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An Improved Set of Design Criteria for Slotted Liners in Steam Assisted Gravity Drainage Operation

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Abstract: Slotted liners are widely used in steam-assisted gravity drainage (SAGD) wells to control sand production and sustain wellbore productivity. The slotted liner can provide desirable performance when appropriately designed. A literature review indicates a limited number of studies that offer design criteria specifically for SAGD wells. Moreover, past criteria seem to neglect some key factors, which may lead to inadequate slot design. This paper proposes a set of graphical design criteria for slotted liners in SAGD production wells, using prepacked sand retention testing (SRT) data. The SRT is designed to incorporate several essential factors that are not present in the past design criteria, such as slot density, steam breakthrough, and particle size distribution (PSD). The proposed design criteria are presented graphically for normal and aggressive conditions, where the aggressive condition accounts for the potential occurrence of the steam breakthrough. It is found that the upper bound of the design window is substantially lower for the aggressive condition due to the higher sand production after the steam breakthrough. The design criteria also indicate that the slotted liner is suitable only for the formations with low fines content.

Keywords: slotted liner; improved design criteria; heavy oil recovery; SAGD

1. Introduction

As the third-largest proven oil reserves globally [1,2], the Canadian oil sands are exploited by the thermal recovery method using steam-assisted gravity drainage (SAGD) [3]. The SAGD consists of two horizontal wells, about 800–1200 m in length, with a horizontal injection well typically five meters above the horizontal production well (Figure 1) [4,5]. Steam is injected from the injection well into the formation to reduce the bitumen viscosity. After forming a steam chamber inside the reservoir, the melted bitumen flows along the steam chamber's edge toward the production well located around 5 m below the injection well [6,7]. The operational temperature and pressure in the Alberta SAGD projects vary, depending on the depth. However, the typical operating temperature of the SAGD well is around 200–250 °C [8,9]. Li et al. [10] reported different injection pressures for various SAGD projects in Alberta, ranging from 2000 to 5000 kPa, depending on the reservoir depth.

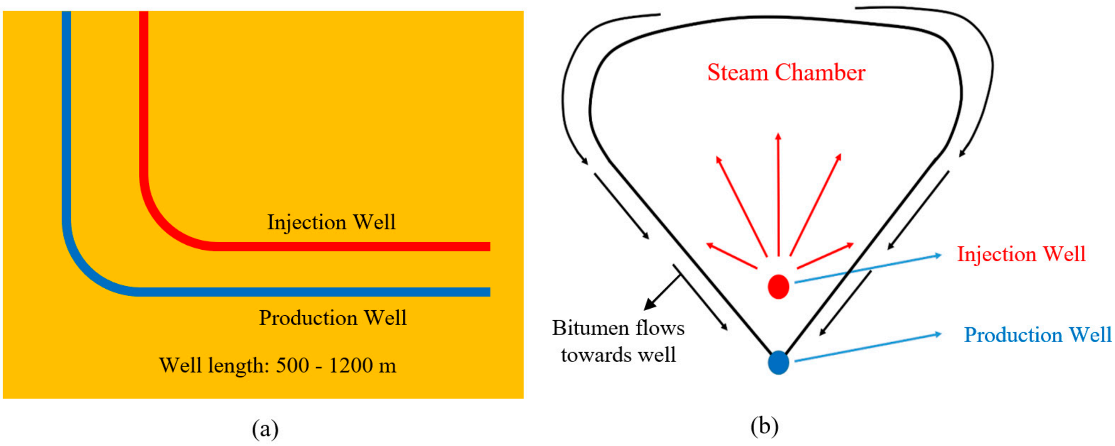

Figure 1. Schematic configuration of (**a**) steam-assisted gravity drainage (SAGD) well pairs and (**b**) steam chamber (modified from Butler [3]).

As the unconsolidated oil-bearing sands are inherently loose, SAGD wells require the implementation of stand-alone screens to support the wellbore and control sand production [11–16]. The slotted liner is currently widely used in Canada's SAGD process due to its economy and adequate mechanical integrity [17–20]. Figure 2a illustrates the slotted liner configuration, and Figure 2b shows different slot geometry designs, which can be manufactured into the straight cut, keystone cut, and seamed profiles.

Improperly designed stand-alone screens can compromise the sand control, damaging the production equipment and causing operational problems and high remediation costs [21–24]. Thus, proper design criteria are needed for the slotted liner to restrict sand production and maintain the flow performance at a desirable level for the SAGD well lifecycle [25].

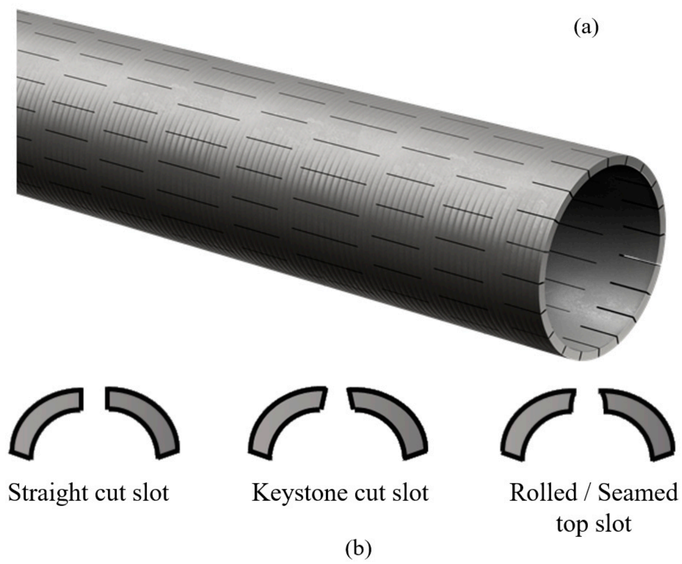

Figure 2. (**a**) The slotted liner schematics [26] and (**b**) schematic of the slot geometries (modified from Bennion et al. [17]).

A literature review shows that various design criteria have been developed for the slotted liner's optimal design. In 1937, Coberly [27] proposed the first criterion for selecting the screen aperture size based on the formation particle size distribution (PSD). From the experimental tests using a single-slot coupon, Coberly found that the aperture size should be smaller than two times of the formation sand's D10 (the sieve size that retains 10% of the material mass) to form a stable sand bridge. Subsequently, several researchers investigated and proposed the design criteria of the slotted liner for various applications. Based on field experience, Fermaniuk [28] proposed an empirical design criterion for slotted liners in SAGD. The maximum slot size in this criterion is 3.5 times D50, and the minimum slot size is two times D70. Other researchers conducted prepacked SRT experiments to determine the proper slot size [17–19,29,30].

During the preheat stage in SAGD, the formation sand collapses and accumulates on the stand-alone screen due to the loss of the bonding strength generated by the bitumen. Thus, researchers believe prepacked SRT reasonably represents the SAGD wellbore condition [31–35]. Past experimental works recognized a few factors that should be incorporated in the slotted liner design criteria, including slot size, slot density, fluid velocity, fluid phase and PSD [18,19,30,36]. However, these factors were only partially incorporated in their experimental study. For example, Bennion et al. [17] and Devere-Bennett [29] neglected the impact of slot density and suggested slotted liner selection protocols based on a single-slot coupon test.

Mahmoudi [37] and Wang et al. [30] conducted single-phase prepacked SRT experiments with multislot coupons and generated design criteria for different formation PSD's. However, the fluid phase change is not considered in their work. Mahmoudi et al. [19] and Wang et al. [30] presented their design criteria graphically by using the "Traffic Light System" (TLS). In the TLS, traffic light colors (green, yellow and red) are employed to a linear axis to indicate the optimal slot size window. The green color in the TLS means an acceptable slot size, in which the amount of sand production is lower than 0.12 lb/ft^2, and retained permeability (RP) is greater than 70% [19,30]. The yellow zone indicates a marginal performance, defined with sand production between 0.12 and 0.15 lb/ft^2, and RP between 50 and 70%. The red zone means an unacceptable slot size, in which sand production is over 0.15 lb/ft^2, and RP is below 50%. The procedure of creating the TLS is summarized as (1) conduct sand control tests, (2) obtain the sand production and retained permeability data, (3) plot the sand production and retained permeability data against the slot size, (4) curve to fit against the testing data with the optimal equations for the sand production and retained permeability, respectively, (5) use the equations to find the boundaries for the sanding and flow performance, (6) build individual TLS bar for the sand production and retained permeability, and (7) combine the two TLS bars to obtain the overall TLS.

Table 1 summarizes the contributions and limitations of the current design criteria for the slotted liner.

