# A Set of Graphical Design Criteria for Slotted Liners in Steam Assisted Gravity Drainage Production Wells

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## Abstract

Slotted liners have been widely used in steam-assisted gravity drainage (SAGD) wells owing to their low cost and superior mechanical integrity. Multiple factors affect the performance of slotted liners, such as particle size distribution (PSD) of formation sands, aperture size, slot density, fluid flow rate, and wellbore operational conditions. Currently, most of the existing design criteria formulate the lower and upper bounds of aperture based on one or several points on the particle size distribution curve of oil sands. Most of these design criteria neglect the slot density, wellbore operational conditions, and shape of the PSD curve.

This study carries out a series of large-scale pre-pack sand retention tests (SRT) step rates. The aim is to investigate the impacts of aperture size, slot density, and fluid flow rate on the slotted liner performance. Comprehensive design criteria for determining the safe aperture window are presented to maintain the sanding and the wellbore plugging of the zone near the slotted liners within an acceptable level. Sand production governs the upper bound of the aperture size, and flow performance guides the lower bound of the aperture size. The new criteria are presented graphically to illustrate the optimal slot window as a function of the sand PSD, slot density, and fluid flow rate. The results of separate tests are used to demonstrate the performance of the new design criteria. The optimal slot window obtained via the new design criteria guides the slot liner selection in the SAGD process.

## 1. Introduction

Alberta's oil sands are the third-largest proven heavy oil reserves in the world (Lunn, 2013; Wilson, 2013). SAGD has emerged as a useful technology for heavy oil recovery in Canada (Butler and Stephens, 1981; Butler, 1985; Gates et al., 2005; Zhang et al., 2007; Montero et al., 2018). The SAGD process involves at least one pair of horizontal wells, one well above the other and separated by about five meters. The typical length for SAGD horizontal wells ranges from 500 to 1200 meters (Nasr et al., 1998; Mahmoudi et al., 2017; Montero et al., 2018). For highly viscous oil, such as Athabasca oil region in Alberta, Canada, steam is circulated through both wells to heat the oil in the zone between the two horizontal wells. (Nasr et al., 1998). Next, steam is injected into the reservoir along the upper horizontal well (injection well) for several months to form and grow a steam chamber (Fig. 1). Melted bitumen and condensed steam are produced through the lower wellbore, which is the producer well. Conduction and convection are the two heat transfer mechanisms in SAGD reservoirs (Butler and Stephens, 1981).

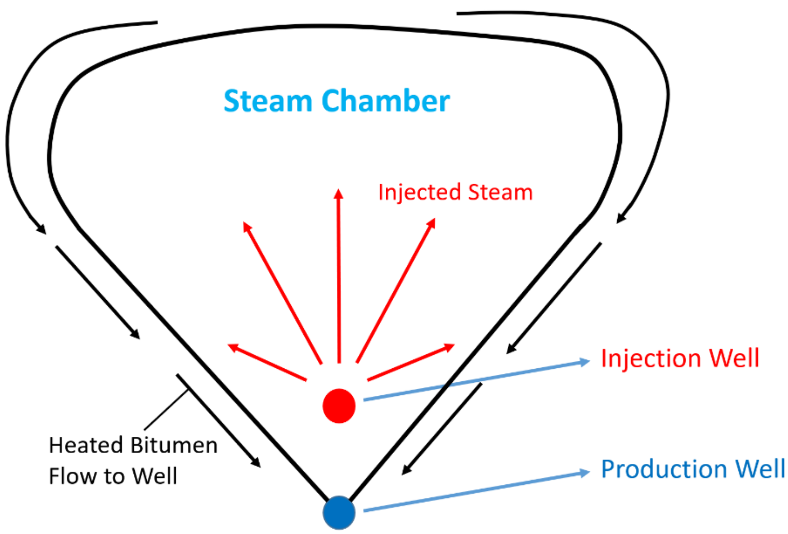


Fig. 1 The schematic concept of the steam chamber (modified from Butler, 1985)

Sand production is a common issue in oil sands fields (Tausch and Corley Jr, 1958; Islam and George, 1989; Martins et al., 2009; Montero et al., 2018). For unconsolidated sand formations, such as the McMurray Formation, sand production can be a problematic and costly issue that must be prevented (Yi, 2002; Han et al., 2007; Anderson, 2017). Severe sand production could damage the surface facilities and downhole equipment, plug the well, and induce operational problems (Al-Awad et al., 1999; Denney, 2008; Sanyal et al., 2012). Several stand-alone sand control screens, such as slotted liners and wire wrapped screens, have been used for decades to prevent the sand production. Among different sand control solutions for SAGD wells, slotted liners have gained popularity in Western Canada due to low cost and superior mechanical strength (Bennion et al., 2009; Fermaniuk, 2013).

The aperture size is a critical factor in slotted liner design. An appropriate aperture design for the slotted liners can reduce the sanding while maintaining a desirable flow performance over the wellbore life cycle (Bennion et al., 2009; Xie, 2015; Mahmoudi et al., 2016b). Typically, laboratory tests are required to optimize the aperture size.

Slurry and pre-pack sand retention tests (SRT) are two types of laboratory tests that are widely used in the industry to optimize the aperture size of stand-alone screens. For the slurry test, low concentration sand slurry (less than 1% of volume) is pumped into a cell at a constant flow rate, replicating a gradual formation failure around the liner. A sand-pack gradually forms on the screen during the test (Gillespie et al., 2000; Underdown et al., 2001; Ballard and Beare, 2012; Williams et al., 2006; Mathisen et al., 2007; Chanpura et al., 2012). For the pre-pack test, the sand is packed on the screen coupon, emulating the potential annular collapse between the borehole and the screen. Then, fluids are pumped through the sand-pack and the screen coupon. Testing measurements include pressures, flow rates, and solid production (Markestad et al., 1996; Ballard and Beare, 2006; Constien and Skidmore, 2006; Williams et al., 2006; Chanpura et al., 2012).

There are a few screen sizing design criteria published in the literature. Coberly (1937) was the first to suggest that the screen aperture size should be selected as a function of the sand PSD. Based on laboratory results, Coberly recommended using an aperture size equal to twice the formation sand D10, where D10 is the sieve size which retains 10% of the cumulative sand mass. Coberly's experiments used coupons with a single slot to determine the aperture size that forms a stable bridge.

Subsequently, some other studies generated sizing protocols for slotted liners in thermal operations (Bennion et al., 2009; Fermaniuk, 2013; Devere-Bennett, 2015; Mahmoudi et al., 2016b). Bennion et al. (2009) proposed a protocol for the slotted liner size selection based on a single-slot coupon testing facility. They investigated the implications of slot geometry, multi-phase fluid flow, and flow rate on the performance of the slotted liner. However, their testing neglected the impact of inter-slot interactions on sand production and flow performance. Fermaniuk (2013) proposed an ad hoc criterion for the slot window of slotted liners based on field experience. Using the same experimental setup as Bennion used, Devere-Bennett (2015) tested the performance of single-slot coupons with different aperture sizes.

Mahmoudi et al. (2016b) investigated the impacts of slot density, aperture size, and PSD on the selection of slotted liner size by performing SRT tests on multi-slot coupons. They used synthetic sand-packs to replicate the oil sands and developed design criteria of slotted liners. In their study, the cumulative produced sand and retained permeability are used as performance indicators. In the SAGD context, maximum sanding level has been suggested to be 0.12 lb/ft$^2$ for acceptable sanding and 0.15 lb/ft$^2$ for marginal sanding performance (Hodge et al., 2002; Chanpura et al., 2011). The minimum acceptable level for the retained permeability has been proposed to be 50% (Mahmoudi et al.2016b, Mahmoudi, 2017).

Table 1 summarizes the previous slotted liner size design criteria. The table presents essential information about the criteria and their limitations.

Table 1 Summary of existing design criteria

| Author | Contribution | Shortcoming |
|---|---|---|
| Coberly (1937) | Conducted experiments using single-slot coupons to find the aperture size that allows the formation of a stable bridge. | Impacts of slot density and flow rate were neglected. The flow performance was not investigated. |
| Bennion et al. (2009) | Investigated the impact of slot geometry, phase change, and flow rate on the performance of single-slot coupon using a small-scale SRT facility | Impact of slot density was neglected on the design criteria. The flow performance was not quantitatively investigated. |

| | | |
|---|---|---|
| Fermanuik (2013) | Provided a rule-of-thumb criterion for slotted liner design. | It is an ad hoc criterion and does not support all the SAGD conditions. |
| Devere-Bennett (2015) | Used small-scale SRT facility equipped with a single-slot coupon to optimize screen aperture size for specific formation sand. | Slot density was not considered in the design criteria, and the flow performance was only investigated qualitatively. |
| Mahmoudi et al. (2016b) | Investigated the impact of slot density, PSD, and flow rate on the performance of slotted liner using large-scale SRT facility equipped with a multi-slot coupon. | The design criteria were based on single-phase tests on two similar PSDs with limited fines content. |

In this study, a series of pre-pack SRT tests was performed to determine the optimal slotted liner design for the McMurray Formation oil sands. Synthetic sand-packs were prepared by mixing commercial sands and clays to replicate the McMurray oil sands for the tests. The new design criteria are presented using a traffic light system (TLS) approach. Colour codes are used to indicate acceptable or unacceptable sanding and fluid flow performances of the liner. The design criteria contain the aperture size, slot density, and fluid flow rate as the main parameters. The following sections provide details of the experimental apparatus, testing procedure, and the development and application of the proposed design criteria using the TLS method.

## 2. Testing Materials, Devices and Procedure

A pre-pack SRT facility was developed to evaluate the performance of slotted liners using representative multi-slot coupons (Mahmoudi et al., 2016b). This section provides the details of the experimental facility and testing materials.

### 2.1. Sand-pack

Synthetic sand-pack samples were prepared by mixing commercial sands, silts, and clays to obtain materials representative of the oil sands in the McMurray Formation. The mixture was packed layer by layer to ensure a uniform porosity and permeability.

The McMurray Formation oil sands in Alberta have been categorized into four major classes with different PSDs, as shown in Fig. 2 (Abram and Cain, 2014). Among them, DC-I and DC-II are fine sands, and DC-III and DC-IV are medium and coarse sands, respectively (Fattahpour et al., 2017). Commercial sands, silts, and clays were used to replicate the DC-I formation sands for large-scale laboratory testing using a method employed by Mahmoudi et al. (2015) and Fattahpour et al. (2017).

