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# Investigation of Orifice Type Flow-Control Device Properties on the SAGD Process Using Coupled Wellbore Reservoir Modeling

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## Abstract

In order to optimize production of a SAGD process many strategies have been adopted. These strategies may include; a Dual-Tubing completion which contains short and long tubing strings to inject steam in to the reservoir, Proportional-Integral-Derivative (PID) to control steam injection, flow control devices (FCDs), and others. In all these methods; operators try to maximize ultimate recovery by increasing thermal communication between well pairs, enhancing steam conformance, and improving oil displacement efficiency. Currently flow control devices (FCDs) are widely used in thermal operations. This tool can be installed on both production and injection wells in a SAGD well pair. The FCD tool in an injection well is also known as a steam splitter, which gives the operator the opportunity to target sections of the wellbore to receive steam. In a production well, FCDs are used to develop a uniform inflow along the horizontal section of the wellbore. This helps in managing the interface between the injection and production wells to maximize the productivity. The effects of orifice type FCD properties on a SAGD process have not yet been investigated. These properties include port (orifice) size and port quantities. Locations of FCDs in both injector and producer are another important parameter that needs to be addressed and optimized in a SAGD operation. This paper investigates the impact of each of these FCDs properties along with the location of FCDs on a SAGD process through coupled wellbore-reservoir modeling. In addition; a detailed study is carried out to present a workflow for the FCD optimization that can help engineers to design FCDs in both injector and producer in a SAGD well pair.

## Introduction

FCDs are now widely used in thermal operations. This tool can be installed on both production and injection wells in a SAGD well pair. In injection wells, FCDs also known as steam splitters, have been used since 2005(Authors estimate), and deployed through tubing in SAGD injection wells. Injection FCDs have been specifically developed for optimizing SAGD operations by configuring for steam distribution, to allow multiple injection points within a single tubing string, and along the horizontal liner section of a steam injection well. Two types of injection FCDs exist, standard and shiftable.

FCDs were designed for multiple device deployment on a single injection string. The shiftable design with the ability to open and close makes any device located on the tubing selectively engaged and operated

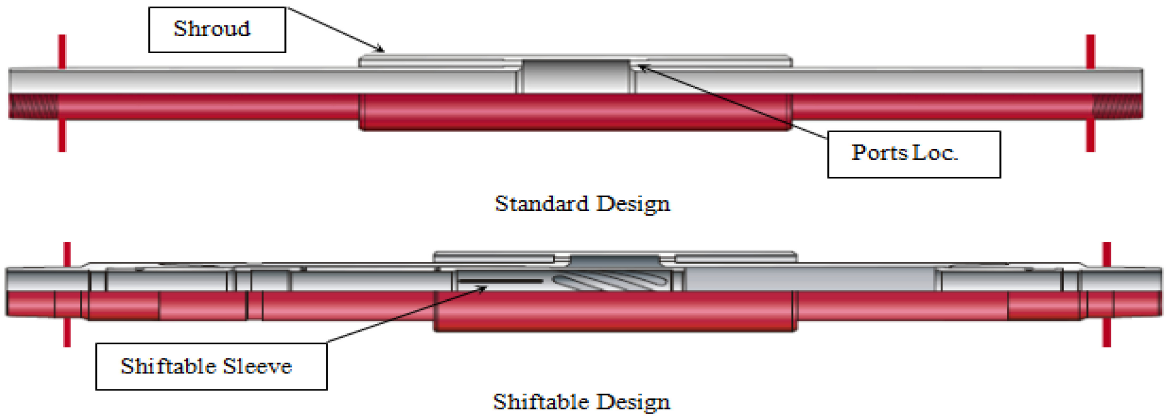



**Figure 1—Production and Injection FCD design**

'Opened or Closed' (or in combination) in one trip via coiled tubing. The device design promotes axial flow distribution and the outer shroud protects the liner from direct impingement.

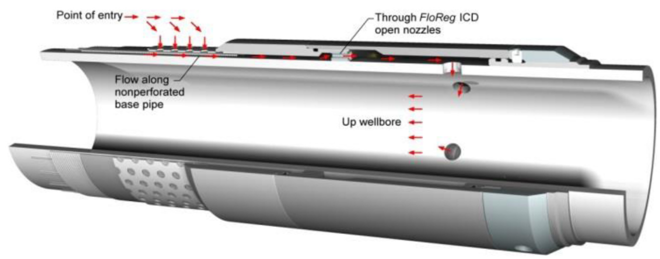



**Figure 2—Production FCD**

In a Production, FCDs, also known as Inflow Control Device (ICD), have been extensively used in horizontal wells for conventional oil and gas production in order to prevent early water break through or gas coning. The benefits associated with this technology have been studied with reservoir simulation and validated with field experience. Some of the benefits associated with production FCDs that have been described in the literature are: easier well clean out during start up because the production FCDs allow application of higher drawdown to poorly performing sections of the reservoir, higher recovery factor caused by delayed water break through or gas coning, uniform production contribution of the horizontal section, and better sand control by limiting the fluid rate per joint.

Production FCDs are a relatively new type of completion component in SAGD applications and in theory. If live steam production is mechanically controlled by the production FCDs, bitumen can be produced by applying a higher drawdown. In this way, the total bitumen production should be increased while the steam oil ratio (SOR) is reduced.[(1)]

There are a number of different types of production FCDs available, all of which rely on generating a pressure drop. This pressure drop is induced either as a consequence of flowing friction resistance in long channels, restricting flow through small ports, or a combination of the two. Restriction type production FCDs are further categorized as orifice and nozzle types. The FCD design reviewed in this paper is an orifice type choke, featuring small flow ports to generate the required pressure drop.[(2)]

## Theory

Injection FCDs distribute steam into the slotted liner, so the choking becomes more complex due to the steam phase changes. The occurrence of choking an orifice in a system is normally defined as the maximum mass flow rate due to downstream pressure. By reducing downstream pressure, the flow of fluid is driven from point 1 to 4 at a rate which increases with pressure drop until the velocity at some point in the orifice reaches the local speed of sound.

At this point, a choked plane is formed, and additional reductions in downstream pressure have no effect on upstream conditions as the rarefaction waves travel at the local speed of sound and are generated at the choked plane. Further reductions in $p_4$ will increase pressure drop across the plane. The ratio of the

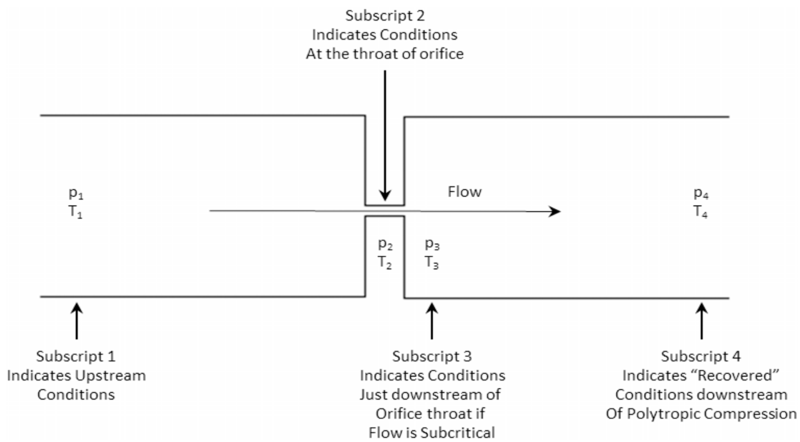



**Figure 3—Diagram of orifice flow system**

critical pressure $p_2$ at the choked plane to the inlet pressure $p_1$ is known as the critical pressure ratio ($p_2/p_1$).

$$\frac{p_2}{p_1} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \tag{1}$$

$\gamma$: Specific heat ratio of the discharged gas

In this study the injection FCDs work in subcritical conditions. $p_2/p_1$ is greater than 0.546 for steam. If steam entering the orifice is saturated, a good approximation of the critical pressure ratio would be 0.577.(3) For subsonic velocities, a decrease in flow area results in an increase in flow velocity. T.K. Perkins (4) developed a methodology to calculate the flow behavior of multiphase mixture through orifices deduced from the general energy equations. These flow equations are valid for both critical and subcritical flow. This work also concluded for subcritical flow, the Perry(5) relationship can be approximated by:

$$p_3 = p_1 - \frac{(p_1 - p_4)}{\left[1-\left(\frac{d_c}{d_d}\right)^{1.85}\right]} \tag{2}$$

For various types of production FCDs several theoretical schemes have been used to fit the pressure data. The theoretical description of orifice type for FCDs is simple. Pressure drop through a port is given by the equation below which is derived from Bernoulli's equation:

$$\Delta P = \frac{8\rho Q^2}{\pi^2 d^4 C_D^4} \tag{3}$$

$C_D$ is the discharge coefficient. This factor is included to account for non-ideal flow, which can be inlet and outlet pressure losses, frictional losses etc.

$$C_D^2 = \frac{1}{\left(K_{in}+K_{out}+\frac{fl}{d}\right)} \tag{4}$$

$$K_{in} = K_{cor} \times 0.5 \times \left(1 - \frac{A_p}{A_{f(in)}}\right)^{0.75} \tag{5}$$

$$K_{out} = K_{cor} \times \left(1 - \frac{A_p}{A_{f(out)}}\right)^{2} \tag{6}$$

$$f = \frac{0.3086}{\left\{\log\left[\frac{6.9}{N_{Re}}+\left(\frac{\varepsilon}{3.7d}\right)^{1.1}\right]\right\}^2} \tag{7}$$

$$N_{Re} = \frac{\rho v d}{\mu} \tag{8}$$

$K_{in}$ and $K_{out}$ are simple functions of the geometry of the system, and f is the friction factor, which is a function of the Reynolds Number $N_{Re}$ and the surface roughness of the port. Equation 7 is a friction factor for turbulent flow.

Equation (3) can be expanded to:

$$\Delta P = \left(K_{in} + K_{out} + \frac{fl}{d}\right)\frac{8\rho Q^2}{\pi^2 d^4} \tag{9}$$

Equation 9 illustrates that port pressure drop exhibits a power law relationship with flow rate Q and is proportional also to fluid density. There is a slight viscosity dependence incorporated into the turbulent friction factor *f*, from the viscosity dependence of Reynolds number shown in equations 7 & 8. Equation 9 was evaluated using the geometry of the production FCD module and the fluid properties. The conclusion was the viscosity dependence reduces with increasing velocity; i.e. increasing Reynolds Number. An analytical solution was developed to compute the pressure drop across the production FCD for any configuration, port size, fluid type and flow rate, and also to determine the discharge coefficient ($C_D$) for the device at realistic production conditions.[2] Consequently, the pressure drop is independent of mixture viscosity changes following water, gas or steam break-through at high $N_{Re}$. However; the production FCD pressure drop does vary in proportion to mixture density and the square of fluid velocity. Therefore; water, gas or steam production in open-hole completions are governed purely by their mobility ratios to oil, and production FCD completions will leverage differences in fluid properties and sensitivity to fluid velocity to restrict flow of the more mobile phases. This process favors oil production owing to its higher viscosity. Hence, the production FCD also has reactive functionality to choke water production following break-through.[6]

## Numerical Simulation

One of the key objectives of this study was to properly investigate the effect of FCDs on the SAGD performance by applying coupled reservoir-wellbore simulation approach. Several studies were conducted to represent the importance of considering wellbore parameters in the simulation of SAGD operations.[7, 8] A Wellbore model incorporates heat transfer effects and multiphase flow inside the wellbore. Using wellbore calculations coupled to the reservoir simulation, one can understand critical aspects of the SAGD process such as, steam chamber distribution, pressure drop along the wellbore, and the general efficiency of the SAGD performance. Hence, coupling wellbore reservoir simulation is more accurate when compared to a conventional numerical simulation approach.

A sensitivity analysis was conducted to first analyze the effect of the injection and production FCD properties like discharge coefficient, orifice (port) size and port numbers on a SAGD process. A workflow followed that was based on the NPV maximization to show how to optimize injection and production FCDs for a typical SAGD wellpair. The workflow explored optimization of the placement and number of injection and production FCDs. It also shows the detailed steps required for automatic optimization of the number of ports for each flow control device installed on the wellpairs. The summary of all the tasks is presented below:

- Phase 1 Sensitivity Analysis
  - Number of FCDs

    *Step-i* Injection FCDs
    *Step-ii* Production FCDs
  - Location

    *Step-iii* Injection FCDs
    *Step-iv* Production FCDs

Table 1—General Properties of the Simulation Model

| Formation | Average Porosity (%) | Average Permeability (md) $k_x = k_y$ | Average Permeability (md) $k_z$ | Average Water Saturation (%) |
|---|---|---|---|---|
| Sandstone | 35 | 6000 | 4000 | 20 |
| Shale | 0.0001 | 0.0001 | 0.0001 | 100 |

- ○ Properties of FCDs

  *Step-v* Injection FCDs
  *Step-vi* Production FCDs

– Phase 2 Optimization

- ○ *Step-1* Optimizing location and total number of injection FCDs
- ○ *Step-2* Optimizing number of ports for injection FCDs
- ○ *Step-3* Optimizing location and total number of production FCDs
- ○ *Step-4* Optimizing number of ports for production FCDs

Numerical simulation was performed with commercially available thermal simulation software that has the feature of a wellbore modeling tool that can couple to the reservoir model. Additionally, optimization software was utilized to perform the sensitivity analysis studies and the automatic optimization of the number of ports. [(9)]

## Reservoir model

A heterogeneous model was created in a Cartesian system, comprising 40 × 40 × 30 grid blocks (Total of 48000 grids) along the x, y and z axis respectively. The numerical grid size was 30 m and 2 m in the i and j planes. The vertical plane consisted of 1 m thick k layers. A single horizontal well pair with 5 meter vertical spacing and 1140 m length was used in the model. A gas cap or aquifer was not included in this model. Table 1 summarizes the general properties of the simulation model.

In order to impose some heterogeneity to the analysis, selected intervals in the top and bottom of the model were assumed to be shaly and shale properties were assigned to these intervals. Therefore the pay zone thickness is not constant along the well pair in this model. Figure 4 depicts the 2-D schematic of the oil saturation distribution in the simulation model. Initial pressure and temperature were 2000 kpa and 15 °C at a reference depth of 400 m.