Table 1. Summary of current design criteria.

Author	Contribution	Limitation
Coberly [27]	Found the aperture size, which can form a stable bridge through experiments on a single-slot coupon.	Neglected the key factors, including slot density and flow rate.
Bennion et al. [17] and Devere-Bennett [29]	Conducted multi-phase small-scale SRT tests investigating the impact of phase change, slot geometry, and flow rate on the slotted liner's performance using a single-slot coupon.	Neglected the impact of slot density on the liner performance.
Fermanuik [28]	Proposed an empirical criterion for slotted liner design.	It is a rule-of-thumb.
Mahmoudi et al. [18,19] and Wang et al. [30]	Conducted large-scale SRT tests to investigate the impact of slot density and flow rate on the slotted liner's performance.	Single-phase brine flow test. Neglected the impact of fluid phase change.

In summary, limited design criteria are currently available for SAGD production wells, and they often neglect essential factors in the design. This paper develops new design criteria for the slotted liner in SAGD production wells. The criteria are obtained by employing a multi-phase SRT and incorporating several critical factors such as the slot size, slot density, fluid velocity, fluid phase and PSD. The new design criteria account for more realistic flow scenarios than the current criteria.

2. Experimental Method

2.1. Testing Equipment

Figure 3 shows the prepacked SRT equipment used in this study. This setup can accommodate a multislot liner coupon of 6-inches-diameter, allowing one to analyze the impact of slot density and aperture size on the liner performance. Figure 4 presents rolled top (seamed) slotted liner coupons with different slot density indicated by slots per foot (SPF).

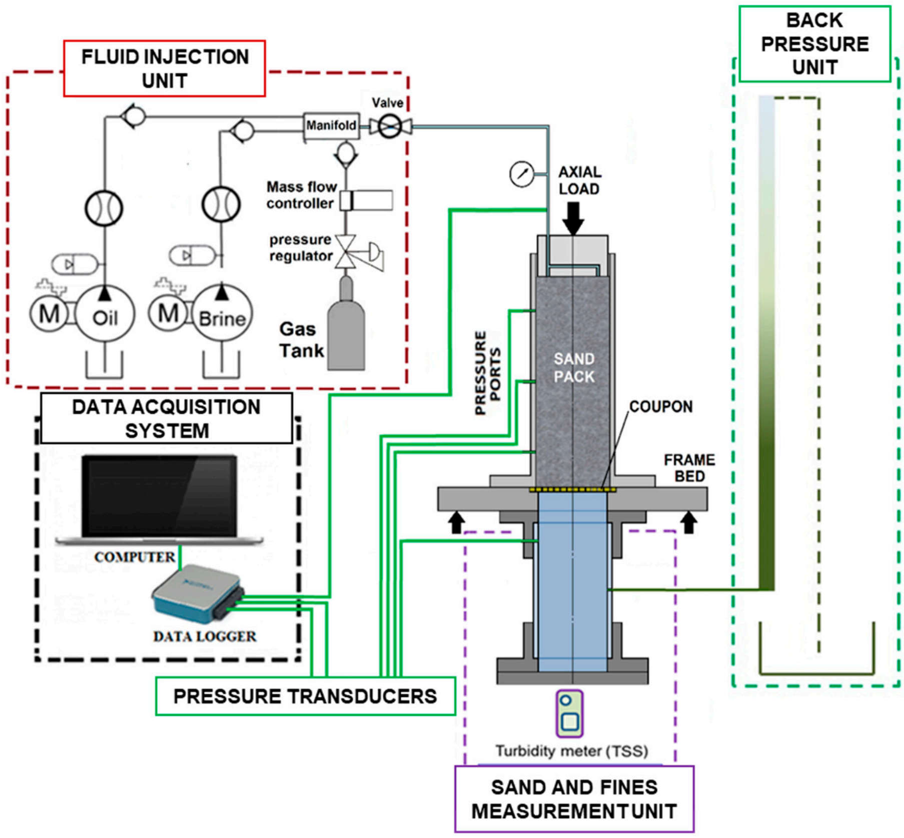

Figure 3. Improved testing facility schematic.

Figure 4. Slotted liner coupons.

The moist sand was packed in several layers on top of the coupon inside the SRT cell to prepare a homogeneous sand-pack. Three ports along the cell were connected to three different pressure transducers to measure the pressure evolutions at various intervals (top, middle and bottom) during the tests. The top and middle sections had a length of 5 inches. The bottom section measured differential pressure from 2 inches above the coupon to below the coupon. The accuracy of the pressure transducers was 0.0375 psi. Pressure transducers were connected to the LABVIEW data acquisition system.

An axial load of 60 psi was applied over the top of the sample by a platen to prevent sand-pack fluidization during the test. The fluid injection system consists of two pumps for oil and brine injection and one nitrogen gas cylinder. During the flow test, all fluids were injected from the top of the sample toward the coupon at room temperature. The produced sand sample was collected and measured by the sand trap located below the coupon. The back-pressure column was connected to the sand trap to provide around three psi back-pressure to the system for the sample saturation and liquid discharge during the test.

2.2. Materials

2.2.1. Sand-Pack Samples

Mixed synthetic samples were used in the sand-pack preparation due to their low cost and excellent repeatability control. These samples aim at replicating the PSD and mineralogy of the target sands from the McMurray formation.

Four typical PSD's of the McMurray formation are shown in Figure 5 [38]. This study attempted to develop design criteria for the three dominant PSD's (DC-I, II and III). Figure 6 presents the PSD matching results between the synthetic sand-pack sample and the formation PSD. The clay used in the synthetic samples is kaolinite as it is rich and dominant in the McMurray formation [39].

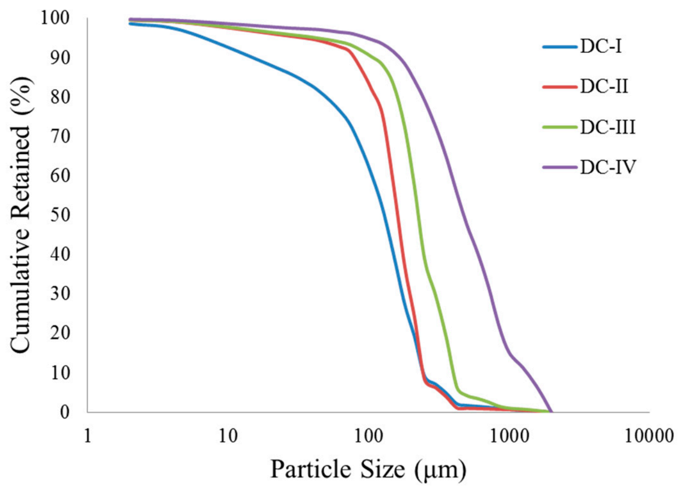

Figure 5. Particle size distribution (PSD) classes of McMurray formation oil sands (modified from Abram and Cain [38]).

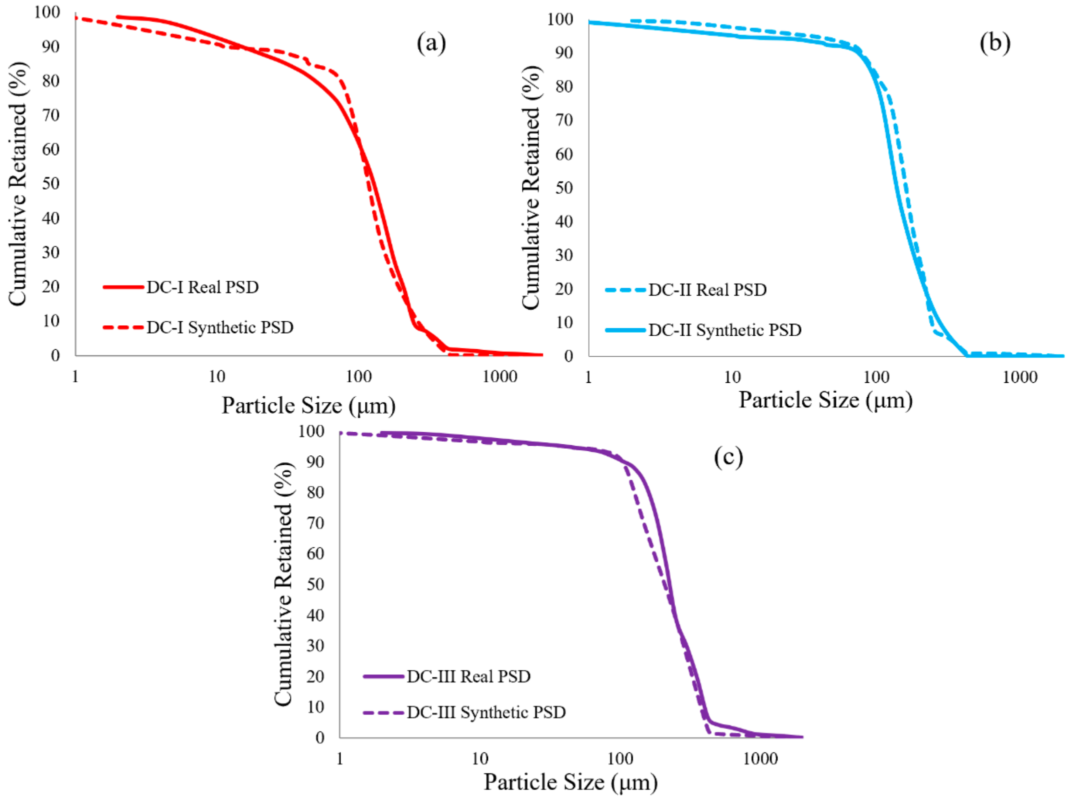

Figure 6. PSD replication of (**a**) DC-I, (**b**) DC-II and (**c**) DC-III.