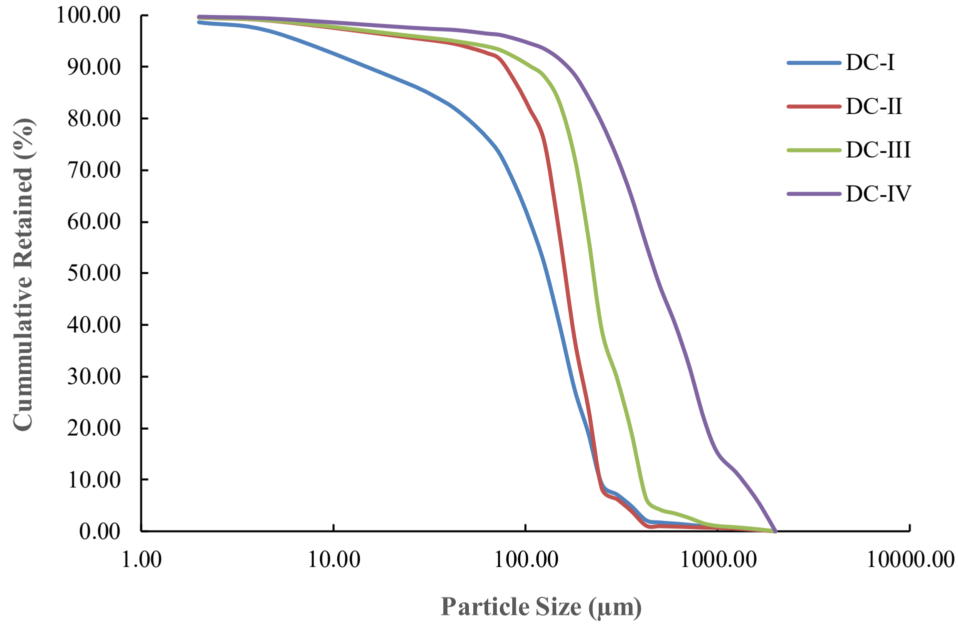


Fig. 2 PSD classes for McMurray Formation oil sands (Abram and Cain, 2014)

Figure 3 shows the PSD of commercial sands, slits, and clays that were mixed to replicate the PSD of DC-I oil sands. Kaolinite was used as the clay mineral in the samples as it is considered to be the dominant clay in the McMurray Formation (Romanova et al., 2015; Mahmoudi et al., 2016a). Kaolinite is a non-swelling clay material (Zhou et al., 1997; Matmon and Hayden, 2003; Farrokhpay et al., 2016; Sharifipour et al., 2019).

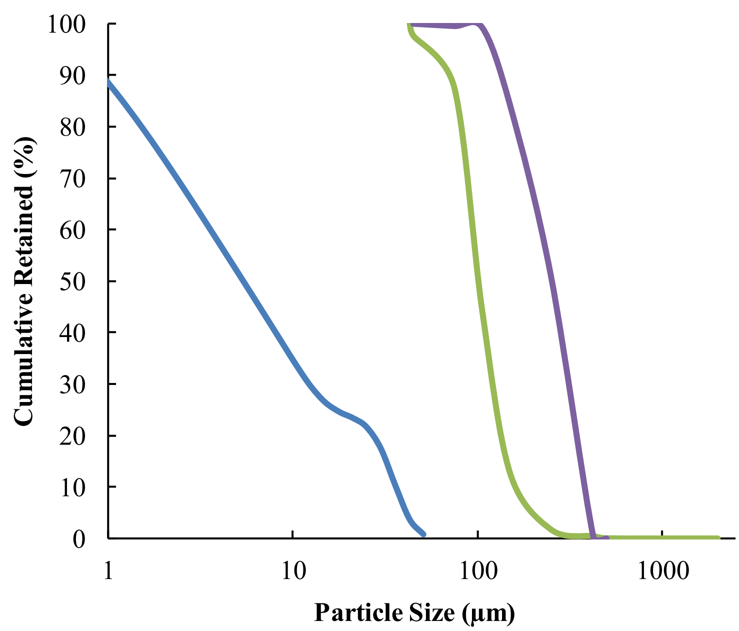


Fig. 3 PSD classes for three commercial sands

The DC-I PSD was matched by a mixture consisting of 71.5 wt% silica sand, 17.2 wt% silica silt and 11.3 wt% kaolinite. The PSD curves of the actual and replicated DC-I are illustrated in Fig. 4 with a reasonable match.

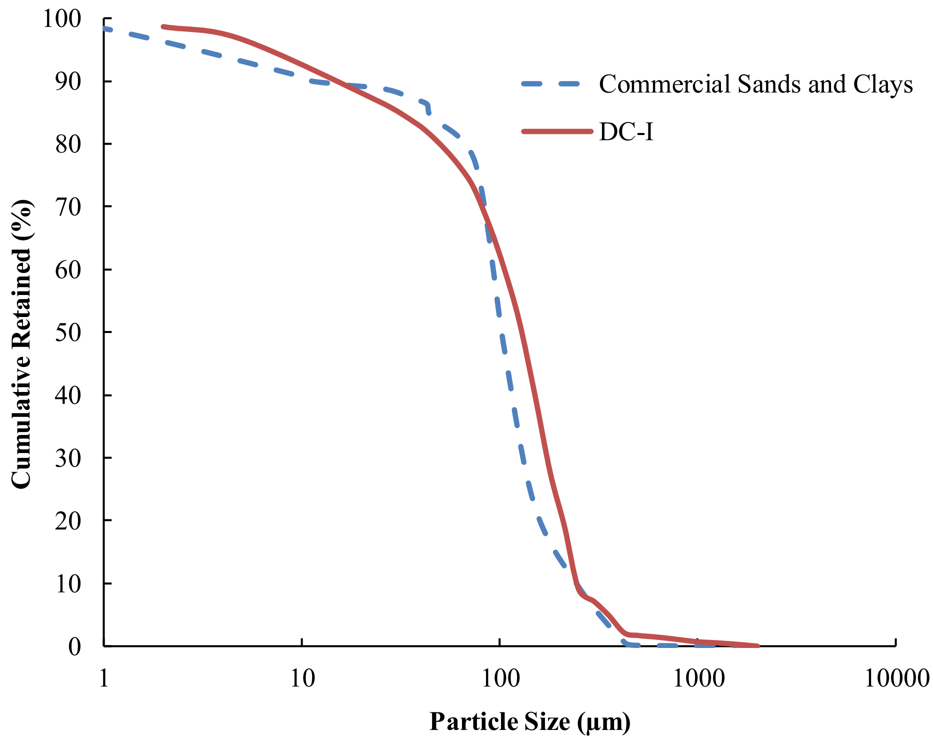


Fig. 4 PSD curves for DC-I and the commercial sand mixture

**2.2. Saturation and Flowing Fluids**

Factors such as the pH and salinity of formation brine influence the fines migration (Khilar and Fogler 1984; Kia et al. 1987; Civan, 2007). In this study, Sodium Chloride brine with 7.9 pH and 7000 ppm salinity was used as the saturating and flowing fluid. These values constitute proper pH and salinity levels in the produced water from SAGD wells (Mahmoudi et al., 2016a).

**2.3. Liner Coupons**

The multi-slot coupons were all manufactured with a seamed slot opening (Fig. 5a) with different slot densities. Slot density, denoted by SPC, is quantified by the number of slots per column (or row) of slots on a liner with a 7-inch diameter. Each one SPC equals to four SPF (slots per foot). As shown in Fig. 5b, three coupons with SPC=30, SPC=42, and SPC=54 were selected to represent the low to high slot density commonly used in industry (Kaiser et al., 2000). The aperture sizes were 0.022 seamed to 0.014 inch, 0.026 seamed to 0.018 inch, 0.030 seamed to 0.022 inch, and 0.034 seamed to 0.026 inch. The use of multi-slot coupons enabled to investigate the effects of both aperture size and slot density on the performance of sand control liners.

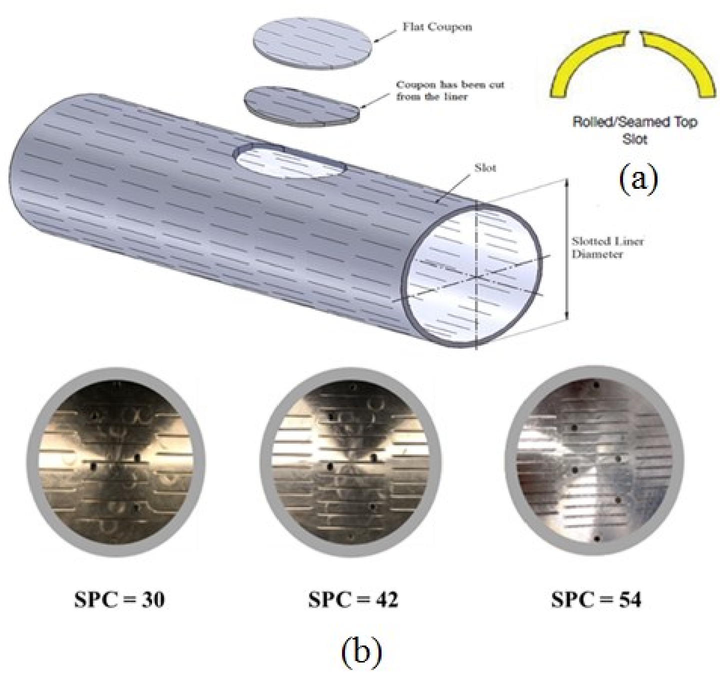


Fig. 5 Multi-slot coupons with seamed slots

**2.4. Experimental Apparatus**

Figure 6 shows the pre-pack SRT apparatus for the physical model tests. The SRT set-up consists of five major units: (1) the SRT cell, (2) fluid injection unit, (3) data acquisition and monitoring unit, (4) sand and fines measurement unit, and (5) back-pressure and saturation unit.

