This task includes developing a test matrix to investigate the effect of stress, slot width and slot density on the liner performance.

3) The SCT tests were conducted based on the test matrix; the retained permeability, the cumulative produced sand, fines content and fines PSD along the sand pack as well as the PSD of produced fines were measured.

4) The liner performance at various effective stresses, various slot widths, slot densities, and OFA was analyzed.

5) The effect of effective stress on design criteria was qualitatively studied and recommendations for slotted liner design based on testing results were provided.

1.6. Thesis Structure

This thesis consists of six chapters.

Chapter 1 presents a brief overview of the research background and introduces the scope of this research.

Chapter 2 provides a literature review on SAGD with emphasis on sand production, and sand control methods. The current sand control design criteria for SAGD are also summarized.

Chapter 3 introduces the experimental setup testing materials, testing procedure, and the test matrix.

Chapter 4 presents the results of the experimental work on the role of effective stress in slotted liner performance in terms of retained permeability and sand production. Results of post-mortem analysis for fines migration along the specimen are presented in terms of fines content and particle size distribution. The chapter also presents how the stress effect should be incorporated in the design criteria for a liner design that works for the entire life of the well.

Chapter 5 presents the results of the experimental work on the effect of slot size and slot density on the liner performance. The results of post-mortem analysis, retained permeability and sand production are presented as the flow and sand control performance indicators of the slotted liner.

Chapter 6 summarizes the important findings and results of this research and provides recommendations for future studies.

Chapter 2: Literature Review

2.1 Introduction

Canada's oil sands and heavy oil resources are among the world's greatest petroleum deposits (Romanova and Ma, 2013). The vast bitumen resources are mainly located in northern Alberta, by the Cold Lake, Peace River and Athabasca. Tarry bitumen and oil sands are virtually immobile in the reservoir due to their high viscosity under reservoir conditions. Although the extent of these resources is well known, better technologies to produce oil from them are still being developed.

Although conventional crude oil resources in Canada are limited and dwindling (Butler, 1998), heavy oil and, in particular, bitumen resources are enormous, and their quantity approaches the Middle East’s conventional oil (Butler, 1998). Without bitumen and heavy oil, Canada would encounter a growing need to import foreign oil (Butler, 1998).

Imperial Oil’s cyclic steaming at Cold Lake and open pit mining of shallow Athabasca deposits by Suncor Energy and Syncrude Canada although being economical and satisfying much of the country’s demand, both have serious limitations (Butler, 1998). Open pit mining is only applicable to shallow deposits, making only less than 10% of total Athabasca resource available (Butler, 1998). Additionally, open pit mining brings about severe environmental problems as it requires the disruption of the landscape and the handling and disposal of a massive amount of tailings, at least ten times greater than the produced bitumen (Butler et al., 1981). Cyclic steaming has considerable environmental advantages since reservoir solids are left in place, yet its fresh water requirement, equal in volume to the produced oil (Al-bahlani and Babadagly, 2008), is environmentally demanding. In addition, high-pressure injection of steam (up to 14 MPa) and consequent large cyclic, thermal well stresses, typically results in well failure (Al-bahlani and Babadagly, 2008). Another important limitation of cyclic steam stimulation is its low recovery ratio of around 25% (Jimenez, 2008).

SAGD operation is more attractive as it presents a higher recovery ratio, requiring less water, consuming less energy and demanding fewer wells (Underdown and Hopkins, 2008). Compared to cyclic steam stimulation, since SAGD is continuous and steam is not required to be at high pressures. Operation of the process is simpler too.

Although SAGD is theoretically simple, and has been widely applied in heavy oil exploitation, there are some pitfalls or concerns regarding the technology. One of the crucial issues is that progressive disaggregation of the unconsolidated formation and the wellbore completion may cause massive sand production (Wan and Wang, 2008). Sand production may lead to severe erosion of production equipment, instability of the wellbore, and creation of production cavities (Fjaer et al., 2008). The current research is a noticeable step towards improving the efficiency of SAGD operation by investigating an essential element of the SAGD operation, which is effectiveness of a common sand control technique in SAGD: slotted liners.

2.2 Overview of Steam Assisted Gravity Drainage (SAGD)

Tar sands in Alberta contain 5-20 weight percent bitumen with an extremely high viscosity at reservoir conditions (Butler and Stephens, 1981). Therefore, the key of the oil sands exploitation is to reduce oil viscosity. SAGD technology was firstly introduced by Roger Butler and his colleagues during the late 1970s. SAGD has been widely and successfully applied in the oil sands exploitation (Ito et al. 2004, Gates et al. 2007, Keshavarz et al. 2016). Over the past 30 years, the technique has been successfully commercialized to the extent that many think of SAGD as a standard heavy oil recovery method. As shown in Figures 2.1 and 2.2, the SAGD concept was developed with the objective of continuously introducing steam into the reservoir and removing its condensate along with the heated oil. This formed the basic idea that due to density differences, if steam is introduced near the bottom of the reservoir, it will tend to rise, and condensate and heavy oil tend to fall to the bottom.

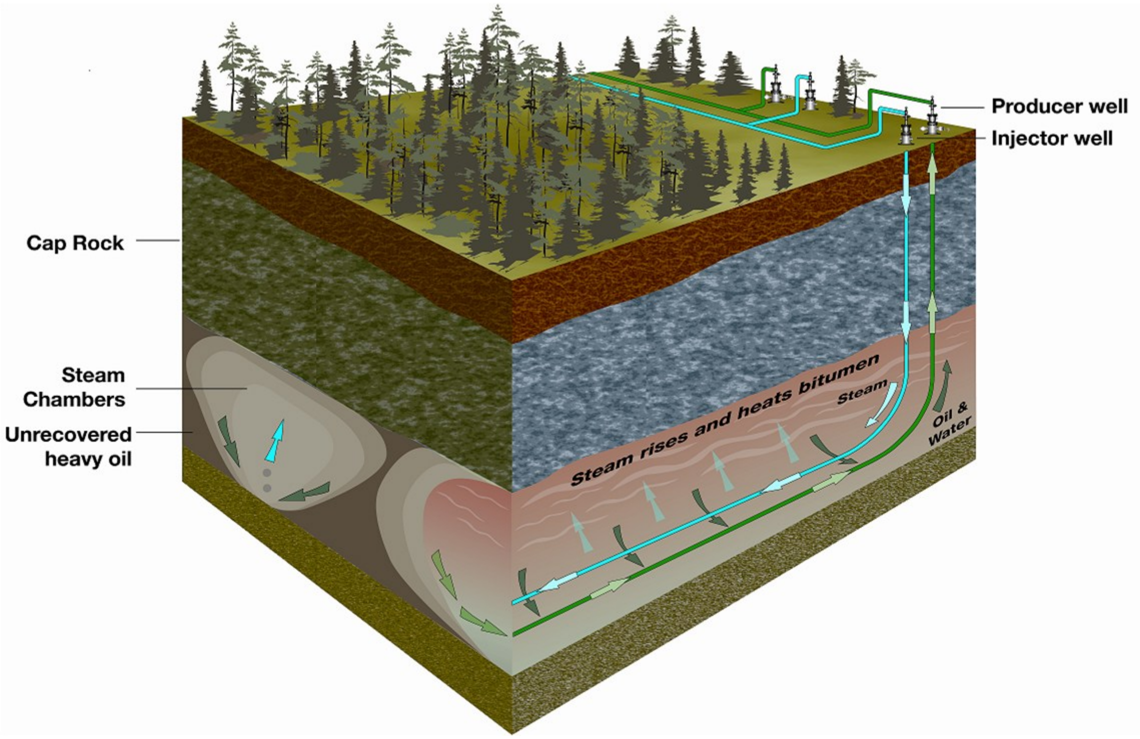


Figure 2.1: Schematics of SAGD Operation (Desiderata Energy Consulting Inc.)

To introduce steam into the reservoir, a horizontal well is drilled. In addition, 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. The injector is located at the top and the producer is located at the bottom, as shown in Figure 2.2. By introducing the steam into the reservoir, a steam saturated zone called steam chamber whose temperature is essentially that of the steam is formed. 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 Babadagly., 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.

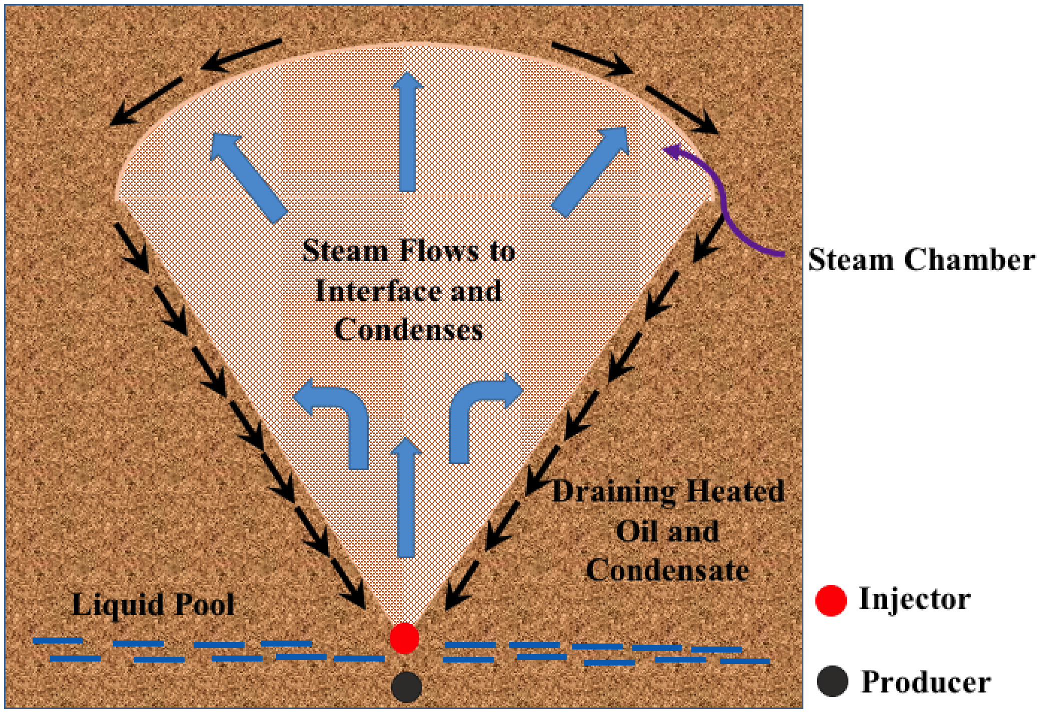


Figure 2.2: Schematic Concept of Steam Chamber in SAGD Operation

It should be noted that while SAGD concept is based on steam chamber development, the oil production is mostly from the chamber and heated oil interface (Edmunds et al., 1994). There are many simultaneous processes occurring in steam chamber development, e.g. counter-current and co-current flow, water imbibition, and emulsification and steam fingering (Al-bahlani and Babadagly, 2008). Recent studies of SAGD process confirms that the steam chamber is not connected to the producer and a pool of liquid exists above the producer (Al-bahlani and Babadagly, 2008). Existence of such a pool is essential as it prevents the flow of steam into the production well (Gates et al., 2005).

Beyond the theoretical studies, Butler et al. (1981) and Butler (1982) also performed scaled experiments to simulate the SAGD operation and to predict the rate of drainage during the SAGD process. From the operation of full-scale SAGD pilots in Athabasca, Cold Lake, Peace River and Lloydminster, it has been confirmed that the expected oil production rate from a SAGD operation, from well pairs of about 500-m long can be of the order of several hundreds to over a thousand bbl/day (Butler, 1982). Das (2005) pointed out the expected oil and water production rate for most commercial SAGD wells is in the range of 600-1500 m^3/day. The injector should also have the capacity of 400-1200 m^3/day Cold Water Equivalent (CWE) of steam injection.

McCormack (2001) provided different reservoir cut-offs for a successful and economical SAGD project. The cut-offs are: 1) continuous high-quality pay thickness of greater than 12 m with more than 10wt% of oil; 2) permeability of more than 3 Darcies; 3) absence of bottom water; 4) absence of top gas; and 5) competent cap rock. According to McCormack (2001), existence of a thicker pay zone may relax the permeability requirement or absence of bottom water and top gas.

The government of Alberta carried out some field pilot projects to examine the SAGD concept during the 1980s to 1990s. A well-known facility, named Underground Test Facility (UTF-Phase A), was constructed at 40 km northwest of Fort McMurray from 1985 to 1987 (Edmunds et al., 1994). This facility consists of three pairs of 60-m long horizontal wells with the angles of 15° to 20°to the horizontal. The UTF-Phase A project demonstrated the feasibility of the SAGD concept for heavy oil exploitation (Chung et al., 2011). After the completion of Phase A, the first commercial field pilot test, named UTF-Phase B, was built. This facility consists of three pairs of 500-m long horizontal wells. The facility was operated for around 12 years and the ultimate oil recovery was more than 50% (Chung et al., 2011).

Since the successful field demonstration of SAGD, more than ten commercial projects have been carried out in Canada, mainly in Athabasca area. SAGD has become the preferred technology for oil sands exploitation (Jimenez, 2008). Along with the field application of SAGD technology, extensive analytical and numerical studies have also been performed to predict the steam chamber rising rate and drainage rate. Butler (1987) firstly introduce an analytical model to predict the rate of steam chamber rise in a reservoir. Based on Butler’s study, Edmunds et al. (1989) presented a more generalized model depending on the production data obtained from UTF-Phase A project. Reis (1992) developed a new analytical model based on the experimental observation that the steam zone can be approximated as an inverted triangle. Birrell (2001) validated the accuracy of the Butler’s equation by comparing the predicting results with the production data in the field. Chen et al. (2007) improved Butler’s model by taking the heterogeneity of the reservoir into consideration.

Although SAGD is a highly promising technique, some uncertainties and unanswered questions still exist that prohibit its worldwide application. This research has been focused on the study of the most generic form of completion in SAGD wells, which is slotted liners. The aim is examining the effect of stress build-up around the liners on the sand control and flow performance of slotted liners. This goal was achieved by utilizing a pre-pack SRT facility, which allows the application of realistic normal and lateral stresses on the sand pack sample and is also capable of accommodating multi-slot coupons, which captures the effect of both slot density and slot width on the liner performance.

2.3 Sand Production: Mechanisms and Influencing Parameters

In certain reservoirs during the production of hydrocarbons, solid particles follow the reservoir fluids into the well as an unintended by-product (Fjar et al., 2008). The amount of this unplanned solid production can vary from a minor volume of a few grams per cubic meter of reservoir fluids to massive volumes that can lead to complete filling of the borehole. Solid production is a serious problem in many petroleum assests around the world. It has been estimated that 70% of total hydrocarbon reserves in the world are prone to solid production at some point during the life of the reservoir (Fjar et al., 2008). Historically, sand production has attracted most attention since solid production is most pronounced in sand reservoirs. However, it should be noted that solid production can be a major concern in chalk or coal reservoirs as well. In this section, mechanisms that may cause sand production are briefly described. However, detailed description of formulations related to sand production is outside the scope of our work and can be found elsewhere.

2.3.1 Origins of Sand Production

Morita and Boyd (1991) presented five possible origins of the sanding problem: (1) unconsolidated formations; (2) water breakthrough in weak to intermediate strength formations; (3) reservoir pressure depletion in relatively strong formations; (4) abnormally high lateral tectonic forces in relatively strong formations; and (5) sudden change in flow rate or high flow rates. Among those origins, poorly consolidated sandstone is considered as the most typical origin of the sand production (Morita and Boyd, 1991).

2.3.2 Types of Sand Production

Sand production can be roughly divided into three main types (Veeken et al., 1991): transient sand production, continuous sand production and catastrophic sand production. In transient sand production under constant well production condition, a burst of sand is produced which is followed with a declining rate of continuous sand production with the elapse of time. Transient sand production is frequently observed during the clean-up process after perforation or acidizing, after a change in production condition, e.g. a reduction in the well pressure or after water breakthrough. The cumulative volume of produced sand and the decline period vary considerably. Continuous sand production is a phenomenon in which sand is continuously produced at a constant rate. In catastrophic sand production, sand is produced at such an extremely high flow rates that the well suddenly chokes or even dies. The volume of produced sand in this scenario may amount from several to tens of cubic meter (m^3).

The acceptable level of produced sand depends on operational constrains regarding sand disposal, erosion, separator capacity or artificial lift. Ghalambor et al. (1989) proposed the acceptable sand cut levels for oil and gas production, which are 6-600 g/m^3 for oil wells and 16 $Kg/10^6\ m^3$ for a gas well at surface conditions. After several years of production, even a small sand production rate of a few grams per m^3 may add up to amounts up to hundreds of kilograms per meter of the well. Consequently, the hold-up depth inside the wellbore may increase as part of the continuously produced sand settles inside the borehole and it might be necessary to stop the normal production process to clean-out the wellbore.

2.3.3 Sanding Stages

It is well known that flowing fluids do not exert enough drag force to pull sand grains out of an intact rock even if the rock is poorly consolidated (Fjar et al., 2008). As shown in Figure 2.3, sand production may occur only in the case that the rock near the producing cavity is unconsolidated or damaged due to the stress concentration around an open hole. However, the absence of rock bonding or cement bonding degradation is only a necessary but not a sufficient condition for sand production (Fjar et al., 2008). After some initial sand production, a production cavity forms and may become stabilized due higher open flow areas and due to the increased permeability in the damaged area around the cavity (Fjar et al., 2008). In addition, as shown in Figure 2.3**,** creation of stable sand arches may prevent sand production even at high drawdowns. If hydrodynamic drag forces acting on the grains adjacent to free surfaces overcome the restraining stresses, the most weakly held grains may be dislodged.

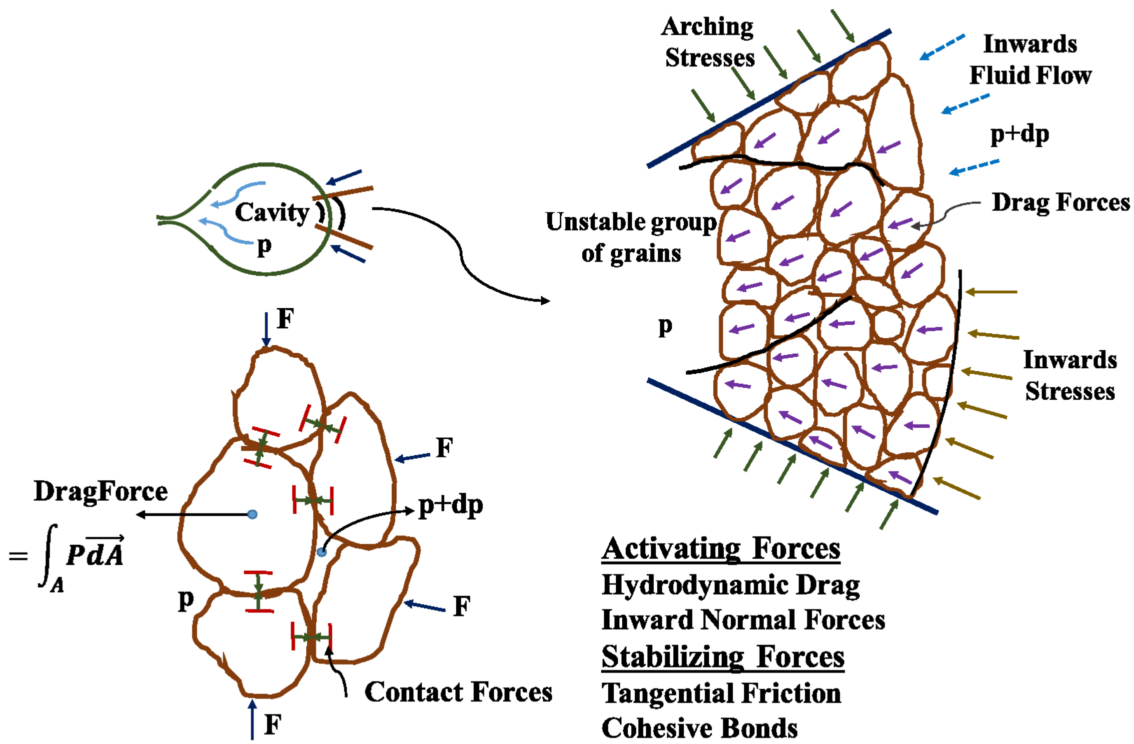


Figure 2.3: Instabilities in Sand Production

2.3.4 Sandstone Degradation Mechanisms

Two primary mechanisms for sandstone degradation include shear failure and tensile failure (Morita et al., 1987). Shear failure occurs when the wellbore pressure becomes too low (Morita et al., 1987). The near wellbore region would suffer high shear stress which it cannot sustain. Tensile failure is mostly related to extremely high pressure gradients (Morita et al., 1987). As shown in Eq. (2.1), fluid drag force (F_D) on the grains increases with the increase of pressure gradient, higher production rates or fast production ramp ups may result in higher sand production.

$$F_D = \int_A P\overrightarrow{dA} \tag{2.1}$$

Santarelli et al. (1989) also mentioned fines migration as a contributing mechanism for sand production. As the fluid flows towards the wellbore, some of the fine particles would migrate and accumulate in the near-wellbore region. This may contribute to the permeability reduction since the migrated clay particles would reduce the size of conduits. Smaller conduits sizes would lead to higher local flow velocity, and the higher velocity would cause higher sand production.

2.3.5 Sanding Prediction

The prediction of sand production is crucial for evaluating the necessity of sand control and selecting the appropriate sand control method. Veeken et al. (1991) performed a comprehensive review on the existing sand prediction techniques. The techniques are classified into three main categories. The first category is predicting sand production based on the available field data, such as logs, cores and experience from nearby wells (Fjar et al., 2008). The second category is simulating sand production process by laboratory experiments. So far, several groups of researchers have carried out experimental studies on sand control prediction by using unconsolidated sands (Hall and Harrisberger, 1970; Selby and Ali, 1988; Papamichos et al., 2001; Bennion et al., 2009; Mahmoudi et al., 2016). Beyond field data analysis and experimental tests, the third category, which is theoretical modeling, which is considered to be a significant technique for sand production prediction.

Morita et al. (1989) proposed a set of finite-element models for simulating complex stress/stain behavior and predicting potential sand production. Papamichos et al. (2001) developed a sand production prediction model which takes the effect of the external stresses and fluid flow rate into consideration. Nouri et al. (2004) conducted comprehensive laboratory tests on a synthetic sandstone under various conditions. A new numerical model, which is more suitable for time-dependent analysis of the rock, was developed and the modeling result was validated with experiments.

2.3.6 Sanding Consequences

A series of major problems can be a consequent of sand production:

1. Erosion of the production equipment and casing collapse due to abrasiveness of quartz grains, which is a safety and economical concern (Dusseault and Santarelli, 1989). Abrasion and erosion

of the production equipment, both downhole and on the ground surface, may require frequent workovers. Haugen et al. (1995) mentioned that the severity of erosion by a certain amount of sand strongly depends on the fluid velocity. Accordingly, in gas wells, where fluid velocity is higher compared to oil wells, the acceptable sand production is smaller.

2. Wellbore abandonment due to instability of production cavities and wellbore itself, which can lead to sand bridge and wellbore plugging or, in the worst-case scenario, a complete filling of the borehole ("sand up")

3. The necessity of handling, separation and disposal of the produced sand on the surface is another burden that should be considered

It should be noted that sand production is an integral part of a production technique known as Cold Heavy Oil Production with Sand (CHOPS). In CHOPS, sand production has a positive effect and is actually encouraged due to the difficulty of heavy oil production (Geilikman et al., 1994; Geilikman and Dusseault, 1997).

A proper and efficient sand control approach is essential for the oil and gas production from unconsolidated sandstone reservoirs. Additionally, during the development of any oil or gas reservoir, prediction of sand production is required in selecting the most economical sand control technique. The completion cost and the possible reduction or loss of well productivity due to accompanied sand production are the basis for economic incentive of predicting sand production. The following sections provide a review of some of the operational preventive techniques relevant to sand production.

2.4 Overview of Sand Control Methods

Sand production from a poorly consolidated reservoir could give rise to some severe problems during the production. Holding the load bearing solids in place is the main goal of any sand control technique. Completion methods that are especially designed for sand control are either reducing drag forces, bridging sand mechanically or increasing formation strength. Conventional treatments applied to minimize sand production include: restriction of flow rate, gravel packing, frac-packing, selected or oriented perforation, application of wire-wrap screens or slotted liners, chemical consolidation or a combination of these methods. It should be noted that sand control methods implicate additional expenses and typically reduce production rate. Therefore, a justified tolerance for produced sand should be considered and the completion method should be simple, reliable, and safe and able to maintain as much flexibility as possible for future operations.

The most popular sand control methods can be classified as restriction of production rate, mechanical methods (e.g. slotted liners, screens, gravel pack) and chemical methods. However, it should be noted that the only sand control techniques that have found applications in SAGD are some of the mechanical methods including wire wrapped screens, slotted liners and more recently, punched screens. Due to the very small flow rates encountered in SAGD wells, restriction of production rate, is not applicable to SAGD wells. Additionally, gravel packing a long horizontal well is impractical and expensive.

This section presents a brief description of a few popular sand control methods.

2.4.1 Restriction of Production Rate

Based on previous experience in sand producing formations, sand production is manageably decreased when the production rate is below a critical level (Abass et al., 2002). Restriction of production rate is the simplest but most effective way to minimize sand production. As discussed before, the fluid with higher flow velocity would exert stronger drag force and, in turn, produce more sand. Thus, the reduction in production rate could directly lead to the reduction in the sand influx. Although this critical rate is possibly below economic production level, it should be determined before designing a completion strategy.

Several studies (Stein and Hilchie, 1972; Veeken et al., 1991; Morita and Boyd, 1991; Abass et al., 2002) have been carried out to investigate the critical flow rate of the production well. The critical flow rate is found to depend on the fluid properties as well as rock types. The best approach in finding critical flow rate is by gradually increasing the flow rate until unacceptable rate of sand production is reached. The method is also called “bean-up”. As shown in Figure 2.4, step-wise increase of flow rate causes an increase in sand concentration which after some time tapers off to the previous concentration. However, sand production may continue at or above critical fluid velocity since no stable bridges around the wellbore can be formed anymore (Matanovic et al., 2012).