2.2.2. Injection Fluid Properties

Mineral oil with representative viscosity (8 cp) was used to replicate the melted bitumen viscosity in the real SAGD condition, which is around 10 cp [40]. The brine used in the tests contained 400 ppm sodium chloride with a pH of 7.9, representing the typical SAGD produced water properties [41–44]. Nitrogen was used as the gas phase to emulate the steam.

2.3. Testing Matrix

This study generated design criteria for three PSD's of the McMurray formation in Alberta, Canada. Additionally, for each PSD, the criteria were developed for different slot densities. Table 2 summarizes the slot size and density used for each PSD in the test matrix.

Table 2. Slot sizes of coupons for each PSD.

PSD	DC-I			DC-II			DC-III		
SPF	**120**	**168**	**216**	**120**	**168**	**216**	**120**	**168**	**216**
Slot Sizes (inches)	0.010 0.014 0.018 -	0.010 0.014 0.018 -	0.010 0.014 0.016 -	0.010 0.014 0.018 -	0.010 0.014 0.018 -	0.010 0.014 0.016 -	0.010 0.014 0.018 0.022	0.010 0.014 0.018 -	0.010 0.014 0.016 0.022

2.4. Testing Procedure

A consistent procedure was followed to prepare the sand-pack for the SRT test as below:

- The commercial sand was mixed with 10 wt% brine to prepare a moist sample.
- The moist mix was packed in the cell in multiple layers.
- The sample was saturated with brine from bottom to top using a low flow rate to avoid sample fluidization.

- The absolute permeability of the sand-pack was measured at a low flow rate.

Figure 7 shows a testing procedure designed to enable the inclusion of the fluid velocity and fluid phase into the design criteria. The test starts with a single-phase oil flow to emulate the preheat stage of SAGD operation, in which only melted bitumen flows towards the production well. The next five testing stages consist of two-phase flow (oil and brine) with gradually increasing water cut levels. These five stages emulate the condensed steam production and the bitumen with a gradual increase in water production over the life of the SAGD well. The last two flow stages consist of three-phase flow that mimics the potential steam-breakthrough at two different steam flux levels. Different flow rate levels are included to analyze the impact of fluid velocity on the liner performance and design criteria. It has been found that there are non-uniform flow distribution and plugging of slots in SAGD wells [45]. The elevated flow rates, shown in Figure 7, account for such conditions. The flow rates used in the tests represent typical SAGD production rates [46,47].

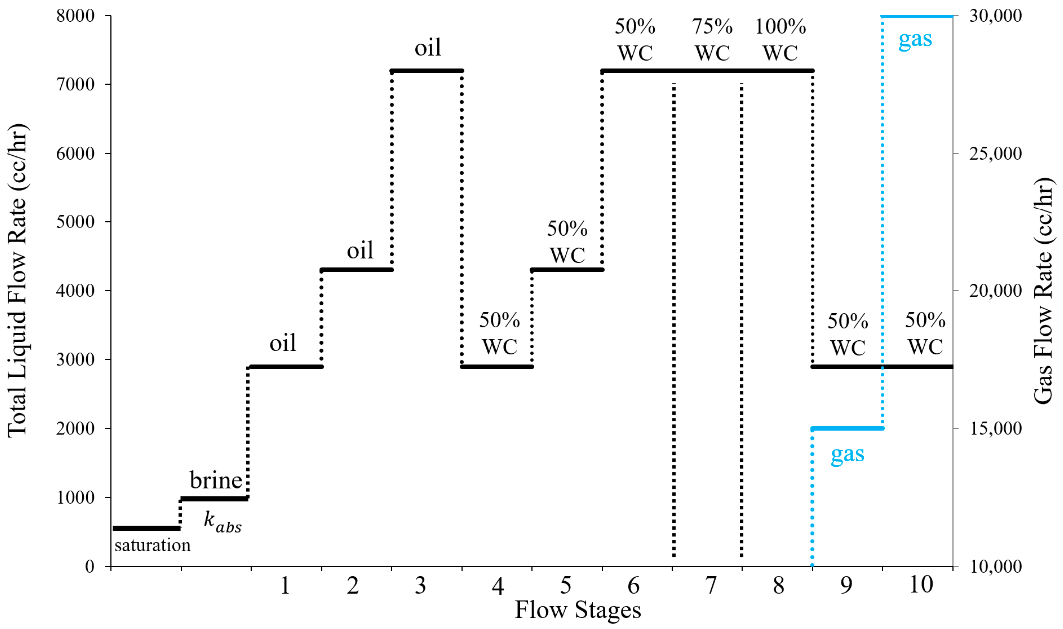

Figure 7. Improved testing procedure design.

3. Testing Results

This section presents the testing results, including sand production and retained permeability from the prepacked SRT experiments.

3.1. Sand Production

Figures 8–10 present the overall cumulative sand production for DC-I, II and III, respectively. It is found that the amount of sand production increases with the increase of slot size and slot density for all three sand types. However, the slot size plays a more critical role in sand production than the slot density. Besides, for the same coupon specifications and testing conditions, the sanding is higher for finer PSD (DC-I). Additionally, there is only a minor sanding for the single-phase oil flow (Stages 1–3), attributed to the strong capillary bonding in the sand-pack [48,49]. However, water injection in the next stages increases water saturation and reduces capillary bonding, resulting in higher sand production (Stage 4). Stages 5–8 also involves higher fluid velocities; hence, stronger drag forces on the sand grains and more sanding (Stages 5–8).

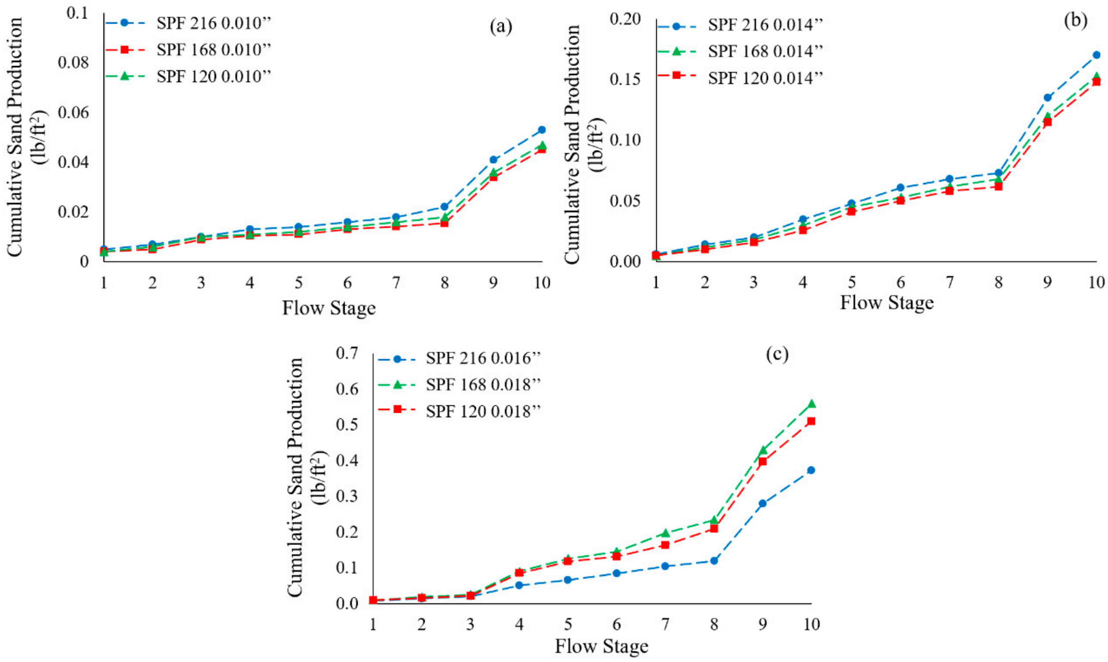

Figure 8. Produced sand results for DC-I using slot apertures of (**a**) 0.010′′, (**b**) 0.014′′, and (**c**) (0.016′′) 0.018′′.