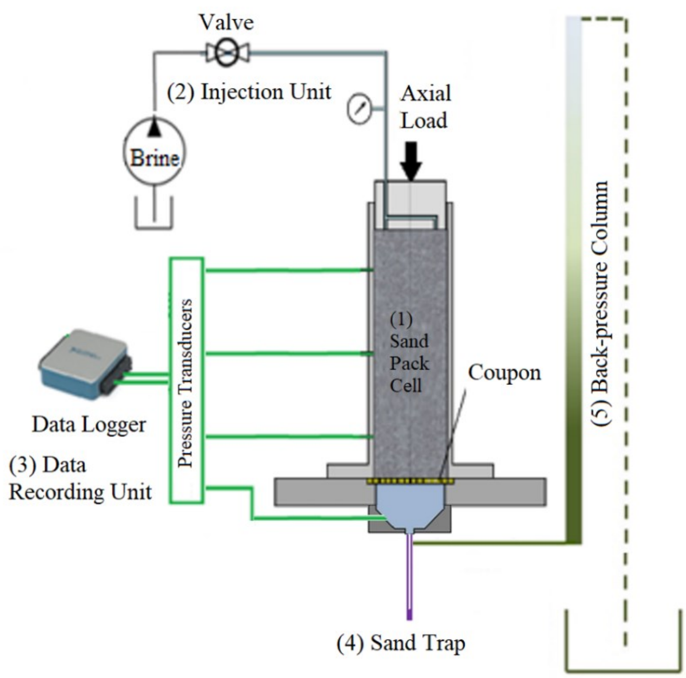


Fig. 6 The schematic view of the SRT apparatus

The apparatus accommodates multi-slot coupon disks 6 inches in diameter. The coupon sits at the bottom of the SRT cell, on which the sands are packed. Several porous disks (coarse to fine) are placed at the top of the sand-pack to ensure uniform flow. Axial stress is applied to the sand-pack to prevent channelling and fluidization in the sand-pack while saturating the sample. A solenoid diaphragm pump is used to inject brine into the sample. The pump has both digital pulse and manual stroke controllers. The brine is injected from the top of the SRT cell and flows downwards toward the coupon.

The data acquisition and monitoring unit consists of three differential pressure transducers with 0.25% accuracy, a manometer, data acquisition system (LabVIEW), and a rotameter. The differential pressure transducers record the pressure drop along with the sand-pack, and the rotameter measures the fluid flow rate at the outlet. The outlet is designed to collect the produced sand and fines. The produced sand is collected in a narrow pipe at the outlet and is monitored by a camera. Finally, the back-pressure unit provides a minor back-pressure (up to 3 psi) on the sand-pack during the saturation and flow stages.

### 2.5. Testing Procedure

First, dry commercial sands and clays are mixed for 20 minutes to reach a uniform mixture with the desired PSD (DC-I). Then, the dry sample is mixed with brine to produce a uniformly moist mixture. Next, the mixture is compacted in layers to obtain uniform compaction throughout the sample. Then brine is injected from the cell bottom at low flow rates (around 150 cc/hr) to saturate the sand-pack without disturbing it. Each test consists of seven stages with fluid flow rates increasing in steps from 0.31 to 1.90 bbl/day/ft$^2$. These rates were chosen to represent typical fluid flux levels in SAGD wells (Medina, 2010; Mahmoudi, 2017; Montero et al., 2018). Each fluid flow rate is kept constant to reach the steady-state condition (typically about 30 minutes).

## 3. Testing Program and Evaluation Method

The testing program consists of 12 SRT tests with fluid flow rates ranging from 0.31 to 1.90 bbl/day/ft$^2$. The test matrix for the testing program is provided in Table 2.

Table 2: Test matrix for sand-packs with the DC-I type of PSD

| Aperture Size | SPC = 30 | SPC = 42 | SPC = 54 |
|---|---|---|---|
| **0.014-0.022 inch** | Flow rate: 0.31 to 1.9 bbl/day/ft$^2$ | Flow rate: 0.31 to 1.9 bbl/day/ft$^2$ | Flow rate: 0.31 to 1.9 bbl/day/ft$^2$ |
| **0.018-0.026 inch** | Flow rate: 0.31 to 1.9 bbl/day/ft$^2$ | Flow rate: 0.31 to 1.9 bbl/day/ft$^2$ | Flow rate: 0.31 to 1.9 bbl/day/ft$^2$ |
| **0.022-0.030 inch** | Flow rate: 0.31 to 1.9 bbl/day/ft$^2$ | Flow rate: 0.31 to 1.9 bbl/day/ft$^2$ | Flow rate: 0.31 to 1.9 bbl/day/ft$^2$ |
| **0.026-0.034 inch** | Flow rate: 0.31 to 1.9 bbl/day/ft$^2$ | Flow rate: 0.31 to 1.9 bbl/day/ft$^2$ | Flow rate: 0.31 to 1.9 bbl/day/ft$^2$ |

Investigators have found that over 90% of the slots in SGAD wells are plugged late in the wellbore lifetime (Romanova and Ma, 2013; Montero et al., 2018). Three different flow scenarios are considered to investigate the effect of operational conditions on the liner design and performance.

These are: aggressive (> 1.31 bbl/day/ft2), moderate (between 0.72 and 1.31 bbl/day/ft2), and mild (< 0.72 bbl/day/ft$^2$) flow conditions. These three flow scenarios aim to emulate different levels of effective flow due to slots plugging, non-uniform flow regime, and non-contributing liner segments. The basic flow rate (0.31 bbl/day/ft$^2$) corresponds to a typical SAGD production rate of 1800 bbl/day considering a liner of 7 inches in diameter and 800 meters in length. Then, the three flow conditions account for different levels of effective flow: less than 25%, between 50% and 75%, and more than 50%, respectively. The testing results are presented in terms of two performance indicators: sand production and flow performance.

### 3.1. Sanding Performance

The amount of produced sand is a critical parameter in evaluating the performance of slotted liners and is a function of aperture size, slot density, fluid flow rates, flowing fluids, and sand characteristics (Mahmoudi et al., 2016b). In SAGD wells, an acceptable sand production level highly depends on sand transport in the produced fluids, artificial lift requirements, susceptibility of downhole and surface equipment (such as tubing, choke, fittings) to erosion, and surface separator capacity (Carlson et al., 1992; Markestad et al., 1996; Bennion et al., 2009). The general rule of thumb is that the lifetime sand production should be limited to less than 1% of the liner volume.

Most SAGD wells use 7-inch or 8-5/8-inch liner with production tubing size ranging from 2-7/8 inch to 4-1/2 inch. The 1% limit for this typical liner size results in an approximately 0.15 lb/ft$^2$ sanding, which is the cumulative sand produced over the entire SAGD well life cycle per unit area of the outer surface of the liner. Usually, the limit of 0.12 to 0.15 lb/ft$^2$ is adopted for the maximum acceptable sand production in laboratory sand control tests (Hodge et al., 2002; Chanpura et al., 2012; Mahmoudi et al., 2016b). Herein, sand production is considered to be within an acceptable level if it is less than 0.12 lb/ft$^2$, marginal if it is between 0.12 and 0.15 lb/ft$^2$, and unacceptable if it is over 0.15 lb/ft$^2$.

### 3.2. Flow Performance

The lower bound for the aperture size is governed by plugging which is determined by a parameter called retained permeability. The definition of retained permeability in this paper is the ratio of the screen permeability to the original sand-pack permeability. The screen permeability applies to the 2-inch sand-pack in the coupon vicinity plus the screen coupon (Mahmoudi et al., 2016b).

The flow performance limitation is determined by two terms: the flow-dependent term and the flow-independent term (Furui et al., 2007). The flow-dependent term is attributed to the flow convergence that changes the flow velocity and geometry near the wellbore. The flow-independent term is related to the pore space alteration, sand retention on the slotted liner, and the pressure drop within the slots. In the past SRT tests, a value of 50% to 70% has been considered as the lowest acceptable retained permeability (Mahmoudi, 2017).

### 3.3 Traffic Light System Method

Sand production and retained permeability results are used to develop a set of design criteria for slotted liners. While past design criteria provide the safe aperture window as a function of specific points on the sand PSD curve based on single-slot tests (Coberly, 1937; Markestad et al., 1996;

Gillespie et al., 2000; Fermaniuk, 2013), the new design criteria here account for inter-slot interactions, slot density, and fluid flow rates.

The safe aperture window consists of an upper bound and a lower bound. Sand production sets the upper bound for aperture size while flow performance sets the lower bound for the aperture size. The traffic light system uses green, yellow, and red colour to indicate an acceptable, marginal, and unacceptable performance. Table 3 presents the colour definitions for the sanding and flow performance indicators.

Table 3: Design criteria of the traffic light system

| | |
|---|---|
| **Sand production performance** | |
| Red | Sand production more than 0.15 $lb/ft^2$ |
| Yellow | Sand production between 0.12 and 0.15 $lb/ft^2$ |
| Green | Sand production less than 0.12 $lb/ft^2$ |
| **Flow performance** | |
| Red | Retained permeability less than 50% |
| Yellow | Retained permeability between 50% and 70% |
| Green | Retained permeability higher than 70% |

A linear axis is used to present the design criteria in the traffic light system. Figure 7 shows the axis as also labelled with D values, such as D10, for DC-I PSD.

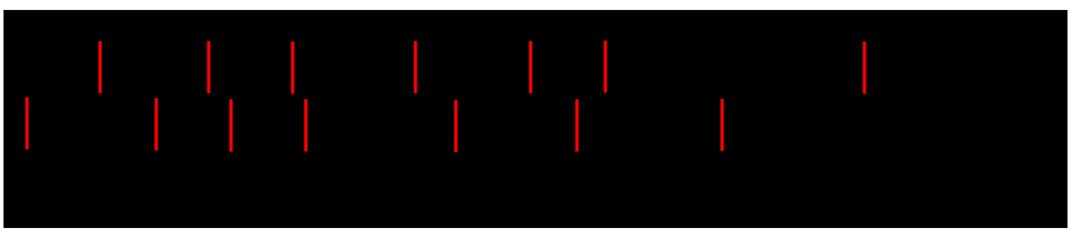

Fig. 7 Linear axis for the presentation of the safe aperture window for DC-I PSD

## 4. Testing Results

### 4.1. Sand Production and Flow Performance

Figure 8 shows the cumulative produced sand as a function of flow rates. The figure also presents the threshold values (0.12 and 0.15 $lb/ft^2$) for the maximum acceptable sand production per unit surface area of the slotted liner. According to Fig. 8, slot aperture size, slot density, and flow rate impact cumulative sand production. Results indicate only a slight increase in sanding with high flow rates when for aperture size less than 0.018 inches. However, for slot size greater than 0.022 inches, cumulative sand production increases sharply with flow rate. This observation indicates that the cumulative sand production changes from insensitive to flow rate to sensitive to flow rate with the increase of aperture size.