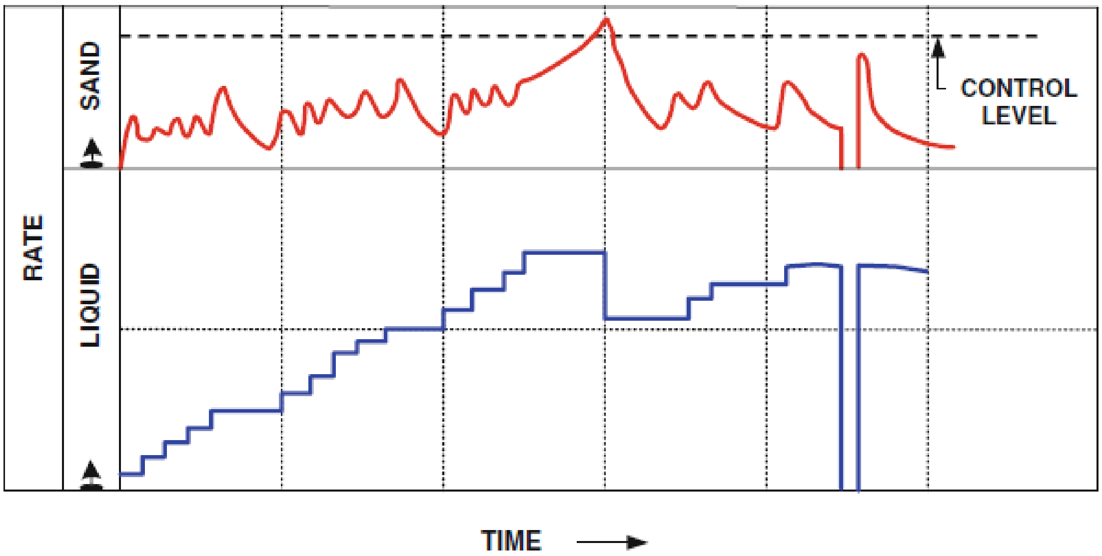


Figure 2.4: Determination of Critical Flow Rate Based on Manageable Sand Production (Matanovic et al., 2012)

2.4.2 Mechanical Methods

Mechanical sand control methods keep the sand out of the wellbore by stopping larger formation grains and they, in turn, stop smaller grains and at the same time provide the flow channel for hydrocarbon. There are three main mechanical methods for controlling the sand influx, namely slotted liners, screens and gravel packs. A combination of two different types of mechanical sand control devices are utilized, based on various conditions (Tiffin et al., 1998).

2.4.2.1 Slotted Liners

Slotted liner is one of the most effective mechanical sand control methods in the unconsolidated reservoir exploitation (Bennion et al., 2009). This device has proven to be the preferred sand control method in the SAGD operations (Bennion et al., 2009). The main advantage of the slotted liners that makes them suitable for SAGD operations is their superior mechanical integrity for the completion of long horizontal wells (Bennion et al., 2009).

Slotted liners are usually used to control the sand influx without the implementation of gravel pack. Kaiser et al. (2000) proposed that a good sand control device should not only have effective sand control performance but also good inflow performance. However, these two considerations are competing against each other.

As for slotted liners, inflow and sand control performance are mainly determined by the Open Area to Flow (OAF) and slot opening size, respectively. Given a constant slot density, slot opening size must be decreased to control the sand influx but the reduction in slot size would lead to the reduction in the OAF and affect the inflow performance of the slotted liners. Additionally, extremely narrow slots are also very difficult to manufacture (Kaiser et al., 2000).

Kaiser et al. (2000) by performing an analytical evaluation of inflow performance of slotted liners found several interesting conclusions, the most significant of which was that slot density has a strong effect on the inflow resistance.

Slot Types

Three main configurations of slotted liners have been introduced based on the slot profile, as shown in Figure 2.5 (Bennion et al., 2009). The straight cut slot is made by a single blade plunge into the liner. This type is the most conventional slotted liner. The keystone cut slot is prepared by two separate blade plunges into the liner to form a 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 more and even finer sand out of the wellbore; (2) the wider outlet makes the passage of the produced sand grains/fines easier and prevents plugging occurrence inside the slot as well. The ratio of the aperture size at the top over that at the bottom is called "aspect ratio". This is an important parameter that can control the performance of the keystone cut slotted liner. Rolled/seamed top slot is a modified type of the keystone cut slot. This type of slot is made by applying the concentric or longitudinal surface stresses on the surface of the slot. Under the stress, the slot is plastically deformed around 1 mm inwards and the 'aspect ratio' becomes higher.

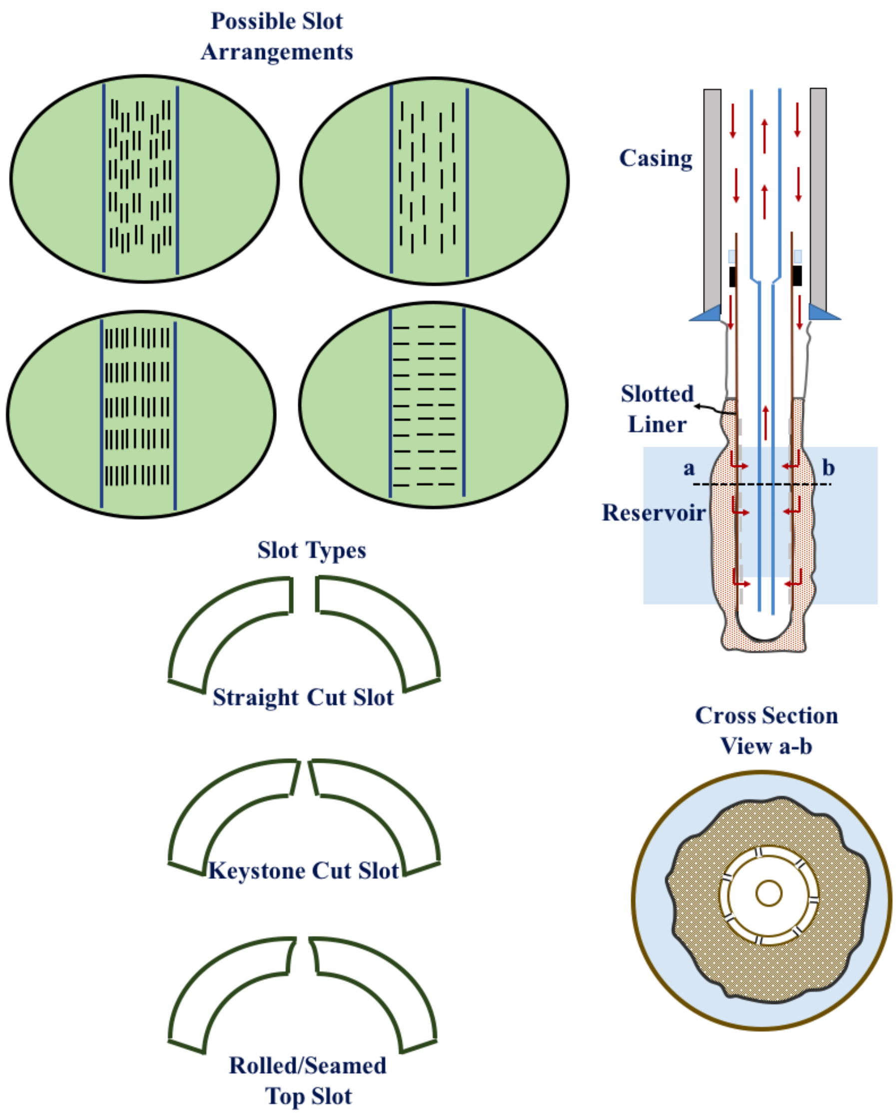


Figure 2.5: Configurations of Slotted Liners

Performance of Slotted Liners

Researchers have found the performance of slotted liners is affected by the slot profile, wettability characteristics and clay content of the porous media, flow velocity, and pH of the flowing phases.

Bennion et al. (2009) performed a comprehensive study on how these parameters could affect the slotted liner performance. Firstly, slot geometry could affect the plugging tendency above the slot. It is reported that straight cut slots are prone to severe plugging problems, but keystone and seamed/roll top slots perform better in this regard. The extent of the effect of formation wettability depends on the flowing liquid phases in the porous medium. Bennion et al. (2009) found that almost no plugging can be observed when just non-wetting phases are flowing in the porous medium. However, fines migration and plugging may occur if there is some flow of the wetting phase in the porous medium. Bennion et al. (2009) also conducted experimental tests on the McMurray sand samples with the help of ultrasonation technique. They concluded clay plugging at the top portion of the slot was the dominant damage mechanism for clay-rich oil sands.

Failure of Slotted Liners

It has been proven that the plugging plays a critical role in slotted liner's damage (Bennion et al., 2009; Ramonava and Ma, 2013). Plugging in slotted liner can be attributed to two main mechanisms: (1) pore plugging, in which the pore throats in the porous media are plugged by migrated fines, clays or other byproducts; and (2) slot plugging, which is defined as the reduction in the slot open area due to trapped sands and fines, scaling, and corrosion. The consequence of plugging is the increase of inflow resistance and production decline, as well as the increase in drawdown pressure.

A primary source of plugging in porous media is flow-induced fines migration. The fines migration occurs in four stages: (1) fines generation, (2) fines mobilization, (3) fines transportation, and (4) fines entrapment (Valdez, 2006). It has been found that, in addition to the clay particle size, porous structure, mineralogy and electro-chemical interaction of the fines, the saturating fluids also influence the fines migration.

Several studies have been conducted to investigate the plugging mechanisms of slots. Ramonava and Ma (2013) took mosaic images of clean and plugged slots by using the backscattered electron detector on a scanning electron microscope. By analyzing the images, they concluded that the slot plugging starts with the formation of a microfilm clay on the surface of the slot. The microfilm tends to grow upwards on the slot surface, infills the pores between the sand grains inside the slot and finally fully plugs the slot. Based on the results proposed by Ramonava and Ma (2013), clay products are the main plugging materials.

Scaling in downhole completion tools is another factor which is considered to be one of the major reasons of production impairment (Brown, 1998). When the equilibrium of the fluid and solution ions is disrupted due to physical or chemical changes, the dissolved components of the solution may precipitate and cause scaling. The common scaling materials are calcium carbonate, silica, strontium sulfate and barium sulfate (Schulien, 1997; Fermaniuk et al., 2015).

Another factor that can contribute to plugging of the liners is corrosion (Fermaniuk et al., 2015). The main reason of corrosion in casing and downhole equipment is the presence of sour gases and a variety of ions in produced hydrocarbons.

Finally, fluid pH affects the slotted liner performance by affecting the clay aggregation or dispersion in the porous media. Clay particles tend to aggregate in low pH condition while tend to disperse at high pH condition. Aggregation of clay particles can disrupt the blocking film and make it easier for clay to be produced. In other words, low-pH condition shows less plugging tendency.

2.4.2.2 Sand Control Screens

Sand control screens are widely used as sand control devices due to their low installation cost. The screens are mainly made of stainless steel and are specially designed to protect the completion and surface facilities from the erosion of produced sands. Screens are usually installed inside the open-hole section along with inflatable or swelling packers, inflow control devices and some other specially designed tools (Matanovic et al., 2012).

Plugging of the screen slots may result in a permanent damage to the sand control system. Therefore, it is very important to characterize the formation sand when designing the screens. Moreover, the installation of screens should not limit the oil and gas production when stopping the sand influx. Therefore, a careful selection of screen type and the aperture sizes is needed to ensure an effective screen design. Ott and Woods (2003) proposed some parameters such as screen strength, damage resistance, plugging resistance and erosion resistance should be taken into consideration during the screen type selection and design.

There are several screen types, including wire wrapped screens, pre-packed screens, premium screens, expandable screens, alternate-path screens and so on.

Wire Wrapped Screens

Wire wrapped screens (Figure 2.6), which were firstly introduced by Layne (1918), have been recognized as an important sand control technique around the world. Wire wrapped screens are made by helically wrapping a wire around and securing it to a longitudinally grooved or perforated pipe (Gerwick and Layne, 1973). There are some kinds of wire wrapped screens with lighter weights, which are specifically designed for horizontal wells (Matanovic et al., 2012). Wire wrapped screens come in different wire shapes: trapezoid shaped and 'V' shaped. Additionally, some wire wrapped screens are multilayered devices. They usually consist of two or more layers and the outer layer has the largest slot opening size (Dusterhoft, 1994).

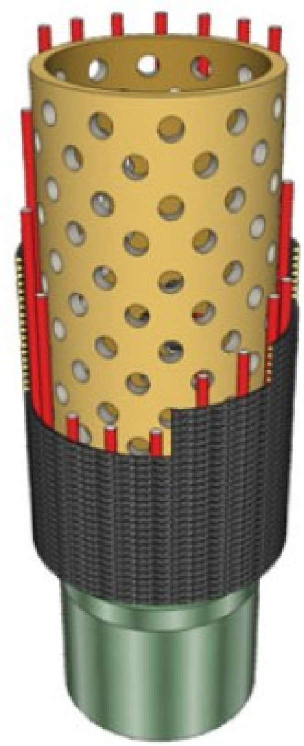


Figure 2.6: Wire Wrapped Screen (Matanovic et al., 2012)

As mentioned in Section 1.1, OFA is one of the most important governing parameters for sand control design as it influences the inflow performance of the sand control device. The total OFA of the screens depends mainly on the wire thickness and slot width and is usually larger than the slotted liners (Bellarby, 2009), as shown in Figure 2.7.

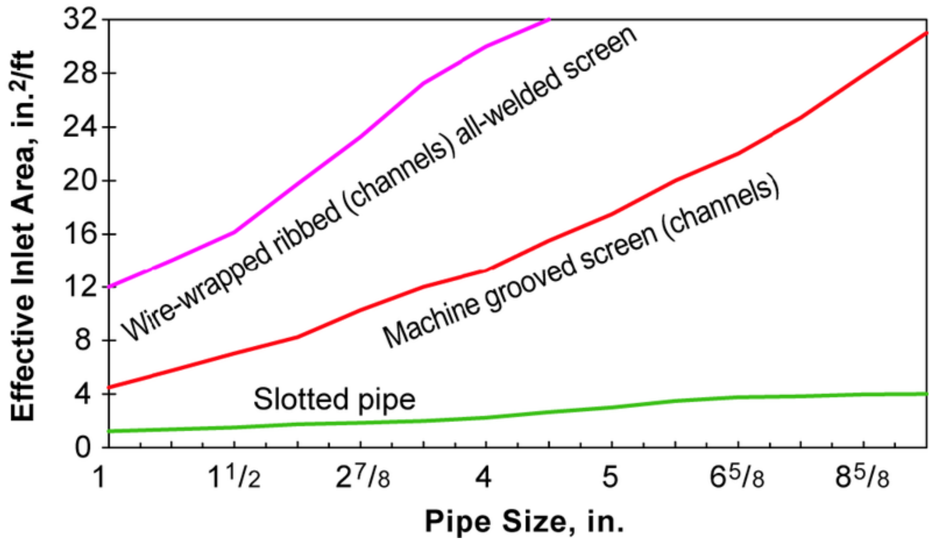


Figure 2.7: Comparison OFAs of Screens and Slotted Liners (Petrowiki, 2013)

Precise Punched Screens

Traditionally, in SAGD operations slotted liners and wire wrapped screens have been the chosen sand control techniques. Recently, a new sand control screen, called precise punch slot (PPS), has found applications in oil-well completions. Originally, punched screens were developed for water well completion. The central distinction of the punched slots used in water well completion compared to oil well completion is that for most cases screens are punched outward and are usually called Bridge slot or louvered slots (Driscol, 1986; Lehr et al., 1988; Roscoe, 1990). The open area to flow of precise punched screens is between 3-15%, compared to 1-3% in slotted liners and 6-12% in wire wrapped screens (Spronk et al., 2015).

As shown in Figure 2.8, PPS is composed of a perforated or slotted central pipe, stainless steel filtration punched slots jacket and backup ring. Many holes are drilled in the base pipe to obtain an effective OFA. The base pipe is usually of API casing or API tubing to provide the structural stability of the screen. The filtration jacket with punched slot, which is often made of high quality stainless steel, is welded onto the perforated base pipe through the backup ring (Anton Energy Services) and serves as a filtration device. In practice, the formation sand cannot easily enter the filtration jacket while the formation fluid can easily flow into the screen through the space between punched slots.

The filtration jacket is very durable against corrosion. Existing criteria for slotted liner and WWS are employed to design PPS slot apertures. The slot aperture is usually designed based on the formation PSD and is between 0.3 to 0.8 mm (0.012” to 0.031”).

PPS screen has been widely used in heavy oil reservoirs such as the Xinjiang Oilfield (CNPC) in china and Fula field in Sudan (Naganathan et al., 2006) and is getting more attention in Canada (Spronk et al., 2015).

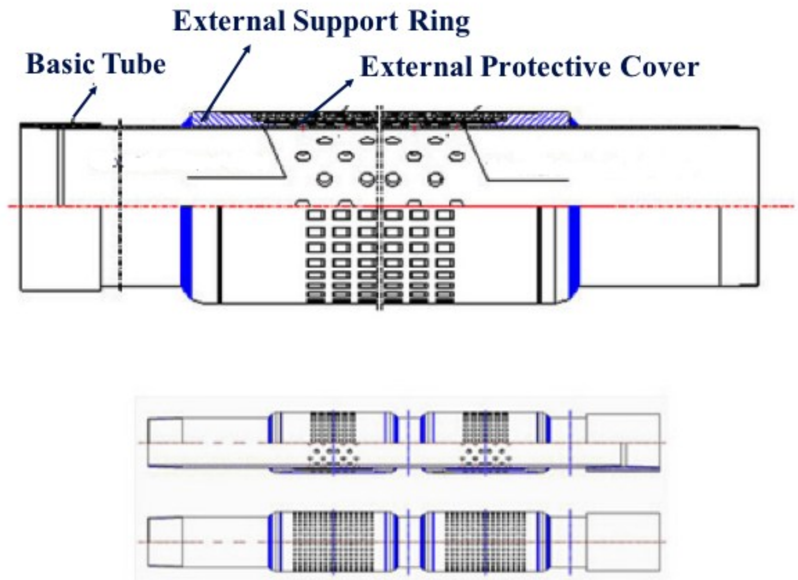
The major characteristics of PPS are (Driscol, 1986; Roscoe, 1990):

1) Precisely controlled width: The aperture of the PPS can be accurately controlled within 0.012”~0.039” and the degree of accuracy is approximately ± 0.00079”.

2) Excellent corrosion resistance: PPS jacket can resist corrosion from acid, alkali and salt as it is made of high quality stainless steel.

3) High body strength and low deformation

4) Lower flow resistance compared to slotted liners due to the higher slot density.



(a)

(b) **(c)**

Figure 2.8: (a) Cross Section of PPS, (b) Precise Punched Screen, (c) Enlarged PPS Mesh (Anton Energy Services)

2.4.2.3 Gravel Packs

Since the first application of gravel pack in oil industry in the 1930s, gravel packs have become the most used mechanical sand control method so far. The implementation of the gravel packs can be simply summarized as preparing the accurately sized gravel slurry on the surface and then pumping the gravel particles together with carrier fluid into the annular space between a screen and open-hole or casing. In this technique, screens are always installed, as shown in Figure 2.9. In other words, this sand control technique consists of implementing a screen in the wellbore and then placing the gravel pack around it. As observed in Figure 2.9, the produced sand from the formation can be retained by the gravel pack and the gravel can be retained by screens (Saucier, 1974). This is a very effective sand control method and can be implemented in both open-hole and cased-hole completions (Figure 2.9).

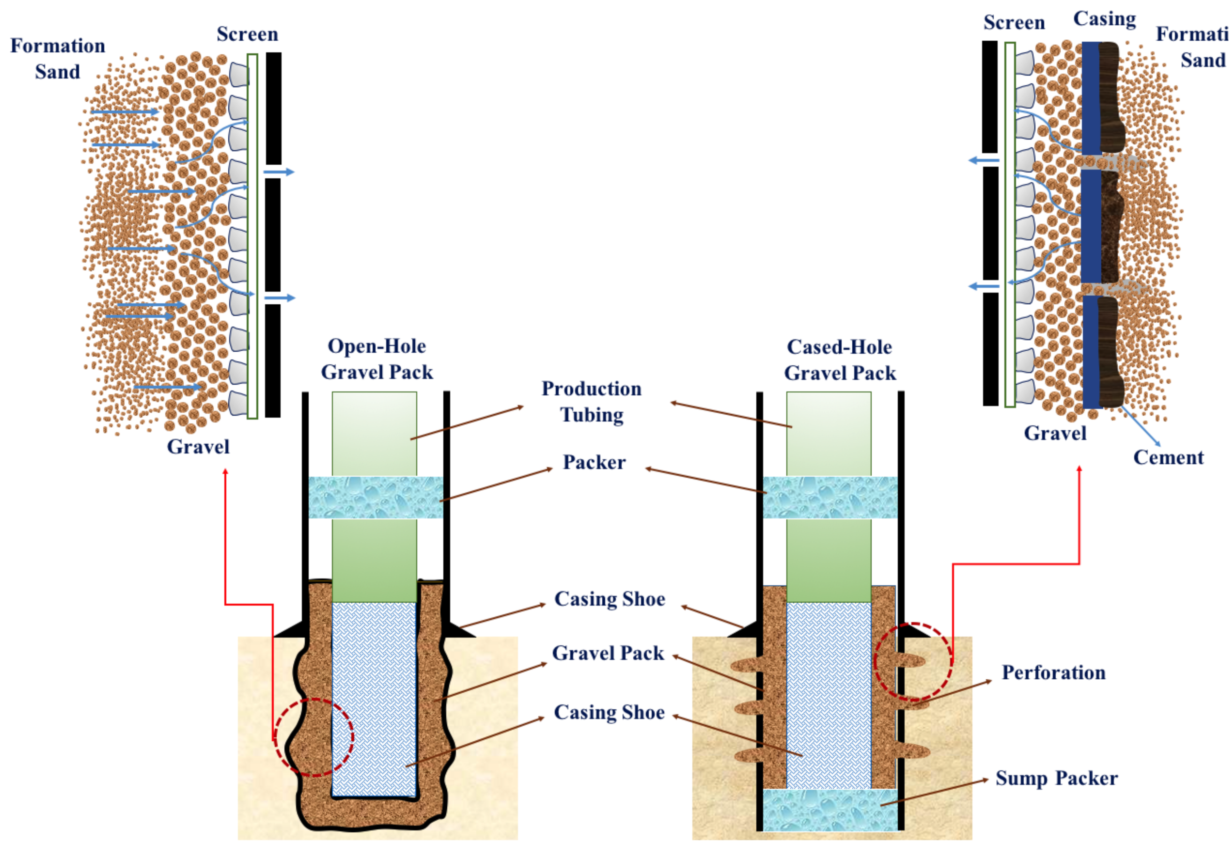


Figure 2.9: Schematic Illustration of the Gravel Pack and Screen Set (a) Open-Hole Completion (b) Cased Hole Completion

Open-hole sand control completions are usually used in consolidated formations with moderate sand production tendency. For the open-hole condition, engineers should pay great attention to the wellbore stability and the formation damage problem. The pressure and temperature changes as well as the presence of sour gases may impair the wellbore completion facilities. In these situations, special equipment capable of withstanding high temperature and high pressure (HT/HP) during the implementation of the gravel packs are installed. With the help of gravel packs and screens, the open-hole completions can have a higher productivity index compared to the cased-hole completion.

Cased hole sand control completions are usually employed to control the sand influx in poorly consolidated formations. This completion requires the engineers to finish the casing installation process to avoid the collapse of the loose formation sands and ensure the safety of downhole facilities. Before the installation of the gravel packs and screens, a sand free condition inside the bore hole is needed. Standalone screens are firstly installed before gravel packs and the inflatable or swelling packers are not needed in the cased hole. Although the cased hole completion would sustain the unconsolidated formation, the production of the hydrocarbon is somewhat impeded compared to the open-hole completion.

2.4.3 Chemical Methods

Since severe sand production problem arises from the weak grain-to-grain bonding in the unconsolidated formation, chemical methods provide an option to prevent the sand influx by enhancing the bonding strength among the formation grains, with the help of chemical treatments. There are different types of chemicals that are used in sand control process (Larsen et al., 2006). The most popular substance is polymer-based chemicals such as resins. In addition, there are some other chemical methods such as precipitation of calcium carbonate. In chemical methods, the focus is placed on the resin injection method. The injected resin would go through the perforations and bond the formation particles. The result of this process is a stable matrix of permeable but consolidated grains formed around the well. Figure 2.10 shows the effect of injected resin on the consolidation of the formation particles. Phenolic, furan and epoxy resins are mostly used in resin injection operations (Carlson et al., 1992).

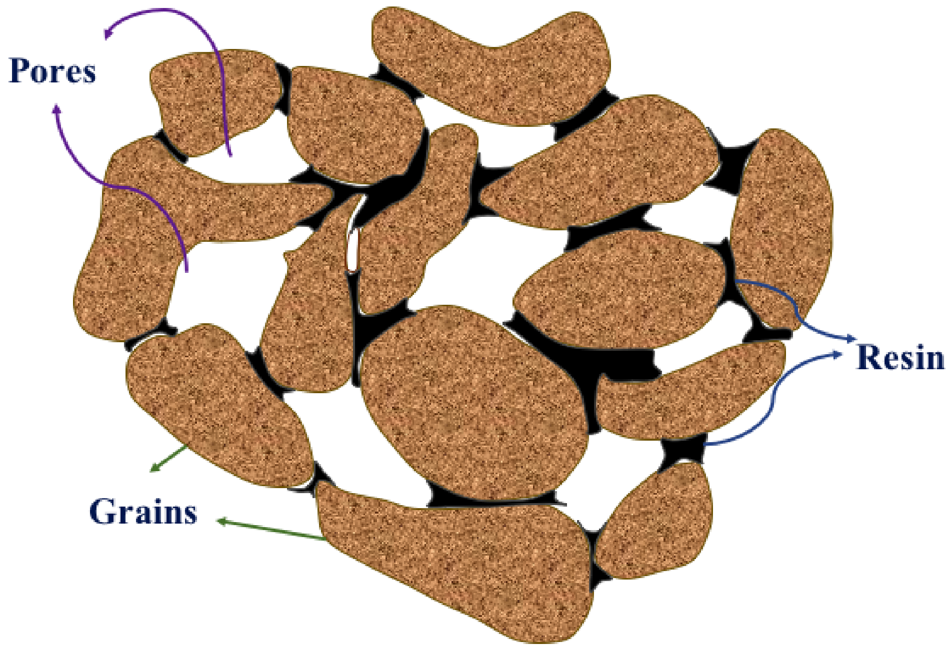


Figure 2.10: Schematic Illustration of Consolidated Grain Matrix After Resin Injection

Several considerations should be taken into account during the resin injection process. Residual water saturation is one of the parameters which can affect the effectiveness of the resin injection (Pelgrom and Wilson, 1990). The existence of the water would prevent the development of the consolidated particle matrix and weaken the consolidation strength. Clay concentration can also impact the formation of stable matrix (Carlson et al., 1992). Therefore, clay stabilizer is usually used in the pre-flush period to minimize the effect of the clay on the sand control performance. Additionally, the amount of injected resin also plays a key role in the success of resin injection. If too much resin is injected into the formation, the permeability of the formed matrix would be too low for hydrocarbon to go through, which would lead to extra pressure loss in the near-wellbore zone. However, no stable matrix would be formed if the amount of the injected resin is not enough. Therefore, an optimization study is required before the resin injection starts.

2.5 Sand Control Tests

The most common types of experimental tests to optimize sand control design consist of slurry sand retention test (Underdown et al., 2001; Williams et al., 2006; Underdown and Hopkins, 2008) and pre-pack sand retention test (Markestad et al., 1996; Hodge et al., 2002; Constien and

Skidmore, 2006; Chanpura et al., 2011). Granular suspension flow through restrictions are the basis for these screen evaluation experiments.

2.5.1 Slurry SRT

The slurry sand retention test is designed to mimic the initial period of circulation/production stage in real-field cases. At that time, 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. Meanwhile, the formation hasn't been disturbed; so, the petro-physical characteristics of the formation (i.e., porosity, permeability, wettability) remain the same.