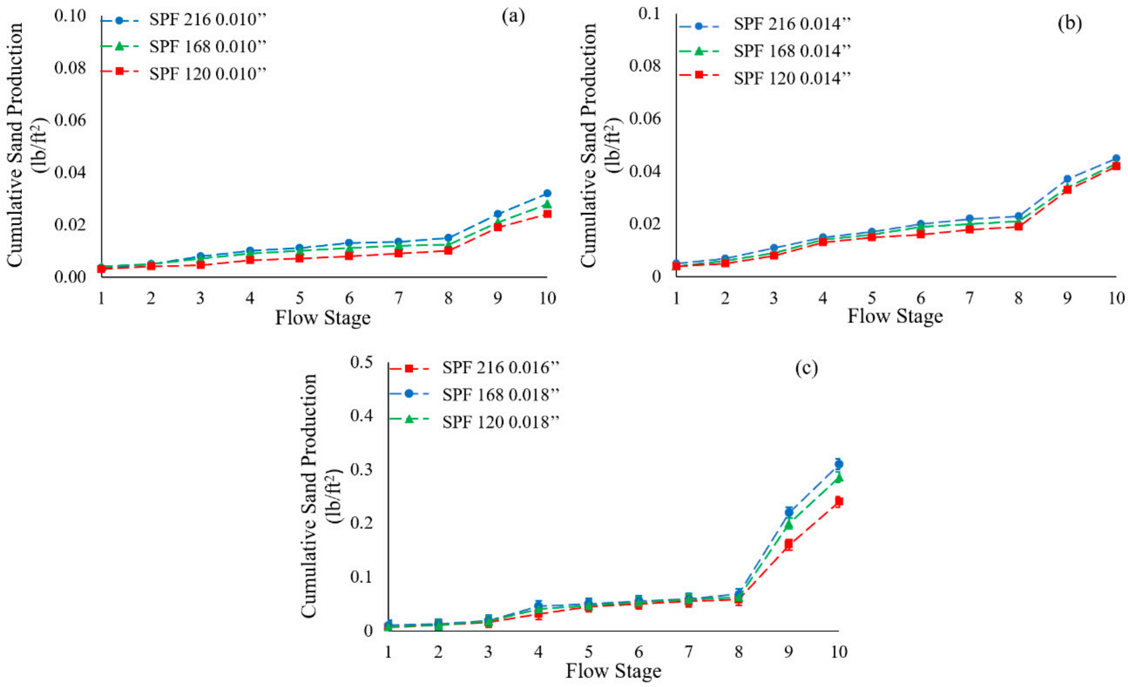

Figure 9. Produced sand results for DC-II using slot apertures of (**a**) 0.010′′, (**b**) 0.014′′, and (**c**) (0.016′′) 0.018′′.

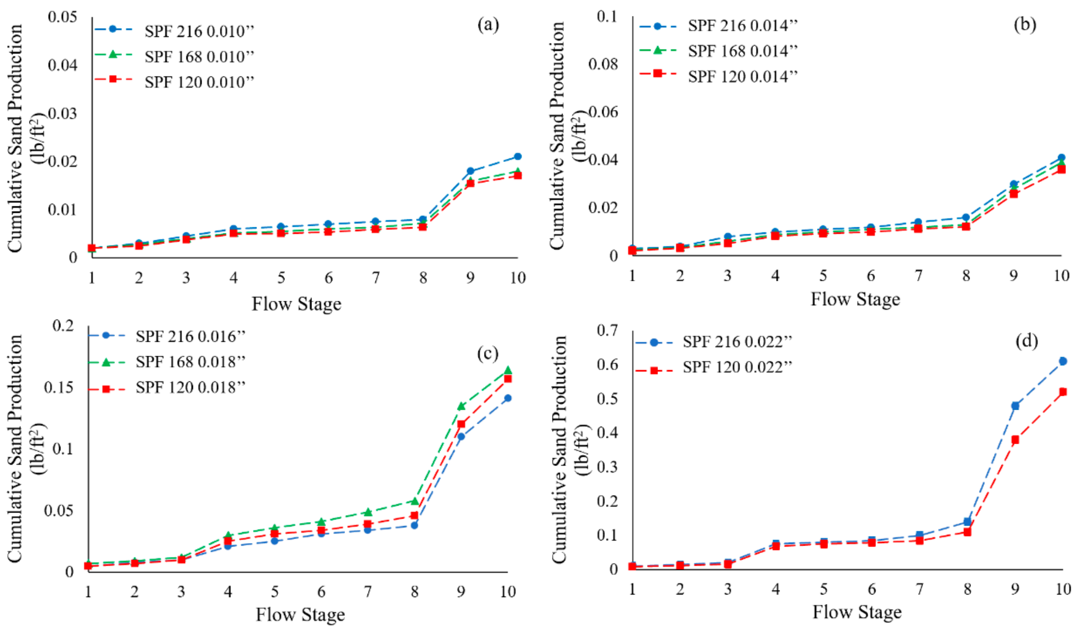

Figure 10. Produced sand results for DC-III using slot apertures of (**a**) 0.010′′, (**b**) 0.014′′, (**c**) (0.016′′) 0.018′′, and (**d**) 0.022′′.

Another notable finding is substantial sand production observed after the gas breakthrough (Stages 9–10), which is due to the greater actual velocity (i.e., interstitial velocity) of the fluid developed inside the sand-pack. In the three-phase injection condition, brine, oil, and gas were simultaneously injected into the sand-pack, causing a higher actual velocity of each fluid. The higher actual fluid velocity generates a stronger drag force that may destabilize the sand arches formed on the slots and increases sand production.

Sanding results in Figures 8–10 indicate that the coupon specifications, PSD and flow conditions impact the slotted liner's sanding performance. The sanding results were used to analyze the sanding performance and build the new design criteria.

3.2. Retained Permeability

Researchers commonly use retained permeability in the SRT context to characterize formation damage and flow performance of screens [50]. The definition of retained permeability is the near-screen sand-pack permeability during the test over the initial sand-pack permeability.

This study calculated the retained permeability at the end of Stage 8 (Figure 7) of the test. The flow condition in Stage 8 is 100% brine flow with residual oil saturation in the sand-pack. Wang et al. [47] proposed a methodology to calculate the retained permeability under a multi-phase flow condition by measuring the sample's relative permeability. Table 3 presents the absolute permeability and relative permeability to water measured at the residual oil saturation condition for all three PSD's.

Table 3. Initial sand-pack permeability and relative permeability (water) at residual oil saturation.

Permeability	DC-I	DC-II	DC-III
k_{abs} (md)	950	1800	2400
k_{rw}	0.48	0.52	0.54

One example of the retained permeability for DC-I sand using the coupon with the aperture of 0.014″ and SPF 168 was calculated using Equations (1) and (2). The differential pressure reading in the near-screen zone during the test was 3.6 psi.

$$k_{screen} = \frac{q_{water} \cdot \mu_{water} \cdot L}{k_{rw} \cdot A \cdot \Delta P_{near-screen}} = \frac{(7200 \times 0.000151) \cdot 1 \cdot (2/12)}{0.48 \cdot (0.19635 \times 0.001127) \cdot 3.6} = 474 \text{ md} \quad (1)$$

$$\text{RP } \% = \frac{k_{screen}}{k_{abs}} \times 100 = 50\% \quad (2)$$

Table 4 presents the retained permeability results. The results show that wider slots and higher slot density increase the retained permeability value, meaning a better flow performance. This is due to the higher open-flow-area, allowing for the passage of more fine particles and fewer fines accumulation in the near-screen zone. When comparing the retained permeability based on the PSD, it is found that finer PSDs with higher fines concentration, like DC-I, show lower retained permeability values. This is because DC-I contains more fines and smaller pore throat size than DC-II and III, increasing the pore plugging potential.

Table 4. Retained permeability for different PSDs.