The reservoir rock was assumed to be water-wet and capillary pressure was ignored. As the temperature is variable during the operation, relative permeability end points were assumed to be temperature dependent. Figure 5 and Figure 6 show the final relative permeability curves that were used in the analysis.

## Wellbore model

The production well was completed with 7 inch slotted liner, 4.5 inch scab liner and it has a short tubing string landed at 50 m from the heel. Total length of the producer was 1140 m. The 1100 m scab liner was landed all the way to near the toe of the producer. The injector was assumed to have the same perforation interval and wellbore length as the producer. It has a single 4.5 inch long tubing string which was run to the total measured depth of the well. Steam was injected through the long string. The wellbore schematics for the wellpair are shown in Figure 7. These wellbore models couple to the reservoir model.

The injector was operated at maximum bottom-hole pressure (BHP) of 3200 Kpa (Primary constraint). An injection rate of 300 $m^3$/day was set as the secondary constraint. Steam was injected at 237 °C and a quality of 0.95. A minimum BHP of 2200 Kpa was set for the producer. The well flowing bottom-hole

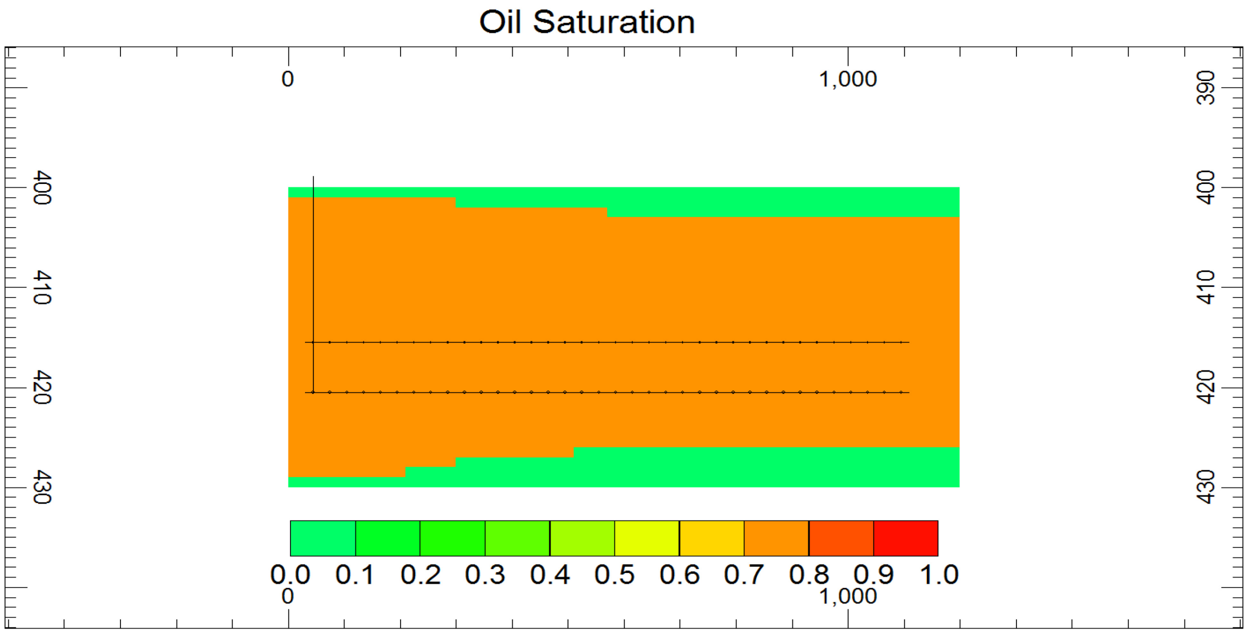



**Figure 4—2-D schemetac of oil saturation in the reservoir**

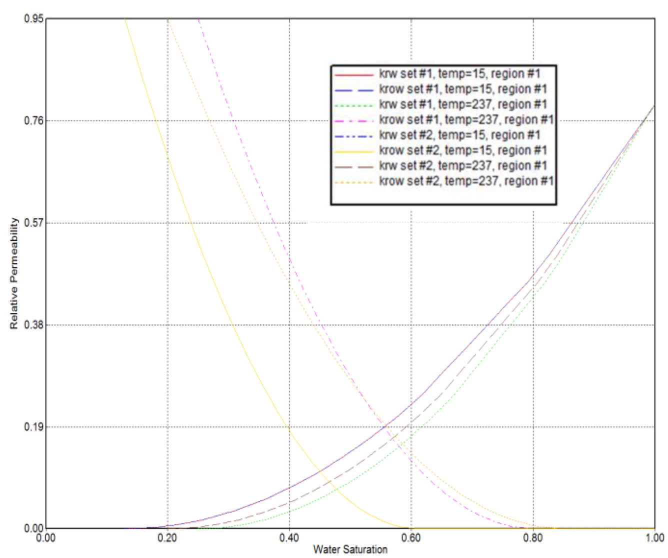



**Figure 5—Oil-Water relative permeability curves at different temperature**

pressure was kept high enough to prevent live steam production. A maximum steam production rate allowed in the wellbore was set to be 5 $m^3$/day.

In a SAGD process, it is essential to establish thermal and hydraulic communication between the SAGD injection and production wells at the start of the operation. This is usually referred as the start-up or initialization stage. Conduction is the main heating mechanism during the initialization stage. Different methods can be implemented to initialize a SAGD operation. The circulation start-up is the conventional approach in which steam is simultaneously circulated through both injection and production wells. Electrical heat is another start-up operation that can be used to initialize a SAGD operation. In this method, electrical heaters are placed along the horizontal portion of a well. This is similar to the circulation method but the energy source is electrical instead of steam. In this paper, electrical heaters were used for the start-up stage. The temperature of the heaters was set at 237 °C and the heating period was 90 days.

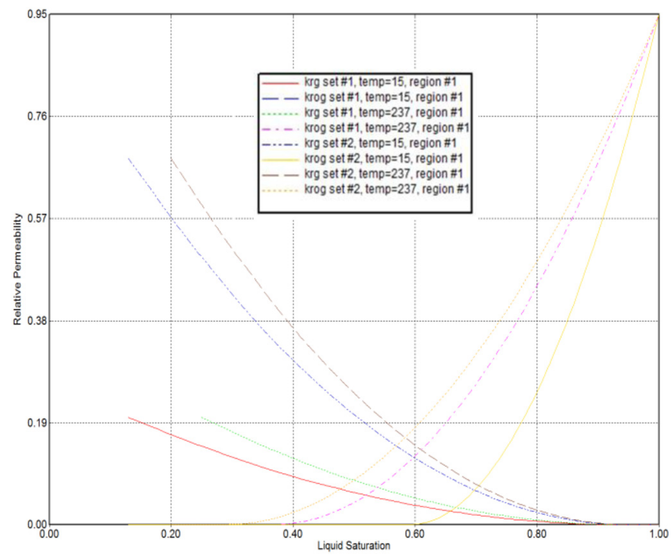



**Figure 6—Liquid-Gas relative permeability curves at different temperature**

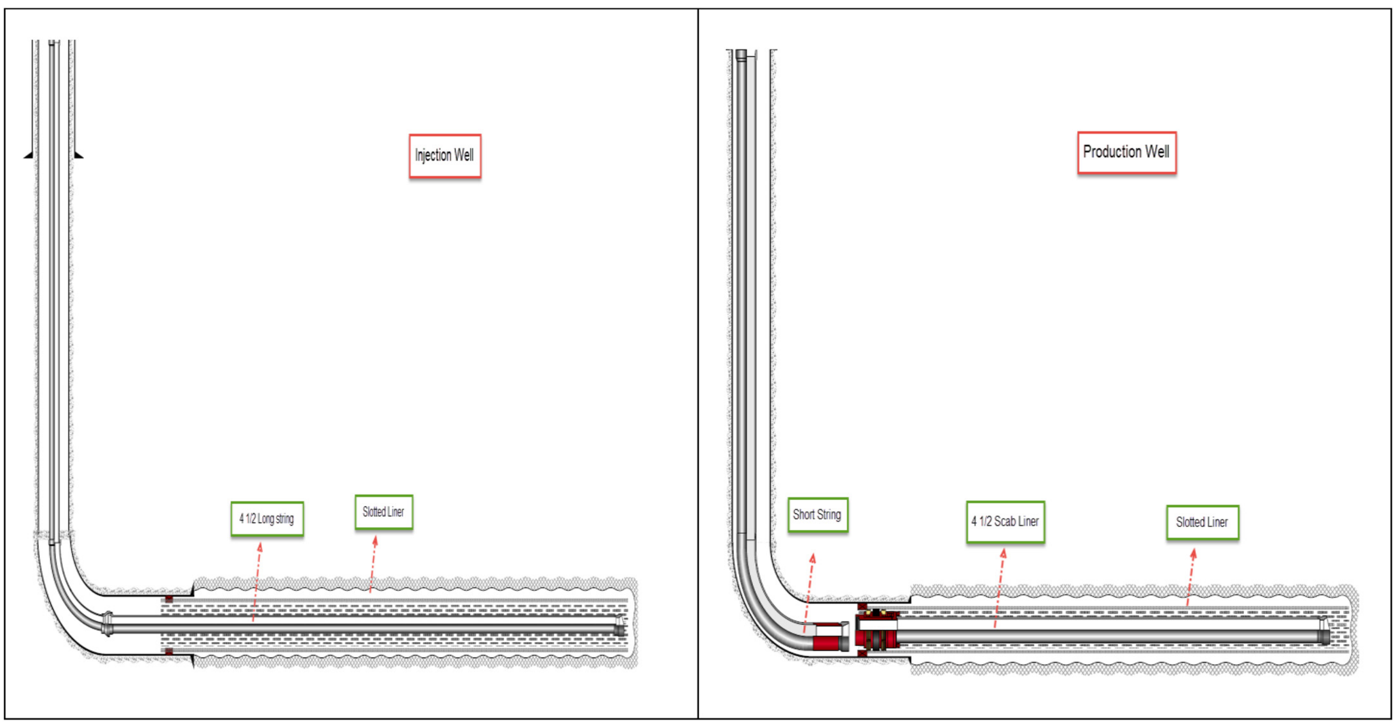



**Figure 7—Wellbore schematics**

## Phase 1: Sensitivity analysis

**Table 2—FCD properties used in the sensitivity analysis**

| Parameter | Injection FCD | Production FCD |
|---|---|---|
| Port size (mm) | 10 | 0.003175 |
| Number of ports | 10 | 5 |
| Discharge coefficient | 0.82 | 0.8 |

In order to understand the impacts of implementing production/injection FCDs on a SAGD operation a detailed sensitivity analysis was performed. The objective was to evaluate the effects of location of FCDs, total number of FCDs and also properties of FCDs such as discharge coefficient, port diameter, and port number on a SAGD performance. A 6 year forecast was run. Table 2 shows the FCD properties that were used in all the scenarios except for the cases in which these properties were used as sensitivity

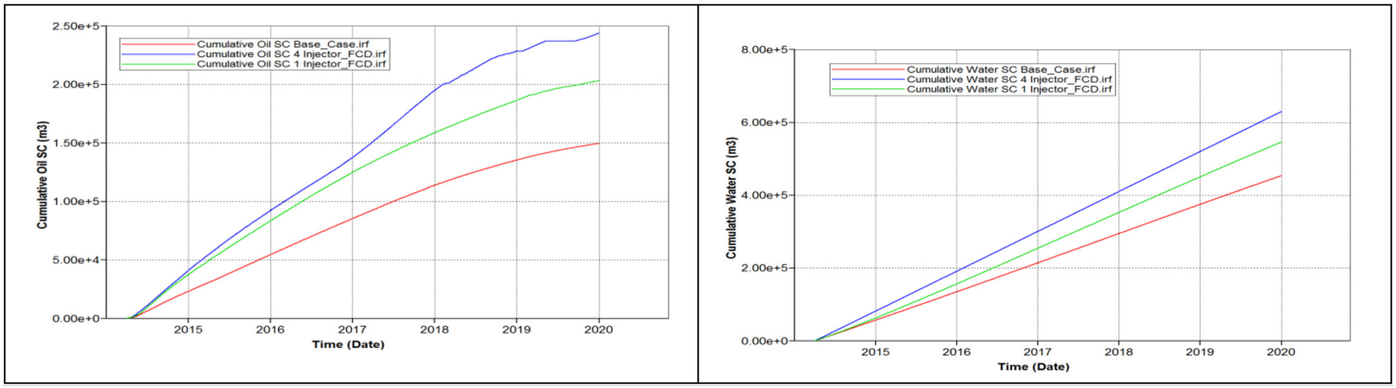



**Figure 8—Cumulative oil and water production after 6 years**

parameters. The injection FCDs and the production FCDs were installed on the injection long tubing and the scab liner respectively.

The reservoir model was the same for all the scenarios that were analyzed in the sensitivity analysis.

## Total number of FCDs

The impact of the total number of FCDs on the SAGD performance was investigated first. The number of FCDs is one of the important parameters that directly controls the capital expenditure of the project and could have a significant effect on the NPV calculation by increasing the production or decreasing the SOR. Knowledge of how it affects the overall performance of the SAGD operation will help the FCD optimization phase.

### Step-i: Injection FCDs

Three different scenarios were evaluated in this step. The base case had no production or injection FCDs, the second case included one injection FCD installed at 670m from the heel, and the third case included four injection FCDs installed at 70, 370, 670 and 970m from the heel.

All the other simulation data were held constant. No production FCD was used in these scenarios.

Figure 8 compares the cumulative oil production and cumulative water injection for these cases. As can be seen in these graphs, the total number of injection FCDs could have a huge impact on maximizing the productivity of the SAGD process. The cumulative oil production was increased by 36% with only one injection FCD and 63% with four injection FCDs after 6 years of production. On the other side, the cumulative injected water was also increased by installing FCDs on the injection string. With one injection FCD, water injection increased by 20%. Four injection FCDs increased water injection by 39%. This clearly indicates a comparison of SAGD performance by only cumulative oil production is not the entire approach for optimizing FCDs.