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). In addition, 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 screens can be positioned relative to the flow in two different ways. In down position, the screen coupon sits at the sample bottom and fluid flow is from the sample top towards the screen coupon. For the up position, the coupon is placed at the sample top and the slurry flow is in the upward direction. In the up-position SRT set up built by Markestad et al. (1996), larger particles hardly flow towards the screen since the flow velocities are not strong enough to lift these sand particles (Underdown et al., 2001; Gillespie et al., 2000; Ballard and Beare, 2003; Mathiasen et al., 2007). Experiments for the flow of granular suspensions through restrictions have been carried out with different solid concentrations, opening sizes and opening shapes (Valdes and Santamarina, 2006; Wakeman, 2007; Agbangla et al., 2012; Guariguta et al. 2012; Lafond et al., 2013; Xie et al., 2014).

According to Vitthal and Sharma (1999), there are several mechanisms for the particle capture in slurry SRT tests. The first mechanism, which is called surface deposition, occurs only if the particles are very close to the collector surface (≈100Å). In this case, the attractive forces between particles and the surface i.e., van der Waals electrostatic or hydration forces, become important.

In the second mechanism which is purely mechanical and is called size exclusion, clogging or straining, the particles are captured when their size is bigger than the opening. In the bridging mechanism, previously captured particles are holding flowing particles to form bridges across the opening. In the last mechanism termed multi-particle hydrodynamic exclusion, many particles attempt to simultaneously pass through the opening, resulting in their capture.

2.5.2 Pre-Pack SRT

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 synthesized commercial sand) 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).

2.6 Design of Sand Control Devices

The overall design objectives of a sand control device are: (1) allowing the maximum production flow rate with lowest pressure drop, or in other words, providing the optimal formation-specific sand control with the lowest plugging level, (2) providing stability of the wellbore against geological stresses, and (3) prevention of the production of the formation sand and the erosion of downhole equipment (Bennion et al., 2009).

Inflow efficiency and sand control performance are the two key parameters in the design. The flow efficiency is mostly controlled by the OFA and the slot width. A larger slot width will result in a lower plugging and, therefore, higher flow efficiency. However, a larger slot width will lead to a lower sand retention performance in the formation. Consequently, an optimum slot aperture must be determined to keep both sanding and plugging at an acceptable level.

2.6.1 Criteria for Sand Control Devices in Conventional Production Wells

Most of studies for developing design criteria for sand control devices are experimental. The earliest work in this area is attributed to Coberly (1937) who conducted a series of tests to establish the mechanism of stable sand bridge behind a slot. He found that a stable bridge of typical unconsolidated oil sands forms when the screen opening is smaller than $2D_{10}$, *with* D_{10} being the sieve opening size that retains 10% of the sample's mass comprised of particles with a diameter larger than this value. No sand bridge can form when the opening aperture exceeds two timesD_{10},. He concluded that the slot width shouldn't be larger than twice the diameter of the coarse 10% in PSD ($w < 2D_{10}$). He also mentioned that when facing a mixture of particles with different diameters, the sand control performance of screens is dependent on the coarse portion of the mixture. The guideline for slot size design that was proposed in that study mainly focused on the acceptable produced sand.

Like Coberly, Suman (1985) proposed his design criterion based on the experimental investigations on synthesized grains with certain particle size distributions to mimic the natural formation sand. He proposed that the slot width should be equal or less than the formation sand's *D10* ($w < D_{10}$). Although he used synthesized grains with certain PSD, both criteria use a single point on PSD curve and the only difference is on the implicitly assumed amount of acceptable sand. Furthermore, to select slot opening based on only one PSD indicator is oversimplified.

Instead of relying on one data point from the particle size distribution (PSD) to describe the entire formation sand character, Markestad et al. (1996) used a more complete description of particle size distribution to characterize the sand control performance and plugging tendency of single wrapped screens. They stated that when considering the sand retention capacity, the slot width should not exceed a certain level. Therefore, the proposed design criteria are given in relation to the sizes of larger particles on the PSD curve. However, when the purpose is to predict the plugging tendency, the fines portion of the PSD curve is of greater importance. In their study, a range of acceptable slot width was provided for a typical sand type. The upper limit was determined by sand retention performance, and the lower limit was selected to avoid plugging. To represent the entire particle size distribution (PSD), they created a descriptive method based on the fractal theory. A series of laboratory experiments was performed to find the safe intervals of slot width. From their result, four slot widths were defined: (1) d_{++}, which is defined as the largest slot width for which severe sanding is observed; (2) d_{--}, which is defined as the smallest slot width for which plugging did occur; (3) d_{+}, which is the largest slot width for which sanding did not occur; and (4) d_{-}, which is the smallest slot width for which plugging was not likely to occur. "d_{++}" and "d_{--}" are the extreme upper and lower limitations that should not be exceeded. The so called "safe interval" was considered to be between d_{+} and d_{-}. However, they didn't quantify such evaluative parameters as "continuous sand production" or "severe plugging" in their research.

Tiffin et al. (1998) suggested to use the formation sand sorting characteristics to develop the selection criteria for different screens. The parameter that they suggested to use was the sorting coefficient. Different from the uniformity coefficient, sorting coefficient represents the entire range of the PSD. They also took the fines (Mesh #325, 44μm) into consideration since they may induce or promote plugging at the near-liner zone.

Williams et al. (2006) tested gravel pack and other screen control devices with two modes of testing: conformance (pre-pack sand retention test) and non-conformance (slurry sand retention test). It was suggested that the openings should be designed to allow less than 6% of sand in the effluent to pass through and the size of the produced sand should be less than 50 μm ($D_{50} \leqslant 50\mu m$).

2.6.2 Criteria for Sand Control Devices in Horizontal Production Wells

Underdown et al. (2001) proposed a standard method to evaluate the performance of sand control screens from different manufacturing companies. Experimental investigations were conducted on several screen types for screen type selection for some wellbores in North Sea and Western Africa. They believed that the design criteria of sand control screen should account for both sand retention and screen plugging. Underdown et al. (2001) defined a parameter called sand control factor and used it to characterize sand retention. The screen plugging was represented by a performance factor which is an indication of the time it takes for the screen to plug. A perfect sand control screen would have a value equal to one for both factors.

Gillespie et al. (2000) proposed a similar method to that of Underdown et al. (2001), named screen efficiency plot. Nomographs were created by plotting the percentage of produced sand versus the rate of pressure build-up. In this situation, the ideal screen should have nearly zero value in the plot. Their experimental work was based on two types of samples: a very fine and uniform sand, and a non-uniform sand. The results of their tests show that for premium mesh-type screens, the recommended slot opening should be 2.5 times mean grain size ($2.5D_{50}$), when the Uniformity Coefficient (UC) does not exceed 6, , while only $2D_{50}$ for wire-wrapped screens. The uniformity coefficient is defined as the ratio of D_{60} to D_{10}in soil mechanics.

In addition to the amount of produced sand and flow capacity reduction, Hodge et al. (2002) developed a new evaluation method that account for the actual permeability reduction of the near-screen layer (sand-retention layer). This procedure, for the first time, quantified the screen plugging. Based on the author's field production experience, the acceptable value of produced sand for long horizontal wellbores in poorly consolidated reservoirs was considered to be 0.12 lbm/sq ft (pound per square feet of screen inflow area). Same parameter of 0.15 lbm/sq ft has been presented for horizontal, open-hole completion by Adams et al. (2009) for oil wells.

In terms of the flow impairment, Markestad et al. (1996) proposed a skin value of less than 0.5 for a well-functioning screen. Burton and Hodge (1998) suggested 20% retained screen permeability for a minimal productivity impairment. Later, Constien and Skidmore (2006) defined the 'effective formation-particle size' which is equal to the media sand size divided by the uniformity coefficient (D_{50}/UC). Based on the effective formation-particle size, they developed the performance master curves to predict the performance of standalone screens. The critical values of three performance indicators were also given: produced sand less than or equal to 0.12 lbm/sq ft; the retained permeability more than or equal to 50%; the size of upper ten percent of produced sand less than or equal to 50 microns ($D_{10} \leqslant 50\mu m$).

2.6.3 Existing Criteria for Sand Control Devices in Thermal Production Wells

Slotted liner is widely used in SAGD operation due to its lower cost and outstanding mechanical strength. However, the sizing rules proposed by previous researchers may not applicable for thermal recovery sand-control device selection. Bennion et al. (2009) presented a lab protocol for accurately simulate the downhole multiphase flow conditions during SAGD operations. Based on over 200 sand retention tests, they found that the clay content of the formation, flow velocity, wettability of formation and pH play crucial roles in the plugging mechanism and productivity of slotted liners. According to Bennion et al. (2009), clays are the main plugging medium in slots, meaning, higher clay concentrations lead to higher plugging potential. In addition, the plugging starts by clay adhering to the slot walls then growing upward to the slot entry.

Fermaniuk (2013) formulated a safe range for the slot opening size for slotted liners in relation to the formation PSD size indicators. The upper and lower bounds for the aperture size in these criteria were set at 3.5 times the mean formation sand size (MaxSW=$3.5D_{50}$), and two times the smaller 30% sand size (MinSW=$2D_{70}$), respectively.

Mahmoudi et al. (2016) provided a set of new design criteria described by a novel traffic light system (TLS). Like Fermaniuk (2013), the design criteria that he proposed was considered as a safe slot window with respect to sand control performance and flow capacity. In his study, a novel pre-pack SRT facility which can be used to test multi-slot coupons was designed to investigate the effect of both slot width and slot density. Furthermore, he also incorporated the flow rate in the design criteria to include wellbore operation practices in the criteria.

2.7 Summary

This chapter presented an overview of the steam assisted gravity drainage (SAGD) technique and the causes, mechanisms, categories as well as the predicative assessments of sand production. The three main techniques of sand control in the field, which are production rate control as well as the mechanical and chemical methods, were also discussed.

The slotted liner is considered as one of the most effective mechanical sand control methods. The most common facilities that have been used for sand retention tests are pre-packed SRT and slurry SRT. Pre-pack SRT simulates the early stage of SAGD process during which the formation collapses on the gap between the sand-face and sand control device, creating a high porosity region in that area. In pre-pack SRT, the mass of produced solids passed through the sand control device as well as the pressure drop along the sand pack and across the screen is measured during the experiment.

This chapter also presented the most common types of experimental tests to optimize sand control design: slurry sand retention test and pre-pack sand retention test. Based on past field experiences, the plugging tendency and flow performance of screens and slotted liners differs greatly depending on the recovery method or formation characteristics. For this reason, the existing design criteria for sand control devices were introduced in this chapter based on their application to (1) conventional production wells; (2) horizontal non-thermal wells; and (3) SAGD wells.

Chapter 3: Experimental Set-Up and Testing Procedure

3.1 Introduction

The experimental research in this thesis was conducted by utilizing a large scale sand control testing facility, named Scaled Completion Test (SCT). The SCT is versatile in accommodating the coupon of any sand control completion. Compared to the conventional SRT set-ups, the SCT facility can employ multi-slot slotted liner coupons with the desired slot density and slot width and can apply different levels of axial and lateral stresses to the sand pack.

This chapter presents a detailed description of the experimental set-up and procedures employed in the current research as well as preparation, packing, and saturation of the specimens. At the end of the chapter, post-mortem analysis and the test matrix are presented.

The hazard assessment for testing procedures is mentioned in Appendix C.

3.2 Experimental Set-Up

A novel pre-pack sand control testing facility was commissioned to study the effect of stress build-up at the oil-sand/liner interface on plugging, stability of sand bridges, and sand production. The test facility allows to simulate different stress conditions (stress levels corresponding to stress variations during the life cycle of a SAGD producer), and through flow tests, the facility can assess the performance of the liner under these different stress levels. The use of multi-slot coupons instead of single slot coupons allows to investigate the role of both slot width and slot density. Figure 3.1 is a schematic view of 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 back-pressure unit.

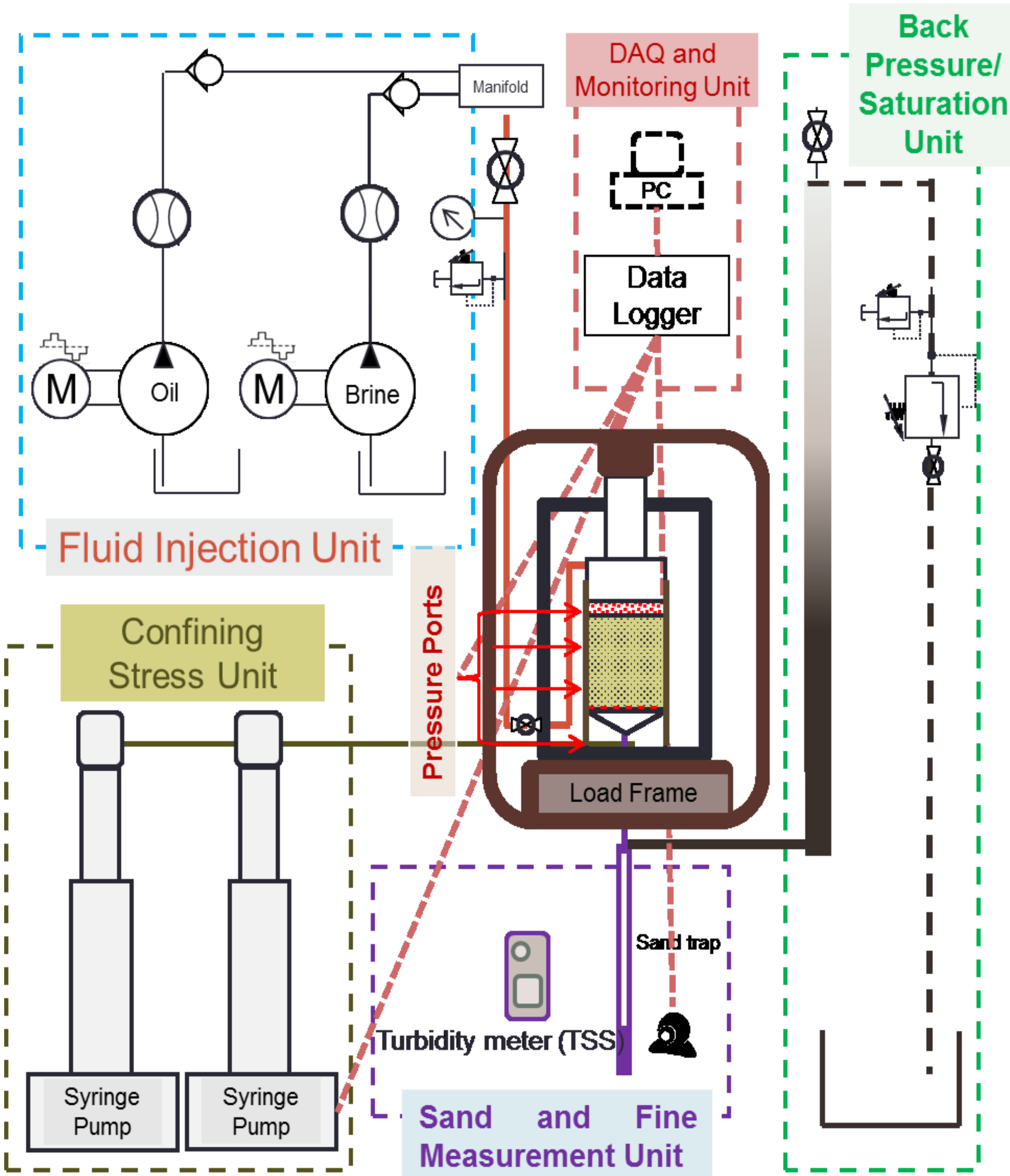


Figure 3.1: Schematic View of Different Units of the SCT Facility

3.2.1 Fluid Injection Unit

The fluid injection unit includes two solenoid diaphragm metering pumps for oil and brine injection. The pumps control the flow rate with a high ratio of 1:33 through manual stroke control and digital pulse control.

Each pump has a maximum flow rate of 22.7 L/hr (6.31×10^{-6} m^3/s) at 2080 psi (14.3 MPa) pressure. The steady state flow accuracy is $\pm1\%$ over a turndown ratio of 10:1. Both pumps are capable to inject brine and oil to the SCT cell at different flow rates. There are two 150-liter reservoirs for brine and oil storage which are acting as the inlet of the pumps. A rotameter (FLDHE 3301S) with maximum flow of 65 ml/min and the standard accuracy of $\pm5\%$ of fall scale is installed at the outlet of the SCT cell to measure the flow-rate every ten to fifteen minutes for verification use. The linear flow variation with the change of stroke and input pulse was verified by calibration curves. The outflow of pumps was also measured for a period of two minutes for verification purposes. Due to the presence of the fines, the outflow of the system was not recirculated.

3.2.2 SCT Cell and Accessories

The SCT cell is a modified large-scale triaxial cell, which can apply axial and lateral stresses onto the sand pack. The triaxial cell has been design for a working pressure up to 5000 psi. The load frame is used to apply axial stress to the SCT cell. It is an Instron frame with the design capacity of 270,000 lbf. Accuracy of the load cell is +/- 0.5% of measured load (reading) from 0.2% to 100% of the load cell capacity. The sand pack (7” in diameter and 8” in height) is enclosed by a membrane in the center of the SCT cell (Figure 3.2). There is an annular space around the sand pack through which oil can be injected to apply confining stress. 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 differentials in the top 4-in. sand pack interval, and the 2-in. interval right above the multi-slot coupon (as shown in Figure 3.3). The permeability changes due to flow disturbance and possible fines migration above the coupon can be investigated through the measurement of pressure differentials.

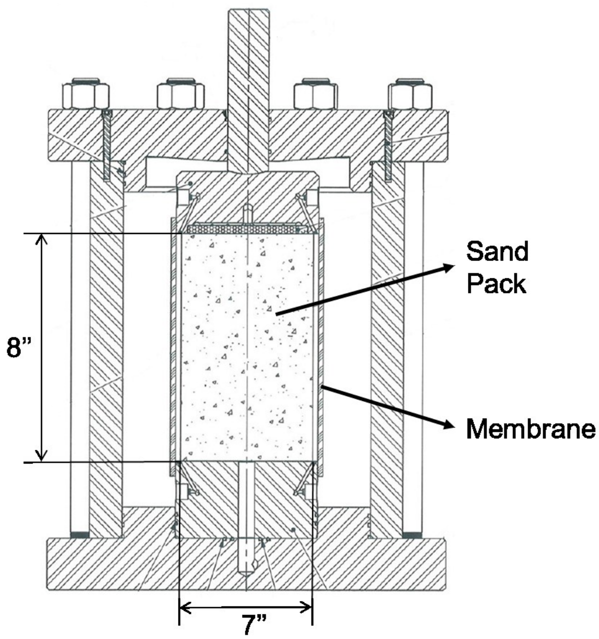


Figure 3.2: Schematic View of the SCT Cell

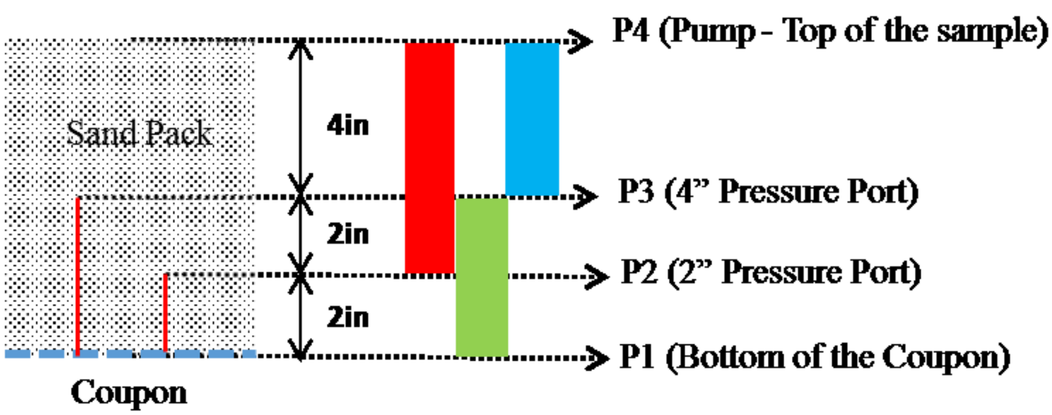


Figure 3.3: Schematic View of Pressure Measurements along the Sand Pack

3.2.3 Confining Stress Unit

The confining stress unit consists of two ISCO pumps (1000D Syringe Pump) with capacity of 1015 ml. The pressure range of the ISCO pump is 10-10000 psi and the standard pressure accuracy is ±0.5% full scale. The flow range of the ISCO pumps is 0.01-408 ml/min and the flow accuracy is $\pm$0.5% of set point. They are used to de-air the annular space of the SCT cell and apply required confining stress on the sand pack.

3.2.4 Data Acquisition and Monitoring Unit

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 (Model USB-6210, National Instruments) is used to collect and record signals from three 0-15 psi pressure transducers (Lucas Schaevitz P3081-15PSIG) through LabVIEW Signal Express software. The combined nonlinearity and nonrepeatability are less than $\pm$5%. An absolute pressure gauge (WINTERS PFQ-ZR) ranging from 0-60 psi with accuracy of $\pm$1.5% of full scale value is installed at the outlet of the pump to record the pump pressure.

3.2.5 Produced Sand and Fines Measurement Unit

The sand and fines measurement unit consists of a specially designed sand trap to capture the produced sand and fines. A back-pressure is applied on the sand trap by the back-pressure unit, so that the sand trap can trap any size of produced sand at the outlet of SCT cell. The rate of produced sand is monitored by a camera (Logitech Webcam HD Pro C920) which monitors the height of produced sand column in a graduated cylinder in the outlet. The total produced sand is collected and weighed at the end of each test and is reported in terms of pound per square foot of the screen to indicate the sand control performance of the liner. A $\frac{1}{8}$-inch tube is also installed exactly beneath one of the slots to collect a representative sample of the produced fines. The effluent through this tube is collected at certain intervals. A metering needle valve is connected to the tubing to collect 100-cc outflow samples at certain time intervals. The particle size distribution (PSD) of the produced fines is determined by using a laser diffraction sensor (Sympatec GmbH, HELOS/BR) with $\pm$1% deviation with respect to the standard meter.

3.2.6 Back-pressure Unit

The backpressure unit consists of a column that allows the application of up to 200 psi backpressure using a pressure regulator, and provide the required path for effluent. The hydrostatic pressure supplied by the back-pressure column provides a low flow rate (60 cc/min for the sand pack used in these experiments) to avoid channeling and fingering during the sand saturation process.

3.3 Pre-Pack SRT Facility

In addition to the SCT facility, the pre-pack SRT facility (Figure 3.4) was also employed to complete the test matrix. Since the primary difference between the pre-pack SRT and SCT is the near-zero-stress for the SRT, it can be assumed that SRT simulates the early life of the SAGD well, when the effective stress around the liner is low. A review of the main units of this facility is presented below. Further details about the pre-pack SRT facility and the testing procedure can be found in Mahmoudi et al. (2016).

1) Fluid injection unit, which includes a diaphragm pump to inject brine at the rate and pressure of 7.6 L/hr and 50 psi, respectively.

2) SRT cell, which includes: (a) a sand pack, (b) a multi-slot coupon at the bottom of the sand pack, and (c) porous stones at the top of the sand pack to provide a homogenous fluid flow regime.

3) Sand and fines measurement unit, which comprises of the sand trap to capture the produced sand and a tube for sampling the produced fluid. The mass of the produced fines (< 44 μm) is measured using the turbidity of the produced fluid samples. The PSD of the produced fines is determined by using a particle size analyzer.

4) Back-pressure unit, which provides a minor pressure on the sand pack during the saturation phase and on the sand trap.

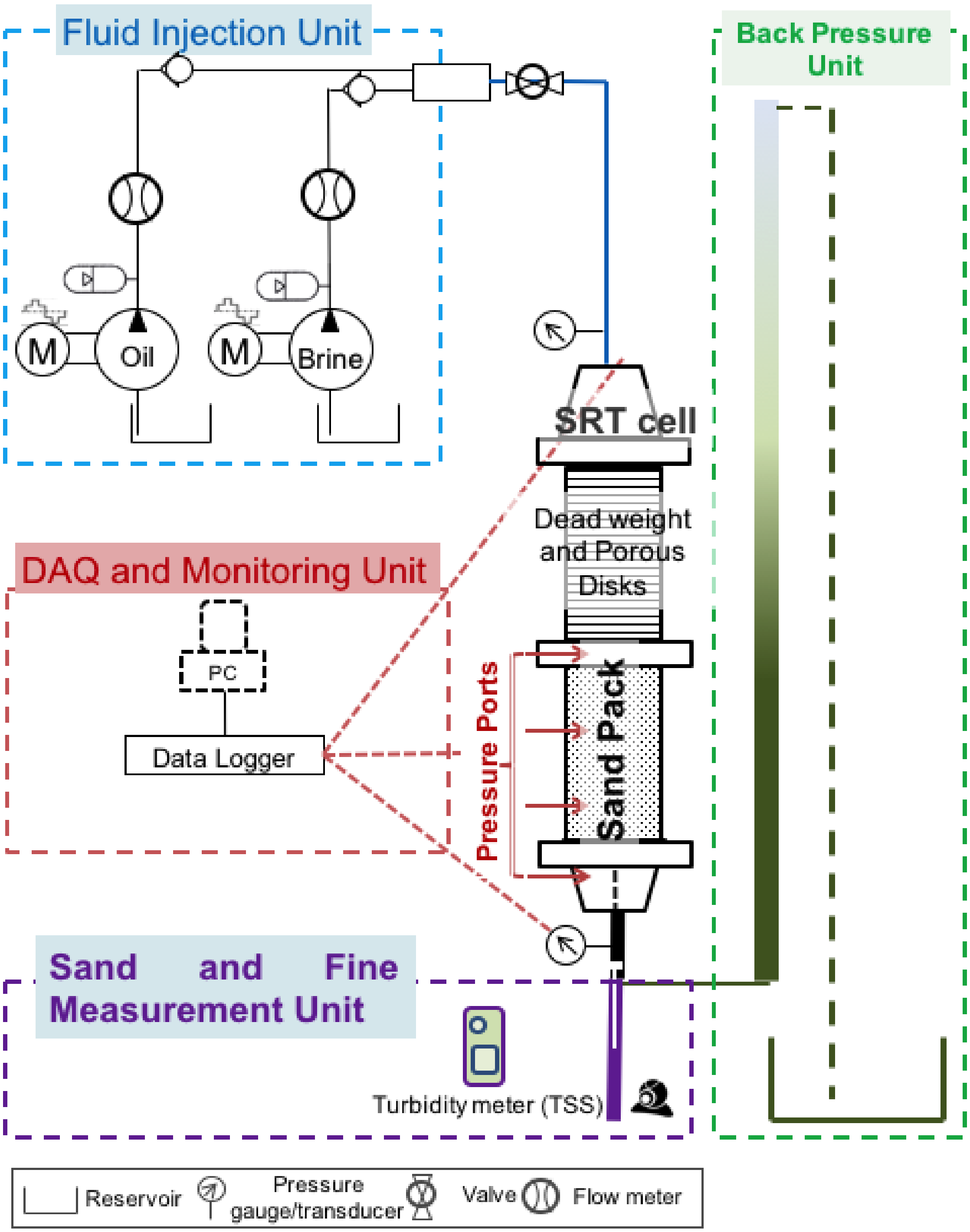


Figure 3.4: Schematic View of Different Units of the SRT Facility

3.4 Testing Material

Fluid pH and salinity in SAGD environment are highly variable due to the injection of steam as well as invasion of underground water and formation acid gases. Several researches have attempted to investigate the effect of salinity and pH on screen plugging tendency (Khilar and Fogler et al., 1984; Bennion et al., 2009; Mahmoudi et al., 2015). They found that 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). In this study, sodium chloride brine was used with a salinity of 0.7% (7000 ppm) as the injection fluid since the dominant ions that are present in SAGD effluent are sodium and chloride. The use of NaCl (monovalent cations) seems to result in a strong tendency for fines migration and plugging. Therefore, NaCl can be used for simulating the worst-case scenario 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 SAGD operation since such an environment tends to disperse and mobilize fines and, consequently, increase plugging. The sodium chloride brine was prepared by dissolving sodium chloride into deionized water, and the pH of brine was calibrated by a pH booster (sodium bisulfate $NaHSO_4$) right before testing. All tests were conducted at a constant fluid salinity and pH value.