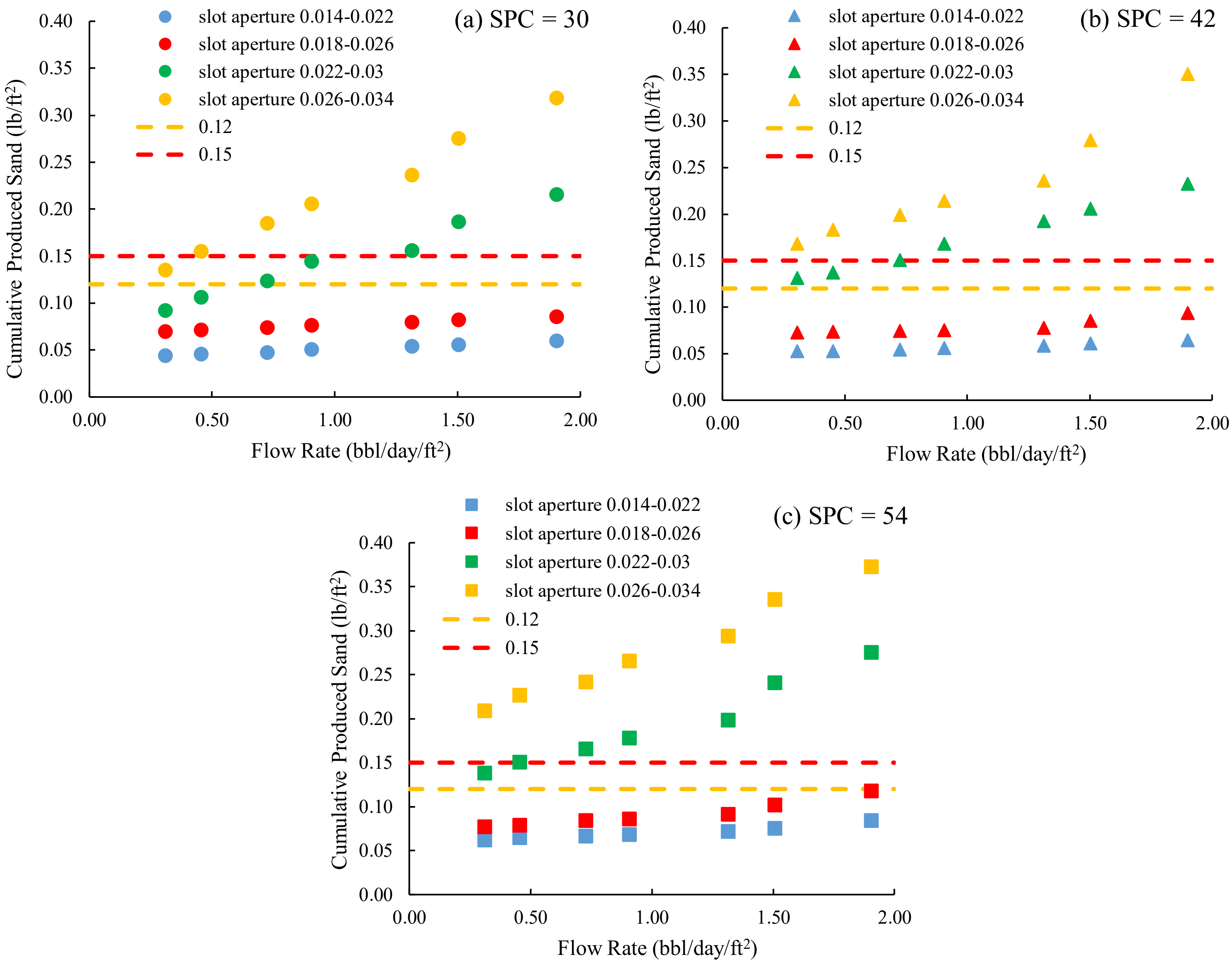


Fig. 8 Cumulative produced sand for different fluid flow rates (a) SPC=30, (b) SPC =42, and (c) SPC=54

Figure 9 shows the retained permeability for all the SRT tests at different flow rates. In this study, the initial permeability at the top of the sand-pack was calculated using the measured pressure drop at the low fluid flow velocity of 0.001 cm/s. The low flow rate is selected to ensure little fines migration when determining the original (unaltered) permeability of the sand-pack. During the test, the screen permeability (sand-pack within the 2-inch vicinity of the coupon plus the coupon) was calculated using the measured pressure drop in that interval for each flow stage. The figure also shows the threshold values (50% and 70%) for the acceptable retained permeability. Figure 9 indicates that the retained permeability decreases with the increase of fluid flow rate due to a stronger fines migration at higher flow rates.

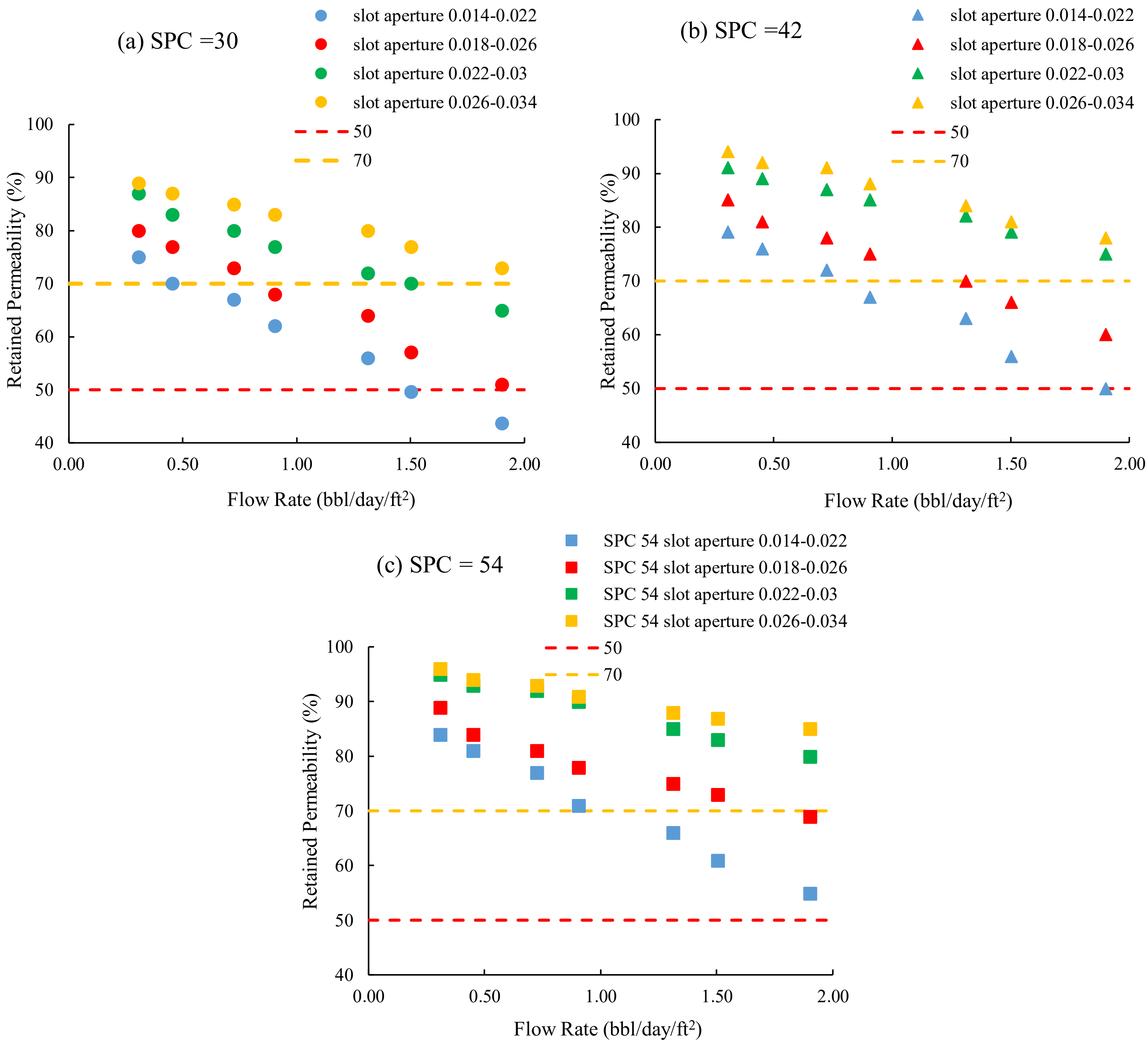


Fig. 9 Retained permeability at different fluid flow rates (a) SPC=30, (b) SPC=42, and (c) SPC=54

### 4.2. Design Criteria for DC-I Sand

The cumulative sand production and retained permeability results in Figs. 8 and 9 are used to develop the design criteria for DC-I sand concerning SPC 30, 42, and 54 for three different flow scenarios. Similar design criteria can be developed for other PSD classes.

The traffic light bar for sand production at the mild fluid flow rate for SPC=30 is displayed in Fig. 10. In this figure, the aperture sizes resulting in produced solids of 0.12 and 0.15 lb/ft2 are interpolated from the measured produced solids. The data used for the interpolation includes the four tested slot sizes at the flow rate of 0.72 bpd/ft2 in Fig 8(a). Figure 11 shows the interpolation procedure, which plots the amount of the final cumulative sand production against the aperture size. An equation is created by curve fitting, and the two aperture sizes that correspond with sand production of 0.12 and 0.15 lb/ft2 are obtained from the equation.

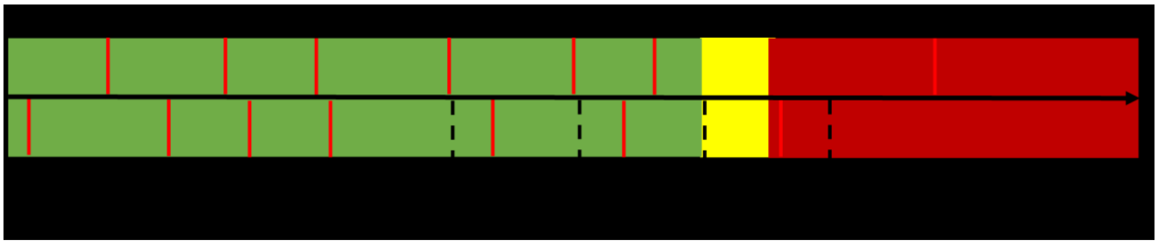

Fig. 10 Traffic light bar of sand production for SPC=30 at the mild fluid flow rate (< 0.72 bbl/day/ft$^2$)

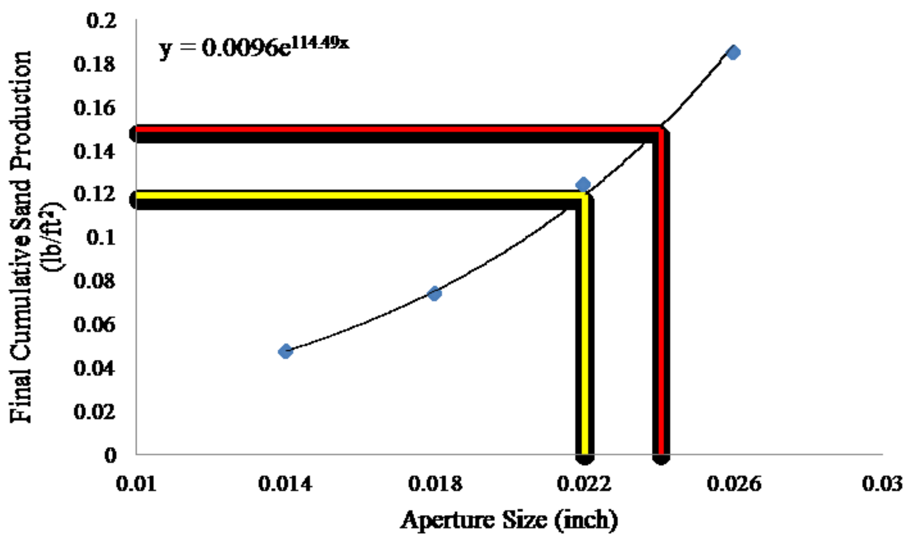


Fig. 11 Interpolation procedure in Traffic light bar of sand production for SPC=30 at the mild fluid flow rate (< 0.72 bbl/day/ft2)

Similarly, the traffic light bar for retained permeability at the mild fluid flow rate for SPC=30 is obtained from Fig. 9a, which is presented in Fig. 12. Also, the location showing the colour transition is obtained by interpolation.