PSD	Variables	SPF 120				SPF 168			SPF 216			
DC-I	slot size (inches)	0.010	0.014	0.018	-	0.010	0.014	0.018	0.010	0.014	0.016	-
	RP (%)	42	47	55		46	50	58	48	52	57	
DC-II	slot size (inches)	0.010	0.014	0.018	-	0.010	0.014	0.018	0.010	0.014	0.016	-
	RP (%)	48	54	64		50	58	65	52	60	63	
DC-III	slot size (inches)	0.010	0.014	0.018	0.022	0.010	0.014	0.018	0.010	0.014	0.016	0.022
	RP (%)	58	65	73	79	60	67	75	62	70	74	83

4. Design Criteria for Slotted Liners

The design criteria for slotted liners are developed based on sand production and retained permeability results. Proper design criteria should meet both sanding and flow performance requirements. Mahmoudi et al. [19] and Wang et al. [30] used a graphical method called the traffic light system (TLS) to present their design criteria.

In this paper, the new criteria are also presented in TLS. The procedure for the TLS generation follows the same in Wang et al. [30]. Proposed criteria consider two SAGD scenarios: normal SAGD condition and aggressive SAGD condition. The three-phase flow was regarded as the aggressive SAGD condition to emulate the steam breakthrough in real SAGD. Figures 11–16 show the new criteria for slotted liners for different PSD's and different slot densities.

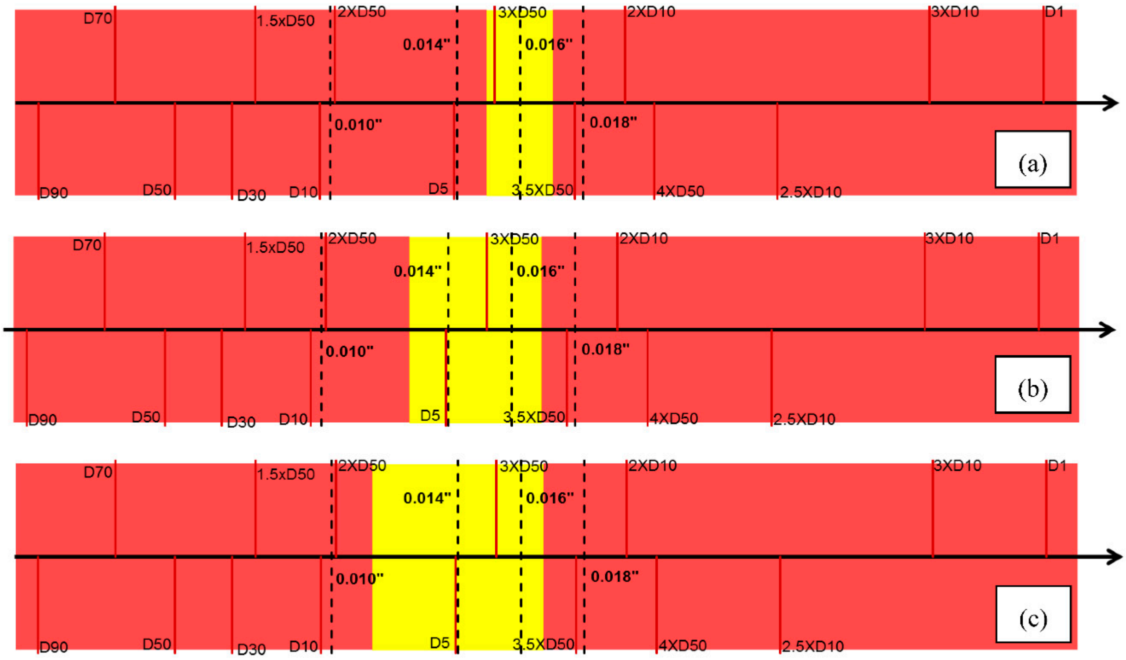

Figure 11. Traffic light system (TLS) of DC-I in the normal condition for SPF 120 (**a**), SPF 168 (**b**), and SPF 216 (**c**).

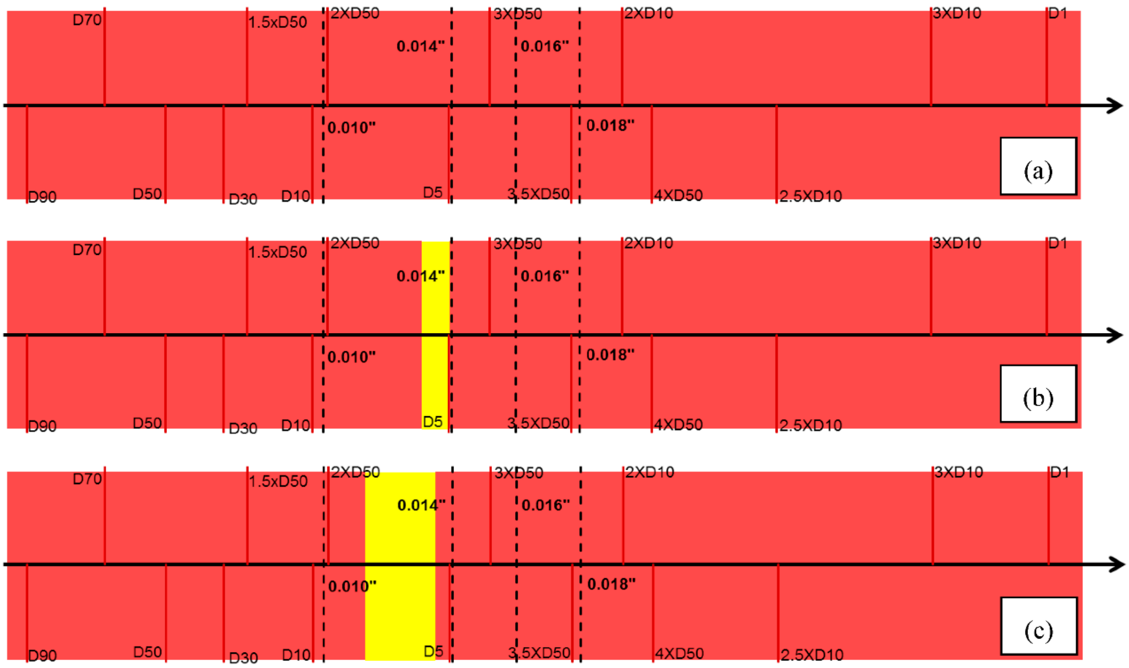

Figure 12. TLS of DC-I in the aggressive condition for SPF 120 (**a**), SPF 168 (**b**), and SPF 216 (**c**).

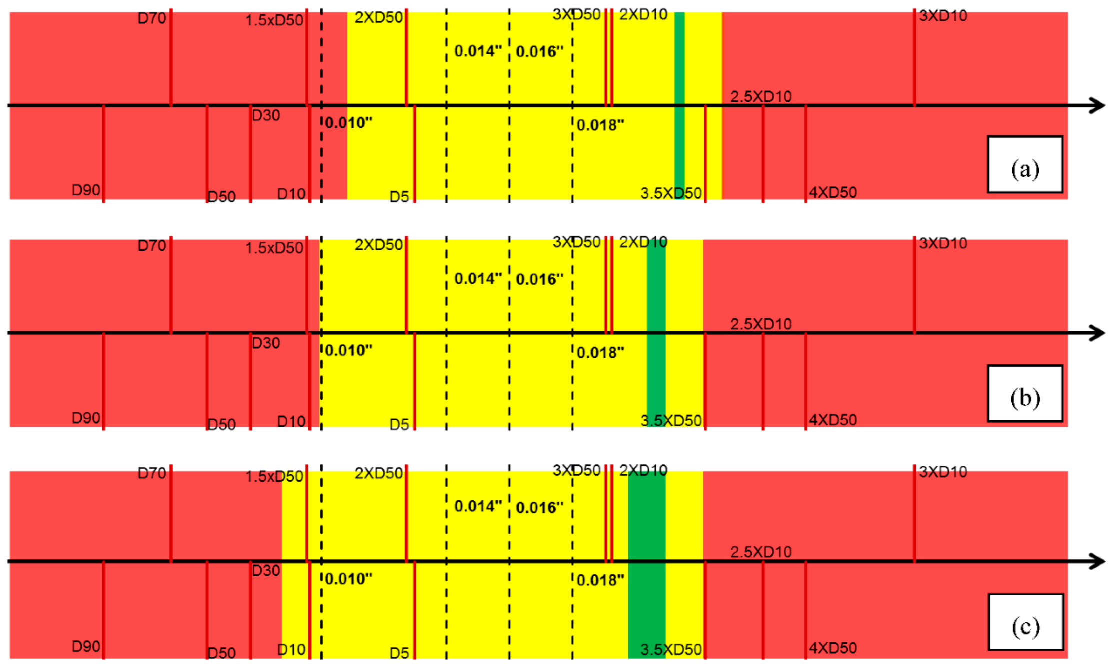

Figure 13. TLS of DC-II in the normal condition for SPF 120 (**a**), SPF 168 (**b**), and SPF 216 (**c**).