Sand pack samples used in the experiments were prepared by mixing commercial sands and fines with a certain proportion to duplicate the Class II Devon Pike 1 PSD for the McMurray formation as proposed by Abram and Cain (2014). According to the mechanical testing presented in 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). The prepared samples using commercial sands mixture shows similar mechanical properties to those of real oil sand at lower cost, which is suitable for large-scale sand retention testing. Figure 3.5 shows the comparison between the PSD of Class II and the PSD of duplicated sands and fines mixture used in the testing.

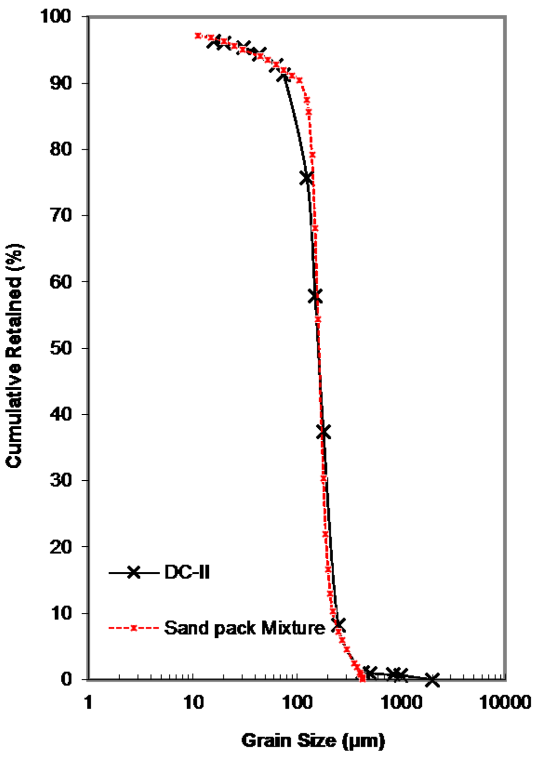


Figure 3.5: Particle Size Distribution (PSD) of the Tested Sand Pack Mixture and Class II Devon Pike 1 (DC-II) Project Categorized by Abram and Cain (2014)

The multi-slot coupons that were used are all manufactured with a seamed slot opening. The coupons were manufactured and provided by the slotted liner manufacturer RGL Reservoir Management to represent a portion of the actual liner as shown in Figure 3.6.

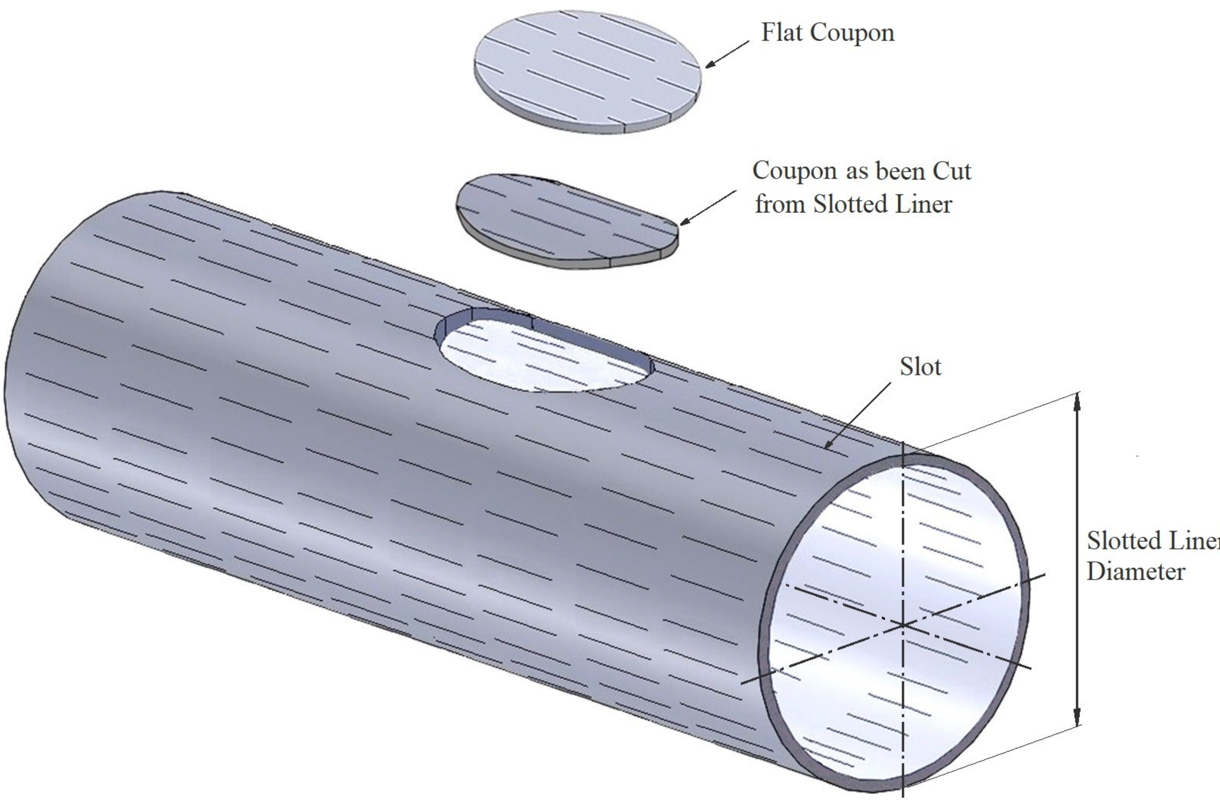
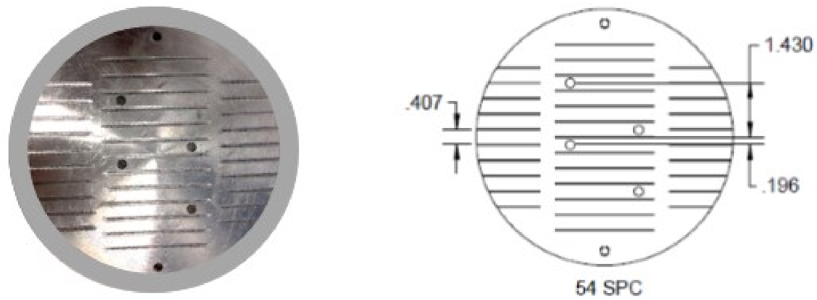
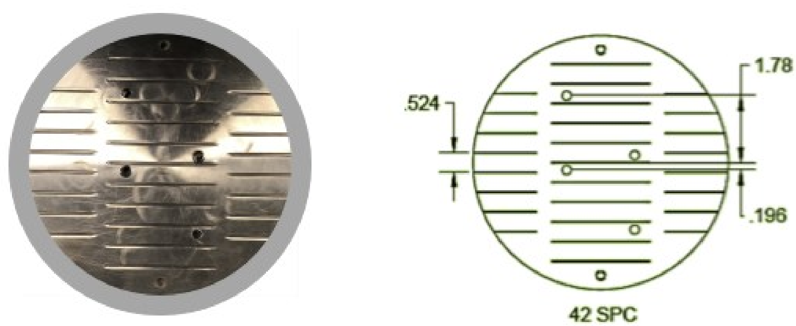


Figure 3.6: Schematic View of Multi-Slot Coupon as a Section of a 7-Inch Slotted Liner

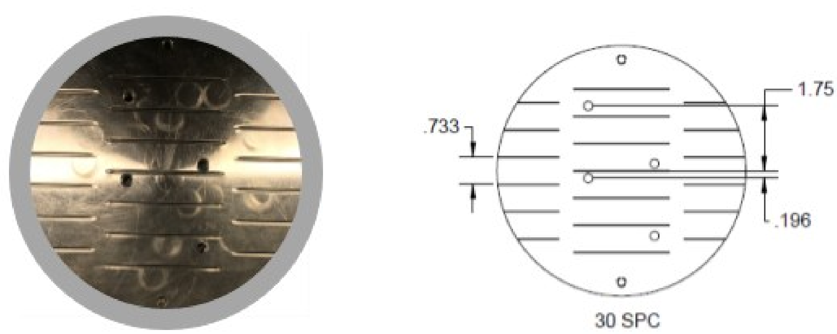
The use of multi-slot coupon instead of single slot coupon allows to capture inter-slot interactions and, consequently, the effect of slot density. Slot density is often represented by Slot Per Column (SPC). In this study, coupons with slot width of 0.014'' to 0.022'' (SPC: 54), 0.018'' to 0.026'' (SPC: 42) 0.026'' to 0.034'' (SPC: 30) and 0.014" to 0.022" (SPC:30) were tested. Figure 3.7 shows the schematic view of the employed coupons.



(a)



(b)



(c)

Figure 3.7: Multi Slot Coupons, (a) Image and Dimension of Seamed Coupon 0.022''-0.014''(in) SPC: 54; (b) Image and Dimension of Seamed Coupon 0.026''-0.018'' (in) SPC: 42; (c) Image and Dimension of Seamed Coupon 0.034''-0.026'' (in) SPC: 30

3.5 Testing Procedure

A testing procedure was designed and strictly followed for all tests. Figure 3.8 shows the SCT testing procedure when the effective stress of 700psi was used, as an example. Synthesized sand packs were made by mixing commercial sands with various proportions. The sand pack was de-aired under 25 psi confining and followed by a 1-hour saturation phase. The applied confining stress was increased to a target value by the load frame and ISCO pump. When the target was reached, fluid was injected to the cell for two hours long enough to allow the pressures and fines migration to reach steady-state condition (Figure 3.9). Next was the unloading step, in which the confining and axial stresses were gradually removed. The detailed description of the whole test is provided in the following sections.

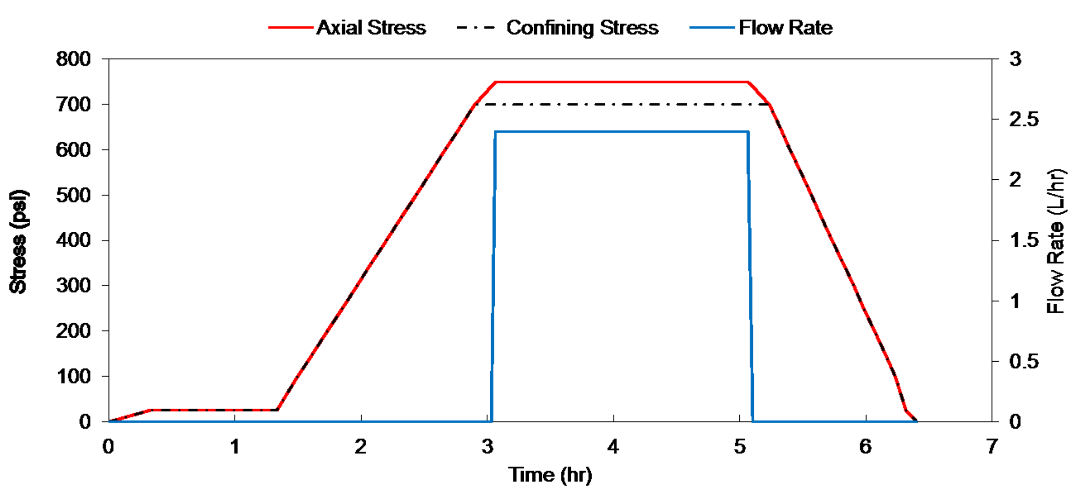
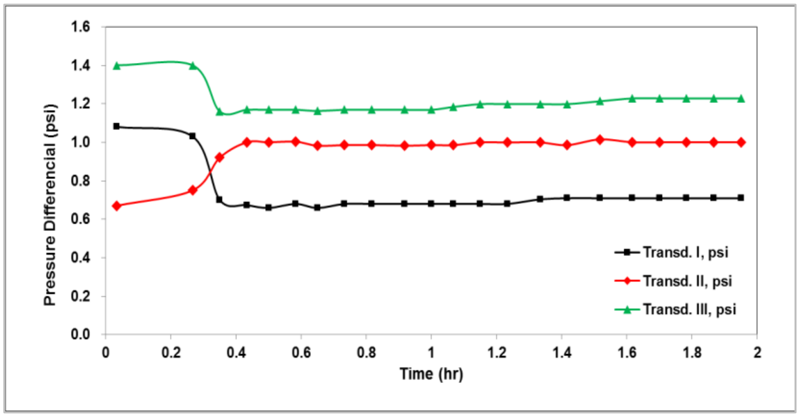
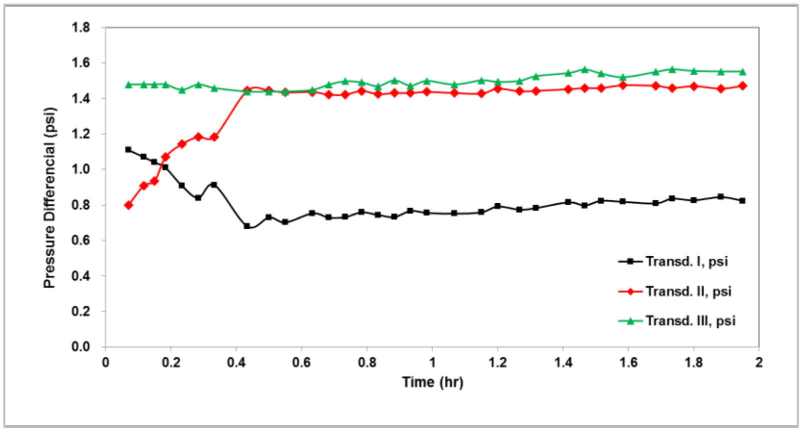


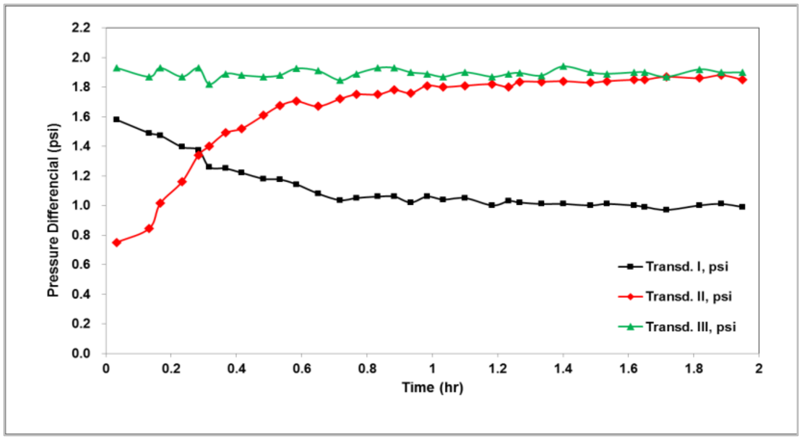
Figure 3.8: Testing Procedure of 700 psi Effective Stress SCT Test


Pressure Differencial (psi)
Time (hr)
Transd. I, psi
Transd. II, psi
Transd. III, psi

(a)


Pressure Differencial (psi)
Time (hr)
Transd. I, psi
Transd. II, psi
Transd. III, psi

(b)


Pressure Differencial (psi)
Time (hr)
Transd. I, psi
Transd. II, psi
Transd. III, psi

(c)

Figure 3.9: Pressure differentials during injection of tests with (a) 300 psi; (b) 500 psi; (c) 700 psi

3.5.1 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 formation sand. The fines part of the sample comprises of 80% kolinite and 20% illite. These two clay types are the dominant clays existing in 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%. Based on the predetermined porosity of the sand pack, the total weight of dry sand needed was 9.29 kilograms. Unlike other published apparatus in which the thin sand layer is not enough to investigate the fines transportation or aggregation in porous media, this adequate amount of sand volume offers a more realistic slot performance under large-scale sample geometry. Different types of dry sands and fines were weighted and mixed in a large plastic 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 moist tamping method to gain uniform porosity and permeability (Ladd, 1978).

3.5.2 SCT Cell Assembling

For the SCT cell assembling, first the bottom platen was mounted, then the multi-slot coupon was installed on the specially designed coupon disk, and then corresponding tubes were connected. The sand was compacted above the multi-slot coupon, and the top platen and porous stone were placed over the sand pack. This step was followed by the installation of the other parts of the triaxial cell. Next, oil was pumped into the annular space of the triaxial cylinder to apply confining pressure onto the sand pack. The piston was installed to close the cell and lay right on top of the platen. The function of the piston was to transfer the axial load to the sand pack. When the cell was ready for testing, it was placed in the load frame, and related tubes were connected.

3.5.3 Sample Saturation

The initial water content 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 back-pressure column (approximately 1.9 psi). This small back-pressure 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. After having about 300 cc of the fluid being produced from the top of the sample, it was assumed the brine saturated the sand pack. Then the saturation process was stopped by closing the valve connected to the top of the sample. When the saturation was completed, the valve arrangement was changed from saturation mode to production mode, and the inlet was switched to the top of the sand pack for the subsequent injection. In the next step, the pressure transducers and related tubes were connected.

3.5.4 Effective Stress

Confining stress was increased gradually to reach the required stress level. The injection rate of ISCO pump was carefully monitored to avoid any leakage inside of the SCT cell. The cumulative injection volume was recorded to estimate the porosity change of the sand pack under compaction. At the same time, the axial stress controlled by the load frame was increased to reach the target input stress. Fluid injection started after confining and axial stress levels were reached.

3.5.5 Flow Injection

Flow injection was the main part of the test in which brine was injected downward through the sand pack and toward the multi-slot coupon. The duration of flow injection was two hours. The total flow rate adopted in this study was 40 cc/min (0.36 bbl/day) which was kept constant during the two hours. The applied flow rate was selected consistent with typical flow rates in SAGD wells.

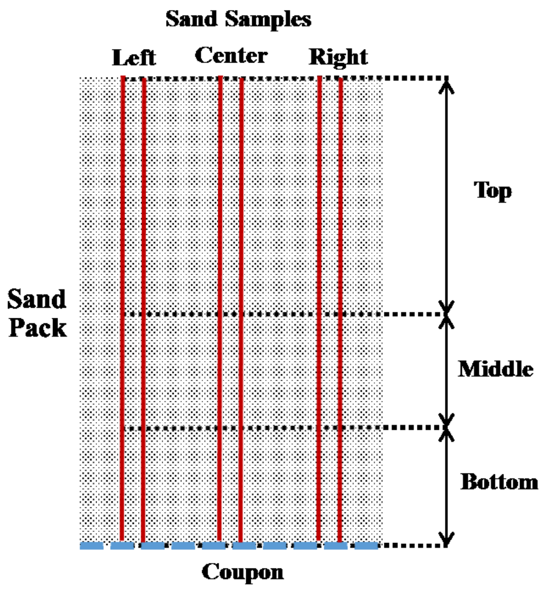
The use of real SAGD flow rate provides a more reliable analysis of screen performance instead of exaggerated rates that may not exist under real-field flow condition.

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 flow injection to measure its fines concentration. The total accumulated sand was collected at the end of flow injection and was considered as the cumulative produced sand.

3.5.6 Post-Mortem Analysis

After disassembling the cell, several samples were collected across the sand pack to investigate the fines concentration. The fines concentration was considered as a direct indicator of fines migration. Before each test, the initial fines concentration was measured as a reference for later comparisons. The after-test samples were taken from different parts of the sand pack by a 0.5-inch PVC tubing (Figure 3.10). The samples were dried at room temperature and then crushed. Then, the crushed powders were wet sieved, and the particles larger than 44 μm were separated and weighed. The fines portion (smaller than 44 μm) was collected, and its particle size distribution (PSD) was determined by a laser diffraction sensor (Sympatec GmbH, HELOS/BR) to investigate the severity of the fines migration and the size range of the migrated fines.

(a)



(b)

Figure 3.10: Sample Obtaining

3.6 Test Measurements 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. The detailed standard procedure for all the measurements is introduced in Appendix B.

The uncertainty analysis is also performed for each measurement. The produced sand is obtained by a lab balance in grams and is converted to lb/sq ft by multiplying by a constant (c) based on the coupon area. The corresponding uncertainty can be calculated by E.q. (3.1). ΔW is the absolute uncertainty of cumulative produced sand and Δw is the uncertainty of measurements read from the lab balance ($\pm$0.001g).

$$\Delta W = c * \Delta w \tag{3.1}$$

The retained permeability is a function of flow rate and corresponding pressure drop adjacent the coupon. The uncertainty of retained permeability is the combination of these two uncertainties, which can be calculated by using Eq. (3.2). $\Delta k_{retained}$ 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.

$$\Delta k_{retained}=\sqrt{\left(\frac{\partial k_{retained}}{\partial P}\right)^2 (\Delta P)^2 + \left(\frac{\partial k_{retained}}{\partial q}\right)^2 (\Delta q)^2} \tag{3.2}$$

The uncertainties of the fines concentration along the sand pack can be obtained by Eq. (3.3) 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.

$$\Delta c = \left|\frac{m_{fine}}{m_{total}}\right| \sqrt{\left(\frac{\Delta m_{fine}}{m_{fine}}\right)^2 + \left(\frac{\Delta m_{total}}{m_{total}}\right)^2} \tag{3.3}$$

The fines PSD 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 measurements in all related figures in next chapters.

3.7 Test assumptions and limitations

The simplifying assumptions of the SCT test include:

1) A typical SAGD well produces oil and condensation induced water with a steam oil ratio of 1.5-4 (Mahmoudi, 2016). However, the research presented in this thesis simulates the worst-case for sand production and pore plugging (without consideration of steam breakthrough) by employing single-phase brine flow (Mahmoudi, 2016). The fines and clays tend to disperse and mobilize in single-phase brine which in turn increases the plugging potential. 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 have been observed to be the dominant ions in produced water from SAGD production wells. The fines and clays are more prone to migration in brine containing monovalent cations (Mahmoudi et al., 2016). 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. However, 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 (Mahmoudi et al., 2015). Since over 10 kg of sand is needed for each test, it was impractical to use real formation sand. Also, it is hard 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’’ 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 stream chambers grows over time and the stresses distribution around the liner also change. However, the stress conditions in all the SCT tests were isotropic. Anisotropic conditions should be investigated in a future study.

3.8 Test Matrix

Based on the existing design criteria from RGL (Appendix A), three slot widths of 0.014'', 0.018'' and 0.026''and three slot densities of 30, 42 and 54 slots per column (SPC) were chosen to conduct the SCT tests. Table 3.1 shows the testing matrix, some of which will be conducted in the future. The slot width covers the proposed upper bound of the screen design criteria for the PSD of Class Ⅱ Devon Pike 1 project (fine to very fine sand) in the McMurray Formation. For each coupon, experiments with five lateral effective stresses ranging from 0 to 700 psi is considered. In each test, the axial effective stress, which was parallel to the direction of the sand pack cylindrical axis, was slightly higher (50 psi) than the radial effective stress. The results of pre-pack SRTs (sand retention test) with consistent coupon and testing material were considered as zero effective stress situation. Five effective stresses were chosen to cover the time-dependent effective stress changes around the liner during the production. The testing consisted of three coupons with effective stresses 0 psi, 300 psi, 500 psi, and 700 psi. The rest of the experiments will be performed in the future to gain a better understanding of the liner performance under compaction and effective stress build-up.

Table 3.1 Testing Matrix

SW, thou	SPC	OAF, %	Applied Confining Stress, psi	Flow rate, L/hr
0.014"-0.022"	54	3	0, 300, 500, 700	2.4
0.014"-0.022"	42	2.2	Not Performed	
0.014"-0.022"	30	1.6	300	
0.018"-0.026"	54	3.7	Not Performed	
0.018"-0.026"	42	3	0, 300, 500, 700	
0.018"-0.026"	30	2.05	Not Performed	
0.026"-0.034"	54	5.4	Not Performed	
0.026"-0.034"	42	4.2	Not Performed	
0.026"-0.034"	30	3	0, 100, 300, 500, 700	

3.9 Summary

This chapter presented a novel pre-pack SRT test facility, named Scaled Completion Test (SCT). It can apply stress both axially and radially onto the large-scale sand pack. The SCT facility consisted of six main units: fluid injection, SCT cell, data acquisition and monitoring unit, sand and fines measurement unit, confining stress and back-pressure unit. Brine with monovalent cation (Na^+) was used as the injection fluid. Synthesized commercial sands with similar PSD to that of Class II Devon Pike 1of the McMurray Formation (DC-II) were used as the sand pack. The testing procedures were also introduced in this chapter. This study used the method of parametric testing to investigate the effect of stress buildup, slot width as well as the slot density. The testing matrix was also included to provide a better understanding of the parameters that were used.

Chapter 4: Effect of Effective Stress on Liner Performance in SAGD Operations

4.1 Introduction

The main considerations in slotted liner design are avoiding excessive sanding while maintaining high flow efficiency. Therefore, two indicators, the sanding resistance performance and the flow performance, were considered in this research to evaluate the performance of the slotted liners. In this study, the cumulative produced sand at the end of testing is measured as a direct indicator of sanding resistance performance. The value of 0.12 lb/sq ft is adopted as the maximum acceptable sand production (Mahmoudi, 2017). The calculated retained permeability is chosen as the indicator of screen flow performance, and 50% of original permeability value is considered to be the minimum acceptable limit.

The retained permeability is defined as the ratio of near-screen permeability to the initial formation permeability (Figure 4.1). The sand pack is separated into three sections: top, middle and bottom. The permeability for each section is shown in Eq. 4.1-4.3. In this study, the 2-inch interval immediately above the coupon was considered as the near-screen zone. It is noted that the calculated retained permeability is the ratio of permeability of this 2-inch sand interval to its initial permeability (Eq. 4.1).

$$k_t = \frac{q\mu L_t}{\Delta P_t A} \tag{4.1}$$

$$k_m = \frac{q\mu L_m}{\Delta P_m A} \tag{4.2}$$

$$k_b = \frac{q\mu L_b}{\Delta P_b A} \tag{4.3}$$

$$k_{retained} = \frac{k_b}{k_{original}} \tag{4.4}$$

Where q is the flow rate; μ is the viscosity of the flowing fluid; A is the cross-section area of the sand pack. L_t, L_m and L_b represent the length of top, middle and bottom sections of sand pack, respectively. ΔP_t, ΔP_m and ΔP_b represent the pressure drop of top, middle and bottom sections of sand pack, respectively. k_t, k_m and k_b represent the permeability of top, middle and bottom sections of sand pack, respectively. $k_{retained}$ is the retained permeability of the near coupon zone (bottom section) and $k_{original}$ is the original permeability of the sand pack.The retained permeability drops below unity because of the combined effect of the plugged slots, pore plugging, and the flow convergence above the slot openings. In this study, the focus is on the effect of pore plugging on retained permeability. To quantify the fines migration and plugging tendency, the fines concentration of the near-coupon zone (2'' above the coupon) and the produced fines in the outflow are measured and analyzed.