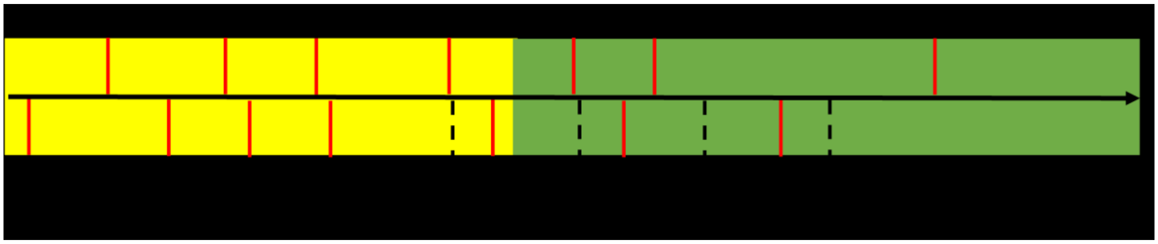

Fig. 12 Traffic light bar of retained permeability for SPC=30 at the mild fluid flow rate (< 0.72 bbl/day/$ft^2$)

Finally, combining the traffic light bars of sand production (Fig. 10) and retained permeability (Fig. 12), the overall traffic light bar for SPC=30 at mild fluid flow rate is generated as shown in Fig. 13.

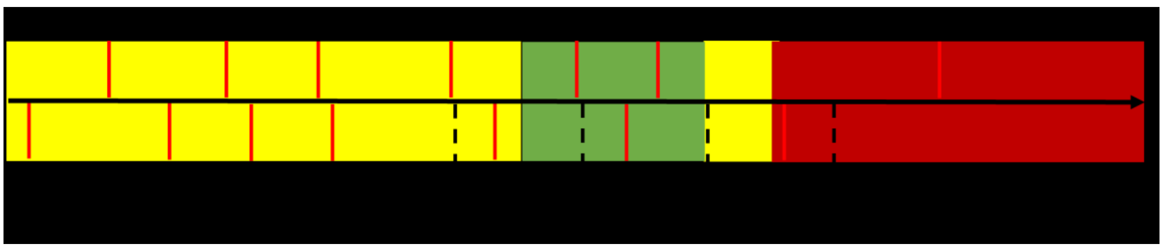

Fig. 13 Traffic light bars for SPC=30 at mild fluid flow rates (< 0.72 bbl/day/$ft^2$)

Similarly, the traffic light bar for SPC=30 for moderate and aggressive operational conditions are shown in Figs. 14 and 15, respectively. Subsequently, the overall traffic light bars for SPC=30 can be summarized in Fig. 16.

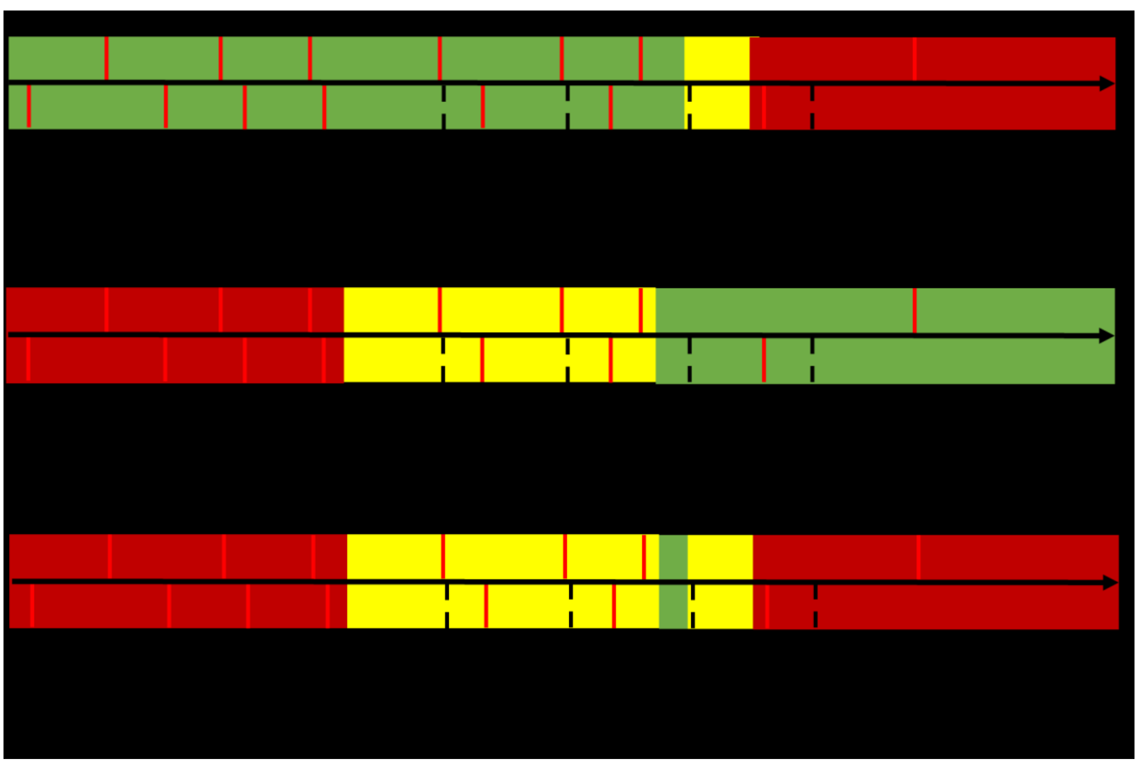

Fig. 14 Traffic light bars for SPC=30 at moderate fluid flow rates (0.72 to 1.31 bbl/day/ft$^2$), (a) sand production, (b) retained permeability, and (c) overall design criteria

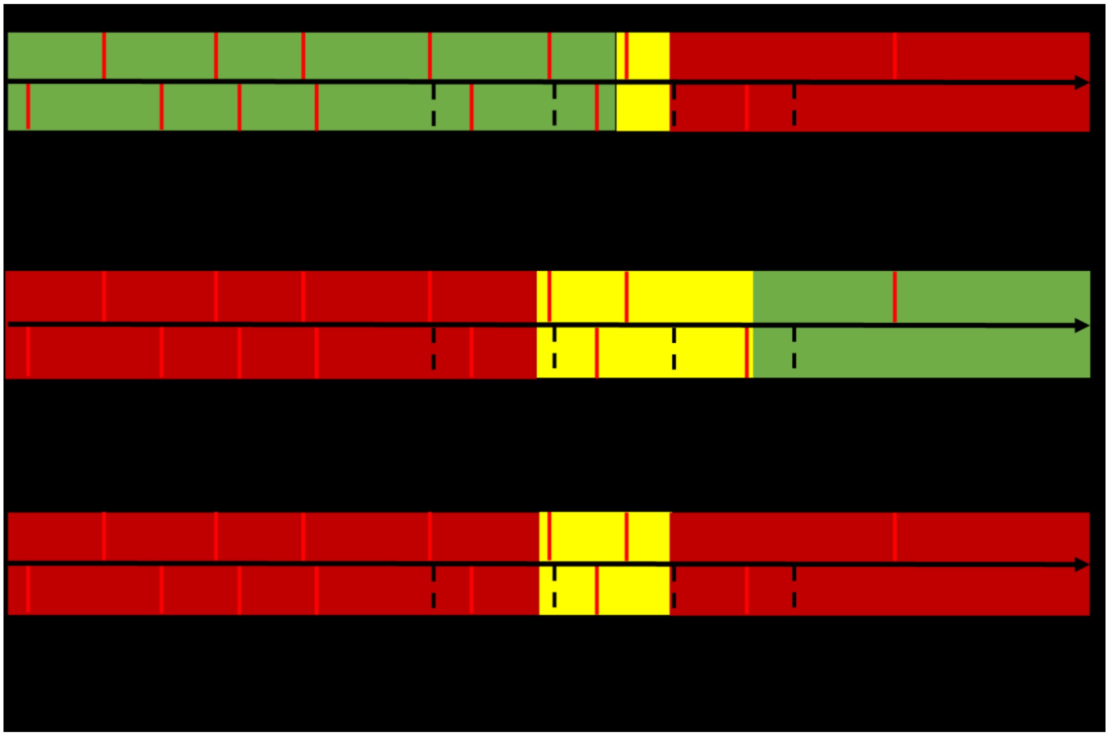

Fig. 15 Traffic light bars for SPC=30 at aggressive fluid flow rate (> 1.31 bbl/day/ft$^2$), (a) sand production, (b) retained permeability, and (c) overall design criteria