Steam-Oil Ratio (SOR) in the comparative analysis of a SAGD performance can be useful, and will be discussed further in the optimization phase of this study. Optimizing a SAGD process based on the NPV calculation that accounts for the cost and revenue of all streams would be a precise approach for optimizing FCDs in a SAGD process.

Figure 9 compares the steam distribution profile along the injector for the three scenarios. This indicates insufficient heating of the reservoir near the heel of the injector in the base case (No FCDs). Steam conformance has significantly improved when four injection FCDs were used.

SOR is another parameter that plays an important role in efficiency of a SAGD project. The cumulative SOR for the three scenarios is illustrated in Figure 10.

Figure 10 shows that installing injection FCDs can potentially decrease the SOR. In this analysis, one injection FCD decreased SOR to 11%. There was an additional 4% reduction in cumulative SOR by

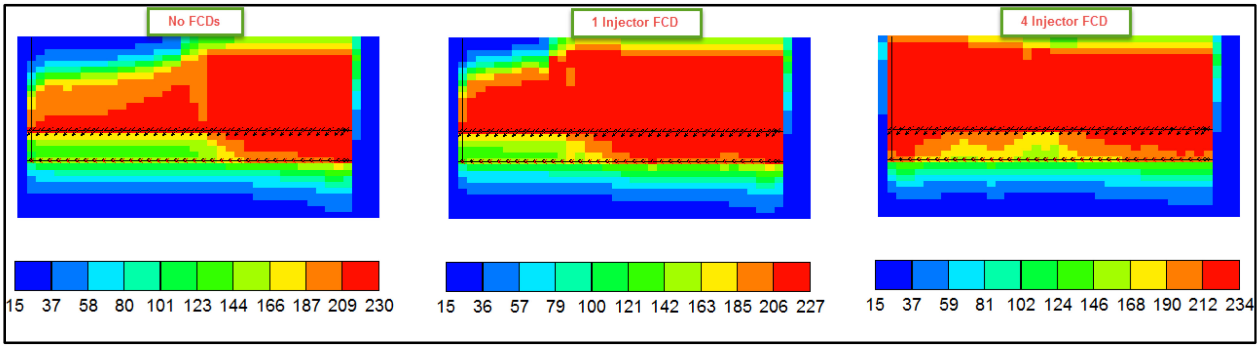



**Figure 9—Temperature profile after 2 years of simulation**

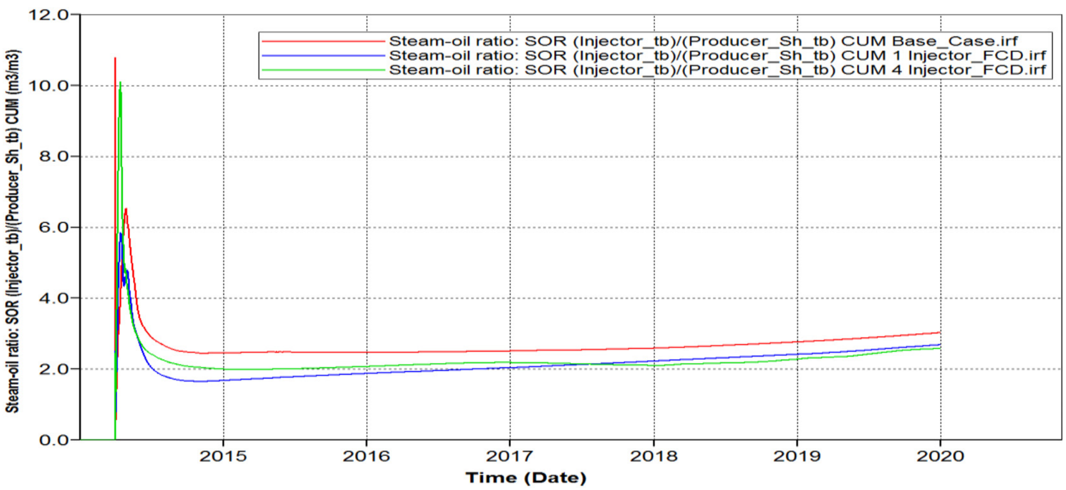



**Figure 10—SOR comparison for the three scenarios**

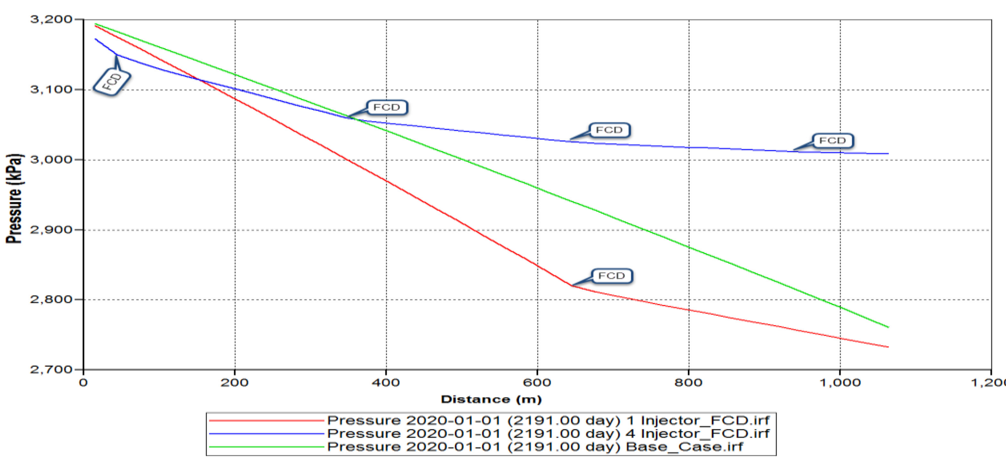



**Figure 11—Pressure profile inside tubing after 6 years of simulation**

installing three more injection FCDs. A sensitivity analysis on SOR demonstrated that there is not much difference in SOR between CASE 2 (one injection FCD) and CASE 3(four injection FCDs). This implies that economic evaluation should be applied for the FCD optimization.

Figure 11 shows the pressure profile along the injection tubing. As can be seen in this plot, CASE 3 with four injection FCDs had more uniform injection pressure profile while it had the highest cumulative steam injection (Figure 5). This sensitivity analysis concludes to this point that injectors with injection FCDs will have higher steam injection rate with lower wellhead pressure.

In order to analyze quantatively the effect of injection FCDs on the pressure profile inside the injection tubing, the pressure loss per meter ($\frac{\Delta P}{L}$) inside the tubing was calculated for each case. The last 150m of the injection string was used for this calculation. Table 3 shows the results of the calculation. By using four FCDs, the pressure loss per meter inside the injection string was reduced by more than one order of magnitude compared to the no FCD case.

**Table 3—Pressure loss per meter along the injection tubing**

| Case | Number of FCDs | $(\frac{\Delta P}{L})$ (Kpa/m) |
|---|---|---|
| 1 | 0 | 0.43 |
| 2 | 1 | 0.2 |
| 3 | 4 | 0.03 |

Pressure profile inside the tubing for the CASE 2 (one injection FCD) showed little improvement compared to the no FCD scenario. This implies that probably the location of FCD is not optimum for this case. However, the pressure loss inside the tubing for this case after installing the FCD, reduced notably. The effect of the position of the injection FCDs will be covered in step-iii.

**Step-ii: Production FCDs**

Three scenarios were analyzed to understand the effects of the number of production FCDs. The base case had no production FCDs, the second case included two production FCDs installed at 220 and 520m from the heel of the producer, and the third case included four production FCDs installed at 130, 280, 520 and 820m from the heel. The three scenarios had two injection FCDs installed on the injection long tubing.

Figure 12 illustrates the cumulative oil and water production for the three cases after 6 years. The overall trends suggest a positive impact of the production FCDs, but the difference is insignificant compared to the effect of injection FCDs, especially during the early life of the production. The gap is more visible at the late stage of the production, as a result of steam breakthrough in the scenario with no production FCDs.

The pressure profile inside the scab liner at 6 years of production is depicted in Figure 13. When production, occurs only through the toe, there is a rapid change in pressure along the scab liner. Use of production FCDs develops a more uniform pressure profile along the scab liner. Figure 14 shows the effects of two production FCDs on the production and pressure distribution along the scab liner. In this case, production FCDs share 44% of the production while 56% of the total production occurs through the toe. Splitting the production, results in higher pressure values in the scab liner. This is particularly important to avoid steam production throughout the process. Figure 15 compares the pressure profile for the base case (No production FCDs) and the case with two production FCDs. The pressure drop from toe to heel in the production scab liner for the base case was 300 Kpa. By installing two production FCDs this pressure difference was reduced to 120 Kpa and as a result a more uniform pressure profile was established.

## Location of FCDs

The sensitivity study for a number of injection FCDs demonstrated that the position of FCDs might affect the overall performance of a SAGD process. This was confirmed when the pressure loss along the wellbore for the case with one injection FCD was compared to the base case (Figure 11). It indicates that the positioning of a single injection FCD towards the heel could provide a more uniform pressure profile. This example demonstrated the importance of the location of FCDs which will be covered in Step-iii and Step-iv.

**Step-iii: Injection FCDs**

Three scenarios were analyzed to understand the effects of the number of injection FCDs. In this step, all the scenarios included 2 injection FCDs. The base case (CASE1) two injection FCDs were installed at 70 and 670m from the heel, the second case (CASE 2) included two injection FCDs installed at 70 and 370m

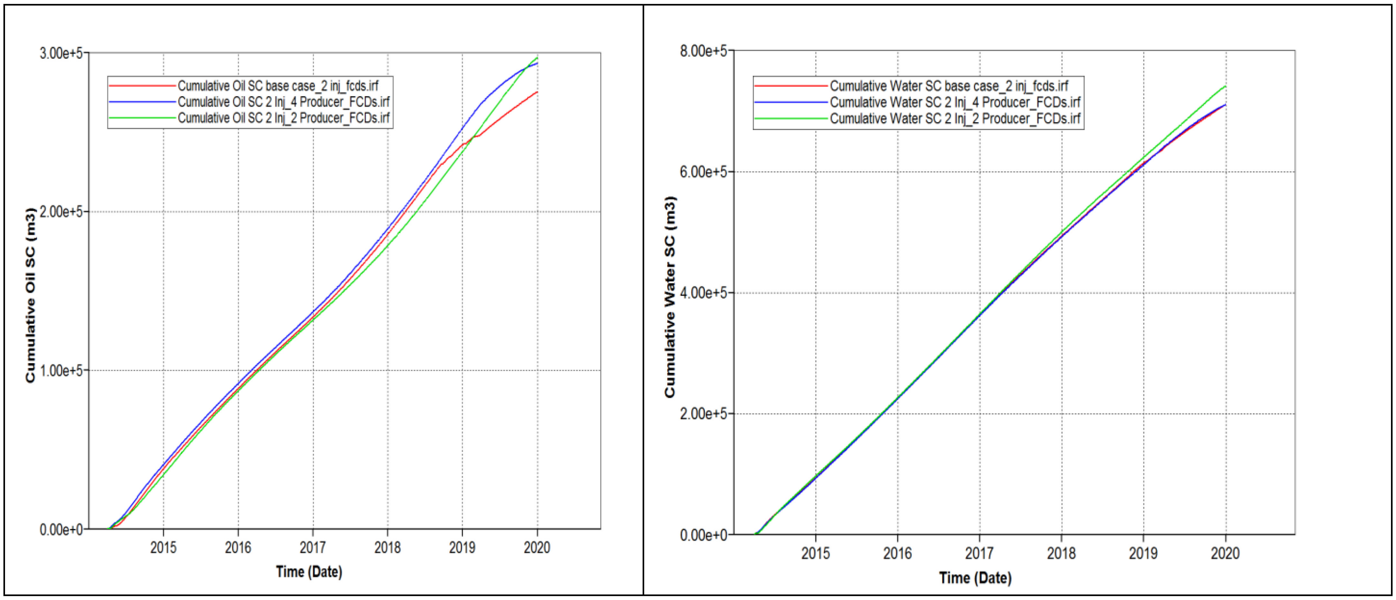



**Figure 12—Cumulative oil and water production for the three scenarios after 6 years**

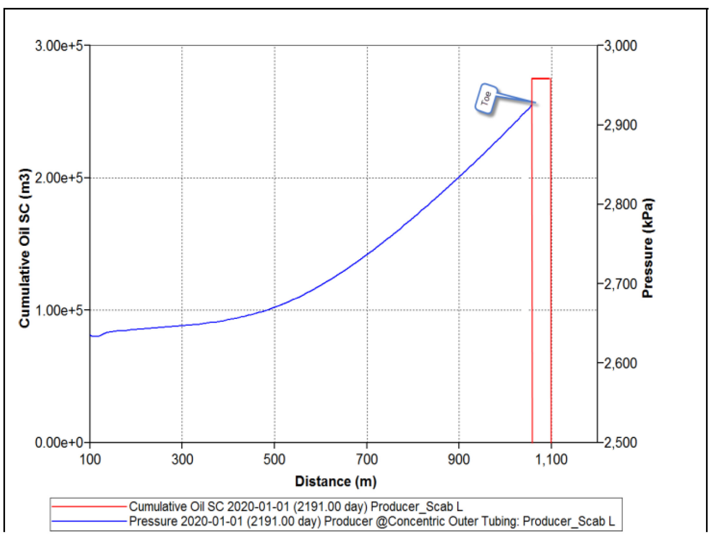



**Figure 13—Pressure profile and cumulative oil distribution along the scab liner for the base case with no production FCDs**

from the heel, and the third case (CASE3) included two injection FCDs installed at 370 and 970m from the heel. No production FCD was used for the analysis.

As discussed earlier, minimizing and delaying the occurrence of the steam breakthrough is one of the key objectives of installing FCDs in a SAGD process. Breakthrough is always detrimental to oil production in thermal operations. Figure 16 depicts the oil production rate profile of CASE 1 and CASE 3 for comparison. As can be seen from this plot, the change in position of the injection FCDs delayed steam breakthrough for more than 1.5 years. This could have a significant impact on the economics of a SAGD operation.