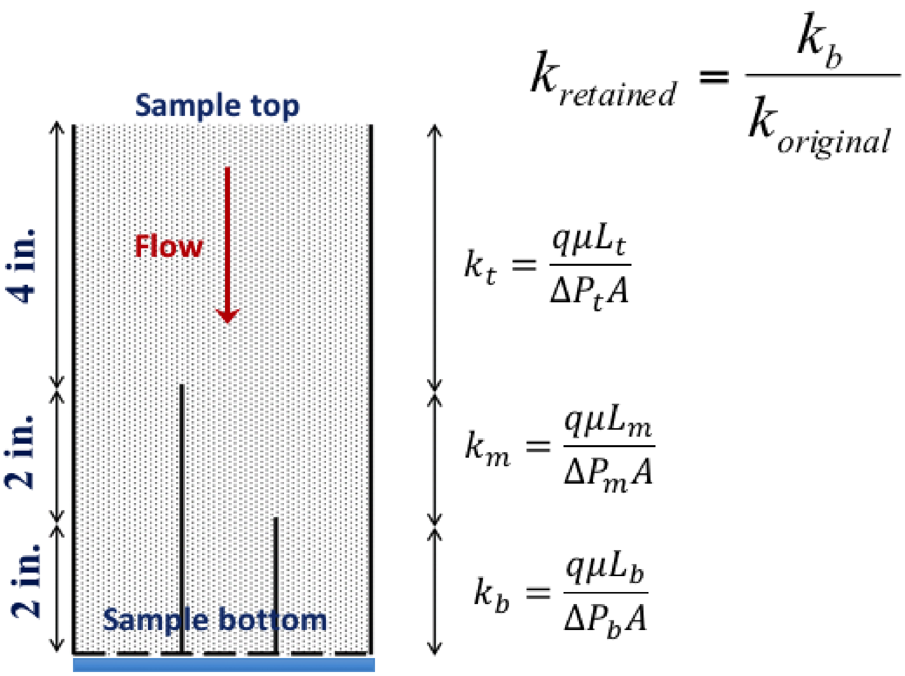


Figure 4.1: Retained Permeability

This chapter presents the results of the investigation on fines migration, sand production, and retained permeability from large-scale testing of unconsolidated sand packs. Artificial sand packs with controlled properties (grain size distribution, grain shape, and mineralogy) were utilized in the SCT assembly and various levels of stresses were applied to the sand packs in directions parallel and perpendicular to the multi-slot coupon. Brine was injected from the top of the samples towards the coupon. At each stress level, the mass of produced sand/fines as well as pressure drop across the sand pack were measured. Furthermore, fines migration phenomenon was investigated by measuring fines/clay concentration along the axis of the sand pack.

4.2 Testing Program

In this section, the Scaled Completion Test (SCT) assembly described in Chapter 3 was utilized with three slotted liner coupons under different effective stresses. Table 4.1 shows the testing matrix which consists of three coupons and different stress levels. According to the particle size distribution of Devon Pike 1 (DC-II), RGL design criteria result a safe slot window from 0.010'' ($2.00D_{70}$) to 0.023'' ($3.50D_{50}$) (Table 4.2). The testing coupons were selected based on the upper and lower bounds of the safe slot window. As the fines content of DC- II was higher than 5.5%, the profiles of all tested coupons were seamed as per the criteria used by RGL Reservoir Management Inc. For each coupon, the testing program was conducted at different lateral effective stresses of 300, 500 and 700 psi. SRT tests with the same testing materials and procedure were also performed and considered for zero 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 typical SAGD operations.

Table 4.1 Testing Matrix to Study the Effect of Stress Build-Up on Liner Performance

Slot Width (thou)	SPC	Effective Stresses
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

Table 4.2 Slot Width from RGL Criteria

DC-II	Min. slot Width	Max. slot Width
	0.010” ($2D_{70}$)	0.023” ($3.5D_{50}$)

Sodium chloride (NaCl) brine with pH 7.9 and salinity of 7000 ppm was injected as the flowing fluid. All tests were conducted under the constant flow rate of 40 cc/min. To duplicate DC-II, the sand pack was prepared by synthesizing commercial sands based on a recipe proposed by Mahmoudi et al. (2015). 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.

4.3 Result and Discussion

4.3.1 Cumulative Produced Sand

Figure 4.2 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 and less produced sand. The testing results indicate that the sand resistance performance of the liner was significantly affected by the effective stresses around the liner.

Figure 4.2 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. Since the slot width of 0.026’’ is slightly higher than the maximum proposed design criteria for DC-II, this result agrees well with the RGL design criteria. 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.

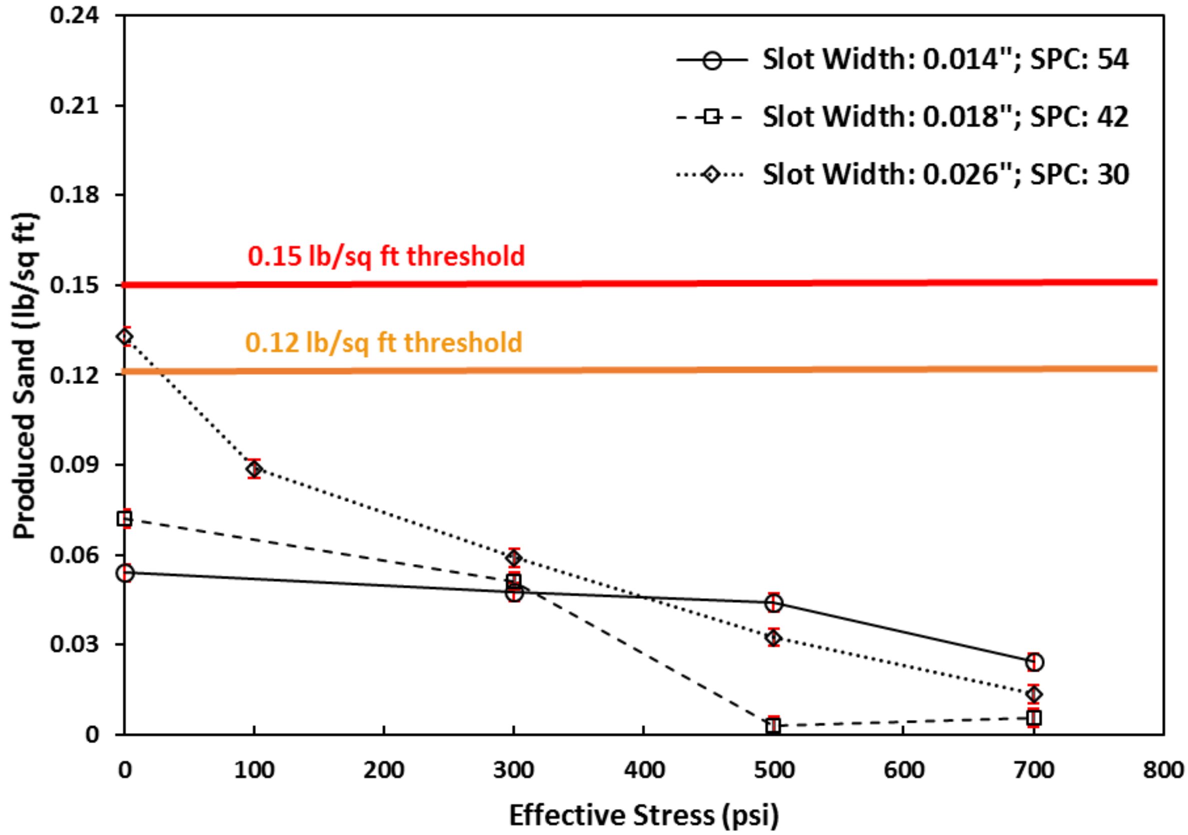


Figure 4.2: Cumulative Produced Sand vs. Effective Stress; Solid Lines are the Upper Limits of Acceptable Produced Sand of 0.12 lb/sq ft and 0.15 lb/sq ft

4.3.2 Retained Permeability

Figure 4.3 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 stress resulting in lower porosity and permeability for the sand pack, hence, narrower pore throats for the flowing fluid to pass through. The narrower pore throat leads 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 result in an increased plugging potential and a lower retained permeability.

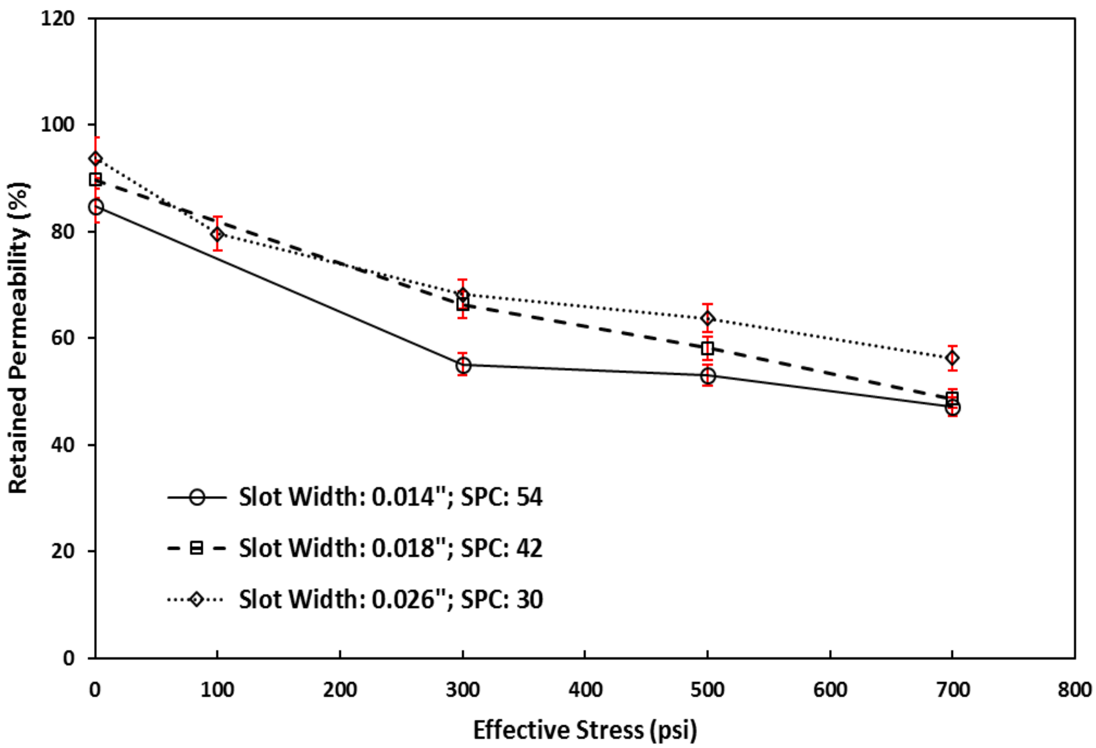


Figure 4.3: Retained Permeability at the Near-Coupon Zone vs. Effective Stress

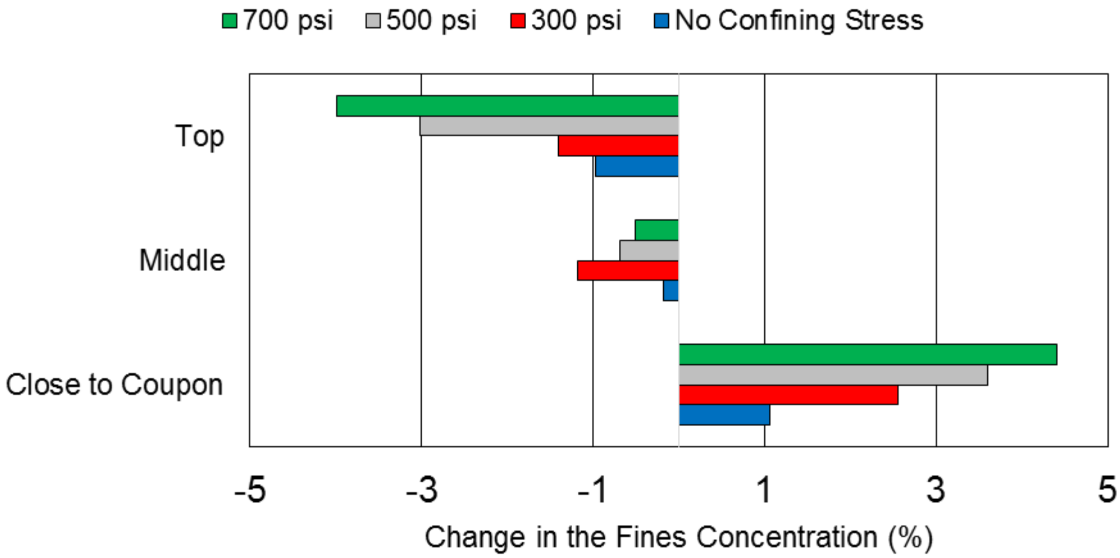
4.3.3 Fines Migration

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/clays 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 slot and gradually infill around the sand grains to partially or fully plug the slot (Romanova et al., 2015). The combination of these two types of plugging results in a reduction in retained permeability. In this study, no severe plugging was observed inside the slots at the end of tests. Pressure measurement also indicated negligible pressure drops across the coupon. Hence, the investigation mainly focuses on the plugging in the sand pack, and the retained permeability in this study is calculated as the ratio of near-coupon permeability (not including the screen) to the original sand pack permeability. To capture the fines migration, the fines content along the sand pack was measured after the test completion.

Figure 4.4 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) should be 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 should be higher than the initial values. Figure 4.4 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) the pore throats are smaller and flow velocity at pore level is higher for same flow rates resulting in stronger drag forces. Further, pressure induced seepage forces are higher for lower permeabilities due to the higher pressure gradients along the sand pack.

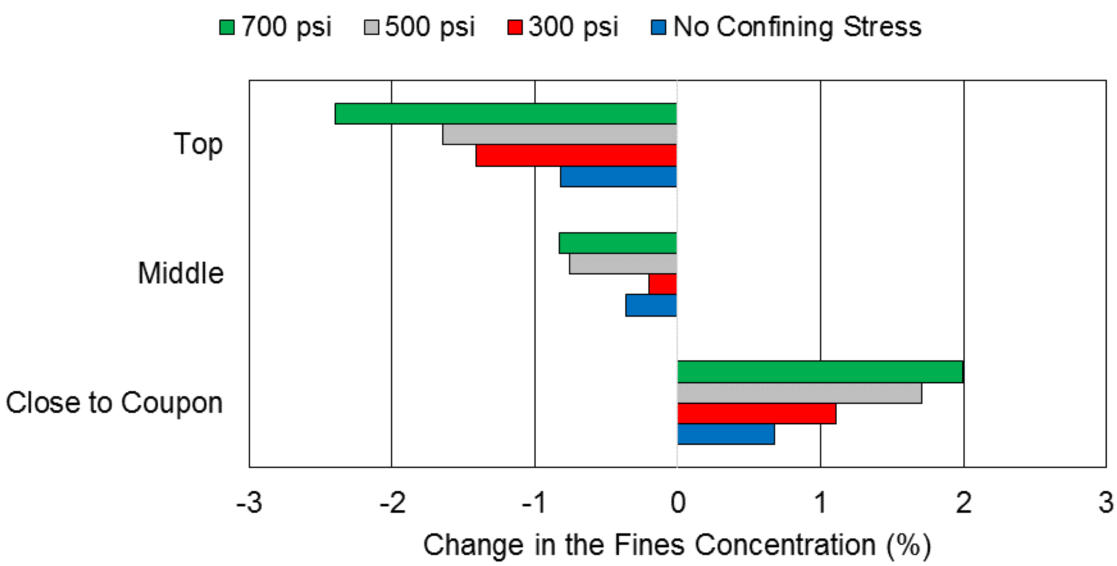
The comparison of Figures 4.4a to 4.4c indicate less fines accumulation at the near-coupon zone for smaller SPC and wider slots. Since the OFA is constant, the effect of slot width on fines migration is stronger compared to slot density. When the OFA is constant, wider slots and smaller SPC force the flow convergence to begin further away from the coupon (Kaiser et al. 2000). A wider extent of the flow convergence disturbs the sample further away from the coupon and produces more fines through the coupon. Therefore, less fines accumulation is observed at the vicinity of the coupon for wider slots and smaller SPC.

The fines concentrations at the top parts of the sample are almost the same for all three coupons at same stress level. This indicates that the fines migration far away from the coupon is mainly affected by the flow velocity in porous media. There is no obvious trend observed for the fines concentration of the middle part.



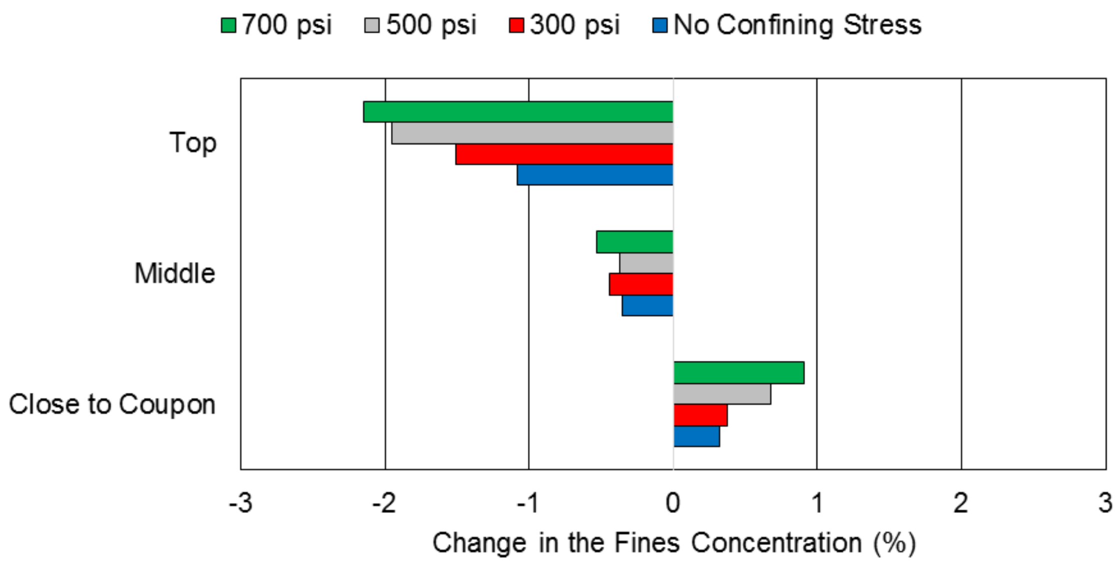
700 psi
500 psi
300 psi
No Confining Stress
Top
Middle
Close to Coupon
-5
-3
-1
1
3
5
Change in the Fines Concentration (%)

(a)



700 psi
500 psi
300 psi
No Confining Stress
Top
Middle
Close to Coupon
-3
-2
-1
0
1
2
3
Change in the Fines Concentration (%)

(b)



(c)

Figure 4.4: Changes in Fines Concentration along the Sand Pack under Different Effective Stresses (a) For Coupon: 0.014’’-0.022’’ SPC: 54; (b) For Coupon: 0.018’’-0.026’’ SPC: 42; (c) For Coupon: 0.026’’-0.034’’ SPC: 30

4.3.4 Particle Size Distribution 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 4.5 shows the fines PSD curves at the top, middle, and bottom of the sand pack as determined by a laser diffraction sensor (Sympatec GmbH, HELOS/BR). Test results indicate that the coarser fines are at the top segment and the finer fines are at the bottom of the sand pack. This is can be attributed to the mobilization of small fines particles with the flow from the sample top to bottom.

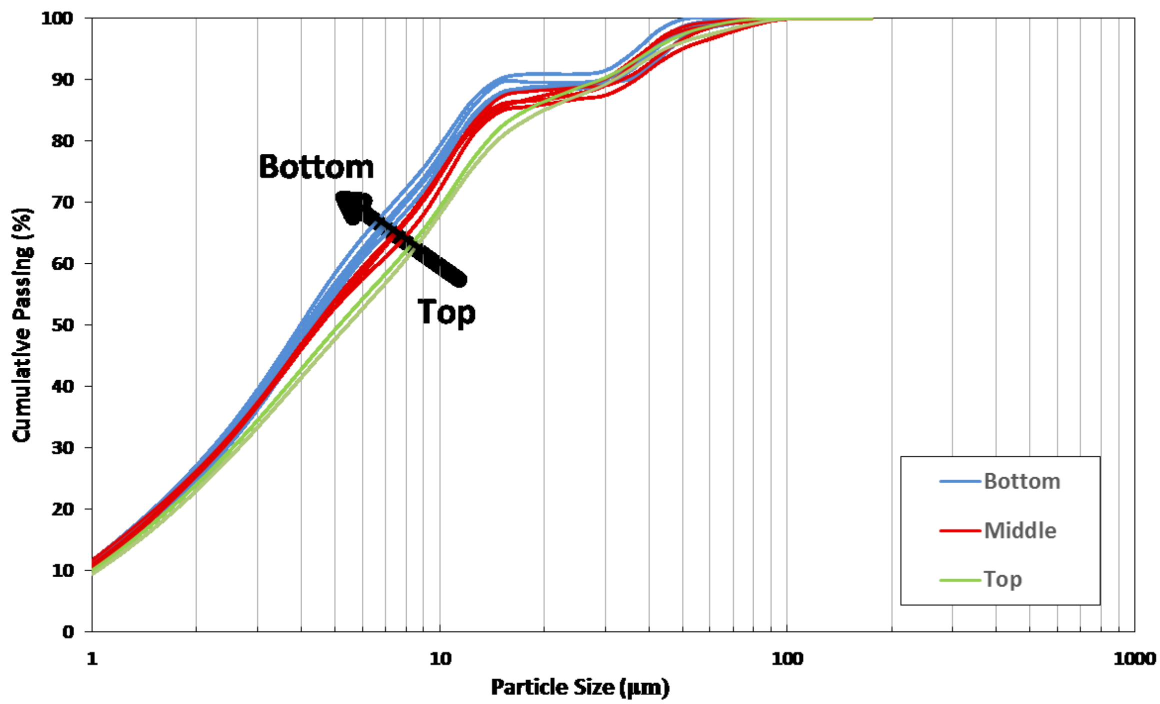


Figure 4.5: PSD of Fines across the Sand Pack for Single Flow Rate Test

4.3.5 PSD of Fines at High Flow Rate

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, which was sufficient to allow the conditions reach the steady state. Figure 4.6 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.

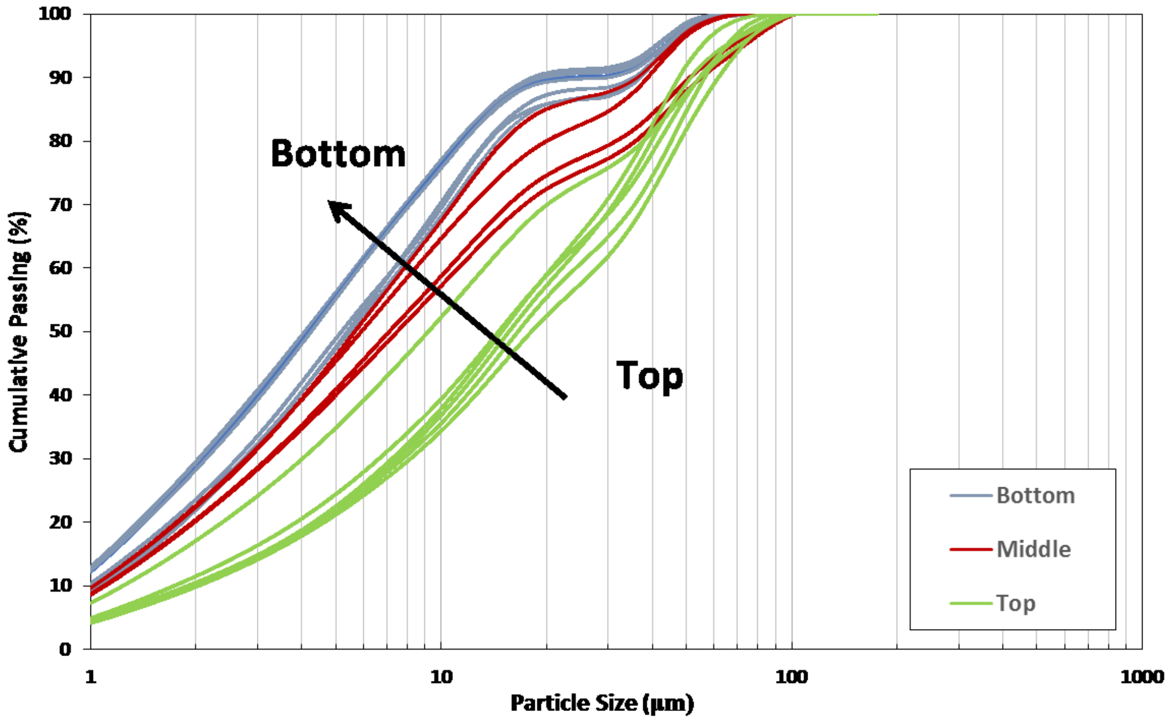


Figure 4.6: PSD of Fines across the Sand Pack for Multi-Flowrate Test

4.3.6 Near-Coupon Fines Concentration

Figure 4.7 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 4.6, 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.

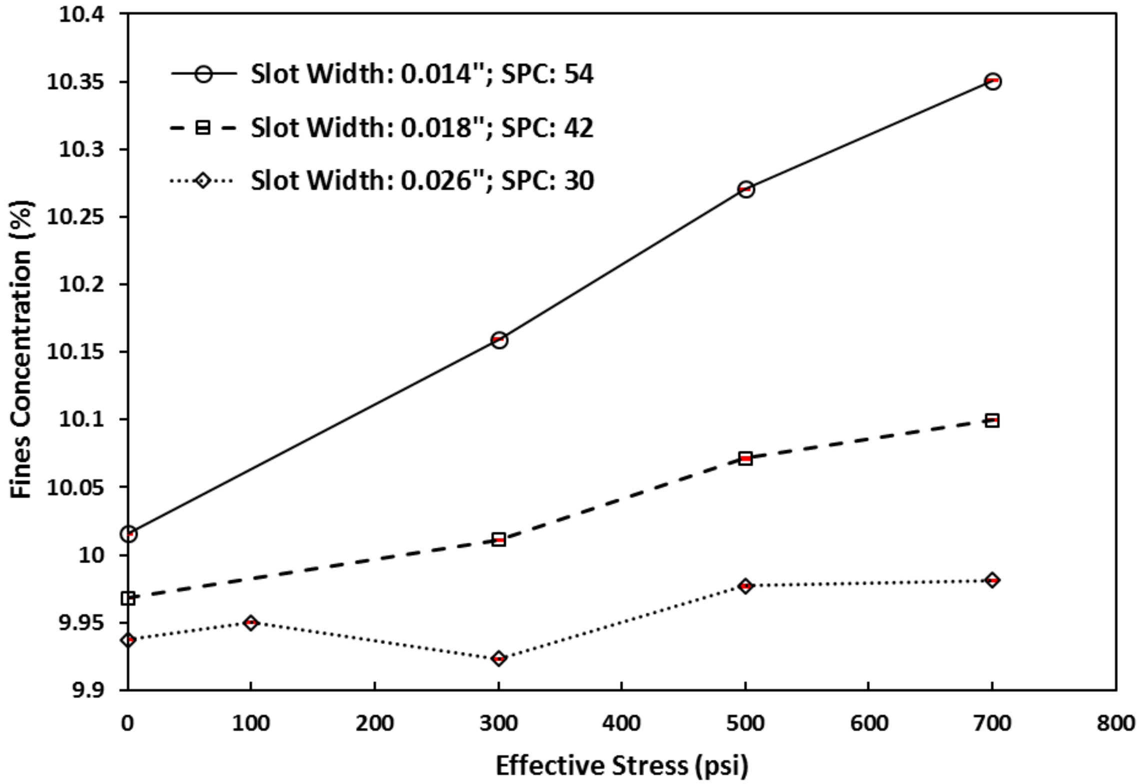


Figure 4.7: Fines Concentration at the Near-Coupon Zone vs. Effective Stress

4.3.7 Median Size of Produced Fines

Figure 4.8 shows the median size of produced fines (D_{50}) versus the effective stress. Fines transportation 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 trap the coarser ones. Figure 4.8 also indicates a greater 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.