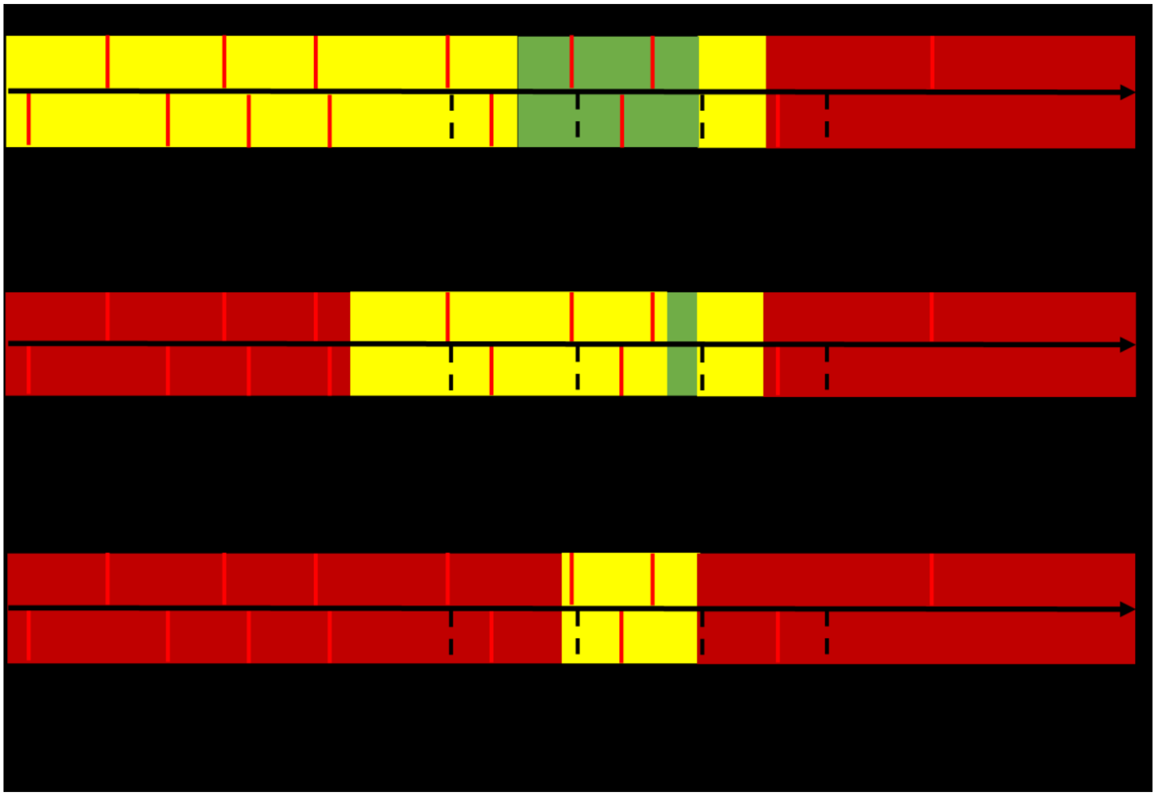

Fig. 16 Traffic light bars for SPC=30 at (a) mild fluid flow rates (< 0.72 bbl/day/$ft^2$), (b) moderate fluid flow rates (0.72 to 1.31 bbl/day/$ft^2$), and (c) aggressive fluid flow rates (> 1.31 bbl/day/$ft^2$)

The traffic light bars for SPC=42 and SPC=54 for the three different flow ranges are presented in Figs. 17 and 18, respectively.

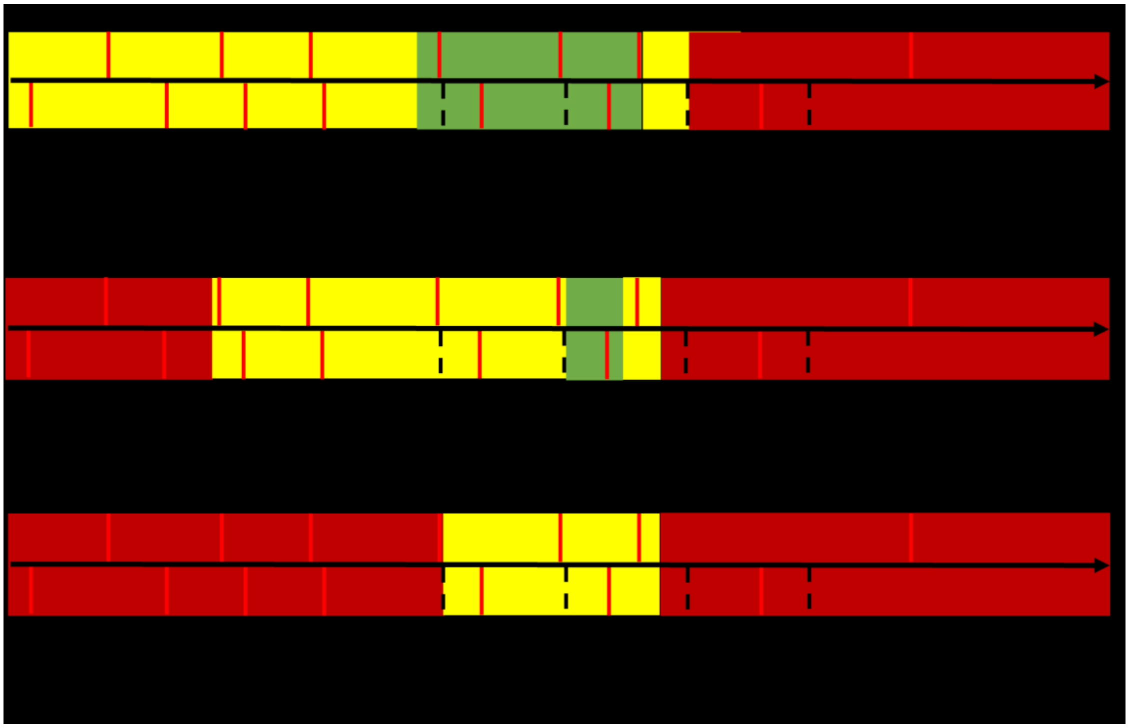

Fig. 17 Traffic light bars for SPC=42 at (a) mild fluid flow rates (< 0.72 bbl/day/ft$^2$), (b) moderate fluid flow rates (0.72 to 1.31 bbl/day/ft$^2$), and (c) aggressive fluid flow rates (> 1.31 bbl/day/ft$^2$)

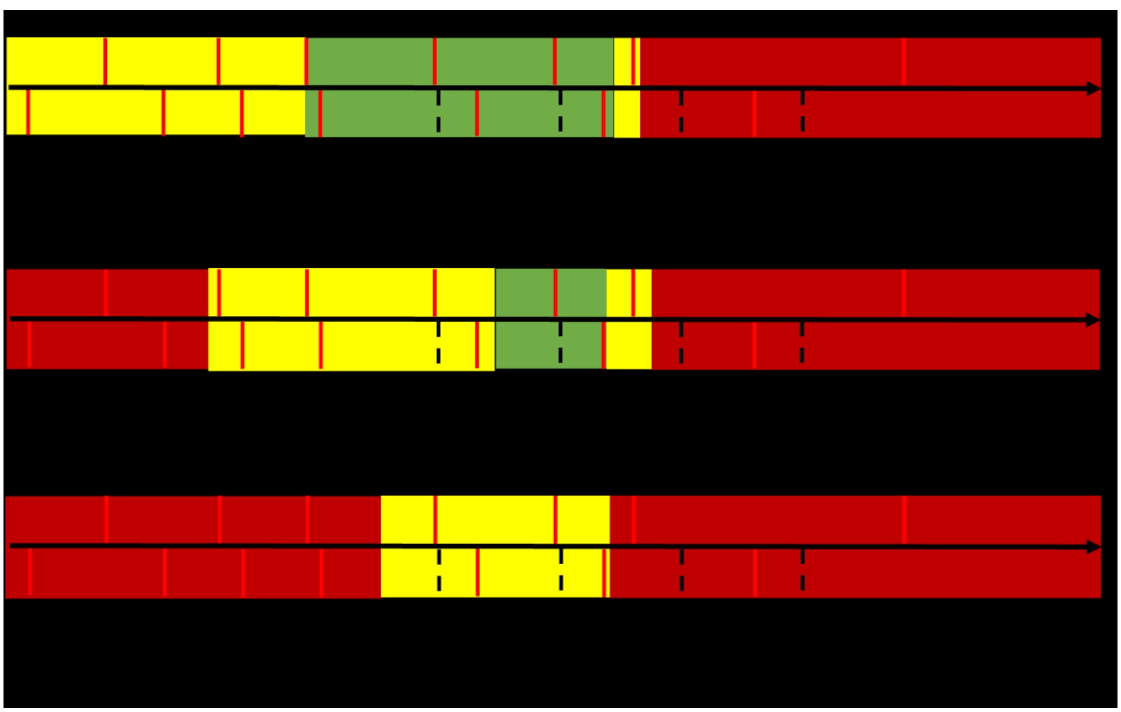

Fig. 18 Traffic light bars for SPC=54 at (a) mild fluid flow rates (< 0.72 bbl/day/ft$^2$), (b) moderate fluid flow rates (0.72 to 1.31 bbl/day/ft$^2$), and (c) aggressive fluid flow rates (> 1.31 bbl/day/ft$^2$)

## 5. Discussion

The proposed TLS method is an improvement over existing design criteria as it accounts for the slot density (SPC), shape of PSD curve, and operational conditions. This section presents a discussion about each of these three factors.

Figures 15 through 17 indicate that the range of acceptable slot sizes becomes narrower as the flow rate increases. Using aggressive production rates, such as fast production ramp-ups or producing at high flow rates, can aggravate the sanding and plugging potentials and reduce the safe aperture window.

Figures 18 through 20 indicate that the lower and upper bounds for acceptable slot sizes shift to the left as the slot density increases. The lower bound shift can be attributed to the fact that the same open flow area can be provided by narrower slots when the slot density increases. At a given aperture size, the higher slot density leads to lower pressure gradients; hence, a lower fines migration and plugging potential. The upper bound also shifts to the left because more sand is produced to create stable bridges when the density (or number) of slots is increased. Overall, acceptable slot sizes decrease with increasing slot density, while the range of acceptable slot sizes increases with slot density. By combining all the testing results at different flow rates and SPCs shown in Figs. 19 to 21, the optimal aperture size applicable to the oil sands with DC-I type of PSD might be 0.018 inches. This aperture size could control the sand production below the sanding threshold value (0.12 lb/ft$^2$) and guarantee the retained permeability above 50%. In other words, this aperture size could maximize oil production without too much sand production.