Injection FCDs can have a notable impact on the pressure distribution in the wellbore. Figure 17 illustrates the pressure profile in the injection long string after 2 years of production. CASE 1 and 2 have more uniform pressure profile compared to CASE 3 and the case with no injection FCDs. As a result, CASE 1 and 2 had better oil recovery. Table 4 shows the cumulative oil production, cumulative steam injection and cumulative SOR for all four cases after 6 years of production.

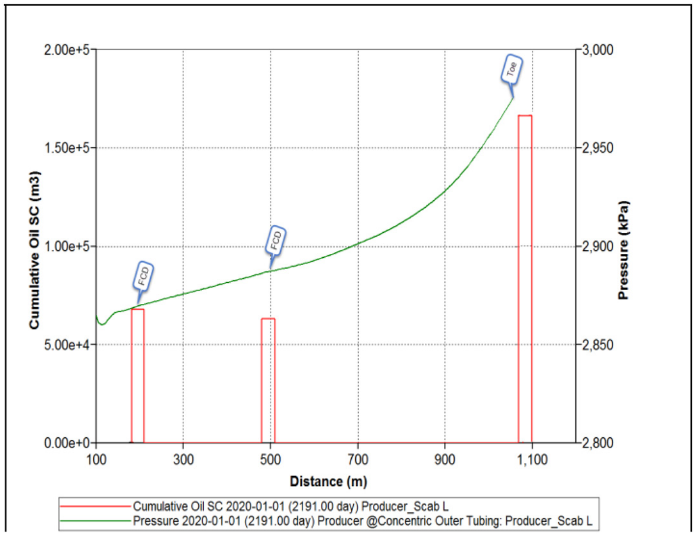



**Figure 14—Pressure profile and cumulative oil distribution along the scab liner for the case with two production FCDs**

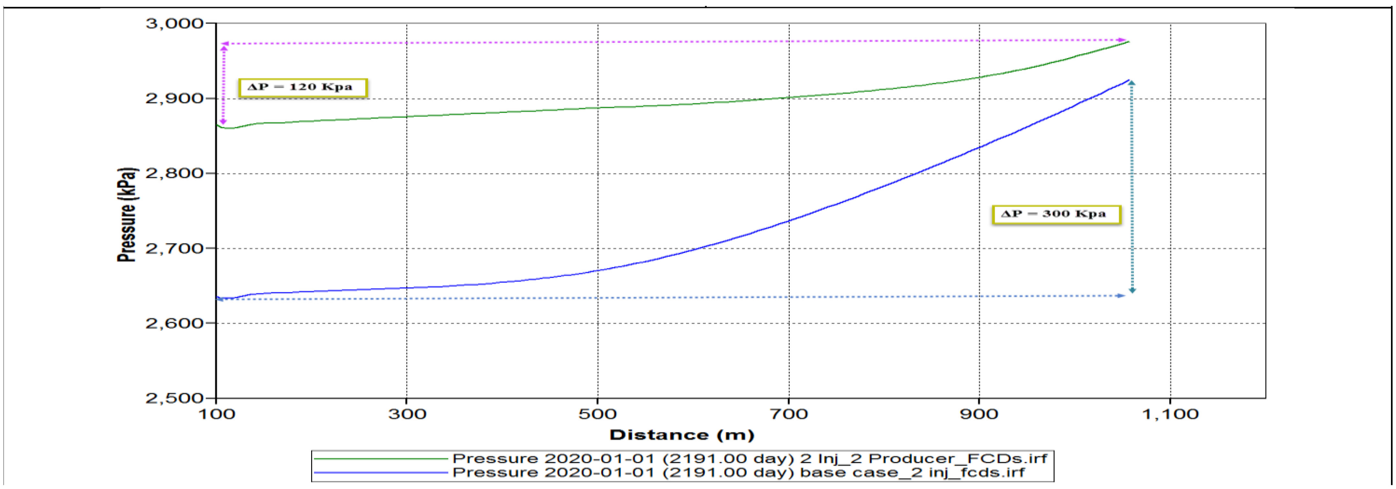



**Figure 15—Comaprison between pressure profiles along the scab liner for the base case and the case with two production FCDs**

Figure 18 shows the temperature profile in the ij plane for all the cases. j/i aspect ratio of 10 was used to generate these plots. It indicates that steam distribution within the reservoir can be customized. This is particularly important for the cases with extreme geological heterogeneities where it is possible to inject steam at specific part of the reservoir along the horizontal wellbore.

## Step-iv: Production FCDs

Three scenarios were analyzed to understand the effects of the number of production FCDs, and in this section, all the scenarios except the base case included 2 production FCDs. The first case (CASE1) production FCDs were installed at 220 and 520m from the heel, the second case (CASE 2) included two production FCDs installed at 220 and 820m from the heel, and the third case (CASE3) included two production FCDs installed at 220 and 520m from the heel. The base case had no production FCDs. All the scenarios included two injection FCDs. Cumulative oil and water production after 6 years are shown in the Figure 19. There is an insignificant change in the production data which demonstrates that the production is not sensitive to the location of production FCDs.

Cumulative SOR (CSOR) values were compared in Figure 20 for the three cases. The overall trend shows that the effect of location of production FCDs on CSOR is more visible early in the life of the

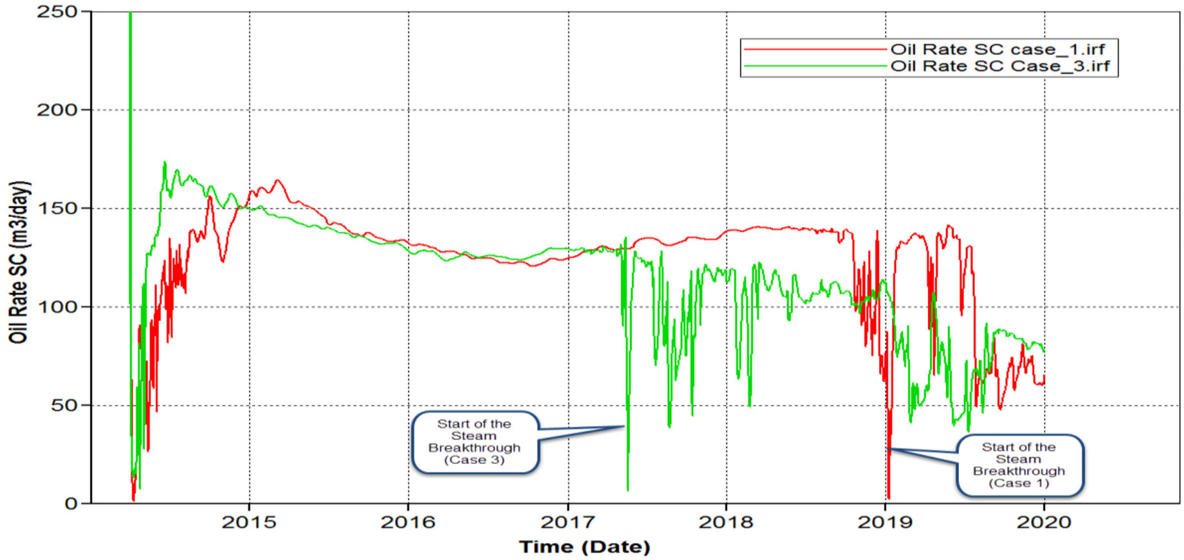



**Figure 16—Oil production rates of CASE 1 and 3**

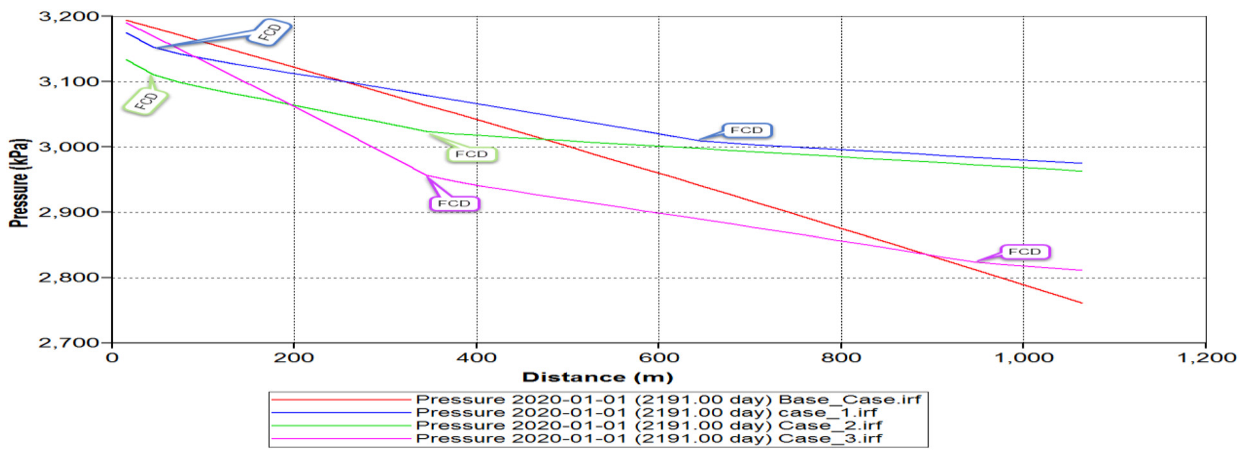



**Figure 17—Pressure distribution in the injectionlong string for the four cases**

**Table 4—Results of the simulation after 6 years**

| Case | Cum Oil Production (m3) | Cum Steam Injection (m3) | Cum SOR (m3/m3) |
|---|---|---|---|
| Base Case (No FCD) | 1.50E+05 | 4.54E+05 | 3.03 |
| Case 1 | 2.62E+05 | 5.95E+05 | 2.27 |
| Case 2 | 2.77E+05 | 6.19E+05 | 2.24 |
| Case 3 | 2.42E+05 | 6.08E+05 | 2.50 |

production (First year). After one year of the production, CSOR is almost the same for all the cases. Figure 20 also shows production FCDs are highly effective to control steam breakthrough. For the scenario without production FCDs (Base case) steam breakthrough occurs after 4 years of production, while none of the scenarios with production FCDs shows the steam breakthrough after 6 years.

Pressure profile in the production annulus was displayed in the Figure 21. In the cases with production FCDs, pressure values are greater compared to the case without production FCDs. This will result in lower drawdown between wellpairs and the minimization of the production of the live steam.

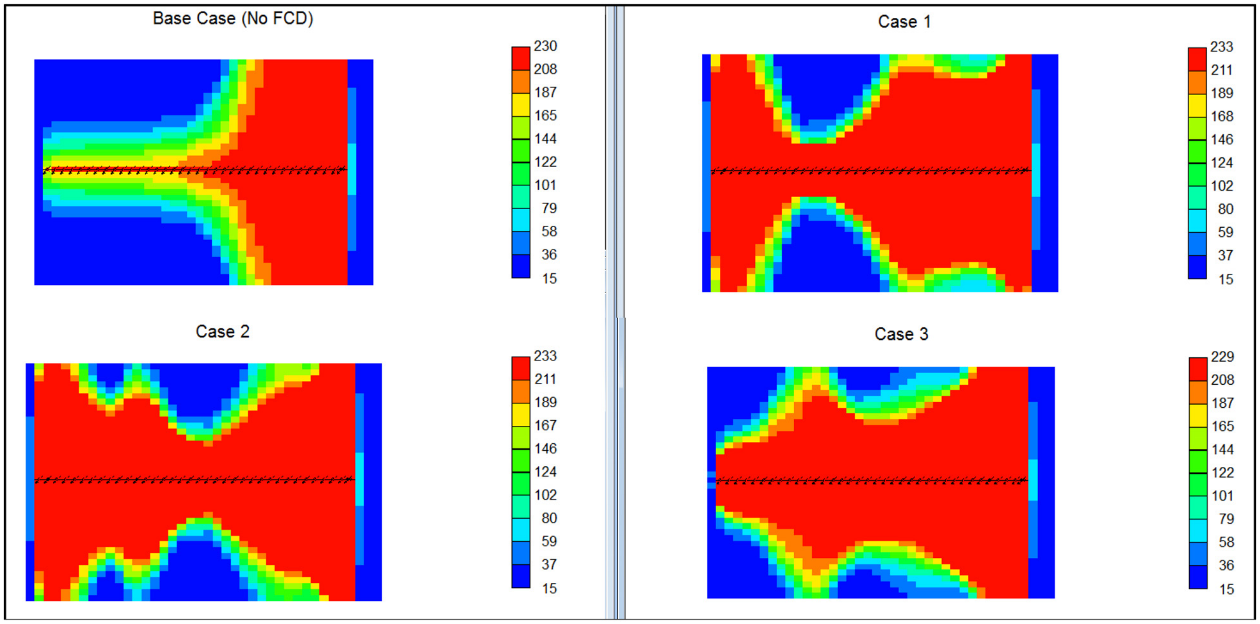



Figure 18—Temperature distribution profile after 2 years of production

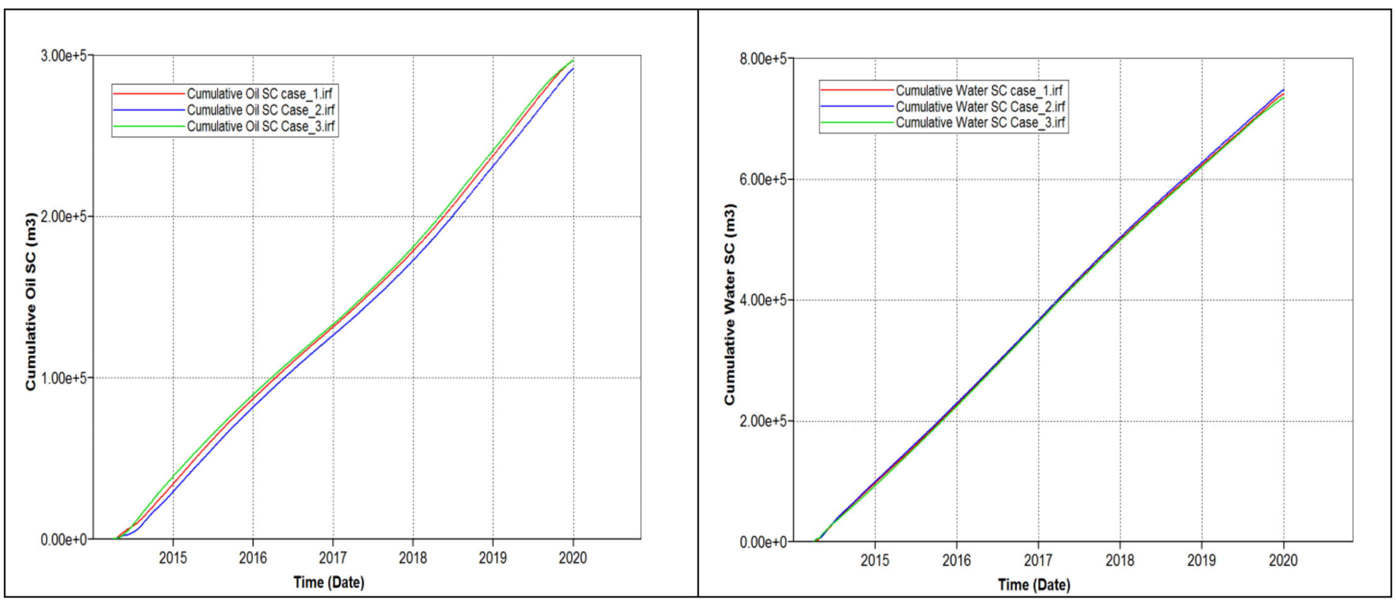



Figure 19—Cumulative oil and water production after 6 years of simulation

## Properties of FCDs

Sensitivity study on the properties of the FCDs was performed using optimization software. A variety of datasets were created by implementing experimental design concepts to best represent the search space. A classical experimental design called Latin Hypercube design was selected as the sampling method.