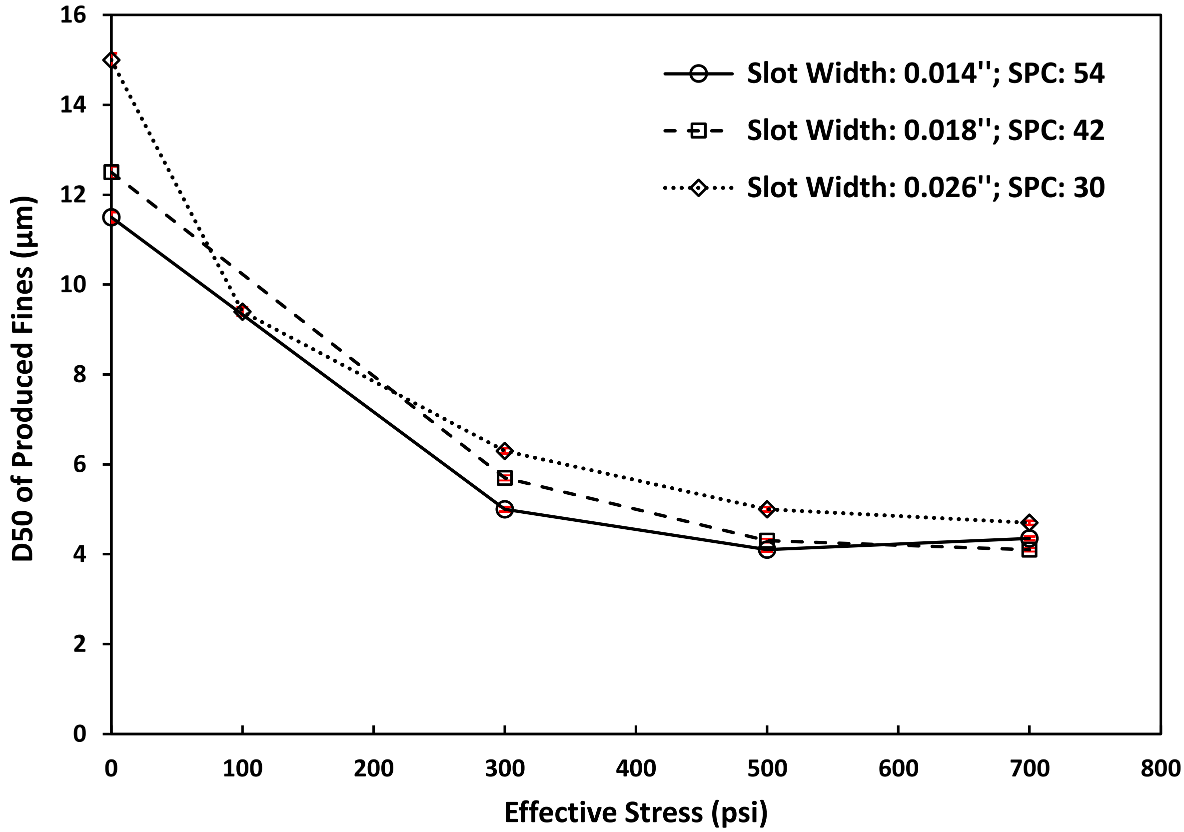


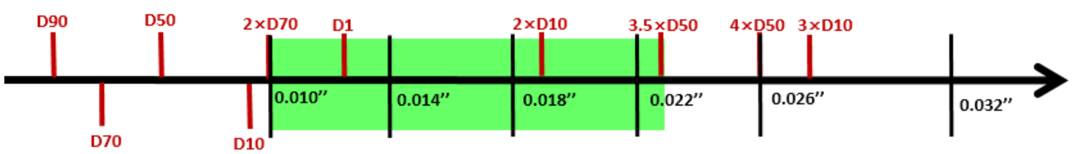
Figure 4.8: D50 of Produced Fines vs. Effective Stress

4.3.8 Acceptable Slot Window

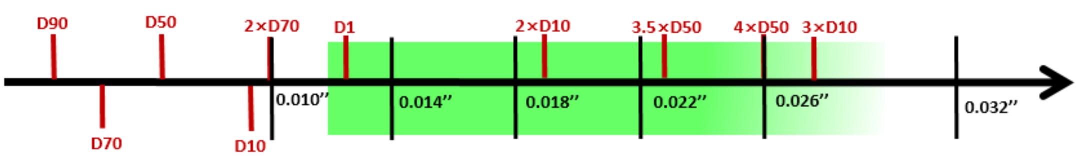
Past design criteria have been based on specifying a safe slot range for acceptable sanding and flow efficiency. The testing program in this thesis follows the work of Mahmoudi (2017) in using cumulative sanding and retained permeability as indicators for the evaluation of sand production and flow performances, respectively. Mahmoudi (2017) proposed a set of new design criteria that present the criteria graphically in analogy with the 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 test 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 than obtained from the criteria developed from zero-stress tests to avoid severe plugging. Hence, the lower bound of the safe slot window should be revised higher. Wider slots can be used than the upper bound of the criteria obtained from zero-stress tests, due to less sanding and more stable bridges at higher effective stresses.

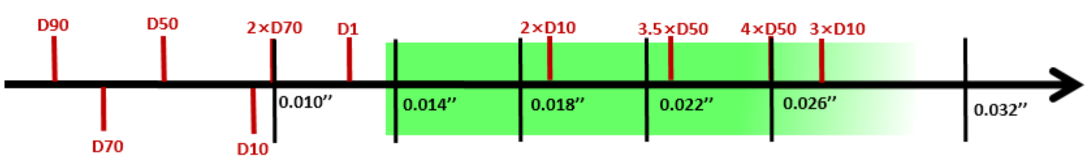
The testing results provide some indication as to how the design criteria are affected by the stress build-up around the liner. Figures 4.9a to 4.9d show the acceptable slot windows under higher effective stress conditions. In the figures, the PSD of DC- II is represented by linear axis and is annotated by the D values (e.g.D_{50}).



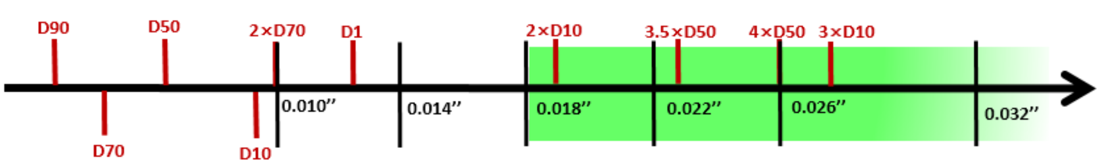
(a)



(b)



(c)



(d)

Figure 4.9: Slot Windows for DC- II Under (a) ~0 psi (Mahmoudi, 2017), (b) 300 psi, (c) 500 psi, (d) 700 psi.

4.4 Conclusion

This chapter presented the results of the SCT testing to investigate the effect of stress build-up around slotted liners on the liner performance with respect to sanding resistance and flow performance. The sanding resistance and flow performance were evaluated by measuring cumulative produced sand and the retained permeability, respectively. Tests were performed under effective stresses ranging from near zero to 700 psi. The SRT results were used for the near-zero effective stress condition. The effect of stress build-up on design criteria was also investigated based on the testing results.

The testing results indicated that effective stress plays a critical role in both sand production and retained permeability values. As the effective stress increases, the sand production decreases. The relatively wider slot, which proved to be unacceptable at zero effective stress due to excessive sanding, showed desirable sanding under higher effective stress conditions.

The results also indicate lower retained permeabilities at higher effective stresses. Post-mortem analysis indicates a more severe fines migration at higher effective stresses, which is the main reason for the retained permeability reduction. Results indicate a higher fines concentration in the vicinity of the coupon for higher effective stresses. The PSD of fines along the sand pack showed 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 increases the average particle size of the mobilized fines. The median size (D_{50}) of produced fines was also affected by effective stress. Higher effective stress resulted in smaller D_{50} for the produced fines.

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.

Chapter 5: Effect of Slot Width and Density on Slotted Liner Performance in SAGD Operations

5.1 Introduction

Sanding, inflow resistance and cost are the main considerations in slotted liner design. These main factors determine the competing factors of slotted liner: the slots must be narrow enough to retain formation sands and yet wide enough to minimize flow resistance/impairment.

This chapter presents the results of: (1) a parametric testing to investigate the effect of slot width at constant slot density on the results (sand production, retained permeability, and fines migration); (2) a parametric testing to investigate the effect of slot density at constant slot width on the results; and (3) tests with different combinations of slot width and slot density but constant OFA.

Previous laboratory studies have employed single-slot coupons to propose slot sizing rules for slotted liners, where the optimum slot opening size is related to one or more points on the formation sand PSD. These research works have investigated the influence of slot opening size on slotted liner performance, but ignored the slot density. Slot density has proven to be an important parameter that affects the inflow resistance as there is a relationship between the slot density and pressure loss due to flow distribution. The OFA of the liner depends on both slot width and slot density: narrower slot openings would demand a higher slot density which increase the manufacturing cost and decrease the mechanical strength. Thus, it is necessary to investigate the influence of slot density on the liner performance.

Sand production and plugging are also affected by the flow velocity (Bennion et al., 2009). For constant flow rate, the OFA of slotted liner would determine the flow velocity inside the slots. Since the design criteria are proposed as a safe slot window, there exist variable combinations of slot width and slot density which result in the same OFA. Manufacturers are prone to choosing the more conservative design of having narrower slot width and higher slot density. The research question in this chapter is, for a constant OFA, is it better to use a narrower slot with a higher slot density or a wider slot with a lower slot density? To address this question, coupons with different combinations of slot width and slot density but the same OFA were tested

5.2 Testing Program

As explained in Chapters 3 and 4, Pre-pack SRT and SCT assemblies were utilized in this study. Table 5.1 shows the test matrix for the investigation of slot width at constant slot density, and Table 5.2 shows the test matrix for the investigation of slot density at constant slot width. These tests were conducted under 300 psi effective stress. Table 5.3 presents the test matrix for variable slot width and density at constant OFA to investigate whether the effect of slot width or density is stronger and to optimise the combination of these two parameters. Varying levels of stress (0, 300, 500, 700 psi) were used for these tests. The flowing fluid was NaCl brine with salinity of 7000 ppm and pH of 7.9. The flow rate for all the tests was kept constant at 40 cc/min for two hours. Cumulative produced sand and retained permeability were measured to evaluate the liner performance. The fines concentration and particle size distribution were measured in post-mortem analysis as direct indicators of fines migration.

Table 5.1 Testing Matrix to Study the Role of Slot Width at Constant Slot Density

Slot Width (thou)	SPC	Effective Stress (psi)
0.014”	30	300
0.026”	30	300

Table 5.2 Testing Matrix to Study the Role of Slot Density at Constant Slot Width

Slot Width (thou)	SPC	Effective Stress (psi)
0.014”	30	300
0.014”	54	300

Table 5.3 Testing Matrix to Study the Performance of Slotted Liners with Constant OFA

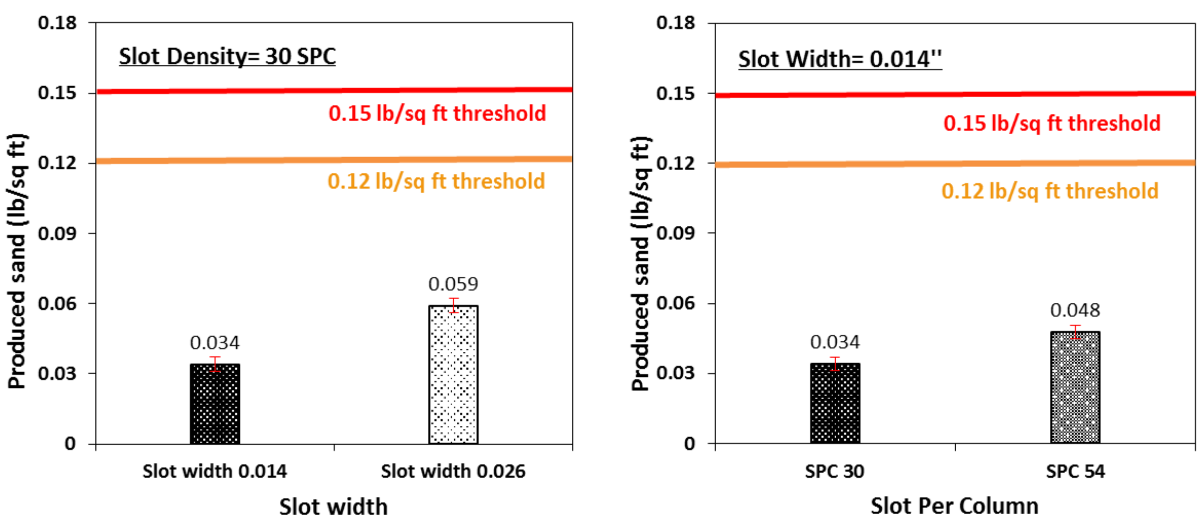
Slot Width (thou)	SPC	OFA (%)	Effective Stress (psi)
0.014” - 0.022”	54	3%	0,300,500,700

0.018” - 0.026”	42	3%	0,300,500,700
0.026” - 0.034”	30	3%	0,100, 300,500,700

5.3 Result and Discussion

5.3.1 Cumulative Produced Sand

Figure 5.1a and 5.1b show the effect of slot width and slot density on cumulative produced sand, respectively. Two acceptable limitations of sand production (0.12 lb/sq ft and 0.15 lb/sq ft) are also shown in the graphs. Figure 5.1a indicates higher sand production for wider slot at constant slot density. Figure 5.1b shows more sanding for higher slot density at constant slot width, which appears to be due to more sanding sites due to the higher number of slots. For wider slots, more sand particles are needed to form the sand bridge above each slot. Therefore, it is more difficult for wider slots to form sand bridges compared to narrower slots. Moreover, the stability of those sand bridges is less, which results in a greater amount of sanding at the initial stage. For narrower slot, the sand production was slightly higher for higher slot density. This is mainly because, in this scenario, more sand particles fall into larger numbers of slots during the sand pack compaction.



(a) **(b)**

Figure 5.1: (a) Effect of Slot Width on Sand Production, (b) Effect of Slot Density on Sand Production

5.3.2 Retained Permeability

Figure 5.2a shows the retained permeability versus slot width at constant slot density. The figure indicates higher retained permeabilities for wider slots. For a constant slot density, narrower slots lead to more fines accumulation in the near-coupon zone, which results in more severe plugging and lower retained permeability. Figure 5.2b shows the retained permeability versus slot density at constant slot width. Test result indicates more reduction in retained permeability for lower slot densities. For a constant slot width, higher slot densities result less fines accumulation above the coupon, hence, a higher retained permeability. Comparison of Figures 5.2a and 5.2b indicates that an increase in both slot width and slot density would cause an increase in the retained permeability. However, retained permeability variation due to the change of slot width is higher than that of change in the slot density.

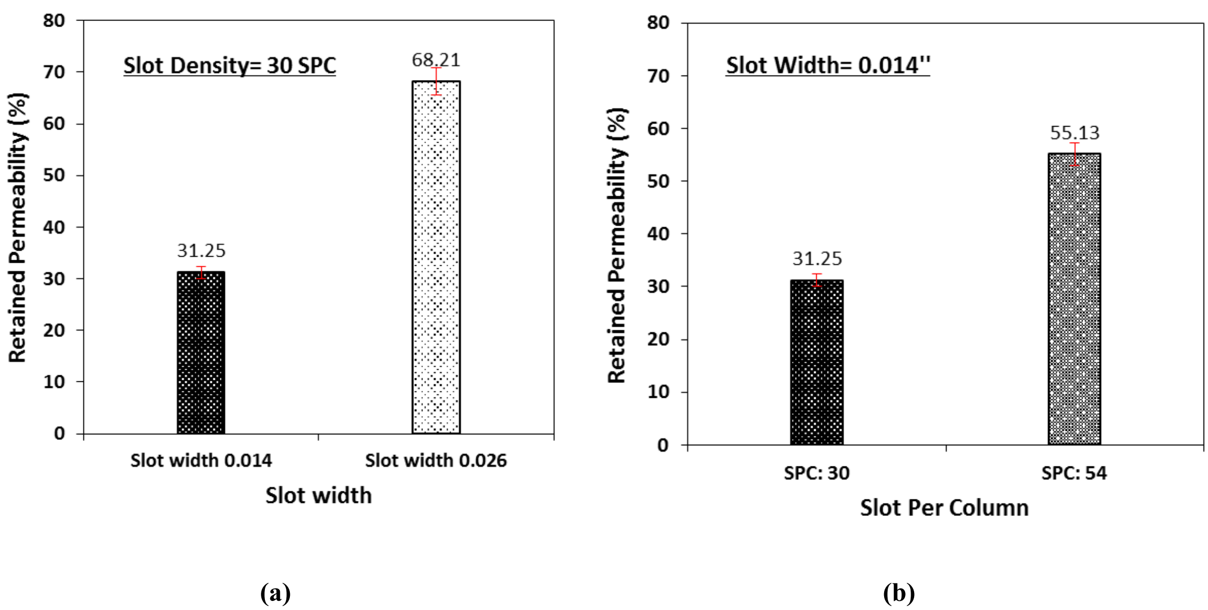
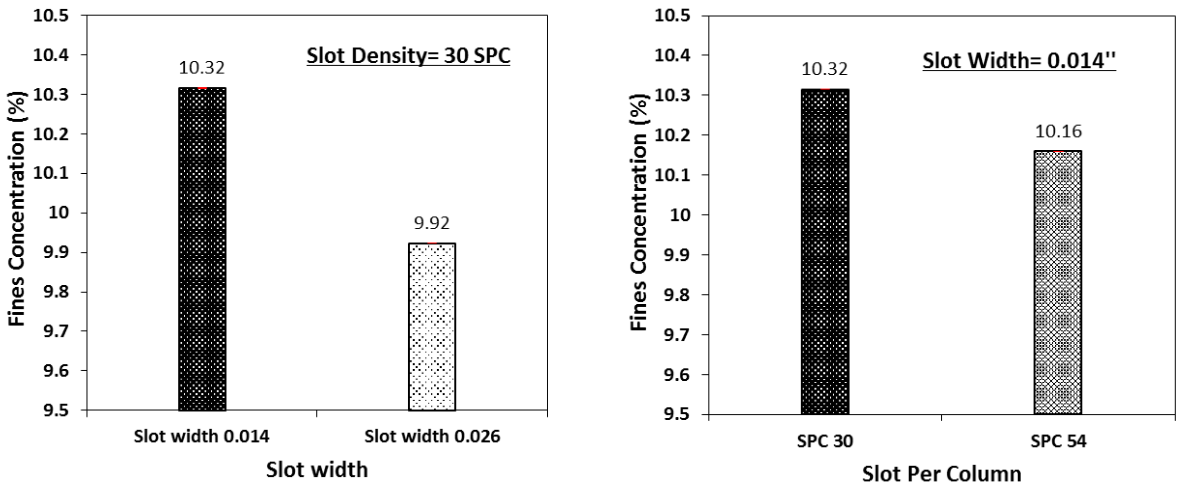


Figure 5.2: (a) Effect of Slot Width on Retained Permeability, (b) Effect of Slot Density on Retained Permeability

5.3.3 Fines Concentration

Figure 5.3a & b show the fines concentration near the screen versus slot width at constant slot density, and versus slot density at constant slot width, respectively. Figure 5.3 indicates lower fines concentrations for wider slots and higher slot densities. However, it is obvious from the figure that the effect of slot width on the fines content is more than that of slot density.

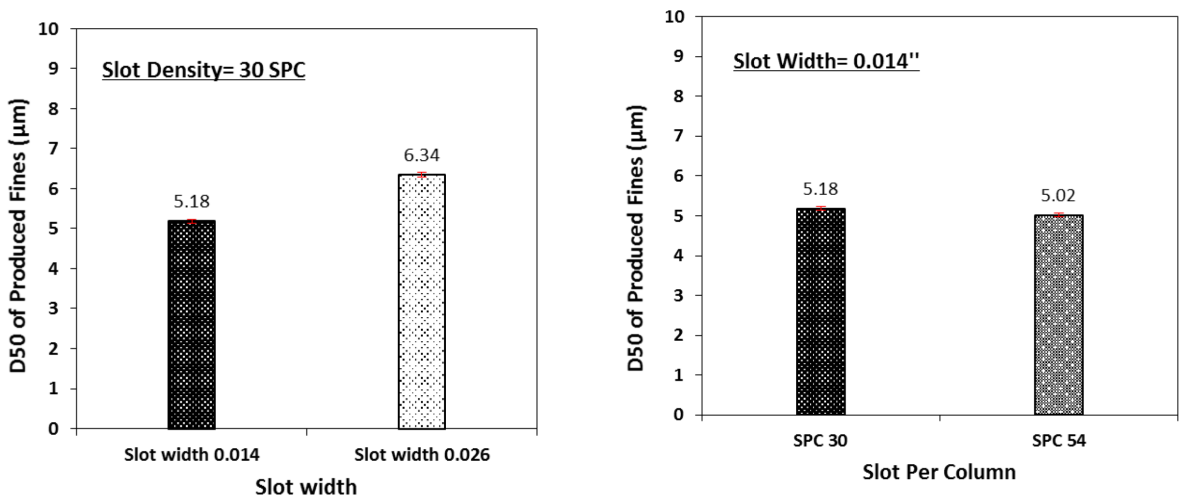


(a) (b)

Figure 5.3: (a) Effect of Slot Width on Concentration of Fines Near the Liner, (b) Effect of Slot Density on Concentration of Fines Near the Screen

Figure 5.4a shows the effect of slot width on the median size of produced fines at constant slot density. According to Figure 5.4a, larger produced fines are observed for wider slots. It should also be recalled from Figure 4.7 that the size of produced fines is also sensitive to the flow rate, where higher flow rates result in larger quantities and sizes for the fines migration. The mobilization of fines is also affected by the porosity. A lower porosity leads to narrower pore throats and hence, smaller produced fines.

Figure 5.4b shows the effect of slot density on the D_{50} of produced fines at a constant slot width. Test results indicate a small change in the size of produced fines when coupons with higher slot density are employed. Therefore, the size of produced fines seems to be little affected by the slot density.



(a) **(b)**

Figure 5.4: (a) Effect of Slot Width on the D_{50} of Produced Fines, (b) Effect of Slot Density on the D_{50} of Produced Fines

5.3.4 Effect of Different Combinations of Slot Width and Slot Density with Constant Open to Flow Area

It is evident that flow velocity plays a critical role for both sand production and plugging. The change in either slot width or slot density would alter the flow velocity by changing the total OFA. To isolate the effect of slot width and slot density on screen performance and remove the effect of flow velocity change, coupons with constant OFA but variable slot width and slot density were tested.

Figure 5.5 shows the cumulative produced sand for three coupons with constant OFA. Two acceptable limits of sand production (0.12 lb/sq ft and 0.15 lb/sq ft) are also shown in the graph. The figure shows more sanding occurs for wider slot and lower slot density. Limited produced sand is observed for slot size of 0.014'' and 0.018''. More sanding occurs when slot size 0.026'' is used, and the amount of produced sand stays beyond the acceptable threshold. The conclusion is that at the constant slot velocity, wider slot openings tend to result in more sanding despite a smaller slot density.

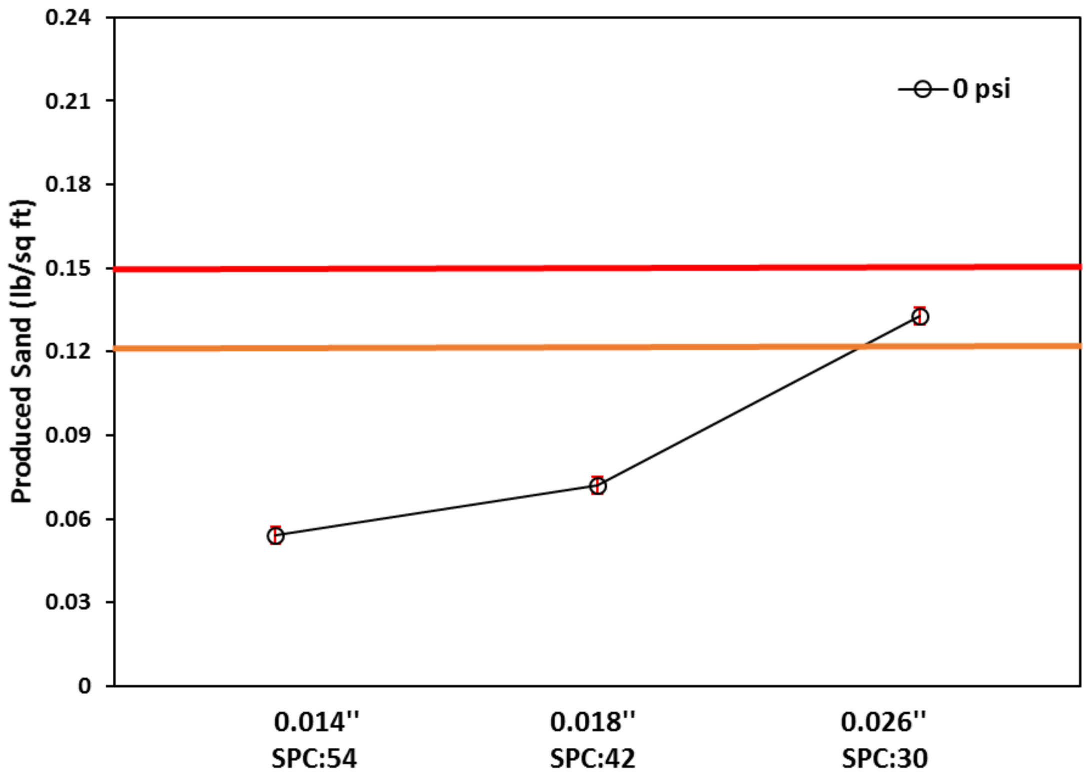


Figure 5.5: Effect of Slot Size and Density on Cumulative Sand Production; Solid Lines Are the Upper Limit of Acceptable Produced Sand of 0.12 lb/sq ft and 0.15 lb/sq ft

Figure 5.6 shows the effect of slot size and density at two effective stress levels on the retained permeability. As expected, the coupon with wider slot shows a better flow performance than that of the higher slot density. The reason is that less fines are accumulated near the coupons with wider slots. The figure also shows a drastic drop in retained permeability at higher effective stress condition, but the change of retained permeability follow the same trend. Based on this, wider slots with lower SPC provides a lower plugging than narrower slots with higher SPC.