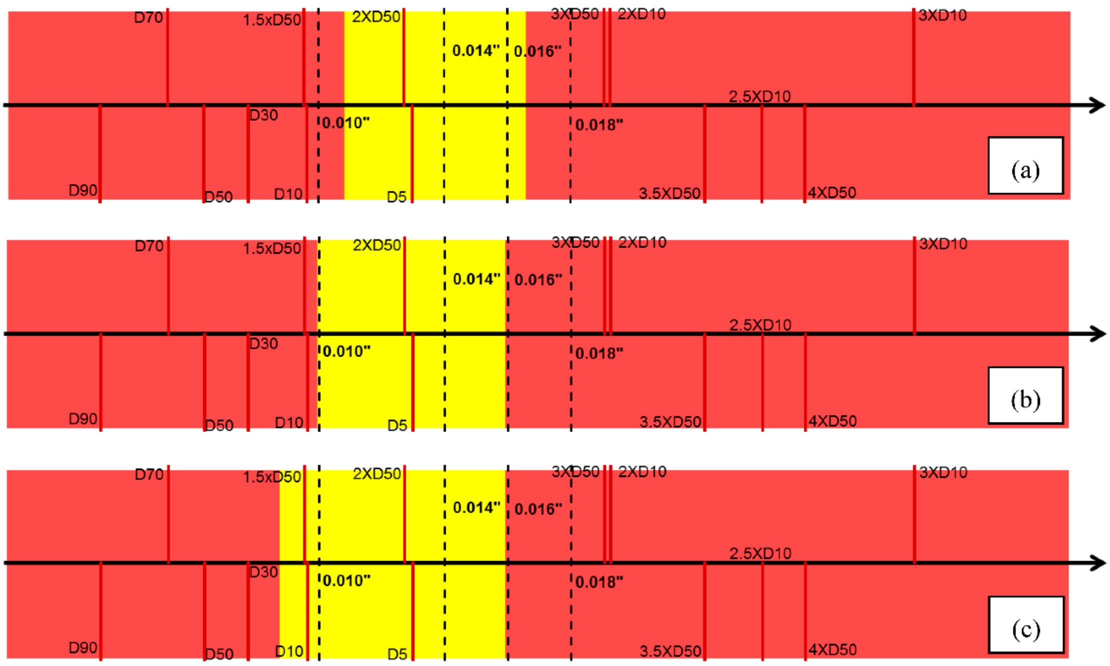

Figure 14. TLS of DC-II in the aggressive condition for SPF 120 (**a**), SPF 168 (**b**), and SPF 216 (**c**).

Figure 15. TLS of DC-III in the normal condition for SPF 120 (**a**), SPF 168 (**b**), and SPF 216 (**c**).

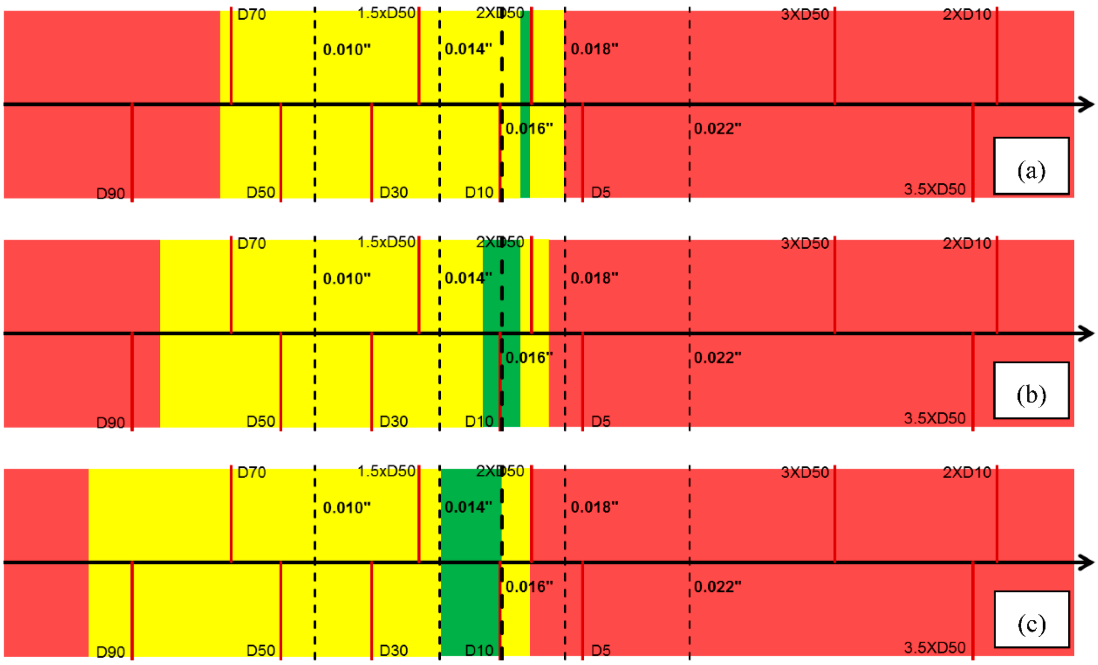

Figure 16. TLS of DC-III in the aggressive condition for SPF 120 (**a**), SPF 168 (**b**), and SPF 216 (**c**).

TLS results in Figure 11 show an absence of the green slot window and only narrow yellow windows for DC-I. This is attributed to the undesirable flow performance of the slotted liner due to the low open-flow-area. DC-I contains the highest fines concentration compared to DC-II and III, making it more vulnerable to the pore plugging.

Due to the limited amount of fines content in DC-II and III and coarser PSD characteristics, the slotted liner can provide a desirable sanding and flow performance, resulting in the green windows for DC-II and III. Particularly in DC-III (Figure 15), the coarsest sand containing the least amount of fines, the green window is wider than the DC-II (Figure 13).

Another finding is with the increase of slot density, the yellow windows in DC-I becomes wider and shifts to the left (Figure 11). A similar observation is made for DC-II and III (Figures 13 and 15), attributed to the increase of the open-flow-area leading to a higher sanding and retained permeability. Thus, both the upper and lower bound of the safe window shift to the left. It is also found that the upper bound of the safe aperture windows for all three PSD types become smaller to keep sanding within the acceptable level during the SAGD steam breakthrough. The finding is justified with the additional sand production caused by the steam breakthrough, which needs to be mitigated by using a narrower slot size. Thus, the design window shrinks for the aggressive SAGD operational conditions compared to the normal SAGD condition.

5. Comparison between Improved and Current Design Criteria

This section compares the new set of design criteria with the criteria in the literature for these three PSD's. Table 5 shows the comparison results for each PSD. As per Coberly [27], the slot size of 2 × D10 could form a stable sand arch and prevent sanding for unconsolidated sands. Based on field data, Fermanuik [28] suggested 2 × D70 to 3.5 × D50 as the safe slot window. However, both criteria are based on one or two points on the PSD curve. Mahmoudi et al. [19] and Wang et al. [30] proposed design criteria for SAGD production wells by conducting single-phase SRT tests. Their criteria considered the PSD curve, slot density, and operational conditions.

Table 5. Comparison of the slot size for DC-I, II, and III for the normal SAGD condition from different design criteria (all sizes are inches).

PSD	Coberly	Fermanuik	Mahmoudi et al. [19]; Wang et al. [30]			Improved Design Criteria		
	[27]	[28]	SPF 120	SPF 168	SPF 216	SPF 120	SPF 168	SPF 216
DC-I	0.019	0.006–0.018	0.011–0.024	0.008–0.0215	0.007–0.021	0.015–0.017	0.013–0.017	0.0115–0.0165
DC-II	0.020	0.010–0.022	0.026	0.025	0.026	0.011–0.0215	0.010–0.022	0.009–0.022
DC-III	0.032	0.014–0.031	0.032	0.0315	0.031	0.006–0.0235	0.005–0.023	0.003–0.023

Table 5 compares the design criteria results for the normal condition. It can be seen that the upper bounds of the proposed new design criteria are close to the same obtained by Coberly and Fermaniuk's criteria. When comparing the proposed criteria with criteria obtained from single-phase SRT experiments by Mahmoudi et al. [19] and Wang et al. [30], it is found that the upper limits of the previous criteria are slightly larger than the new ones. The difference is due to the different testing procedures, where the new testing procedure includes the multi-phase flow at varying water- and gas-cut.

