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Steam Assisted Gravity Drainage – New Perspectives on Recovery Mechanisms and Production

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Summary

Steam Assisted Gravity Drainage (SAGD) operations utilize a three-way strategy that targets production from the steam chamber, conductive heating, and infill wells which has led to a strong impact on SAGD performance and recovery factors. As SAGD well pairs mature, approaching what was thought to be the end of production well life, key economic metrics including steam/oil ratios can be observed to trend lower, bitumen production rates can increase or remain steady, recovery factors can exceed 60%, and economic production continues several years longer than originally predicted. Each recovery mechanism is unique contributing to overall production from different portions of the reservoir, accessing bitumen from a larger heated volume created by multiple amalgamated steam chambers of contiguous well pairs on SAGD pads.

A three-way production strategy is particularly effective for challenging reservoirs such as those with extensive top lean zone intervals. The effects of high water saturation and associated steam losses can be mitigated, and a second ramp-up in production can be achieved with low steam-oil ratios, stabilized production and strong economic results.

Introduction

Steam assisted gravity drainage (SAGD) was a young science when commercial operations started up in the early 1990's. SAGD has evolved and grown with over 1200 SAGD well pairs currently producing. Recent availability of post-steam core, residual saturation tool (RST) data, temperature data and 4-D seismic from SAGD operators has provided convincing evidence for new perspectives on bitumen recovery mechanisms which produce impressive recovery factors and production trends.

Success is a result of utilizing a strategy of pad production consisting of many closely-spaced SAGD well pairs which allows for recovery from a large heated volume on the order of km^2 rather than the additive smaller drainage areas representing individual well pairs. The production type curve for the Underground Test Facility SAGD Phase B Pilot from the 1990's (Figure 1) illustrates progressive decline in production rates and increase in the steam/oil ratios at the end of well life expected for individual SAGD well pairs. Although this type curve is impressive, it may not be valid in the newer SAGD pad development scenarios.

Current SAGD operations utilize a three-way production strategy targeting the steam chamber, conductive heating and infill production which has led to a strong impact on SAGD performance and recovery factors. As SAGD well pairs mature, approaching what should be the end of production well life, key economic metrics including the steam/oil ratios can be observed to trend lower, bitumen production rates can increase or remain steady, recovery factors can exceed 60% with documented examples of recovery >75% and economic production continues several years longer than originally predicted.

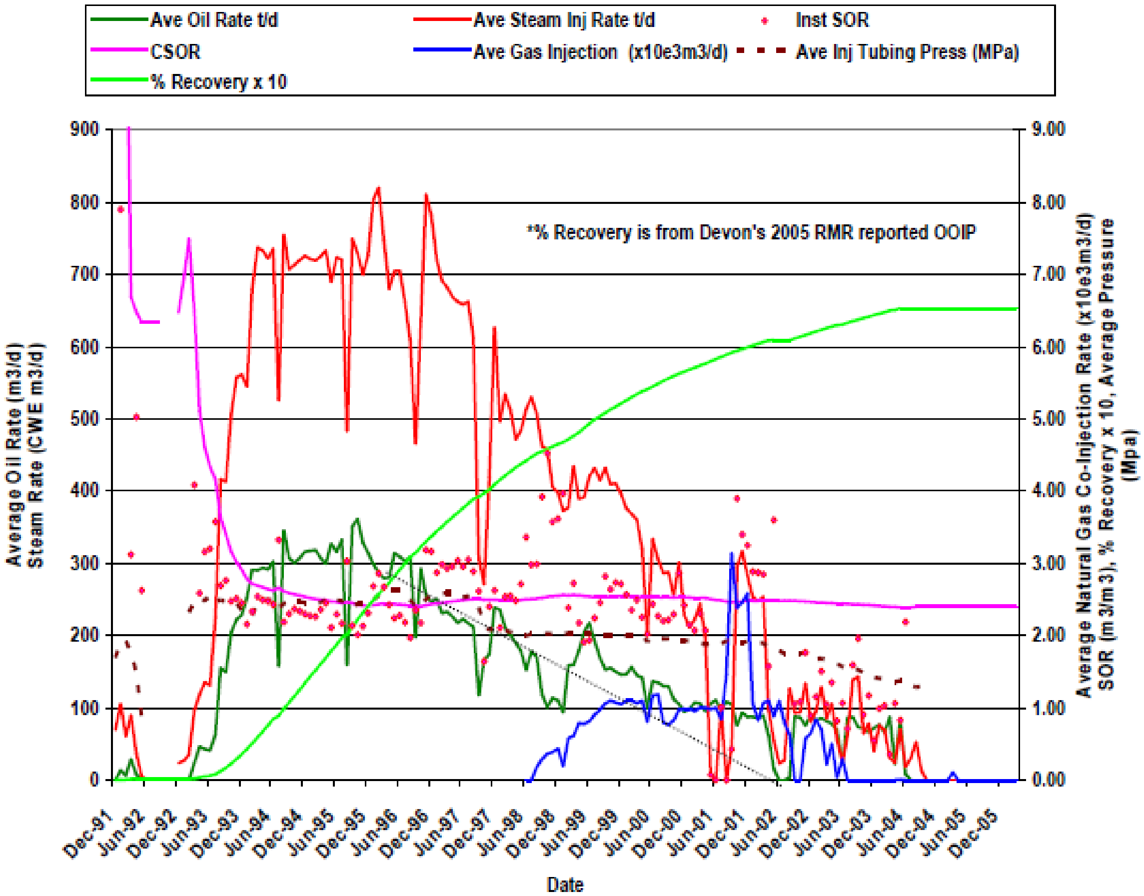

Figure 1. AOSTRA's UTF Phase B Pilot performance graph, 1990's vintage. Cumulative steam/oil ratios on the order of 2.5, balanced steam/water production, and production rates of 1barrel/day/metre are strong accomplishments which led to commercialization of SAGD in Alberta (Application 8623T to AER Cenovus May 2010).