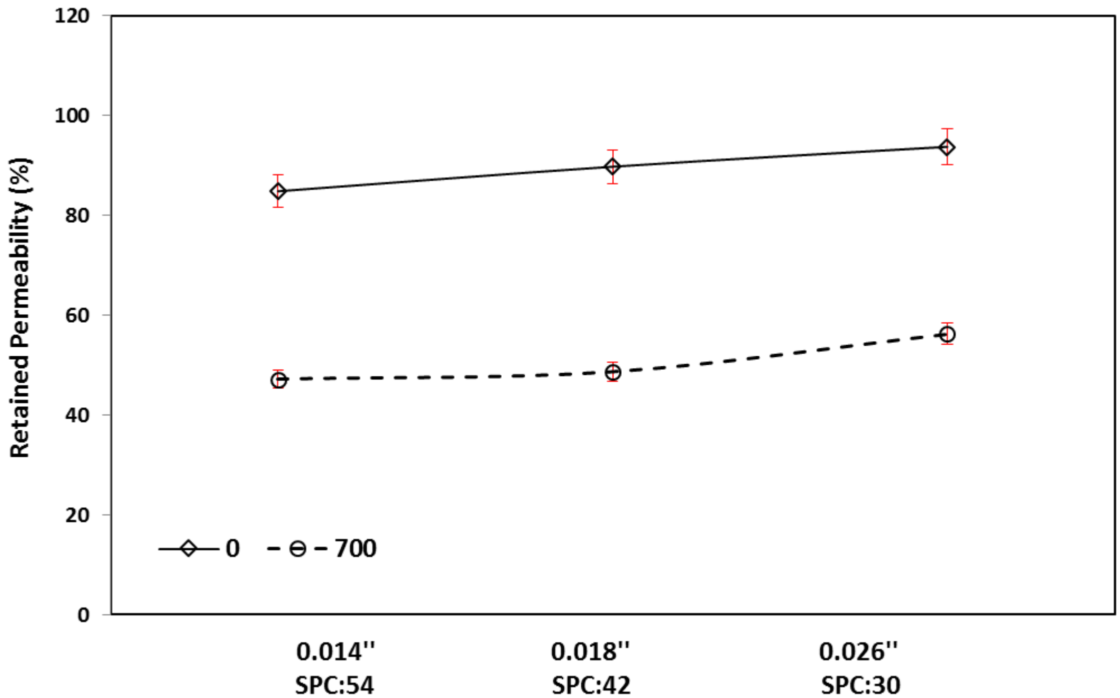


Figure 5.6: Effect of Slot Size and Density on Retained Permeability at the Near-Coupon Zone

Figure 5.7 shows the fines concentration at the near-coupon zone at the end of the test. The result shows higher fines concentration for coupon with narrower slots and larger SPC, which agrees with the results of retained permeability measurements. Figure 5.7 also indicates higher fines concentration for higher effective stress. Moreover, a stronger effect of stress on plugging is observed for narrower slots.

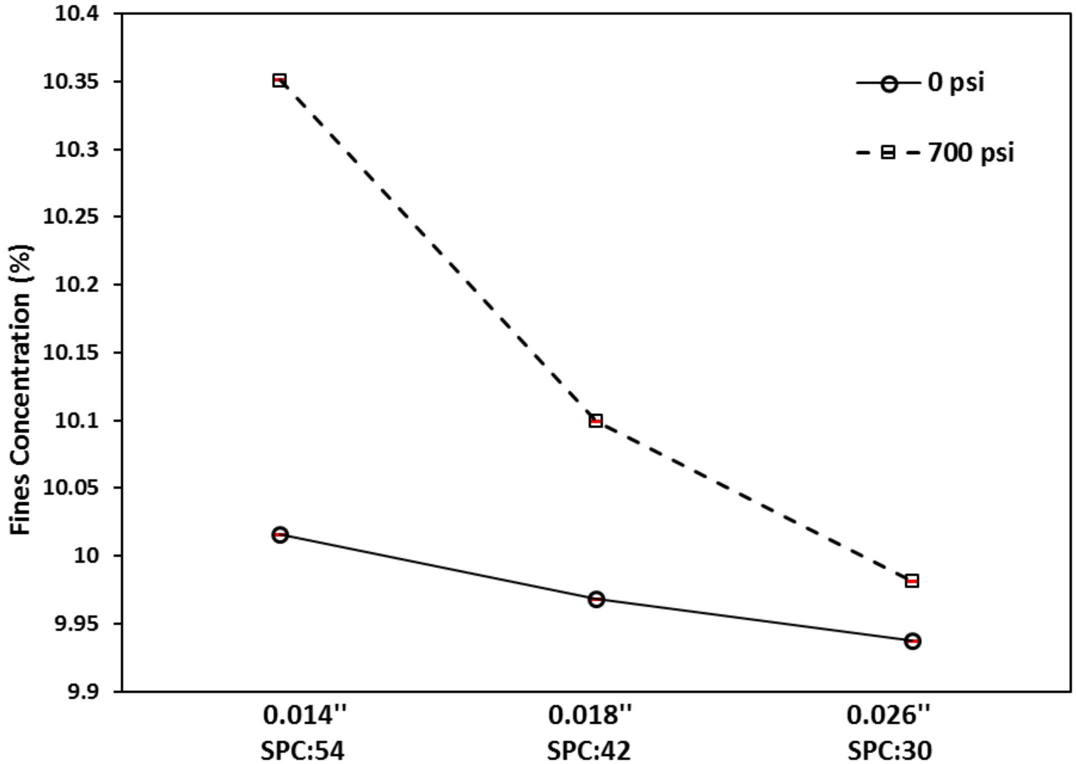


Figure 5.7: Effect of Slot Size and Density on Increased Fines Concentration at the Near-Coupon Zone

Figure 5.8 shows the effect of slot size and slot density on median size of produced fines (D_{50}). Result indicates coupons with wider slot sizes and smaller SPC tend to produce slightly coarser fines. In addition, the size of produced fines decreases sharply for higher effective stress. It seems the sand porosity plays a critical role in the fines transportation and production. The reason lies in the smaller pore throat sizes for lower porosities which only allows the transport of smaller fines.

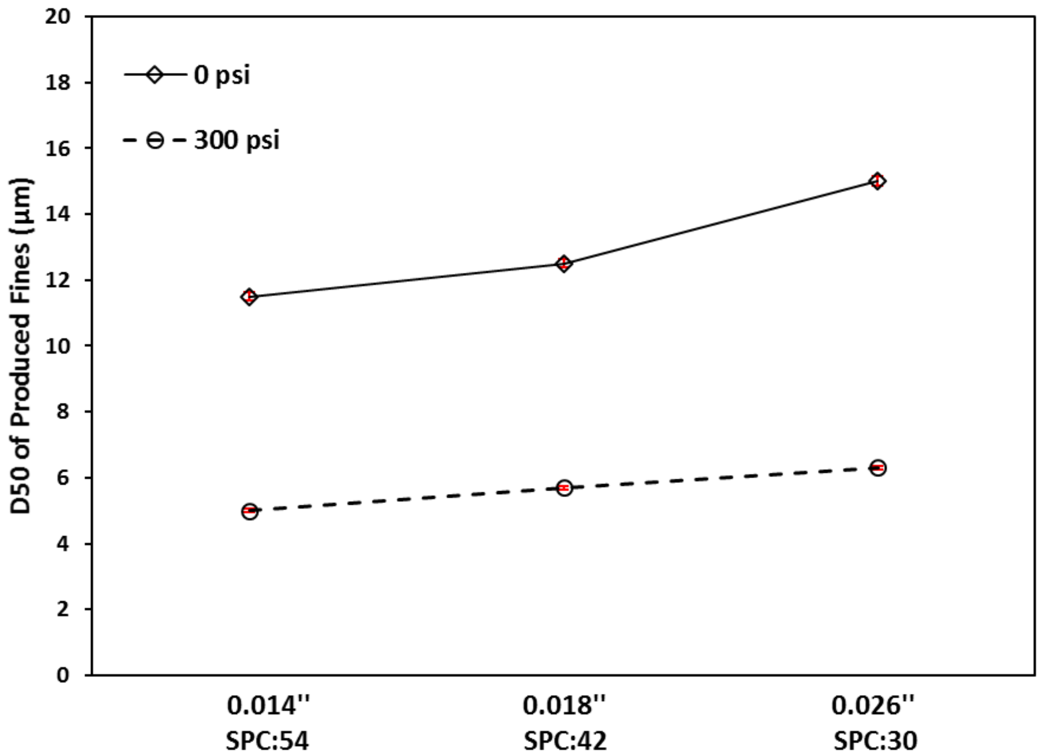


Figure 5.8: Effect of Slot Size and Density on D_{50} of Produced Fines

5.4 Conclusion

This chapter presented the results of pre-pack SRT and SCT to investigate the liner performance at variable slot width at constant slot density, variable slot density at constant slot width, and variable slot width and density at constant OFA. The liner performance was evaluated using two indicators: sand resistance performance and flow performance.

Results indicate higher sand production for wider slots at constant slot density. Test results also show less retained permeabilities for narrower slots. A similar trend was observed for smaller SPC. However, the comparison of the two testing results indicate a stronger effect of slot width than that of slot density on the sanding and retained permeability.

The fines concentration in the near-coupon zone was also measured for each test. Data indicate higher fines concentration for narrower slots and smaller SPC. It is also evident that the fines concentration for wider slot approaches the initial fines concentration, resulting in less pore plugging. Further, wider slots result in coarser produced fines. However, the slot density shows little effect on the size of produced fines. The size of produced fines was proven to be highly sensitive to the flow velocity and the size of pore throats in the formation.

Lastly, various combinations of slot width and slot density at constant OFA were tested. Data indicate a wider slot with smaller SPC results a higher sanding and less reduction in retained permeability. Results also indicate a drastic reduction of sand production for higher effective stresses. A similar trend for permeability reduction was also observed under high effective stress conditions. Test results of this section also showed lower fines content near the coupon with wider slots and smaller SPC. The effective stress seems to have a stronger effect on fines concentration for narrower slot. This suggests the benefit of using wider slots to reduce the plugging potential.

Chapter 6: Conclusions and Recommendations for Future Work

6.1 Main Results and Contributions

This research used a sand control testing facility (Scaled Completion Test, SCT) to study the sand control performance assessment on various stress regimes (triaxial compression/extension). The test facility allows to emulate different stress conditions corresponding to stress variations during the life cycle of a SAGD producer. A detailed testing procedure was also presented to assess the performance of sand control liners/screens at different stress levels. The experimental design utilized a multi-slot liner coupon to study the role of both slot width and density. A series of SCTs was performed to study the role of slot width, slot density and stress on the liner performance. Cumulative produced sand at the end of testing was measured as an indicator of sand control performance. Retained permeability was calculated by pressure drops across the sand pack and considered as the indicator of screen flow performance. Fines/clay concentration along the sand pack was also measured after the test to investigate fines migration, which was considered as the main reason for plugging and permeability reduction.

The most important outcome of this study is the effect of stress buildup on screen performance. Experimental results indicated the liner performance is significantly affected by the stress induced compaction of the oil sand. The stress compacts the sand, leading to a denser pack with a lower porosity and permeability. The lower porosity results in a higher pore-scale flow velocity. The higher flow velocities trigger fines mobilization, and lead to higher skin buildup. The higher stress can stabilize the sand bridges, as higher stresses mobilize inter-particle friction.

Design criteria for slotted liners present a safe slot window for an acceptable liner performance with respect to sanding and plugging for the upper and lower bounds of slot aperture, respectively. Considering the stress effect on plugging and sanding, experimental results showed an upward shift for both the lower and upper bounds at elevated stress conditions. The experimental data lead to design criteria that are valid for the entire life cycle of the well during which the liner is subjected to variable stress conditions.

Based on the test results, both slot width and slot density play important roles in screen performance with respect to sand production and retained permeability. An increase in either slot width or slot density results in a higher retained permeability due to a smaller fines accumulation above the coupon. However, an increase of slot width would affect the retained permeability more than an increase in slot density.

For the combined variation of slot width and slot density at a constant OFA, the liner design with a wider slot but smaller SPC shows a higher retained permeability and more sanding. Results also indicates a higher impact of the slot width on the liner performance than the slot density. A similar trend is observed under various stress levels.

Since the stress build-up reduces the sand production and increase the plugging tendency, it is better to use wider slots and less SPC to reduce plugging, manufacturing cost, and better liner integrity if the sanding is kept within an acceptable level.

6.2 Recommendations for Future Work

(1) Both the lower and upper bound of the safe slot window are shifted upward at higher effective stresses. Additional tests are needed to revise the whole set of design criteria for different stress levels.

(2) The SCT tests can be conducted under multi-phase flow condition to investigate the effect of multiphase flow on plugging, fines migration, fines production and sanding. The involvement of multiphase flow can also be beneficial in the study of the role of wettability and capillary pressure on the liner performance.

(3) The PSDs of the core samples obtained from wells in the McMurray Formation have been categorized in multiple classes in different categorizations. Only one type of PSD (DC-II) has been investigated in this study. As the PSD of the sand pack highly affects the slotted liner performance, additional PSD types should be included in the testing program for further verification of the results and revision of the entire set of design criteria.

(4) As the local plugging of slots would increase fluid velocities in the open slots (Mahmoodi et al., 2016), experiments with higher flow rates can simulate the extreme cases during SAGD operation and help to come up with a better liner design.

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Appendix A: Current Industrial Design Procedures

This appendix summarizes the proposed deign of slotted liner model for slot size, profile, and density by Fermaniuk (2013).

A.1 Slot Width

The PSDs for Pike I project presented by Abram and Cain (2014) are used to illustrate the current approach. Figure A.1 shows the particle size distribution (PSD) of oil sands categorized by Abram and Cain (2014). The PSDs of the core samples obtained from wells in the McMurray Formation are categorized as four classes (Figure A.1). The very fines to fine sands with high clay content are categorized as Class I (DC-I). The clay contents change from 8.5% for upper limit (DC-I UL) to 37.5% for the lower limit (DC-I LL). The layers with class I PSD typically have low permeability and low oil saturation (Carrigy, 1966). The very fine to medium sands with less fines content are categorized as Class II (DC-II). The fine to medium sands with lower fines content and higher permeability are categorized as Class III (DC-III). The medium to coarse sands with low fines content are categorized as Class IV (DC-IV).

D values, fine content and clay content are considered as the essential input data for this model. D values includeD_{10}, D_{40}, D_{50}, D_{70}, D_{90} and D_{95}. Table A.1 lists all the essential input data for the four classes of the PSDs from the core samples drilled in the McMurray Formation.

Based on the field experience from RGL reservoir management Inc., Fermaniuk (2013) defined a series of minimum and maximum slot widths as a function of D values:

$$Max\ SW = 3.5D_{50} \qquad \text{(A.1)}$$

$$Min\ SW = 2D_{70} \qquad \text{(A.2)}$$

Fermaniuk (2013) also proposed four values of Average Slot Width (ASW). The ASW means the estimated slot width which is required to avoid the sand production from the formation. The four values of ASW are as follows:

$$ASW_1 = 2D_{10} \qquad \text{(A.3)}$$

$$ASW_2 = 1.50D_{10} \quad (A.4)$$

$$ASW_3 = 1.36D_{10} \quad (A.5)$$

$$ASW_4 = 2.29D_{50} \quad (A.6)$$

The fines content (<44 μm) and clay content (<5 μm) are also used for the slot profile designing. Table A.2 listed the abovementioned slot widths. Figure A.2 summarizes the slot window for the four classes of PSDs from McMurray Formation. Combined with the extend and the frequency of sand facies, it can be used to select the most appropriate slot width series for the studied well. As shown in Figure A.2, the possible best slot width for a specific slot window can be obtained from the solid horizontal lines. This is attributed to the narrower slot width can decrease the sand production because of the quickly forming stable sand bridge above the slot. The stability of the sand bridge would decrease with the increasing of the slot width.

A.2 Slot Profile

The fines content and clays content of the sand in the studied reservoir play a critical role in the slot profile selection. The straight slot and seamed slot are most commonly used in the industrial operation. The seamed slot is suitable for the fines and clays content larger than 5.5%. **Table A.2** provides the suggested slot profile selection criteria for the four classes of PSDs from McMurray Formation.

A.3 Slot Density

Based on the balance between inflow capability and plugging tendency, Fermaniuk (2013) proposed an optimum ratio of slot density to production rate. Therefore, the optimization of the slot density should take the production rate variability, plugging tendency, properties of the produced liquid and the length of the wellbore into the consideration. Fermaniuk (2013) also provided an essential equation for the determination of the slot density:

$$SD_{opt.} = 0.505\frac{QJ_1}{VLS_1} \quad (A.7)$$

where Q is the production rate (bbl/day), J_1 is the joint length (m), V is the volumetric flow rate per slot (L/hr/slot), L is the horizontal length (m), and S_1 is the slotted portion per joint (m). The experimental results indicate that optimum flow rate that can minimize the pressure drop and plugging of the near coupon zone should lies between 40 ml/hr/slot to 160 ml/hr/slot. In addition, a slot plugging factor (2-9) is used to avoid the possible plugging during the life time of a well.

Table A.1 The Input Values from the PSD Curve into Slot Size Model.

	DC-I LL	DC-I UL	DC-II LL	DC-II UL	DC-III LL	DC-III UL	DC-IV LL	DC-IV UL
D_{10}	114.3	426.7	157.5	388.6	304.8	932.2	607.1	1785.6
D_{40}	73.7	243.8	116.8	218.4	200.7	391.2	350.5	1140.5
D_{50}	63.5	213.4	104.1	200.7	180.3	348.0	292.1	942.3
D_{70}	33.0	142.2	83.8	167.6	134.6	264.2	134.6	652.8
D_{90}	7.6	48.3	10.2	134.6	25.4	185.4	45.7	411.5
D_{95}	5.1	38.1	5.1	68.6	15.2	68.6	38.1	375.9
UC	11.20	5.01	11.24	1.64	8.06	2.12	7.78	2.77
SC	23.06	11.39	27.02	5.62	21.55	13.49	16.00	4.76
Fines content	37.5%	8.5%	16.1%	0.6%	15.2%	0.4%	10.5%	0.5%
Clays content	17.5%	5.9%	8.8%	0.3%	7.8%	0.1%	5.5%	0.1%

Table A.2 Slot Model for the Four Class of Sand of the McMurray Formation

Max. : 3.50D_{50}	0.009	0.029	0.014	0.028	0.025	0.040	0.040	0.040
ASW1: 2.00D_{10}	0.009	0.034	0.012	0.031	0.024	0.040	0.040	0.040
ASW2: 1.50D_{10}	0.007	0.025	0.009	0.023	0.018	0.040	0.036	0.040
ASW3: 1.36D_{10}	0.006	0.023	0.008	0.021	0.016	0.040	0.033	0.040
ASW4: 2.29D_{50}	0.006	0.019	0.009	0.018	0.016	0.031	0.026	0.040
Min. : 2.00D_{70}	0.003	0.011	0.007	0.013	0.011	0.021	0.011	0.040
Seaming required?	Seamed slot required	Seamed slot required	Seamed slot required	Straight slot	Seamed slot required	Straight slot	Seamed slot required	Straight slot

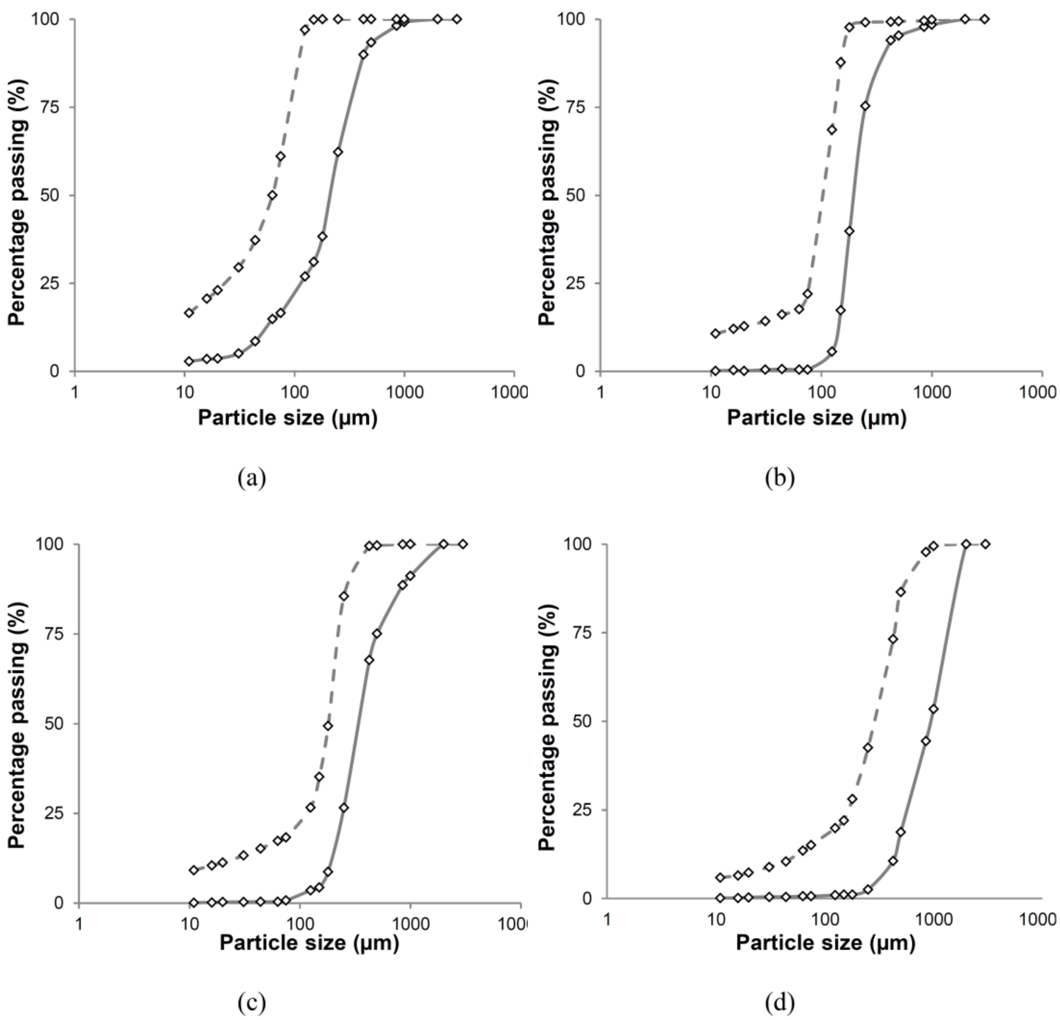


Figure A.1: Particle Size Distribution of Oil Sands Categorized by Abram and Cain (2014); Graphs Show (a) the Upper and Lower Ranges of the DC-I, (b) the Upper and Lower Range of the DC-II, (c) the Upper and Lower Range of the DC-III, and (d) the Upper and Lower Range of the DC-IV.

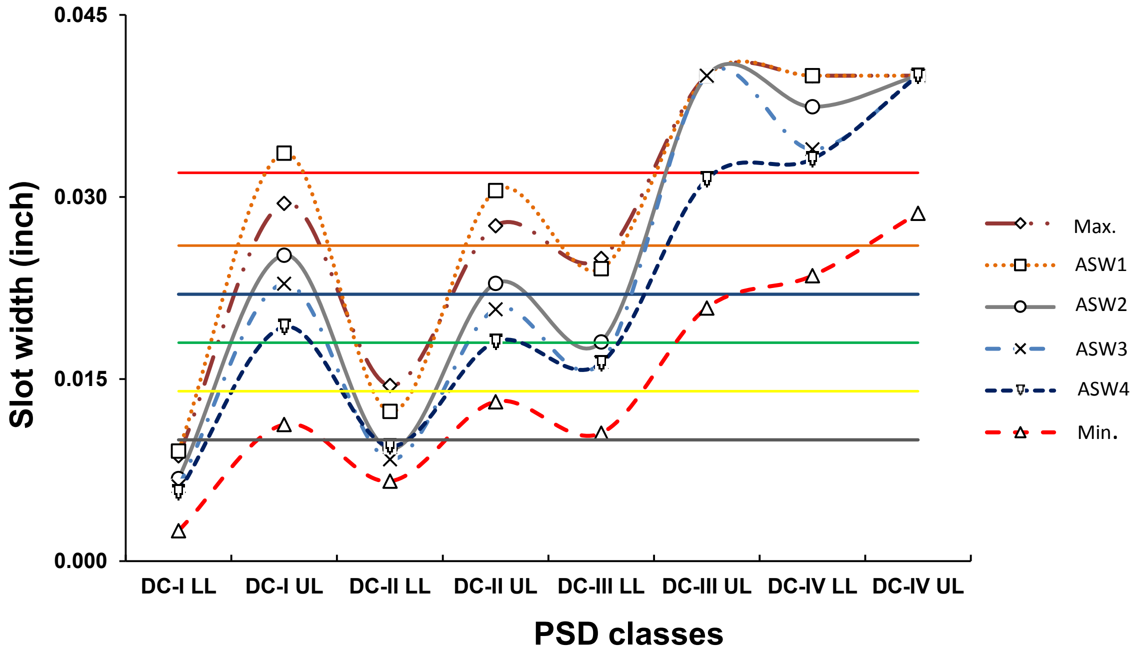


Figure A.2: Slot Window Model for the Different Classes Provided by Abram and Cain (2014)

Appendix B: Standard Operating Procedure (SOP) of Scaled Completion Test

Policy: The Scaled Completion Test (SCT) should be conducted in accordance with predetermined specifications to obtain the desired testing results. All the personnel involved in conducting the test should have a good understanding of the testing procedure and ensure every step is followed by standard operating procedures.

Purpose: The aim is to perform the test consistently according to the predetermined test routine. In addition, facility maintenance is included.

Scope: This procedure applies to all personnel involved in handling and conducting the SCT.

B.1 Preparation

B.1.1 Brine Preparation

1) Brine for single phase test consists of a salinity of 7000 ppm and pH value of 7.9. Reservoir tanks can contain about 40 kg of liquid.

2) For 40 kg of deionized water, it is mixed with 280gr of salt using a stirring drill at high RPM.

B.1.2 Brine pH Calibration

1) Before using the brine for sand preparation or saturation, the pH level is calibrated. The pH values are obtained employing an indicator dye solution and comparing the resultant fluid color with a pH color chart. Five drops of the indicator (Figure B.1) are added to a sample of brine in a small labeled test tube. If adjustment is necessary, sodium bisulfate ($NaHSO_4$) and sodium carbonate (Na_2CO_3) can be used to lower and increase the pH level respectively (Figure B.2). The addition of the small amount to the brine container is followed by mixing with stirring drill so that another representative sample is taken for the pH measurement.