However, as shown in Table 6, the new design criteria' upper bounds for the aggressive condition are much smaller than those in all current criteria. This deviation is attributed to the steam breakthrough impact on sand production considered in the new design criteria. The multiphase liquid–gas flow condition (brine, oil, and gas) resulted in much more sand production than the single-phase brine flow testing condition, hence a narrower slot in the new design criteria for the aggressive condition.

Table 6. Comparison of the slot size for DC-I, II, and III for the aggressive SAGD condition from different design criteria (all sizes are inches).

PSD	Coberly	Fermanuik	Mahmoudi et al. [19]; Wang et al. [30]			Improved Design Criteria		
	[27]	[28]	SPF 120	SPF 168	SPF 216	SPF 120	SPF 168	SPF 216
DC-I	0.019	0.006–0.018	0.0175–0.022	0.014–0.021	0.012–0.020	-	0.013–0.014	0.0115–0.0135
DC-II	0.020	0.010–0.022	0.013–0.021	0.010–0.025	0.011–0.022	0.011–0.0165	0.010–0.016	0.009–0.016
DC-III	0.032	0.014–0.031	0.026	0.030	0.030	0.006–0.018	0.005–0.0175	0.003–0.017

The slot window's lower bounds that are governed by the plugging, obtained from single-phase and multi-phase SRT, show consistent results. However, the lower bound Fermanuik [28] does not compare well, which can be attributed to not incorporating the fines content in the design criterion.

The DC-I formation contains a large amount of fines, which makes it susceptible to plugging. Based on the testing results, if the slot size of 0.006′′ was used in DC-I, the retained permeability would be lower than 50%, leading to undesirable flow performance.

The outcomes from the proposed design criteria and those in the literature seem to agree on the upper bound for the normal condition. The proposed criteria provide further guidance regarding the plugging and steam breakthrough scenario.

6. Conclusions

Comparing the design criteria for slotted liners in the literature with those in this work shows limitations and uncertainties for the literature design criteria. The slot sizes designed based on one point of the whole PSD curve are not appropriate and could result in biased results. Therefore, it is strongly recommended to consider the impact of PSD in the design analysis. The laboratory SRT testing on field samples could provide a superior design than when using the criteria. However, it is obvious that the testing procedure strongly affects the slot design criteria. Therefore, the testing procedure should be designed consistently with field conditions. The proposed design criteria incorporate a multiphase flow testing procedure in the slotted liner design criteria. The new criteria are presented graphically for normal SAGD conditions and steam breakthrough conditions.

This paper improved current slotted liner design criteria by incorporating several influential factors into the testing design. With more key parameters involved, the testing results were more reliable, robust, and representative of the SAGD conditions. However, there were still some other key factors, including temperature, corrosion, erosion, asphaltene precipitation, and clay mineralogy, which were not fully represented in the current testing design. Therefore, field data are needed to validate the proposed design criteria.

SI Metric Conversion Factors

1 cp = 10^{-3} Pa·s; 1 inch = 2.54 cm; 1 ft = 0.3048 m; 1 pound = 453.592 g; 1 psi = 6894.76 pa

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Nomenclature

q_{water}	water flow rate
k_{screen}	screen permeability
A	area
$\Delta P_{near-screen}$	pressure differential in the near-screen zone
μ_{water}	water viscosity
L	length
k_{abs}	absolute permeability
k_{rw}	water relative permeability
RP	retained permeability

References

1. Lunn, S. Water use in Canada's oil-sands industry: The facts. *SPE Econ. Manag.* **2013**, *5*, 17–27. [CrossRef]
2. Wilson, A. Review of water use at Canada's Oil Sands points toward environmental sustainability. *J. Pet. Technol.* **2013**, *65*, 132–134. [CrossRef]

3. Butler, R. A new approach to the modelling of steam-assisted gravity drainage. *J. Can. Pet. Technol.* **1985**, *24*, 42–51. [CrossRef]
4. Butler, R.; Stephens, D. The gravity drainage of steam-heated heavy oil to parallel horizontal wells. *J. Can. Pet. Technol.* **1981**, *20*, 90–96. [CrossRef]
5. Nasr, T.; Golbeck, H.; Pierce, G. SAGD operating strategies. In Proceedings of the SPE International Conference on Horizontal Well Technology, Calgary, AB, Canada, 1–4 November 1998. SPE-50411-MS.
6. Butler, R.M. Some recent developments in SAGD. *J. Can. Pet. Technol.* **2001**, *40*, 18–22. [CrossRef]
7. Gates, I.D.; Kenny, J.; Hernandez-Hdez, I.L.; Bunio, G.L. Steam injection strategy and energetics of steam-assisted gravity drainage. *SPE Reserv. Eval. Eng.* **2005**, *10*, 19–34. [CrossRef]
8. Kaura, J.D.; Sierra, J. Successful field fpplication in continuous DTS monitoring under harsh environment of SAGD wells using improvised optical-fiber technology: Case study from Canada. In Proceedings of the SPE Annual Technical Conference and Exhibition, Denver, CO, USA, 21–24 September 2008. SPE-116149-MS.
9. Stone, T.W.; Brown, G.; Guyaguler, B.; Bailey, W.J.; Law, D.H. Practical control of SAGD wells with dual-tubing strings. *J. Can. Pet. Technol.* **2014**, *53*, 32–47. [CrossRef]
10. Li, P.; Chan, M.; Froehlich, W. Steam injection pressure and the SAGD ramp-up process. *J. Can. Pet. Technol.* **2009**, *48*, 36–41. [CrossRef]
11. Yi, X. Simulation of sand production in unconsolidated heavy oil reservoirs. *J. Can. Pet. Technol.* **2002**, *41*, 11–13. [CrossRef]
12. Han, D.-H.; Yao, Q.; Zhao, H.-Z. Complex properties of heavy oil sand. In Proceedings of the 2007 SEG Annual Meeting, San Antonio, TX, USA, 23–28 September 2007. SEG-2007-1609.
13. Wang, C.; Pang, Y.; Montero Pallares, J.D.; Haftani, M.; Fattahpour, V.; Mahmoudi, M.; Nouri, A. Impact of anisotropic stresses on the slotted liners performance in steam-assisted gravity drainage process. In Proceedings of the SPE Thermal Well Integrity and Design Symposium, Banff, AB, Canada, 27–29 November 2018. SPE-193347-MS.
14. Ma, C.; Deng, J.; Dong, X.; Sun, D.; Feng, Z.; Yan, X.; Hui, C.; Tian, D. Comprehensive experimental study on the sand retention media of pre-filled sand control screens. *Part. Sci. Technol.* **2019**, 1–10. [CrossRef]
15. Ma, C.; Deng, J.; Dong, X.; Sun, D.; Feng, Z.; Luo, C.; Xiao, Q.; Chen, J. A new laboratory protocol to study the plugging and sand control performance of sand control screens. *J. Pet. Sci. Eng.* **2020**, *184*, 106548. [CrossRef]
16. Montero Pallares, J.D.; Wang, C.; Haftani, M.; Nouri, A. Experimental correlations for the performance and aperture selection of wire-wrapped screens in steam-assisted gravity drainage production wells. *SPE Prod. Oper.* **2020**, *35*, 1–12. [CrossRef]
17. Bennion, D.B.; Gupta, S.; Gittins, S.; Hollies, D. Protocols for slotted liner design for optimum SAGD operation. *J. Can. Pet. Technol.* **2009**, *48*, 21–26. [CrossRef]
18. Mahmoudi, M.; Fattahpour, V.; Nouri, A.; Yao, T.; Baudet, B.A.; Leitch, M.; Fermaniuk, B. New criteria for slotted liner design for heavy oil thermal production. In Proceedings of the SPE Thermal Well Integrity and Design Symposium, Banff, AB, Canada, 28 November–1 December 2016. SPE-182511-MS.
19. Mahmoudi, M.; Fattahpour, V.; Velayati, A.; Roostaei, M.; Kyanpour, M.; Alkouh, A.; Sutton, C.; Fermaniuk, B.; Nouri, A. Risk assessment in sand control selection: Introducing a traffic light system in stand-alone screen selection. In Proceedings of the SPE International Heavy Oil Conference and Exhibition, Kuwait City, Kuwait, 10–12 December 2018. SPE-193697-MS.
20. Fattahpour, V.; Mahmoudi, M.; Wang, C.; Kotb, O.; Roostaei, M.; Nouri, A.; Fermaniuk, B.; Sauve, A.; Sutton, C. Comparative study on the performance of different stand-alone sand control screens in thermal wells. In Proceedings of the SPE International Conference and Exhibition on Formation Damage Control, Lafayette, LA, USA, 7–9 February 2018. SPE-189539-MS.
21. Al-Awad, M.N.; El-Sayed, A.; Desouky, S. Factors affecting sand production from unconsolidated sandstone Saudi oil and gas reservoir. *J. King Saud Univ. Eng. Sci.* **1999**, *11*, 151–174. [CrossRef]
22. Denney, D. Near-wellbore modeling: Sand-production issues. *J. Pet. Technol.* **2008**, *60*, 106–111. [CrossRef]
23. Sanyal, T.; Al-Hamad, K.; Jain, A.K.; Al-Haddad, A.A.; Kholosy, S.; Ali, M.A.; Sennah, A.; Farag, H. Laboratory challenges of sand production in unconsolidated cores. In Proceedings of the SPE Kuwait International Petroleum Conference and Exhibition, Kuwait City, Kuwait, 10–12 December 2012. SPE-163275-MS.