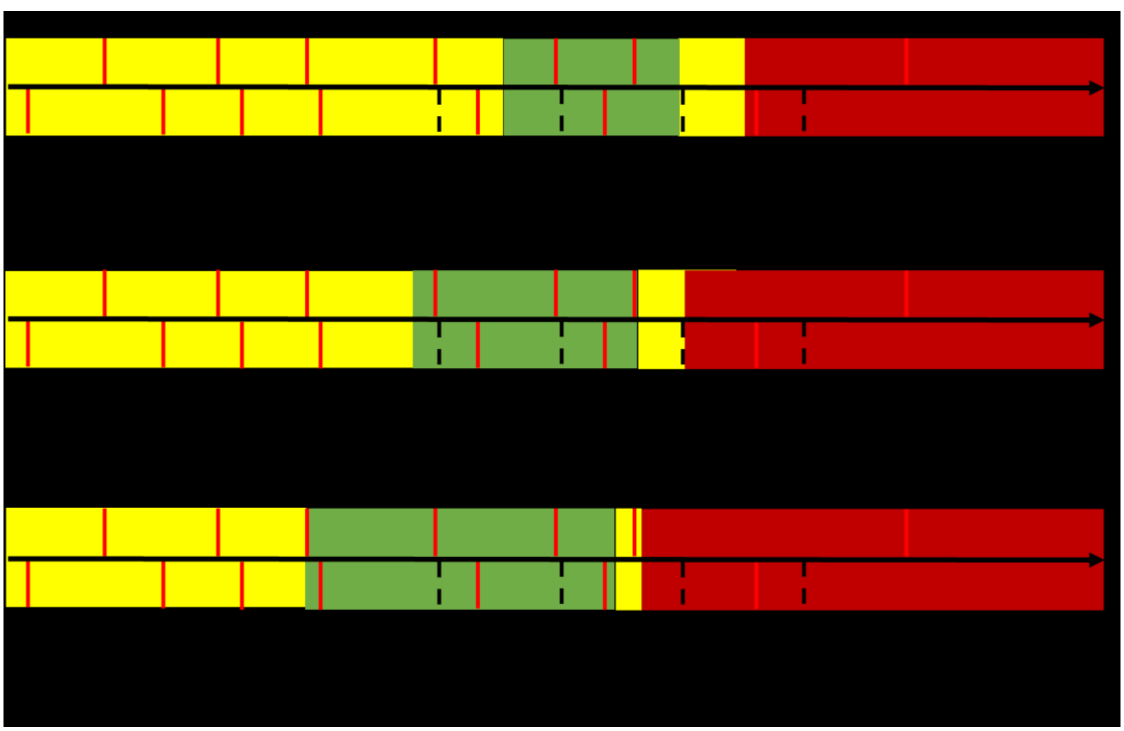

Fig. 19 Traffic light bars for mild fluid flow rates (< 0.72 bbl/day/ft$^2$) (a) SPC=30, (b) SPC=42, and (c) SPC=54

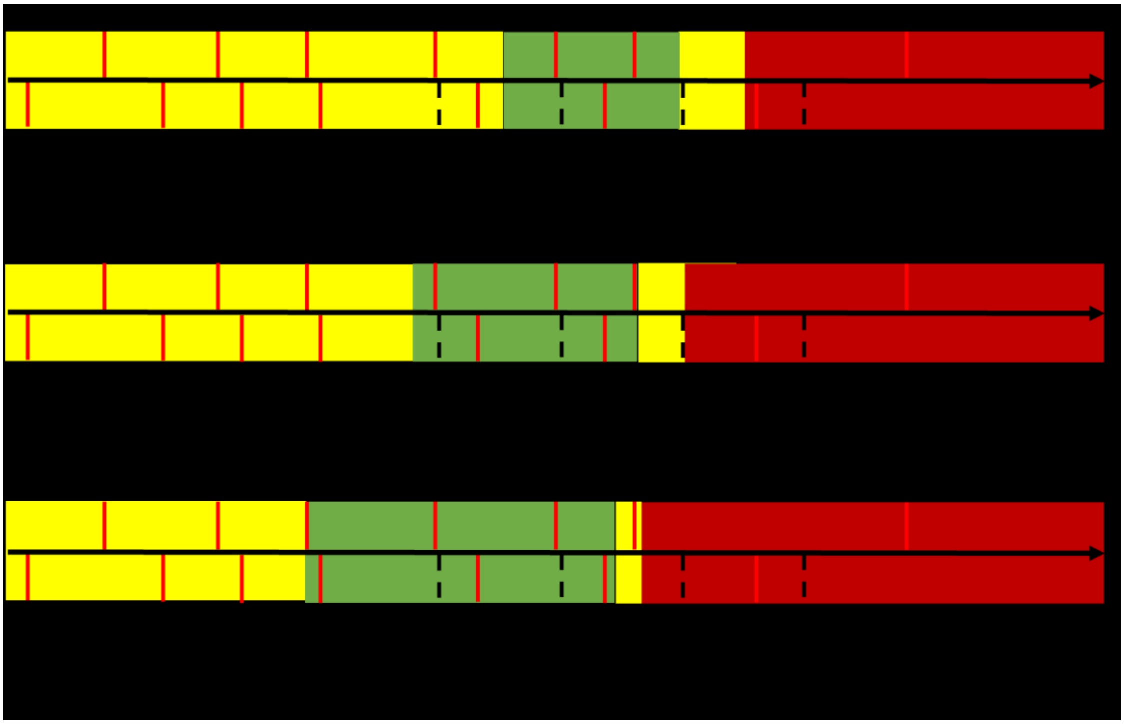

Fig. 20 Traffic light bars for moderate fluid flow rates (0.72 to 1.31 bbl/day/ft$^2$) (a) SPC=30, (b) SPC=42, and (c) SPC=54

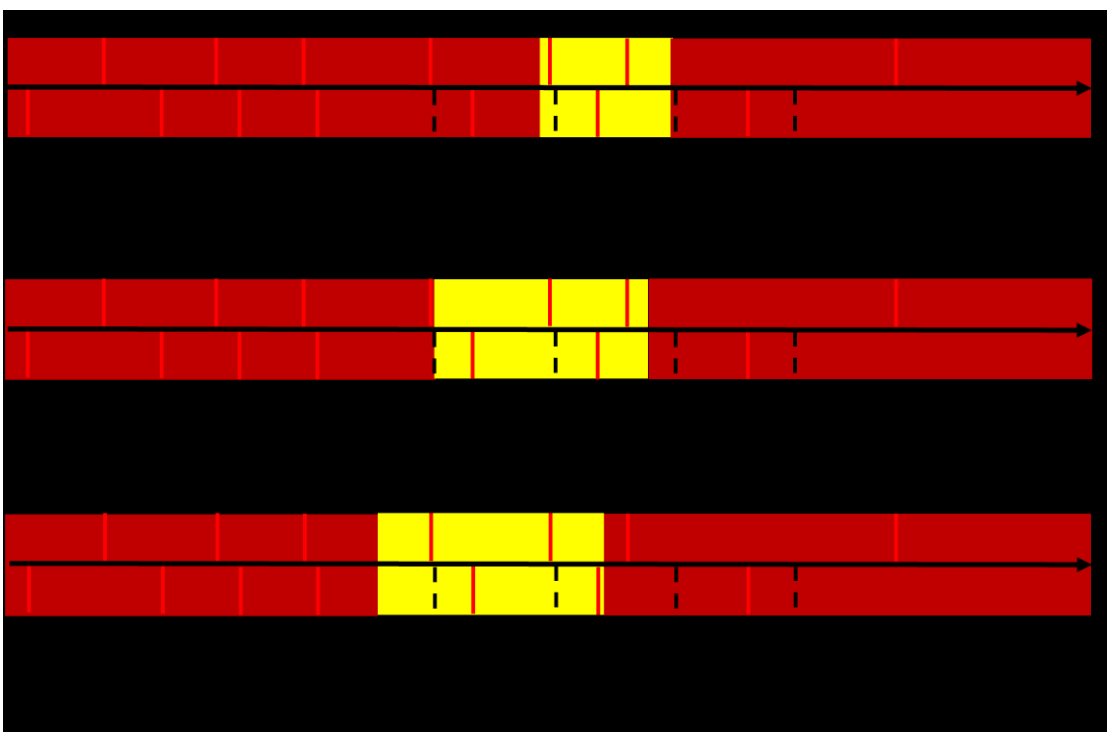

Fig. 21 Traffic light bars for aggressive fluid flow rates (> 1.31 bbl/day/ft$^2$) (a) SPC=30, (b) SPC=42, and (c) SPC=54

The technique proposed here accounts for the full PSD curve to select the acceptable aperture size and slot density range. This approach contrasts the conventional slot sizing methods that use one or two points on the formation PSD.

It should be mentioned that the TLS graphic method is a simplified way to present complex design criteria based on multiple parameters. However, there are several assumptions and limitations in this proposed technique. First, the testing conditions are a simplified idealization of SAGD field conditions. High temperatures, asphaltene precipitation, and steam flow are not accounted for in the laboratory tests. Second, the sand production and flow performance criteria for the TLS method shown in Table 2 are subjective. The applicability of these criteria is yet to be validated and adjusted via industrial practice. If unacceptable sanding is observed in the field, the acceptable sanding level in the criteria should be revised lower. On the other hand, if severe plugging is observed, the acceptable level for retained permeability should be revised higher.

## 6. Conclusions

In this study, a pre-pack SRT facility is employed to develop a set of design criteria. The testing program uses several representative multi-slot coupons and synthetic sands to replicate a specific PSD in the McMurray Formation. The criteria incorporate not only the sand PSD data but also the slot density and fluid flow rates. A set of graphical design criteria for the slotted liners in the SAGD production wells is presented that keeps the plugging and sanding potential within an acceptable range. The main conclusions from this study are summarized as follows:

- The pre-pack SRT facility uses multi-slot coupons, which is an improvement over conventional single-slot testing method. It can account for both aperture size and slot density.
- The proposed criteria incorporate the slot density and fluid flow rate as critical factors in the slotted liner design.
- The proposed criteria provide a safe aperture window. Sand production and fluid flow performance govern the upper bound and lower bounds for the aperture size, respectively.
- Operating condition is a crucial factor, which is considered in the proposed design criteria. The acceptable aperture window is highly influenced by operational practices such as the production ramp-up rate and wellbore production rates.

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## References

Abram, M. and Cain, G. (2014). Particle-Size Analysis for the Pike 1 Project, McMurray Formation. *Journal of Canadian Petroleum Technology, 53*(06), 339-354.

Al-Awad, M. N., El-Sayed, A. and Desouky, S. (1999). Factors affecting sand production from unconsolidated sandstone Saudi oil and gas reservoir. *Journal of King Saud University, Engineering Sciences, 11*(1), 151-174.

Anderson, M. (2017). *SAGD Sand Control: Large Scale Testing Results.* Paper presented at the SPE Canada Heavy Oil Technical Conference.

Ballard, T. and Beare, S. P. (2006). *Sand retention testing: the more you do, the worse it gets.* Paper presented at the SPE International Symposium and Exhibition on Formation Damage Control.