2) Once the brine is ready, this is set to fill the reservoir containers in line with the injection pumps and can be used for the sand mixing phase.

(a) (b)

Figure B.1: (a) pH Indicator, (b): pH Adjuster

B.1.3 Sand Pack Preparation

1) The recipe to prepared composition for DC-Ⅱ is shown in Table B.1.

2) Carefully weigh all the various commercial sands and clays following the recipe, to pour this samples slowly (to prevent loss of fine particles) and uniformly in a plastic mixing container (to ease mixing homogenously).

3) The dry sand samples are repeatedly mixed inside the container manually by hand.

4) Then to achieve the required 10% water saturation, gradually pour 1.2 kg of water to the dry sand mixture and continuously mix the new sample until it is homogenously wetted. It is important to check if there are any fine particles at the inner edges of the container.

Table B.1: Weight Proportion of DC-Ⅱ

Sand Type	Sil-4	Sil-1	Sino Garnet	Kaolinite	Illite
DC-Ⅱ	2.5%	7.5%	80%	8%	2%

B.2 SCT Cell Assembly

B.2.1 Setup and Coupon Assembly

1) Before the packing procedure, there is a verification of the cleanness of the apparatus parts, clean the apparatus with water, air and appropriate detergent in case of oil specifically the following:

    a) The tee sand trap connection

    b) Lower part of the cell (the cone and inside connections)

    c) Fluid injection lines (steel tubes)

    d) Flow outlet line

    e) Two pressure ports

    f) Clean and gauge the size of the coupon

2) The brine metering pump is connected to the back-pressure column to flow brine inside the tube and clean it, then the volume of brine is released.

3) Coupon preparation and installation (Figure B.3)

    a) Attach and secure with Teflon the 2- and 4-inch pressure ports to the top side of the coupon (represent outside of the slotted liner) (Figure B.4)

    b) Fill the pressure ports with iron wool to prevent sand from plugging

    c) Apply corrosion coating for carbon steel coupons

    d) Attach the 2 and 4 in pressure ports the respective Swagelok at the cone, then a 1/8 inches tubing is carefully placed below the coupon with an o-ring close to one slot to take outflow samples

    e) Carefully position the coupon above the cone and make sure the tested coupon is properly threaded

4) Inspect and grease the O-rings around the cone and the base of the setup. Replace new ones if the O-rings are damaged.

Figure B.2: Multi Slot Coupon

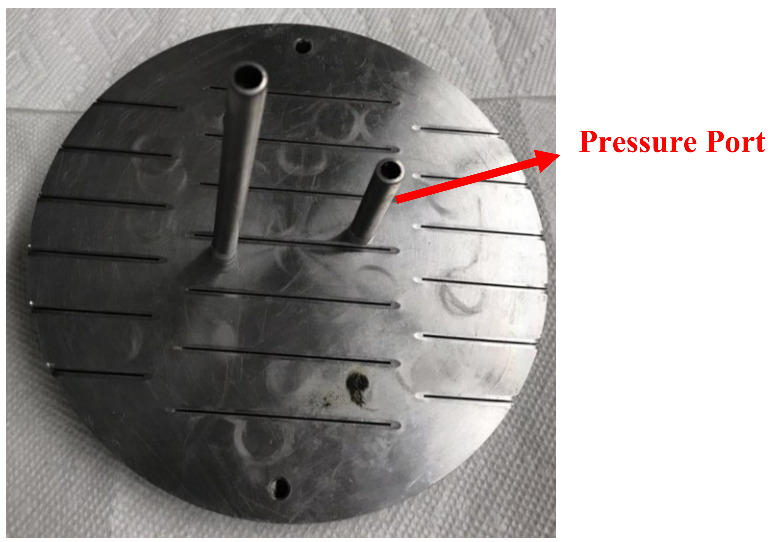


Figure B.3: Multi Slot Coupon with Pressure Ports

B.2.2 Sand Packing

1) After inspection of the membrane, attach it gently to reduce any chance of O-rings (at the cone) dislocation

2) Attach the 4-piece metal packing modes around the membrane to support it during sand packing. Fasten the packing modes by using a steel collar (Figure B.5).

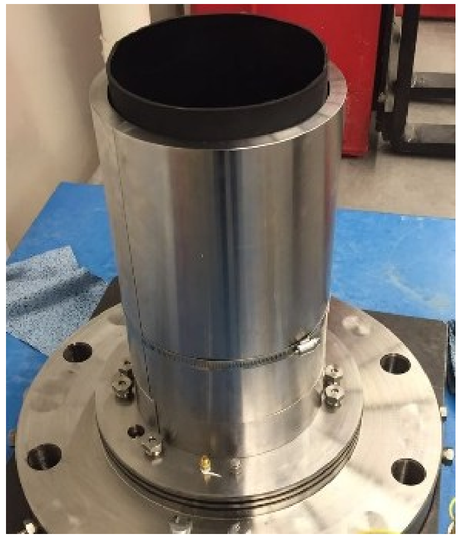


Figure B.4: Packing Mode and the Steel Band

3) Eight sand layers is packed in sequence based on a modified approach of the moist tamping method. This involves preparing 8 in layers with the corresponding weight then pack them uniformly and compact them so that at the end of each layer all the height measurement points (Figure B.5) should match the pre-calculated table. A small rod is used to even out the surface of the sand. The weight of the layer is calculated based on the required porosity of the pack and the grain density. The sand mass of the first 4 layers is slightly less due to the existence of the pressure ports. The mass of the sand mixture per layer is around 1275g. After packing each layer, scratch the surface to allow integration of the packed layers.

4) After packing, fasten the membrane to the cone using a metal fastener. The steel collar should be installed 1 in above the base of the SCT unit.

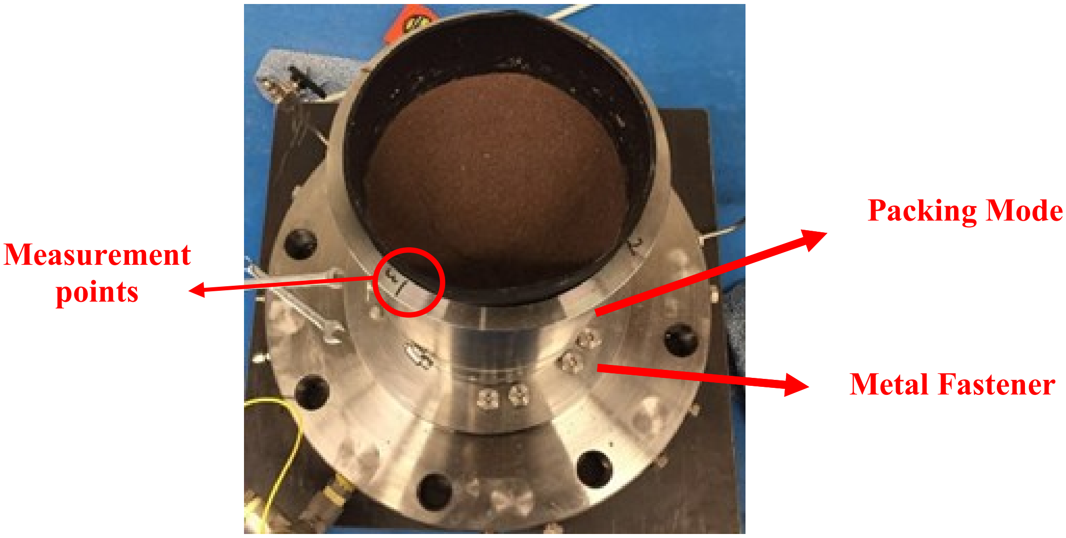


Figure B.5: Measurement Points at the Packing Mode

5) Place the porous disk on top to homogenize the flow into the sand pack. Then using gradienter to make sure the surface is horizontal, so the porous disk won't fracture during stress application. Fill the hole in the center of the porous disk with glass bead to gain a uniform permeability (Figure B.6).

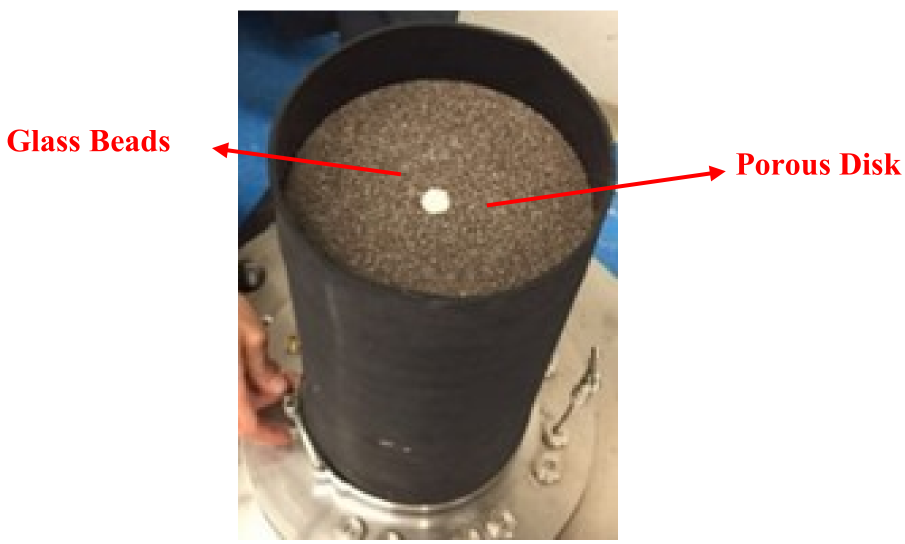
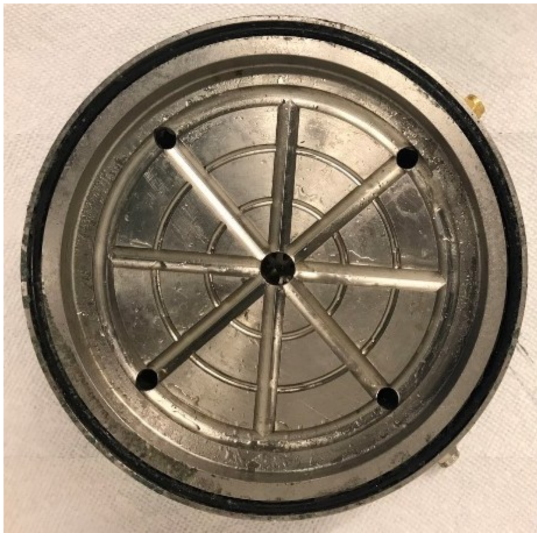


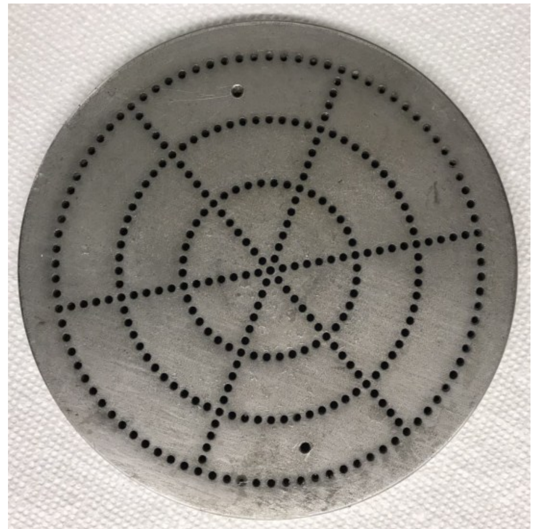
Figure B.6: Porous disk

6) Clean the top platen (Figure B.7 (a)) and flow ports (Figure B.7 (b)) with water and air, make sure there is no sand grains attached. Grease the O-ring and install the top platen on top of the porous disk.

7) Attach a steel collar 1 inch from the top of the top platen to secure the upper O-ring (Figure B.8).



(a)



(b)

Figure B.7: (a) Top Platen, (b) Flow Port

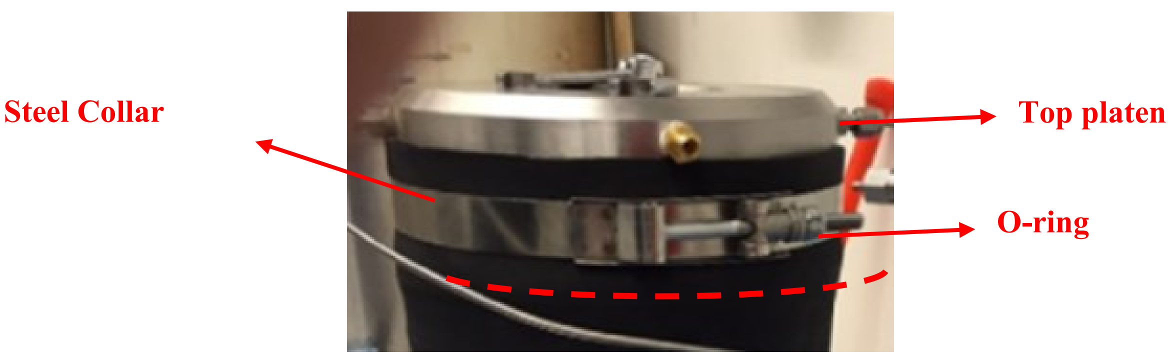


Figure B.8: Top Platen Installation

8) Connect T-junction and the top platen through steel tubes to apply the inlet of fluid during injection. Notice that the tube shouldn't contact to the membrane and cause any compression (Figure B.9).

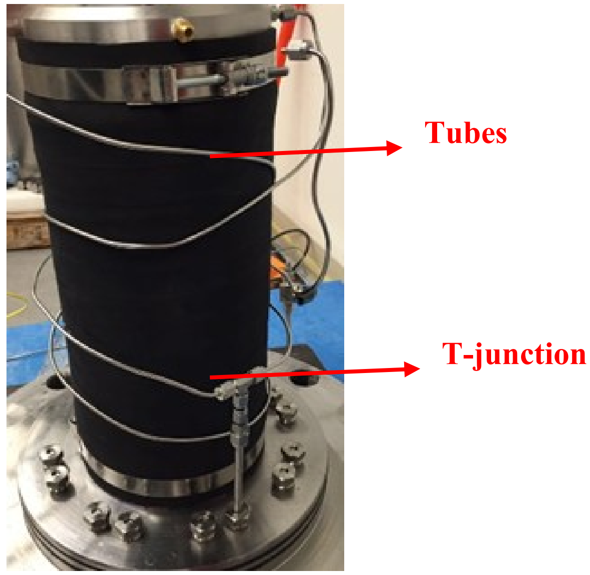


Figure B.9: Tubes Installation

9) Clean and re-grease all the steel supporting rods and screw in them following the labels (Figure B.10). Leave 5-6 threads for each rod (not screw to the bottom) to prevent damage of the load frame.

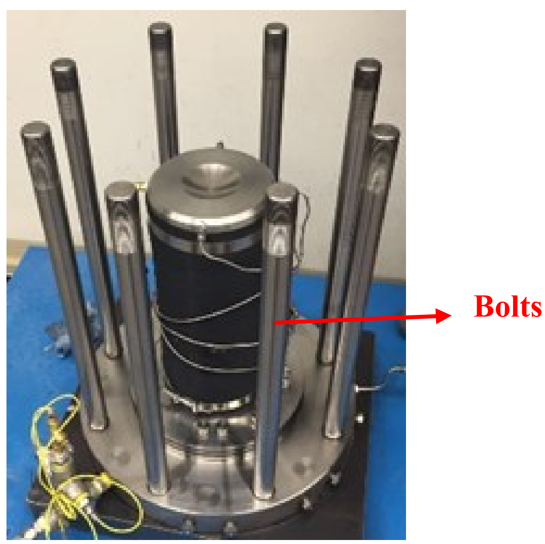


Figure B.10: Steel Supporting Rods Installation

10) Grease the o-rings at the pedestal of the SCT cell.

11) Install the metal shell of the SCT cell using the motorized fork-lift.

12) Tighten the supporting rods to the metal shell by washes and nuts to a torque of 10,000 lb in an opposite manner or following the labeled order. (Figure B.11).

Figure B.11: Nuts and Washes Installation

13) Fill the cell with hydraulic oil by the Moyon pump at a frequency setting of 15. The oil is used for applying confining stress.

14) Apply soil onto the piston, then install it on top of the shell. Press it in slowly until it reaches the bottom.

15) Use the motorized fork-lift to place the cell onto the load frame (operated by technician) (Figure B.12).

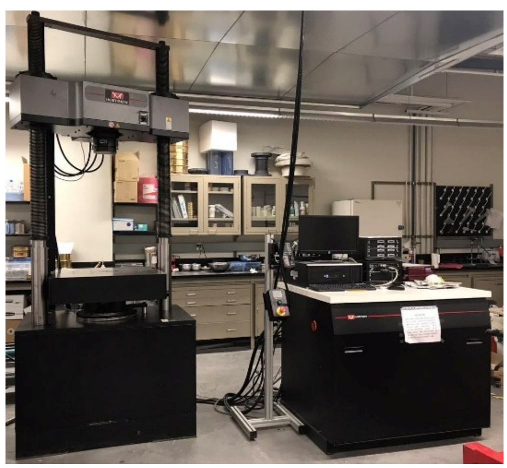


Figure B.12: Load Fame and DAQ system

B.3 Scaled Completion Test Procedure

1) Install the cross union with valve and the sand trap unit at the outlet of the cell.

2) Connect the sand trap unit to the valve arrangement system (Figure B.13).

Figure B.13: Valve Arrangement System

3) Set the load frame (or check the settings of load frame) based on the target effective stress with technician.

4) Connect the ISCO pump to the cell for applying confining stress.

5) Apply little confining pressure (10psi) to the cell for deairing the annular space through the top vent.

B.3.1 Saturation

1) Record the exact start time of each test and apply 25 psi confining pressure into the annular space of the cell and keep it for 20 min.

2) Connect the brine reservoir to the inlet of the metering pump and connect the outlet of the metering pump to the back-pressure column.

3) Switch the valve arrangement system to saturation mode.

4) Open the valve connected to top of the sample and start the metering pump at a frequency setting of 40 (60 cc/min) to saturate the cell.

5) Record the start time of fluid injection for saturation.

6) During the saturation, the confining pressure is kept at 25 psi. Record the residue oil volume and oil flow rate from the ISCO pump (Figure B.14) in case there is leakage of the sample.

Figure B.14: ISCO Pump

7) When there is fluid being produced from top of the sand pack fluently without any bubbly (steady state flow), the sand pack is regarded as fully saturated. Close the valve connecting the saturation column with the core.

B.3.2 Effective Stress Application

1) Keep the outlet of the cell unblocked.

2) Increase confining by ISCO pump 50 psi/7 min until it reaches the maximum confining pressure that we planned. May need to refill the ISCO pump twice or three times when increasing the confining.

3) The axial load will be increased automatically by the load frame at 385 lb/2 min

4) Keep recording the residual oil volume and oil flow rate of the ISCO pump as well as the axial load and displacement from the load frame every three to five minutes.

B.3.3 Fluid Injection

1) Re-adjust connections so that the metering pump (Figure B.15) can inject fluid from top of the cell through the sand pack towards the coupon. Switch the valve arrangement system to production mode.

Figure B.15: Metering Pump

2) Connect the outlet of the back-pressure column to the effluent tank.

3) Connect pressure tubes to the cell according to the labels. De-air the tubes with injected brine (Note: attach the higher-pressure ports first then the lower pressure ports to avoid damaging the transducer). For the SCT facility, the connecting order should be: pump, 4 inches pressure port, 2 inches pressure port and outlet of the cell.

4) Connect the DAQ device to the computer and start the Labview (brine test) for pressure measurement and recording during injection.

5) Record the start time of fluid injection.

6) Start the metering pump at frequency setting of 26. (40 cc/min)

7) Connect the fluid port to the sampling valve for taking fluid sample. The sample should be taken every 20 minutes. For the 120-min fluid flowing, 6 fluid samples should be taken.

9) The total duration of fluid injection is 120 min, every three to five minutes, to the following data should be recorded:

a) The residual oil volume and oil flow rate of the ISCO pump

b) Axial load and displacement from the load frame

c) The pump pressure (shown at the pressure gauge)

d) The flow rate (shown at the rota meter)

e) The pressure differentials for all three pressure transducers (shown at the Labview)

10) Stop the the metering pump when fluid flowing is end. Close the valve connected to the top of the sand pack while keeping the outlet of the cell unblocked.

B.3.4 Unload and Bleed

1) The load frame starts to unload at 385 lb/2 min and usually 10 minutes is needed for unloading.

2) Decrease the confining pressure with ISCO pump at 50 psi/5 min and the axial load will decrease simultaneously.

3) Disconnect the cell to the ISCO pump.

4) Disconnect the inlet of the pump to the cell.

5) Disconnect the outlet of the cell to the valve arrangement system.

B.4 Disassemble the Cell

1) Put the cell back to the pedestal by the motorized fork-lift (operated by technician)

2) Connect air to the top vent of the cell to push the oil back to tank. Connect the bottom vent to the tube and connect the tube to the tank. The pressure of the air is set at 15-20 psi.

3) Use the motorized fork-lift to keep the piston. Always remember to keep the piston during drainage. Otherwise the piston would jump out and cause damage.

4) After drainage the oil, disconnect the air and the tube to the cell.

5) Lift the piston with the motorized fork-lift.

6) Open the nuts in labeled order (follow the numbers labeled) and remove all nuts and washes.

7) Remove the metal shell of the cell by forklift.

8) Unscrew all rods.

9) Disconnect all tubes connecting to the top platen and the T-junction.

10) Remove the top platen and the porous disk

11) Open the valve at the outlet of the cell to drainage the sand pack.

12) Use a 0.5 inch PVC tubing to obtain three samples across the sand pack from different location. When obtaining, make sure all sample are complete (the tubing should reach the bottom). Use a steel stick to extrude samples out of the tubing. Arrange all three samples in a box and label them for further analysis.

13) After taking samples, remove the sand pack little by little with shovels and taking large scale samples at the top, middle (4 inches above the coupon) and above the coupon.

14) Remove the rubber sleeve.

15) Disconnect the coupon to tubes at the cone and remove the coupon.

16) Collect the produced sand by blowing water and air at the cone.

17) Clean the coupon with air and apply corrosion coating or store in mineral oil.

B.5 Post-Mortem Analysis

B.5.1 Wet Sieving

1) Dry all samples at the room temperature.

2) Separate each bar samples into three parts (bottom, middle and top) when they are completely dry.

3) Record the weight of each parts and also the weight of their containers. Usually we record them in a table shown below (**Table B.2**).

Table B.2 Wet sieving recording table

Date:			
Sample:			
	Weight of container	**Weight of sand & clay**	**Weight of dry sand & container**
BL			
BC			
BR			

ML			
MC			
MR			
TL			
TC			
TR			

4) Crash each part of the sample and solve with water. Use a blender to help solving. Dump the mixture into the special designed sieve (#325, 44 microns) to separate sand and fines.

5) Take some fluid sample (with washed fines) in small bottles, label the bottle with test and sample information.

6) Wash sand out of sieve into container. Dry the sand in oven for at least 6 hours.

7) Weight the dry sand with the container and record.

B.5.2 Produced Sand

1) Use the special designed wet sieve to collect the produced sand.

2) Dry the sand at room temperature.

3) Collect the dry sand in small cups and weight them

4) Record the weight of produced sand and label the cup.

B.5.3 Particle Size Analysis of Fines

1) The particle size distribution of fines is measured by laser particle size analyzer.

2) Warm up the device and wait for 10 minutes.

3) Start the application of laser particle size analyzer and initialize parameters of fines (kaolinite and illite) PSD analysis.

4) Conduct reference test with falcon flask full of deionized water.

5) Add samples into the falcon flask for PSD analysis after the reference test. For each test, repeat 3-5 times and save all the data and curves.

B.6 Facility Maintenance Procedure

1) Run the metering pump twice a week with deionized water. The deionized water can help to protect the pump from plugging or corrosion by brine.

2) Apply rust remover onto the stainless-steel coupon after using.

3) Keep the carbon steel coupon in mineral oil after using.

4) Clean and calibrate the pressure transducers once per several months. Clean up all the crystallize salt inside the transducer and fill it with oil.

5) Pump deionized water into the back-pressure column and release to keep it clean.

Appendix C: Hazard Assessment

C.1 Instructions:

Review the Hazard Description (column 3) of each Exposure Condition (column 2) and check the ones that are present (column 1). For every condition present, review the Examples of Engineering Controls and Personal Protective Equipment (column 4) and then complete the Specific Engineering Controls and PPE (column 5) that you intend to use to reduce or eliminate the hazard.

Check if Present	Exposure Condition	Hazard Description	Examples of Engineering Controls and Personal Protective Equipment (PPE)	Specific Engineering Controls and Personal Protective Equipment (PPE)
Biological Hazards				
☐	Nano-particles	Unknown health hazards due to small size	Containment, respirators	Mandatory use of mask
Chemical Hazards				
☐	Chemicals, low hazard with low splash probability	Skin and eye irritation	Safety glasses, chemical resistant gloves, lab coat, closed shoe of good structure, long pants; Be aware of the nearest eyewash and shower	

Check if Present	Exposure Condition	Hazard Description	Examples of Engineering Controls and Personal Protective Equipment (PPE)	Specific Engineering Controls and Personal Protective Equipment (PPE)
☐	Compressed gases	Aphyxiation, accidental tip over, content release, and pinch points	Gas cylinder and line must be secured to stationary objects in a safe location away from danger or impact; Safety glasses and gloves	
☐	Washing glassware	Skin lacerations from broken glass	Safety glasses, rubber gloves, lab coat.	
Physical Hazards				
☐	Compression (pressure)	Injury from sudden release of energy from valves, compression chambers	Energy control, safety classes, shields if necessary, body position	
☐	Confined Spaces	Exposure, falls, dangerous atmospheres, asphyxiation, noise, vibration	Buddy system, lanyards, ventilation, monitoring	

Check if Present	Exposure Condition	Hazard Description	Examples of Engineering Controls and Personal Protective Equipment (PPE)	Specific Engineering Controls and Personal Protective Equipment (PPE)
☐	Sliding hammer	Pinch, crush, caught, pulled in, electrocution	Energy control, signage, guards, no jewelry, tie back long hair	
☐	Impact	Injury to head or body	Hard hat, impact resistant toed shoes, body position	
☐	Manipulation of large objects	Injury, death	Training, proper lifting equipment, procedures, inspections, buddy system	
☐	Material Handling	Physical injury, strains, sprains	Training, buddy system, gloves, standard operating procedures	

Check if Present	Exposure Condition	Hazard Description	Examples of Engineering Controls and Personal Protective Equipment (PPE)	Specific Engineering Controls and Personal Protective Equipment (PPE)
☐	Noise	Deafness, hearing damage, inability to communicate	Noise monitoring, hearing protection if necessary, training, and engineering controls (e.g., enclosures, baffles, mufflers)	
☐	Penetration	Wounds	Training, padding of surfaces, signage, and body position, avoid use of sharp object	
☐	Respirable Dust	Lung damage	Local exhaust ventilation. Monitoring, respirator, access to vented room (soil preparation lab)	