For sensitivity analysis using Latin Hypercube design, a response surface methodology was applied. Response surface methodology (RSM) explores the relationships between input variables (parameters) and responses (objective functions). (10) As an example, this methodology can give a relation between cumulative oil production (objective function) and a parameter like number of FCD ports. It also identifies parameters that affect the model the most.

The objective functions that were considered for this section were:

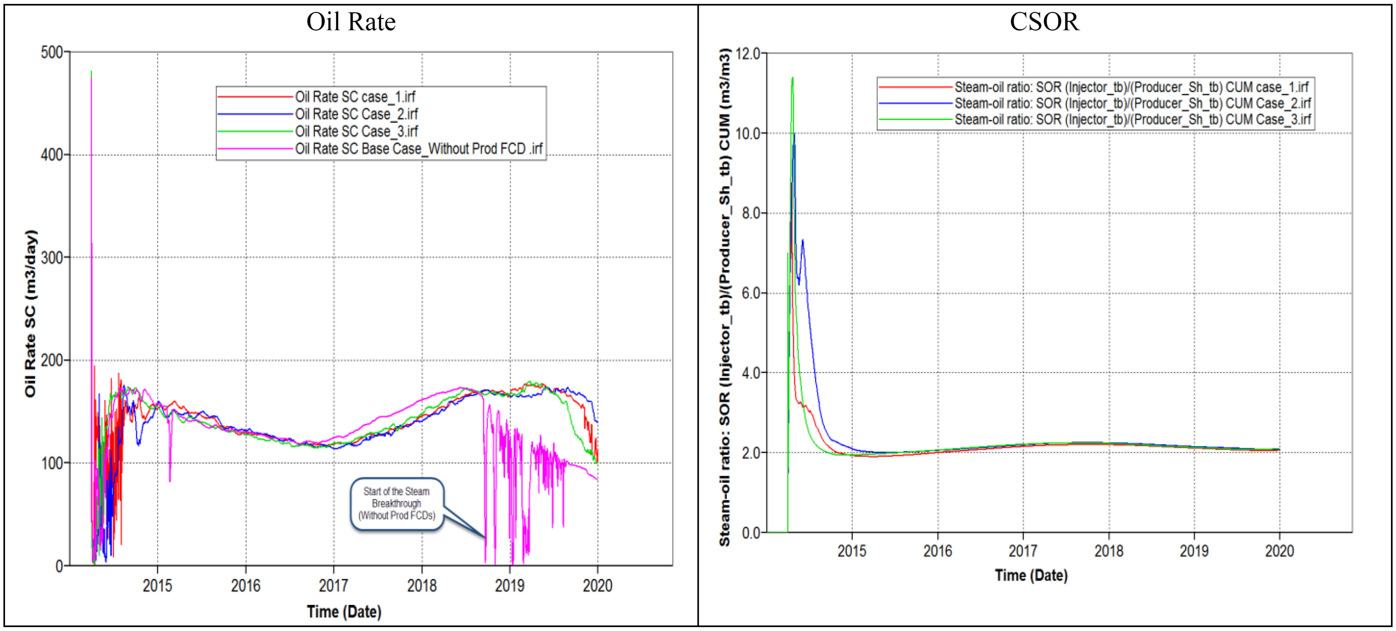



**Figure 20—Oil rate and CSOR after 6 years of simulation**

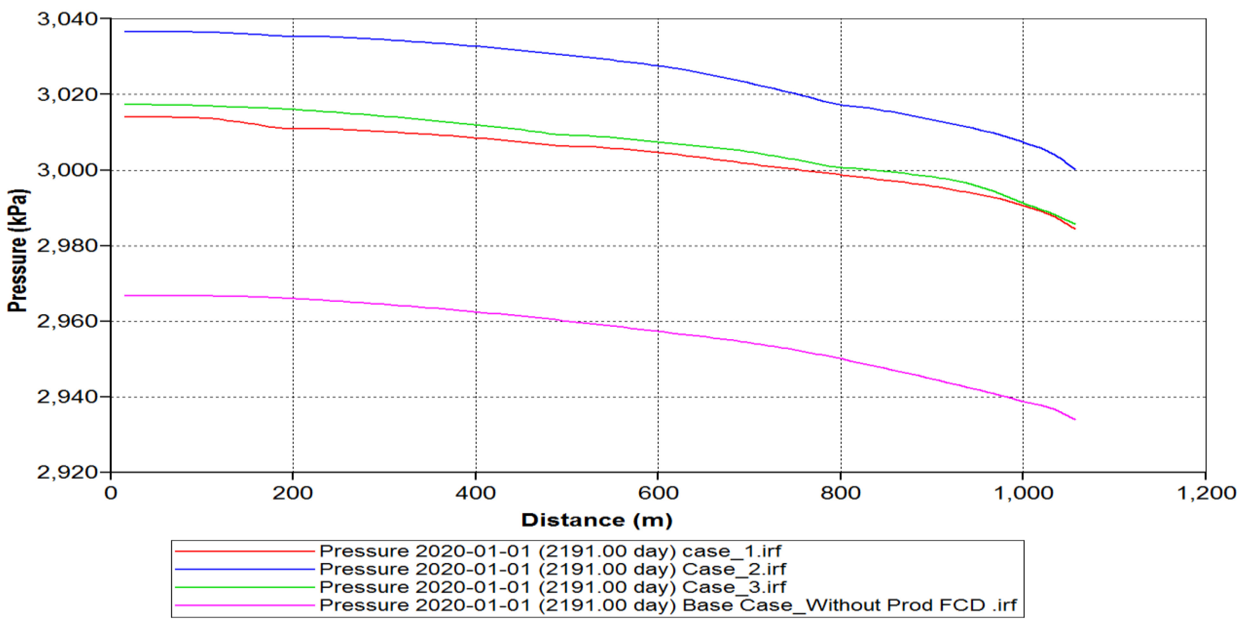



**Figure 21—Pressure profile in the production annulus at the end of the 6 years of SAGD**

1- The cumulative produced oil volume
2- The cumulative produced water volume
3- The cumulative injected steam volume
4- Bottom Hole Pressure of the injection long string
5- Bottom Hole Pressure of the production short string
6- Bottom Hole Pressure of the production scab liner
7- Cumulative SOR

Table 5—Parameters studied on the sensitivity analysis and operating parameter range

| Parameter | Description | Min | Max |
|---|---|---|---|
| Discharge_Coeff | Discharge coefficient | 0.75 | 0.9 |
| Port_Diam | Port diameter (m) | 0.005 | 0.015 |
| Ports | Total number of ports | 5 | 32 |

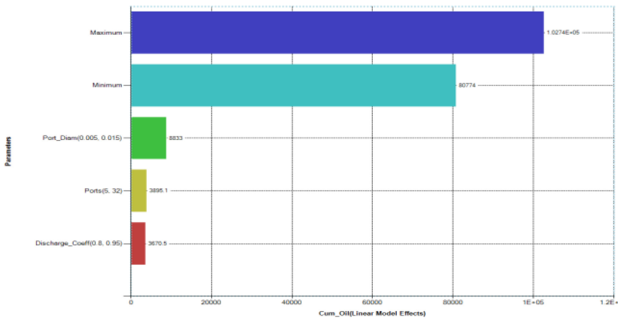



**Figure 22—Relative effects of two Inj. FCD properties on the cumulative oil production**

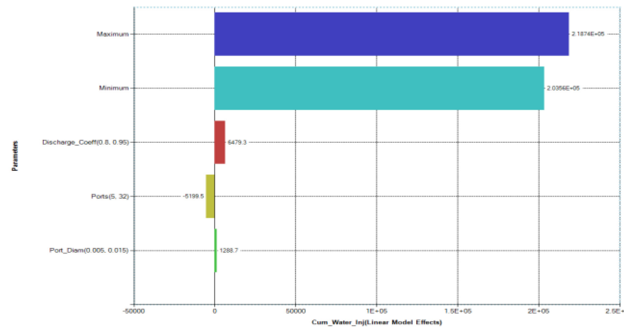



**Figure 23—Relative effects of two Inj. FCD properties on the cumulative water injection**

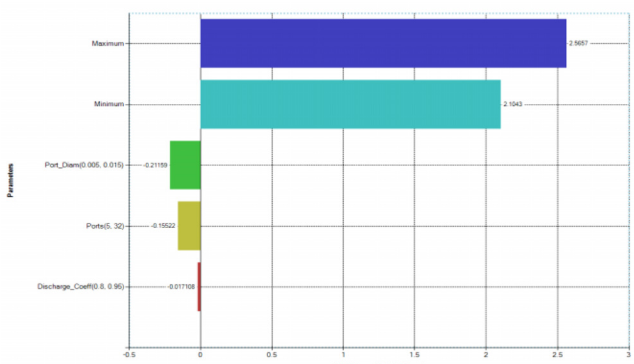



**Figure 24—Relative effects of two Inj. FCD properties on the CSOR**

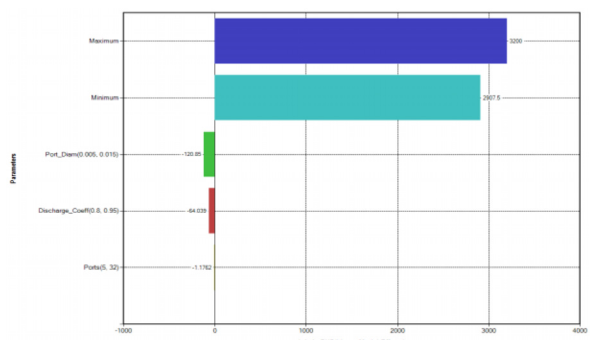



**Figure 25—Relative effects of two inj. FCD properties on the BHP of injection tubing**

## Step-v: Injection FCDs

The selected parameters for the sensitivity study on the properties of the injection FCD were discharge coefficient, port size and total number of ports. Table 5 shows the uncertain parameters and their range of values that was used for the study. In this step all the reservoir and wellbore properties were not changed and 16 months were forecasted. Two injection FCDs installed at 70 and 370m from the heel were assumed for the analysis. In the Phase 2 Optimization Section later in this paper, it will be determined that two injection FCDs would be the optimal case for this SAGD process.

The tornado plots on Figure 22 to Figure 25 demonstrate the results of the sensitivity analysis obtained using the linear model for the three uncertain parameters. Table 6 summarizes the parameters with the highest and lowest influence over the seven local objective functions.

Table 6 shows that the port diameter has the greatest influence over the production data. The total number of ports is the main parameter that controls the BHP of the production well. Cumulative injected water is the only objective function which is highly sensitive to the discharge coefficient. Overall, the discharge coefficient is the least sensitive parameter to most of the local objective functions.

Table 6—List of parameters with highest and lowest influence on different objective functions (injection FCDs)

| Local Objective Function | Parameters with highest influence | Parameters with lowest influence |
|---|---|---|
| Cum Oil | Port Diameter | Discharge Coefficient |
| Cum Produced Water | Port Diameter | Discharge Coefficient |
| Cum Injected Water | Discharge Coefficient | Port Diameter |
| BHP of injection long string | Port Diameter | Total Number of Ports |
| BHP of Scab Liner | Total Number of Ports | Discharge Coefficient |
| BHP of production short string | Total Number of Ports | Discharge Coefficient |
| Cum SOR | Port Diameter | Discharge Coefficient |

Table 7—Parameter ranges for the sensitivity analysis

| Parameter | Description | Min | Max |
|---|---|---|---|
| Discharge_Coeff | Discharge coefficient | 0.75 | 0.9 |
| Port_Diam | Port diameter (m) | 0.00158 | 0.00476 |
| Ports | Total number of ports | 1 | 10 |

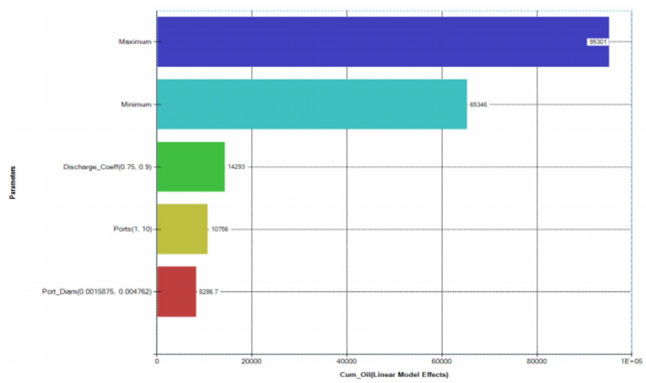



Figure 26—Relative effects of 4 Prod. FCD properties on the cumulative oil production

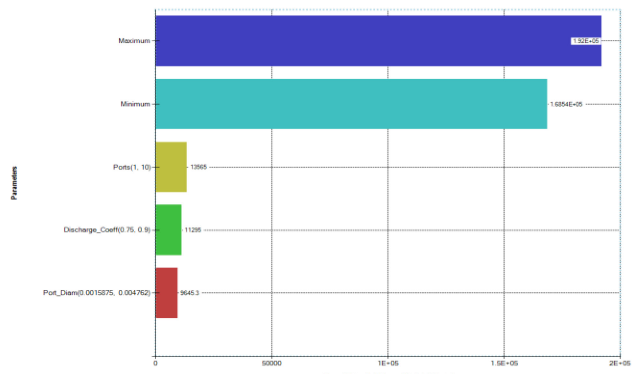



Figure 27—Relative effects of 4 Prod. FCD properties on the cumulative water injection

## Step-vi: Production FCDs

The sensitivity study for the production FCDs used the same approach that was discussed in the Step-v. Table 7 summarizes the uncertain parameters and the range of values that were used. The sensitivity analysis used a one year forecast. A total of four Production FCDs installed at 130, 280, 520 and 820m from the heel were used for the analysis. All the scenarios had two injection FCDs installed at 70 and 370m from the heel of the injector. In the Phase 2 Optimization Section later in this paper, it will be determined that this case is the optimal scenario for this SAGD process.