24. Dong, C.; Li, Y.; Zhang, Q.; Feng, S.; Zhang, L. Experimental study on sand-carrying mechanism and capacity evaluation in water-producing gas wells and its application in artificial lift optimization. In Proceedings of the SPE Middle East Artificial Lift Conference and Exhibition, Manama, Bahrain, 26–27 November 2014. SPE-173700-MS.
25. Xie, J. Slotted liner design optimization for sand control in SAGD wells. In Proceedings of the SPE Thermal Well Integrity and Design Symposium, Banff, AB, Canada, 23–25 November 2015. SPE-178457-MS.
26. RGL Reservoir Management Inc. 2018. Available online: https://www.rglinc.com/solutions/sand-control/proslot/ (accessed on 11 October 2018).
27. Coberly, C. Selection of screen openings for unconsolidated sands. In Proceedings of the Drilling and Production Practice, New York, NY, USA, 1 January 1937. API-37-189.
28. Fermaniuk, B. Sand Control in Steam-Assisted Gravity Drainage (SAGD) Wellbores and Process of Slotted Liner Design and Process. Master's Thesis, University of Calgary, Calgary, AB, Canada, 2013.
29. Devere-Bennett, N. Using prepack sand-retention tests (SRT's) to narrow down liner/screen sizing in SAGD wells. In Proceedings of the SPE Thermal Well Integrity and Design Symposium, Banff, AB, Canada, 23–25 November 2015. SPE-178443-MS.
30. Wang, C.; Pang, Y.; Mahmoudi, M.; Haftani, M.; Salimi, M.; Fattahpour, V.; Nouri, A. A set of graphical design criteria for slotted liners in steam-assisted gravity drainage production wells. *J. Pet. Sci. Eng.* **2020**, *185*, 106608. [CrossRef]
31. Markestad, P.; Christie, O.; Espedal, A.; Rørvik, O. Selection of screen slot width to prevent plugging and sand production. In Proceedings of the SPE Formation Damage Control Symposium, Lafayette, LA, USA, 14–15 February 1996. SPE-31087-MS.
32. Ballard, T.; Beare, S.P. Sand retention testing: The more you do, the worse it gets. In Proceedings of the SPE International Symposium and Exhibition on Formation Damage Control, Lafayette, LA, USA, 15–17 February 2006. SPE-98308-MS.
33. Constien, V.G.; Skidmore, V. Stand-alone screen selection using performance mastercurves. In Proceedings of the SPE International Symposium and Exhibition on Formation Damage Control, Lafayette, LA, USA, 15–17 February 2006. SPE-98363-MS.
34. Williams, C.F.; Richard, B.M.; Horner, D. A new sizing criterion for conformable and nonconformable sand screens based on uniform pore structures. In Proceedings of the SPE International Symposium and Exhibition on Formation Damage Control, Lafayette, LA, USA, 15–17 February 2006. SPE-98235-MS.
35. Chanpura, R.A.; Hodge, R.M.; Andrews, J.S.; Toffanin, E.P.; Moen, T.; Parlar, M. A review of screen selection for stand-alone applications and a new methodology. *SPE Drill. Completion* **2011**, *26*, 84–95. [CrossRef]
36. Guo, Y.; Nouri, A.; Nejadi, S. Effect of slot width and density on slotted liner performance in SAGD operations. *Energies* **2020**, *13*, 268. [CrossRef]
37. Mahmoudi Eshkaftaki, M. New sand Control Design Criteria and Evaluation Testing for Steam Assisted Gravity Drainage (SAGD) Wellbores. Ph.D. Thesis, University of Alberta, Edmonton, AB, Canada, 2017.
38. Abram, M.; Cain, G. Particle-size analysis for the Pike 1 Project, McMurray Formation. *J. Can. Pet. Technol.* **2014**, *53*, 339–354. [CrossRef]
39. Romanova, U.G.; Ma, T.; Piwowar, M.; Strom, R.; Stepic, J. Thermal formation damage and relative permeability of oil sands of the Lower Cretaceous Formations in Western Canada. In Proceedings of the SPE Canada Heavy Oil Technical Conference, Calgary, AB, Canada, 9–11 June 2015. SPE-174449-MS.
40. Romanova, U.G.; Gillespie, G.; Sladic, J.; Ma, T.; Solvoll, T.A.; Andrews, J.S. A comparative study of wire wrapped screens vs. slotted liners for steam-assisted gravity drainage operations. In Proceedings of the World Heavy Oil Congress, New Orleans, LA, USA, 5–7 March 2014. WHOC14-113.
41. Minnich, K.R.; Gamache, D.E.; Kus, J. Process for solidifying organic and inorganic provisional constituents contained in produced water from heavy oil operations. U.S. Patent 8506467, 13 August 2013.
42. Cowie, B.R.; James, B.; Mayer, B. Distribution of total dissolved solids in McMurray Formation water in the Athabasca Oil Sands Region, Alberta, Canada: Implications for regional hydrogeology and resource development. *AAPG Bull.* **2015**, *99*, 77–90. [CrossRef]
43. Birks, J.; Fennell, J.; Yi, Y.; Gibson, J.; Moncur, M. *Regional Geochemistry Study for the Southern Athabasca Oil Sands (SAOS) Area*; COSIA Hydrogeology Working Group: Calgary, AB, Canada, 2017.

44. Haftani, M.; Wang, C.; Montero Pallares, J.D.; Mahmoudi, M.; Fattahpour, V.; Nouri, A. An investigation into the effect of brine salinity on fines migration in SAGD operations. In Proceedings of the SPE Western Regional Meeting, San Jose, CA, USA, 23–26 April 2019. SPE-195370-MS.
45. Romanova, U.G.; Ma, T. An investigation on the plugging mechanisms in a slotted liner from the steam-assisted gravity operations. In Proceedings of the SPE European Formation Damage Conference & Exhibition, Noordwijk, The Netherlands, 5–7 June 2013. SPE-165111-MS.
46. Montero Pallares, J.D.; Chissonde, S.; Kotb, O.; Wang, C.; Roostaei, M.; Nouri, A.; Mahmoudi, M.; Fattahpour, V. A critical review of sand control evaluation testing for SAGD applications. In Proceedings of the SPE Canada Heavy Oil Technical Conference, Calgary, AB, Canada, 13–14 March 2018. SPE-189773-MS.
47. Wang, C.; Montero Pallares, J.D.; Haftani, M.; Nouri, A. Developing a methodology to characterize formation damage (pore plugging) due to fines migration in sand control tests. *J. Pet. Sci. Eng.* **2020**, *186*, 106793. [CrossRef]
48. Skjaerstein, A.; Tronvoll, J.; Santarelli, F.J.; Joranson, H. Effect of water breakthrough on sand production: Experimental and field evidence. In Proceedings of the SPE Annual Technical Conference and Exhibition, San Antonio, TX, USA, 5–8 October 1997. SPE-38806-MS.
49. Vaziri, H.; Barree, B.; Xiao, Y.; Palmer, I.; Kutas, M. What is the magic of water in producing sand? In Proceedings of the SPE Annual Technical Conference and Exhibition, San Antonio, TX, USA, 29 September–2 October 2002. SPE-77683-MS.
50. Hodge, R.M.; Burton, R.C.; Constien, V.; Skidmore, V. An evaluation method for screen-only and gravel-pack completions. In Proceedings of the International Symposium and Exhibition on Formation Damage Control, Lafayette, LA, USA, 20–21 February 2002. SPE-73772-MS.