Ballard, T. J. and Beare, S. P. (2012). *An investigation of sand retention testing with a view to developing better guidelines for screen selection.* Paper presented at the SPE International Symposium and Exhibition on Formation Damage Control.

Bennion, D., Gupta, S., Gittins, S. and Hollies, D. (2009). Protocols for slotted liner design for optimum SAGD operation. *Journal of Canadian Petroleum Technology, 48*(11), 21-26.

Butler, R. (1985). A new approach to the modeling of steam-assisted gravity drainage. *Journal of Canadian Petroleum Technology, 24*(03), 42-51.

Butler, R. and Stephens, D. (1981). The gravity drainage of steam-heated heavy oil to parallel horizontal wells. *Journal of Canadian Petroleum Technology, 20*(02).

Carlson, J., Gurley, D., King, G., Price-Smith, C. and Waters, F. (1992). Sand control: Why and how? *Oilfield Review.*

Chanpura, R. A., Hodge, R. M., Andrews, J. S., Toffanin, E. P., Moen, T. and Parlar, M. (2011). A review of screen selection for standalone applications and a new methodology. *SPE Drilling & Completion, 26*(01), 84-95.

Chanpura, R. A., Mondal, S., Andrews, J. S., Mathisen, A. M., Ayoub, J. A., Parlar, M. and Sharma, M. M. (2012). *Modeling of square mesh screens in slurry test conditions for standalone screen applications.* Paper presented at the SPE International Symposium and Exhibition on Formation Damage Control.

Civan, F. (2007). Reservoir Formation Damage. Second Edition, Burlington: Gulf Professional Publishing.

Coberly, C. (1937). *Selection of screen openings for unconsolidated sands.* Paper presented at the Drilling and Production Practice.

Constien, V. G. and Skidmore, V. (2006). *Standalone Screen Selection Using Performance Mastercurves.* Paper presented at the SPE International Symposium and Exhibition on Formation Damage Control.

Denney, D. (2008). Near-Wellbore Modeling: Sand-Production Issues. *Journal of Petroleum Technology, 60*(09), 106-111.

Devere-Bennett, N. (2015). *Using Prepack Sand-Retention Tests (SRT's) to Narrow Down Liner/Screen Sizing in SAGD Wells.* Paper presented at the SPE Thermal Well Integrity and Design Symposium.

Fattahpour, V., Maciel, V., Mahmoudi, M., Chen, K., Nouri, A. and Leitch, M. (2017). *Classification of Alberta Oil Sands Based on Particle Size Distribution for Sand Control Design and Experimental Applications.* Paper presented at the SPE Canada Heavy Oil Technical Conference.

Farrokhpay, S., Ndlovu, B. and Bradshaw, D., 2016. Behaviour of swelling clays versus non-swelling clays in flotation. Minerals Engineering, 96, pp.59-66.

Fermaniuk, B. (2013). Sand Control in Steam Assisted Gravity Drainage (SAGD) Wellbores and Process of Slotted Liner Design and Process. *Master of Engineering thesis, University of Calgary*.

Furui, K., Zhu, D., Hill, A. D., Davis, E. R. and Buck, B. R. (2007). Optimization of horizontal well-completion design with cased/perforated or slotted liner completions. *SPE Production & Operations, 22*(02), 248-253.

Gates, I. D., Kenny, J., Hernandez-Hdez, I. L. and Bunio, G. L. (2005). *Steam injection strategy and energetics of steam-assisted gravity drainage.* Paper presented at the SPE International Thermal Operations and Heavy Oil Symposium.

Gillespie, G., Deem, C. K. and Malbrel, C. (2000). *Screen selection for sand control based on laboratory tests.* Paper presented at the SPE Asia Pacific Oil and Gas Conference and Exhibition.

Han, D.-H., Yao, Q. and Zhao, H.-z. (2007). *Complex properties of heavy oil sand.* Paper presented at the 2007 SEG Annual Meeting.
Hodge, R. M., Burton, R. C., Constien, V. and Skidmore, V. (2002). *An evaluation method for screen-only and gravel-pack completions.* Paper presented at the International Symposium and Exhibition on Formation Damage Control.
Islam, M. and George, A. (1989). *Sand control in horizontal wells in heavy oil Reservoirs.* Paper presented at the SPE California Regional Meeting.
Kaiser, T., Wilson, S. and Venning, L. (2000). *Inflow analysis and optimization of slotted liners.* Paper presented at the SPE/CIM International Conference on Horizontal Well Technology.
Khilar, K. C., and Fogler, H. S. (1984). The Existence of a Critical Salt Concentration for Particle Release. Journal of Colloid and Interface Science. 101 (1), 214-224
Kia, F., Fogler, H. S., Reed, M. G., and Vaidya, R. N. (1987). Effect of Salt Composition on Clay Release in Berea Sandstones. Presented at the SPE International Symposium on Oilfield Chemistry.
Lunn, S. (2013). Water use in Canada's oil-sands industry: The facts. SPE Economics & Management, *5*(01), 17-27.
Mahmoudi, M. (2017). *New Sand Control Design Criteria and Evaluation Testing for Steam Assisted Gravity Drainage (SAGD) Wellbores.* (Ph.D.), University of Alberta, Canada.
Mahmoudi, M., Fattahpour, V., Nouri, A. and Leitch, M. (2016a). *An Experimental Investigation of the Effect of pH and Salinity on Sand Control Performance for Heavy Oil Thermal Production.* Paper presented at the SPE Canada Heavy Oil Technical Conference.
Mahmoudi, M., Fattahpour, V., Nouri, A. and Leitch, M. (2017). *An Experimental Evaluation of Pore Plugging and Permeability Reduction Near SAGD Sand Control Liners.* Paper presented at the SPE Canada Heavy Oil Technical Conference.
Mahmoudi, M., Fattahpour, V., Nouri, A., Yao, T., Baudet, B. A. and Leitch, M. (2015). *Oil Sand Characterization for Standalone Screen Design and Large-Scale Laboratory Testing for Thermal Operations.* Paper presented at the SPE Thermal Well Integrity and Design Symposium.
Mahmoudi, M., Fattahpour, V., Nouri, A., Yao, T., Baudet, B. A., Leitch, M. and Fermaniuk, B. (2016b). *New Criteria for Slotted Liner Design for Heavy Oil Thermal Production.* Paper presented at the SPE Thermal Well Integrity and Design Symposium.
Markestad, P., Christie, O., Espedal, A. and Rørvik, O. (1996). *Selection of screen slot width to prevent plugging and sand production.* Paper presented at the SPE Formation Damage Control Symposium.
Martins, A. L., de Magalhaes, J. V. M., Ferreira, M., Calderon, A. and de Sa, A. N. (2009). *Sand Control in Long Horizontal Section Wells.* Paper presented at the Offshore Technology Conference.
Mathisen, A. M., Aastveit, G. L. and Alteraas, E. (2007). *Successful installation of stand-alone sand screen in more than 200 wells-The importance of screen selection process and fluid qualification.* Paper presented at the European Formation Damage Conference.
Matmon, D. and Hayden, N.J., 2003. Pore space analysis of NAPL distribution in sand–clay media. Advances in water resources, 26(7), pp.773-785.
Medina, M. (2010). SAGD: R&D for unlocking unconventional heavy-oil resources. *The Way Ahead, 6*(02), 6-9.
Montero, J.D., Chissonde, S., Kotb, O., Wang, C., Roostaei, M., Nouri, A., Mahmoudi, M. and Fattahpour, V., 2018, March. A Critical Review of Sand Control Evaluation Testing for SAGD Applications. In *SPE Canada Heavy Oil Technical Conference*. Society of Petroleum Engineers.
Nasr, T., Golbeck, H. and Pierce, G. (1998). *SAGD operating strategies.* Paper presented at the SPE international conference on horizontal well technology.
Romanova, U. and Ma, T. (2013). *An Investigation on the Plugging Mechanisms in a Slotted Liner from the Steam Assisted Gravity Operations.* Paper presented at the SPE European Formation Damage Conference & Exhibition.
Romanova, U., Ma, T., Piwowar, M., Strom, R. and Stepic, J. (2015). *Thermal Formation Damage and Relative Permeability of Oil Sands of the Lower Cretaceous Formations in Western Canada.* Paper presented at the SPE Canada Heavy Oil Technical Conference.

Romanova, U., Michel, D., Strom, R. and Stepic, J. (2017). *Understanding Sand Control for Thermal Heavy Oil and Bitumen Production Operations.* Paper presented at the SPE Thermal Well Integrity and Design Symposium.

Sanyal, T., Al-Hamad, K., Jain, A. K., Al-Haddad, A. A., Kholosy, S., Ali, M. A., . . . Farag, H. (2012). *Laboratory Challenges of Sand Production in Unconsolidated Cores.* Paper presented at the SPE Kuwait International Petroleum Conference and Exhibition.

Sharifipour, M., Nakhaee, A. and Pourafshary, P., 2019. Model development of permeability impairment due to clay swelling in porous media using micromodels. Journal of Petroleum Science and Engineering, 175, pp.728-742.

Tausch, G. and Corley Jr, B. (1958). *Sand exclusion in oil and gas wells.* Paper presented at the Drilling and Production Practice.

Underdown, D., Dickerson, R. and Vaughan, W. (2001). The nominal sand-control screen: A critical evaluation of screen performance. *SPE Drilling & Completion, 16*(04), 252-260.

Williams, C. F., Richard, B. M. and Horner, D. (2006). *A new sizing criterion for conformable and nonconformable sand screens based on uniform pore structures.* Paper presented at the SPE International Symposium and Exhibition on Formation Damage Control.

Wilson, A. (2013). Review of Water Use at Canada's Oil Sands Points Toward Environmental Sustainability. *Journal of Petroleum Technology, 65*(08), 132-134.

Xie, J. (2015). *Slotted Liner Design Optimization for Sand Control in SAGD Wells.* Paper presented at the SPE Thermal Well Integrity and Design Symposium.

Yi, X. (2002). Simulation of sand production in unconsolidated heavy oil reservoirs. *Journal of Canadian Petroleum Technology, 41*(03).

Zhang, W., Youn, S. and Doan, Q. T. (2007). Understanding reservoir architectures and steam-chamber growth at Christina Lake, Alberta, by using 4D seismic and crosswell seismic imaging. *SPE Reservoir Evaluation & Engineering, 10*(05), 446-452.

Zhou, Z. J., Cameron, S., Kadatz, B., & Gunter, W. D. (1997, June 1). Clay Swelling Diagrams: Their Applications in Formation Damage Control. Society of Petroleum Engineers. doi:10.2118/31123-PA