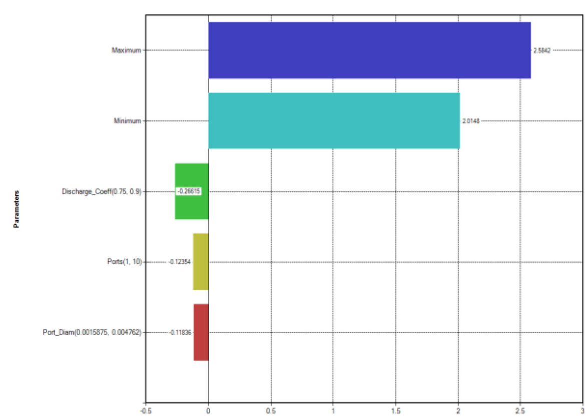



Figure 28—Relative effects of 4 Prod. FCD properties on the SOR

The objective was to find which properties of the production FCDs influence the parameters that usually control the NPV of the SAGD process. The results of the linear model from the sensitivity analysis are presented in Figure 26 to Figure 29.

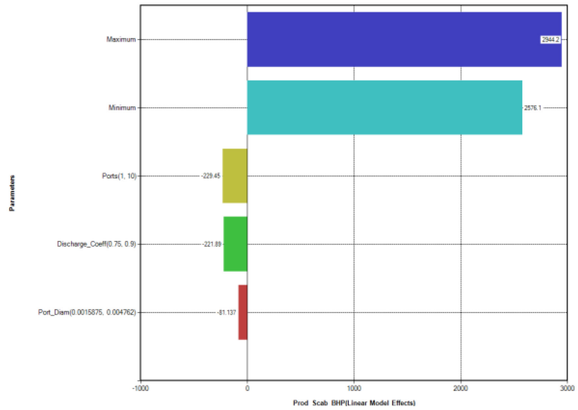



**Figure 29—Relative effects of 4 Prod. FCD properties on the BHP of scab Liner**

**Table 8—List of parameters with highest and lowest influence on different objective functions (production FCDs)**

| Local Objective Function | Parameters with highest influence | Parameters with lowest influence |
|---|---|---|
| Cum Oil | Discharge Coefficient | Port Diameter |
| Cum Produced Water | Total Number of Ports | Discharge Coefficient |
| Cum Injected Water | Total Number of Ports | Port Diameter |
| BHP of Injector long string | Total Number of Ports | Port Diameter |
| BHP of Scab Liner | Total Number of Ports | Port Diameter |
| BHP of Production short string | Total Number of Ports | Port Diameter |
| Cum SOR | Discharge Coefficient | Port Diameter |

Table 8 shows that the total number of ports for production FCDs has a significant impact on the performance of the SAGD operation. Overall, port diameter is the least effective properties of the production FCDs.

## Phase 2: Optimization

Results of the sensitivity analysis performed in Phase 1, clarified the importance of application of FCDs on the SAGD operation. The use of production FCDs should result in developing a uniform pressure and production profile along the horizontal wellbore. This assists with managing the interface between the injector and producer for efficient reservoir drainage, while reducing the steam breakthrough tendency. The injection FCDs, allows for multiple injection within a single tubing along the horizontal wellbore.[6] This could significantly improve the thermal efficiency and productivity of the SAGD operation.

The sensitivity study in Phase 1, also showed that design of the FCDs is crucial. The design for FCD optimization should include the following parameters:

- Total number of FCDs installed on producer and injector
- Location of FCDs
- Properties of FCDs

As discussed in the sensitivity study in Phase I, the properties of the FCDs include the size of the orifices (ports), the total number of orifices, and discharge coefficient. Currently, the sizes of the ports that are available for the FCDs are constant. For injection FCDs, a constant port size equal to 10 mm is available. For production FCDs, the size of the ports is dependent on the wellbore diameter. Table 9 shows the size of the ports recommended for the production FCDs in different borehole diameters. In this paper, discharge coefficient that was used for the FCDs were constant values. Even though this value could be affected by the type of the fluid (Gas or liquid), flow regime, and fluid viscosity etc., it is mainly controlled by the mechanical design of the tool. Therefore, it is difficult to include these two parameters

Table 9—Number of ports and port size of Weatherford production FCD for different borehole sizes

| Size (in.) | 2-3/8 | 2-7/8 | 3-1/2 | 4 | 4-1/2 | 5 | 5-1/2 | 6-5/8 | 7 |
|---|---|---|---|---|---|---|---|---|---|
| Overall tool length (in./mm) | | | | | 10.4<br>264.92 | | | | |
| Minimum Hole Size (in./mm) | 3.88<br>96.52 | 4.50<br>114.30 | 5.00<br>127.00 | 5.50<br>139.70 | 6.00<br>152.40 | 6.50<br>165.10 | 7.00<br>177.80 | 8.25<br>216.41 | 8.50<br>215.90 |
| Run OD (in./mm) | 3.32<br>84.33 | 3.90<br>99.06 | 4.44<br>112.78 | 5.00<br>127.00 | 5.44<br>138.18 | 6.00<br>152.40 | 6.50<br>165.10 | 7.69<br>195.33 | 8.12<br>206.25 |
| Number of ports | 5 | | | | | 10 | | | |
| Flow port sizes (in./mm) | | | | | 1/8 or 3/32<br>3.175 or 2.381 | | | | |

in the optimization process. However; the sensitivity study in Phase 1, confirmed a great influence of these two parameters on the efficiency of the SAGD operation and therefore they need to be considered in the mechanical design of the tool. The total number of ports was the only FCD properties that were considered for optimization in the Optimization Phase 2 of this study.

Table 10—Data used for NPV calculation

| Variable | Unit Value |
|---|---|
| Oil Price ($/bbl) | 85 |
| Steam Cost ($/bbl) | 10 |
| Water treatment cost ($/bbl) | 0.25 |
| Well Capital Cost ($) | 8,000,000 |
| Discount Rate (%) | 10 |

To optimize the FCDs, it is crucial to consider the economic impact of installing FCDs on the SAGD process. To do this, Net Present Value (NPV) of the operation was set to be the base for the optimization process. The NPV was calculated using the following equation: [11]

$$\mathrm{NPV} = \sum_{ny=1}^{N_{yr}} \frac{R_{ny}}{(1+i_r)^{ny}} - I \tag{10}$$

In which, I is the investment made to generate the yearly revenue, $i_r$ is the discount rate and $R_{ny}$ is the total annual revenue after deduction of royalties and operative expenditure for each year of the $N_{yr}$ years given by:

$$R_n = O_{p,ny} \times P \times (1 - f_r) \times (1 - f_o) \times (1 - f_t) \tag{11}$$

Where $O_{p,ny}$ is the cumulative natural oil production in the reference year ny (bbl), P is the price of oil (USD/bbl), $f_r$ is the fraction of gross cash flow as royalties, $f_o$ is the fraction of gross cash flow as expenditures and $f_t$ is the fraction of cash flow as taxes. The total investment included the drilling and completion cost. The cost of each FCDs installed on the producer or the injector was added separately to the capital cost of each case. Table 10 summarizes the data used for the NPV calculation.

## Workflow:

Figure 30 illustrates the proposed workflow for optimizing the FCDs for a SAGD wellpair. The optimization process includes both injection and production FCDs. The presence of a geological model to construct the dynamic reservoir model could assist in reducing potential geological uncertainties. The reservoir simulation could also be conducted with a synthetic rectangular model and geological heterogeneities like changes in porosity, permeability, and geological barriers could be roughly assumed in the model.

Results of the sensitivity analysis, in Phase 1, confirmed the impact of using injection FCDs is more significant when compared to the production FCDs. Therefore, the optimization process should be performed on the injection FCDs first. The second stage involves optimization of the production FCDs, with location and total number of FCDs being optimized simultaneously. The optimization of the number

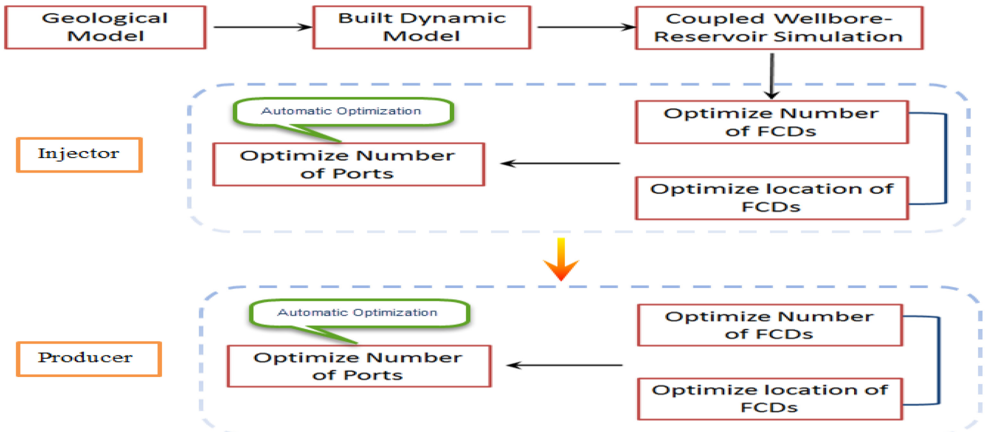
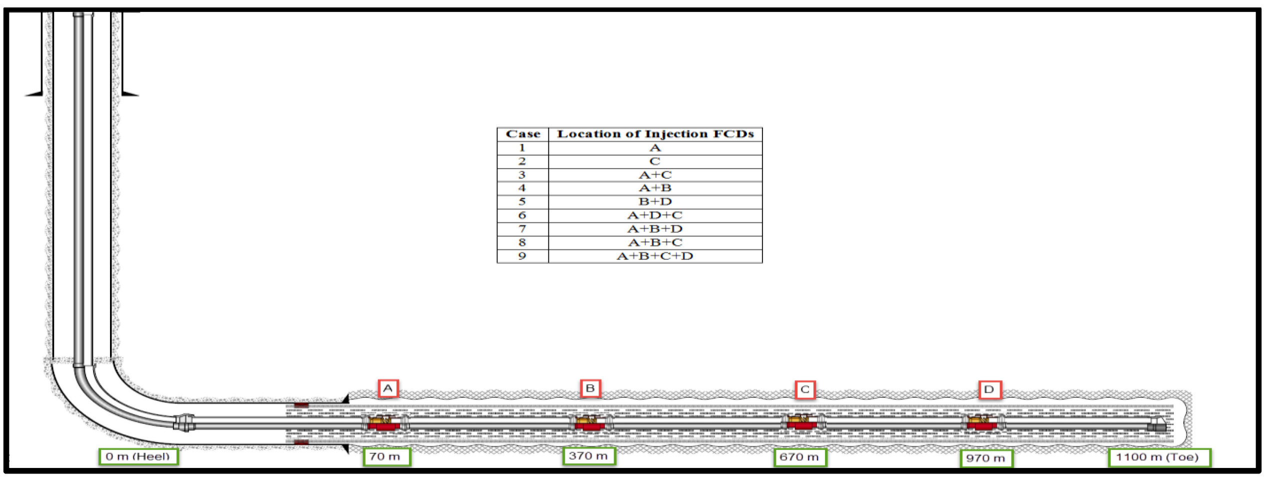



Figure 30—Integrated model for optimizing production and injection FCDs




| Case | Location of Injection FCDs |
|---|---|
| 1 | A |
| 2 | C |
| 3 | A+C |
| 4 | A+B |
| 5 | B+D |
| 6 | A+D+C |
| 7 | A+B+D |
| 8 | A+B+C |
| 9 | A+B+C+D |

Figure 31—Location of injection FCDs for the nine scenarios

of orifices would be performed after determining the location and number of FCDs for both injector and producer. The use of automatic optimization of the number of ports reduces the engineering time considerably. The same dynamic model that was discussed earlier and was utilized in the sensitivity study was also used in this phase. The objective function for the optimization process is to seek the maximum NPV. Cumulative oil production and SOR are crucial components that control the NPV of a SAGD operation. This integrated model assumes that the well constraints such as maximum injection rate were optimized prior to the optimization process of the FCDs. The maximum number of injection/production FCDs that need to be considered in the optimization phase, vary from case to case. NPV calculations can assist in determining maximum number of FCDs. If installing more FCDs do not increase the NPV, it can be assumed the maximum number of injection/production FCDs for the optimization work was reached. In this paper maximum number of four injection FCDs and 5 production FCDs were considered for the optimization.

## Optimizing Injection FCDs

### Step-1: Optimizing location and total number of injection FCDs

In this step, nine different models with various configuration of injection FCDs were analyzed. Figure 31 depicts the four assigned positions of the FCDs along the injection long tubing string.

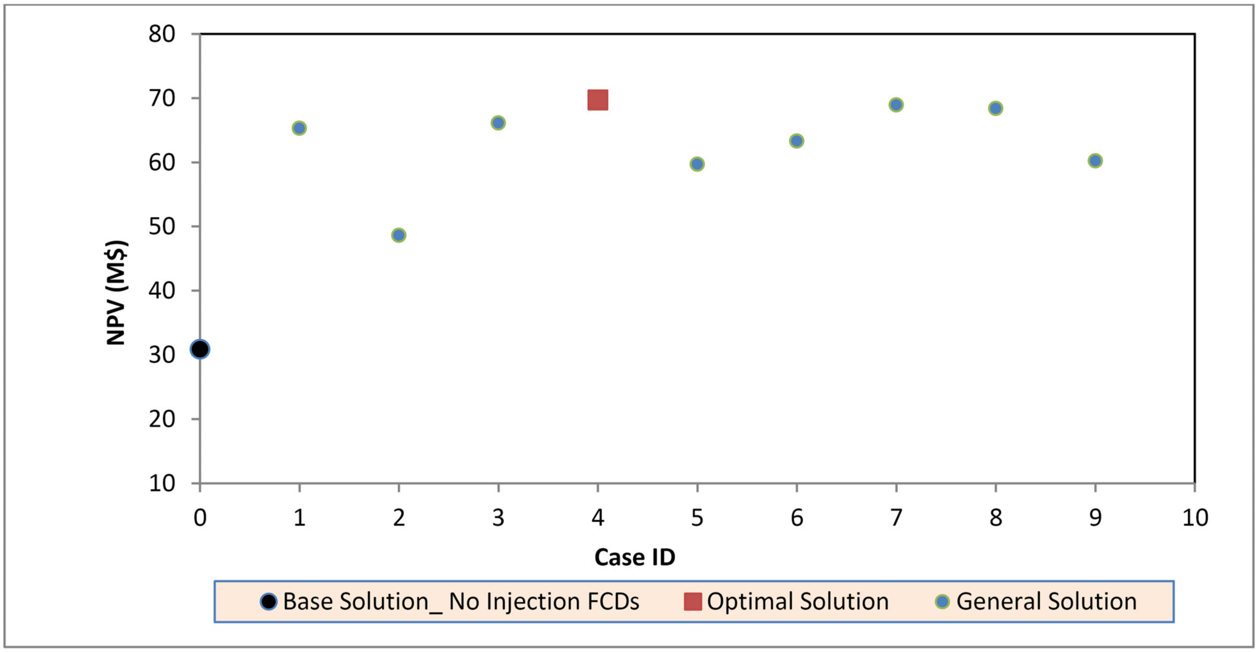



Figure 32—NPV calculation results for all the cases (Optimizing injection FCDs)

Figure 32 shows the results of the NPV calculation for all the scenarios after 6 years of production. CASE 4 with two injection FCDs located at 70 (FCD 2) and 370m (FCD 1) from the heel, had the maximum NPV. This optimized scenario provides approximately $70 Million of profit over a period of 6 years. The NPV of this SAGD operation more than doubled by installing two FCDs and optimizing their locations.

**Step-2: Optimizing number of ports for injection FCDs**

The number of ports for the best case in Step-1 was assumed to be 10. The objective of this step was to find the optimal total number of ports for the two injection FCDs. The software optimization tool was used to perform the automatic analysis. The base case in this step was the optimal solution derived from the Step 1 as referenced in Figure 32.

The first step of optimization confirmed that the cumulative oil production is the main parameter that controls the NPV of this SAGD process when using only the injection FCDs. This is not always applicable as sometimes other factors like cumulative steam injection and cumulative water production could have a big impact on the NPV of the SAGD operation. Consequently; the automatic optimization was constrained by a global objective function that was set to the cumulative oil production. To save time the injection FCD ports was first optimized on a 16 month forecast, and then a 6 year forecast of the best three cases were compared to the best case from Step-1 to specify the optimal solution for the injection FCDs. Automatic optimization was conducted on a range of port numbers for each two injection FCDs that were assumed to be 5, 10, 15, 20, 25 and 32. Port size and discharge coefficients were assumed to be 10 mm and 82 % respectively for scenarios. The fluids were modelled to enter the production scab liner through the toe only (no production FCDs).

The Designed Exploration and Controlled Evolution (DECE) optimization algorithm was utilized to solve for the optimization problem. [10] Total of 21 different scenarios with different number of ports were tested by the DECE algorithm to optimize cumulative oil production. Figure 33 shows the results of the optimization over a 16 month forecast.

Table 11 summarizes the final results of the best three cases.

The NPV of the best three scenarios after 6 years of production were compared to the base case (Optimal case from step-1) and the “Best CASE 2” was determined as the optimal case for the injection

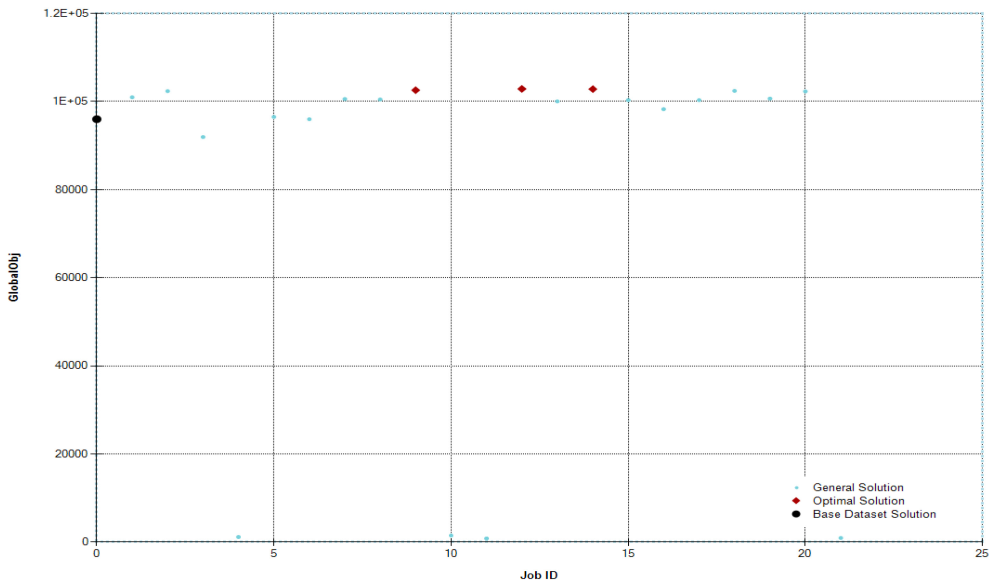



**Figure 33—Optimization of port numbers for injection FCDs (16 month forecast)**

**Table 11—Results of the best three scenarios (Optimizing injection FCDs)**

| Scenario | Ports (Inj. FCD 1) | Ports (Inj. FCD 2) | Cumulative Oil after 16 Months (m3) | SOR @ after 16 Months (m3/m3) |
|---|---|---|---|---|
| Base case (Optimal case from step-1) | 10 | 10 | 95991 | 2.109 |
| Best case 1 | 15 | 15 | 1.0258E+05 | 2.114 |
| Best case 2 | 32 | 15 | 1.0287E+05 | 2.124 |
| Best case 3 | 20 | 20 | 1.0283E+05 | 2.119 |

**Table 12—Variation of NPV with operation year**

| Year | NPV for Base Case (Optimal case from step-1) (M$) | NPV for Optimal Case (M$) | Increase in NPV (M$) |
|---|---|---|---|
| 1 | 5.1 | 5.9 | 0.85 |
| 2 | 21.9 | 22.4 | 0.52 |
| 3 | 34.2 | 35.2 | 0.96 |
| 4 | 47.1 | 49.4 | 2.34 |
| 5 | 61.9 | 63.6 | 1.71 |
| 6 | 69.7 | 69.8 | 0.03 |

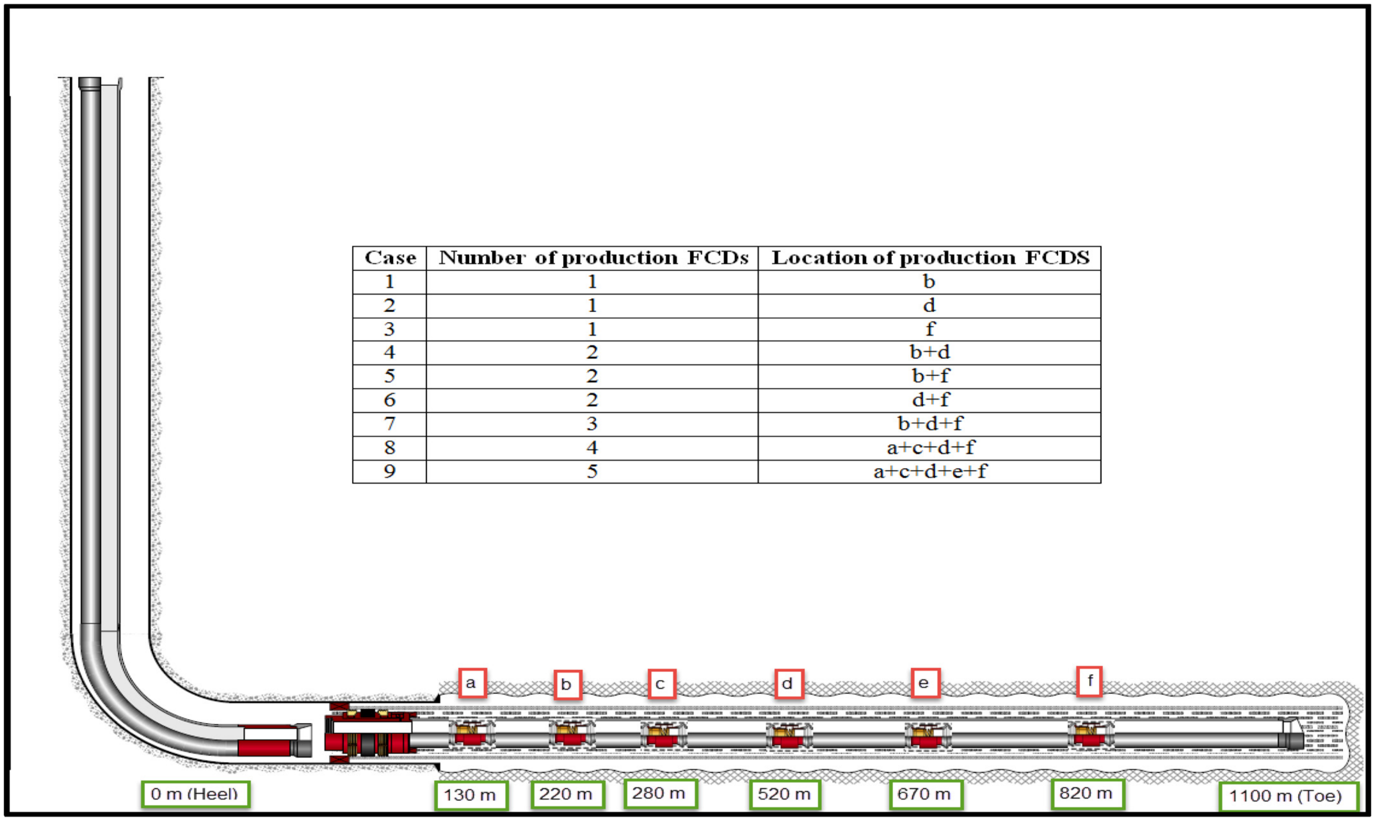
FCDs. Table 12 presents the increase in NPV at each year by optimizing the number of ports to 32 and 15 for injection FCD 1 and FCD 2.

Up to this point; the injection FCDs optimization increased the NPV from $31 million to $70 million or a 125 % increase over a period of 6 years.

## Optimizing production FCDs

### Step-3: Optimizing location and total number of production FCDs

In the step-1 and step-2, injection FCDs were optimized to give the maximum NPV for this SAGD process. The optimization of the production FCDs follow a similar workflow as was shown in Figure 30. Sensitivity analysis that was performed on the Production FCDs indicated that the impacts of the production FCDs are not that significant compared to the injection FCDs. It was shown that FCDs on the producer, provided more uniform pressure along the production wellbore. This should result in less steam




| Case | Number of production FCDs | Location of production FCDS |
|---|---|---|
| 1 | 1 | b |
| 2 | 1 | d |
| 3 | 1 | f |
| 4 | 2 | b+d |
| 5 | 2 | b+f |
| 6 | 2 | d+f |
| 7 | 3 | b+d+f |
| 8 | 4 | a+c+d+f |
| 9 | 5 | a+c+d+e+f |

**Figure 34—Location of production FCDs for the nine scenarios**

breakthrough and more production. The optimal case from Step-2 was used to optimize the production FCDs. Figure 34 depicts the position of the production FCDs along the production scab liner for the nine scenarios. All the production FCDs was assumed to have 5 ports with a 3.175 mm in diameter. In Step-4 the number of ports will be optimized. The scenario with four production FCDs had better performance compared to the scenario with 5 production FCDs. Hence the maximum of five production FCDs was analyzed.

Figure 35 shows the final results of the NPV calculation for the 9 scenarios after 6 years of production. CASE 8 with four production FCDs had the best NPV. The optimized scenario gave $75Million of operating profit over a period of 6 years. This is an 8 % increase in NPV compared to the best case that was determined from the optimization task of the injection FCDs conducted in Step-2.

### Step-4: Optimizing number of ports for production FCDs

The preliminary analysis on the optimization of the number of ports for the production FCDs (step-3) specified that several parameters including cumulative oil production and CSOR control the NPV calculation. Hence, the NPV was selected as the objective function for optimizing the number of ports. Like optimization of the injection FCDs, the DECE optimization algorithm was used to solve the optimization problem. To save time, the production FCD ports were determined using a 2 year forecast and then a 6 year forecast of the best three cases. The number of ports that was assigned to each production FCDs for the optimization study ranged from 1 to 10. Figure 36 presents the final results of the automatic optimization for the 2 year forecast. Three scenarios were selected by the software as the optimal solutions.

The number of ports for each FCDs for the best three scenarios over a 2 year forecast was summarized in Table 13. Number of ports for injection FCDs was optimized in Step-3.

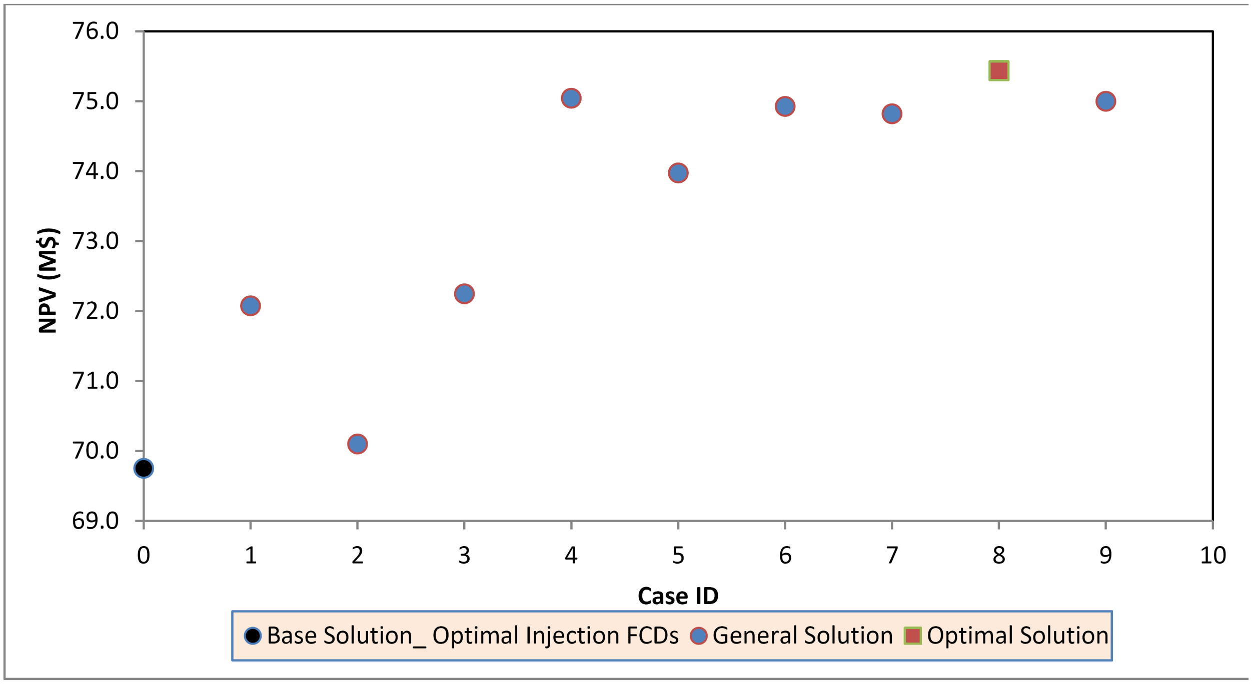



Figure 35—NPV calculation results for all the cases (Optimizing production FCDs)

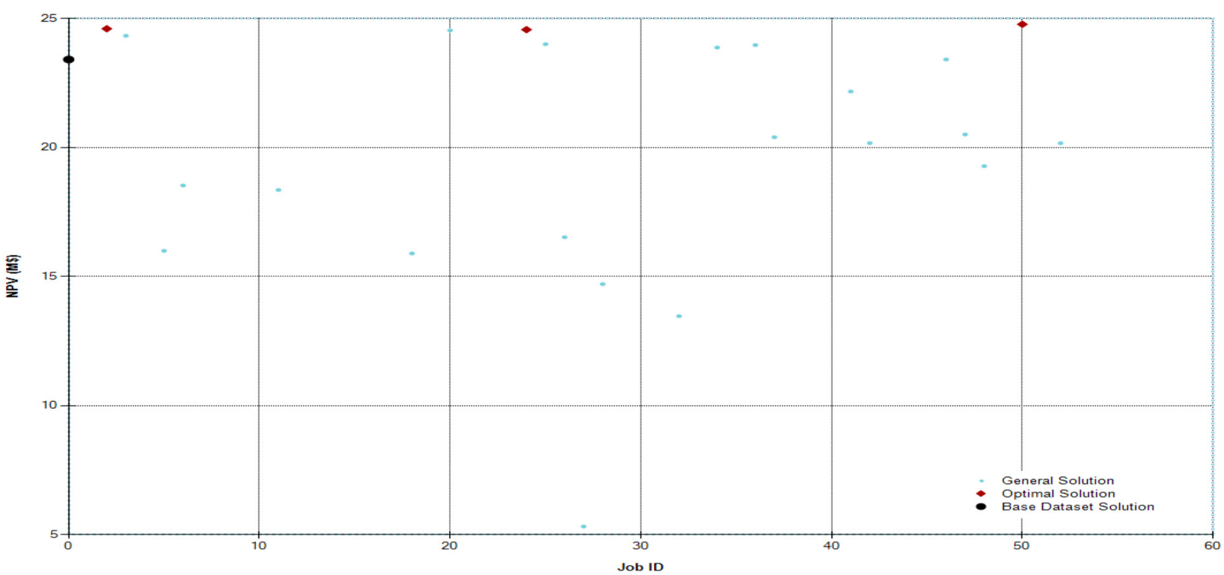



Figure 36—NPV calculations from automatic optimization

The NPV of these scenarios after 6 years of production were compared to the base case (optimal case from Step-3) and the "Best case 1" was determined as the ultimate optimal solution for this SAGD operation. Table 14 presents the increase in NPV at each year by optimizing the number of ports for production FCDs. This scenario includes optimization of both injection and production FCDs and is referred to ultimate optimal solution.

The results of the ultimate optimal scenario (two injection FCDs and four production FCDs) were compared to the case with no FCDs in Figure 37. In summary with applying the proposed workflow the NPV was increased from $31 million to near $76 million over 6 years of production. This is more than 145% increase in the NPV of the project.

Table 13—Optimal number of ports for the best three cases over a 2 year forecast (Optimizing production FCDs)

| Scenario | Ports (Inj. FCD 1) | Ports (Inj. FCD 2) | Ports (Prod. FCD 1) | Ports (Prod. FCD 2) | Ports (Prod. FCD 3) | Ports (Prod. FCD 4) |
|---|---|---|---|---|---|---|
| Base case (Optimal case from step-3) | 32 | 15 | 5 | 5 | 5 | 5 |
| Best case 1 | 32 | 15 | 5 | 10 | 5 | 10 |
| Best case 2 | 32 | 15 | 10 | 10 | 1 | 10 |
| Best case 3 | 32 | 15 | 10 | 5 | 1 | 10 |

Table 14—Summary of variation of NPV with operation year for the base case, case with optimal injection FCDs and the case with optimal injection & production FCDs

| Year | NPV for Base case (No FCDs) (M$) | NPV for optimal case by optimizing injection FCDs (Steps 1 & 2) (M$) | NPV for ultimate Optimal case (Step 3 & 4) (M$) |
|---|---|---|---|
| 1 | 0.4 | 6.7 | 7.7 |
| 2 | 10.2 | 23.4 | 24.8 |
| 3 | 18.7 | 36.2 | 37.9 |
| 4 | 25.5 | 50.6 | 53.7 |
| 5 | 29.5 | 67.2 | 69.1 |
| 6 | 30.9 | 75.4 | 75.9 |

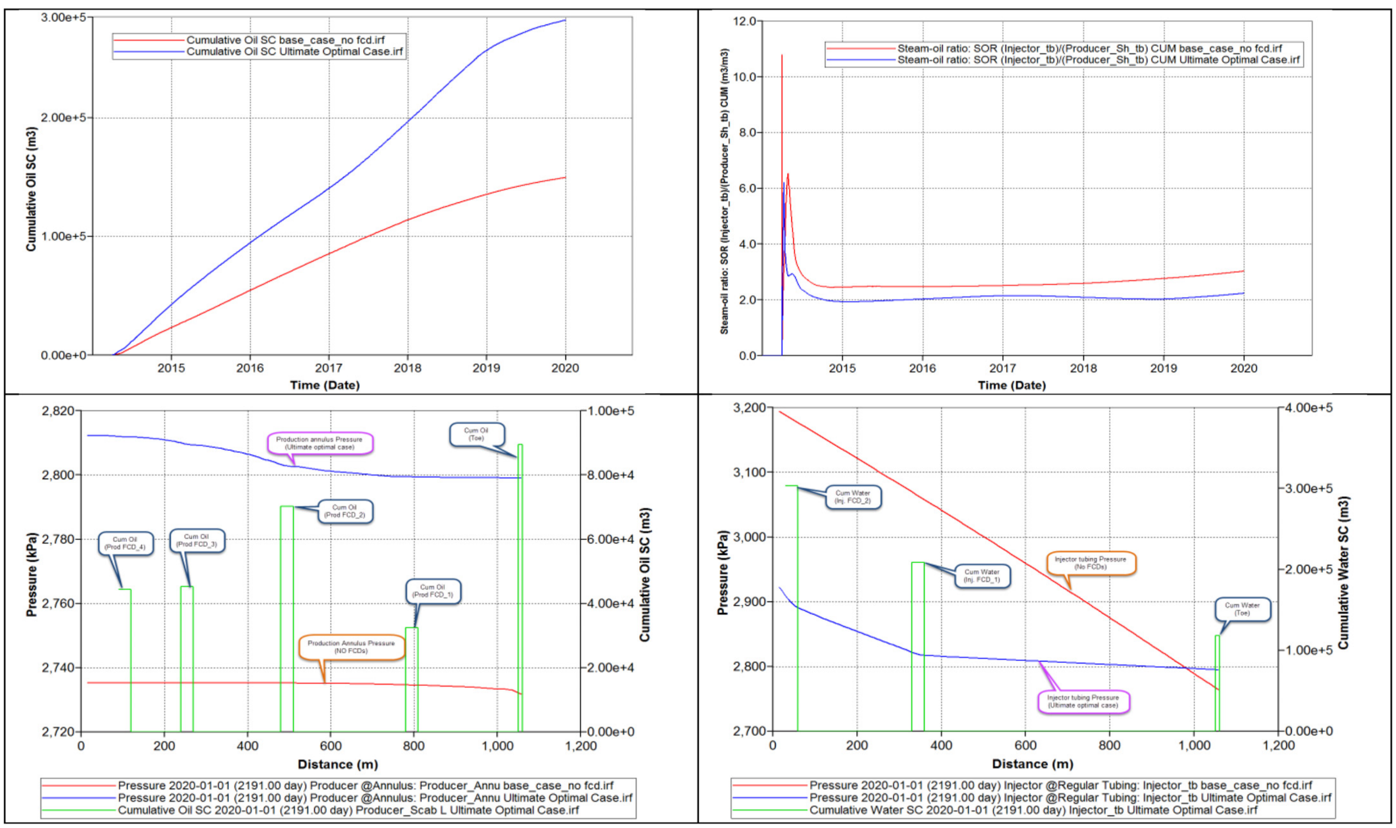



Figure 37—Results of the ultimate optimal case vs. the base case (No FCDS)

## Summary and Conclusion

1- Phase 1 presented a sensitivity study that determined the importance of the Flow Control Devices in SAGD operations. It investigated the effect of location and number of injection & production

FCDs as well as FCD properties. Production and injection FCDs can improve the SAGD performance by enhancing thermal efficiency and preventing steam breakthrough. The injection FCDs, allow for multiple injection points within a single tubing along the horizontal wellbore. The total number of injection FCDs could affect the oil production, water production and SOR in the SAGD process significantly. A customized steam distribution within the reservoir could be achieved by changing the location of injection FCDs. Location of injection FCDs also controls the pressure distribution along the injector and can delay the steam breakthrough. The application of the production FCDs on the productivity of a SAGD operation is not significant compared to the injection FCDs. With production FCDs, a more uniform pressure profile can be achieved along the producer. This could potentially reduce the steam breakthrough tendency. Properties of the FCDs that were investigated were port diameter, total number of ports and discharge coefficient. For the injection FCD, port diameter had the greatest influence over the production data. Discharge coefficient of injection FCD was the least sensitive parameter to most of the defined objective functions. For the production FCDs, total number of ports had a considerable influence on the performance of the operation.

2- Phase 2 presented a workflow for optimizing FCDs based on the NPV of the operation. The workflow underlines the steps for achieving this by coupling wellbore reservoir model and automatic optimization of the FCDs. The optimization phase utilized the findings from Phase 1 (sensitivity study) that specified the impacts of various parameters like location, number and properties of FCDs on a variety of operating parameters such as cumulative oil production, CSOR and pressure profile in the wellbores. The optimization study was designed for maximizing the NPV. Phase 2 concludes that injection FCDs, increased the NPV by 130 % over 6 years of production after optimization. Also the use of production FCDs with injection FCDs could increase the NPV by more than 150 % compared to the case with no FCDs.

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### Nomenclature

| | | |
|---|---|---|
| BHP | = | Bottomhole Pressure |
| DECE | = | Designed Exploration and Controlled Evolution |
| FCD | = | Flow Control Device |
| NPV | = | Net Present Value |
| SAGD | = | Steam Assisted Gravity Drainage |
| SOR | = | Steam Oil Ratio |
| I | = | Investment made to generate the yearly revenue, |
| Ir | = | Discount rate |
| Rny | = | Total annual revenue after deduction of royalties and operative expenditure for each year |
| Nyr | = | Reference year |
| O_(p,ny) | = | Cumulative natural oil production (bbl) |
| P | = | Price of oil (USD/bbl) |
| fr | = | Fraction of gross cash flow as royalties |
| fo | = | Fraction of gross cash flow as expenditures |
| ft | = | Fraction of cash flow as taxes |
| P1 | = | Pressure upstream of choke |
| p3 | = | Pressure at conditions just downstream of the choke throat |

p4 = Pressure at recovered condition downstream of polytropic compression
dc = Orifice diameter
dd = Pipe diameter downstream of the orifice
$\rho$ = Fluid density
Q = Flow rate
d = Port diameter
CD = Discharge coefficient
l = Length of the flow port
f = Friction factor
Ap = Area of the port
Af(in) = Area leading up to the port
Af(out) = Area downstream of the port
Kcor = Correction factor
Kin,Kout = Inlet and the outlet loss coefficient, respectively
NRe = Reynolds number
$\varepsilon$ = Surface roughness
v = Velocity through the ports
$\mu$ = Fluid dynamic viscosity

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