This three-way production strategy is particularly effective for challenging reservoirs with extensive top and middle lean zone intervals. The effects of high water saturation and relatively high steam mobility in water can result in significant steam losses producing high SOR>6 and an associated drop in bitumen rates as the high water-saturation zone is produced. These challenges however can be mitigated. A second ramp-up in production can be achieved with SOR's <3 with increases in production when appropriate operations strategies are implemented. At least 4 years of sustained production rates (from 2010-2014) are demonstrated followed by a further increase in production with the onset of turning on infill wells in 2015 (Figure 2).

Performance results are encouraging, from the perspective of obtaining improved production in challenging reservoirs, as the SAGD well pairs mature. One caveat remains, however, that well pairs (and pads) which are cold will simply not produce. The placement of well pairs within good quality reservoir and associated communication between injector and producer is critical. In most instances, if a conformable steam chamber can be created with a reasonable effective well length, significant recovery factors and production will be achieved due to the combined effects of the three recovery mechanisms.

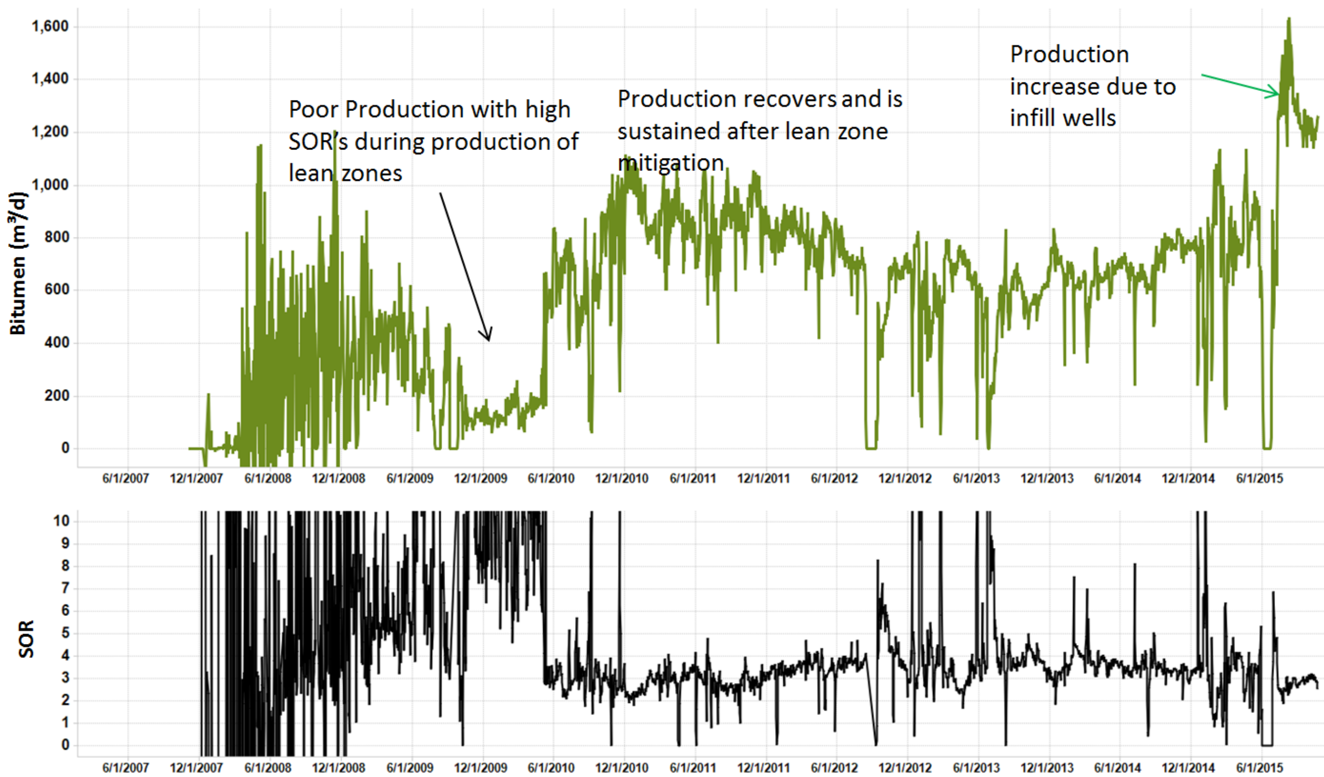

Figure 2. Performance graph of production from a SAGD pad, producing from a challenging reservoir with extensive top lean zone intervals. Impairments can be mitigated and with sustained production increases (second ramp up) after lean zones are produced. Additional production increases are provided by infill wells. (Source: Craig Flowers, pers. corr.).

Theory and Examples

Steam Chamber Production (Classic SAGD)

Significant steam conformance over the majority of the well pairs will provide a peak production rate which will be a function of steam chamber height and effective well length. In the classic SAGD process, emulsion is produced consisting of bitumen and condensing water which flows along the edges of the expanding steam chamber to the underlying production well. Thin but laterally continuous mudstone-dominated inclined heterolithic stratification (I.H.S.) intervals commonly delay steam rise for several years or act as barriers to vertical steam chamber growth for the entire production life (Figure 3). I.H.S. and similar heterogeneities limit vertical steam chamber growth. For all examples of maturing well pads studied, the high recovery factors demonstrated cannot be achieved based on steam chamber production alone. Additional drainage mechanisms exemplified by post-steam core include conductive heating of the bitumen and infill well production.

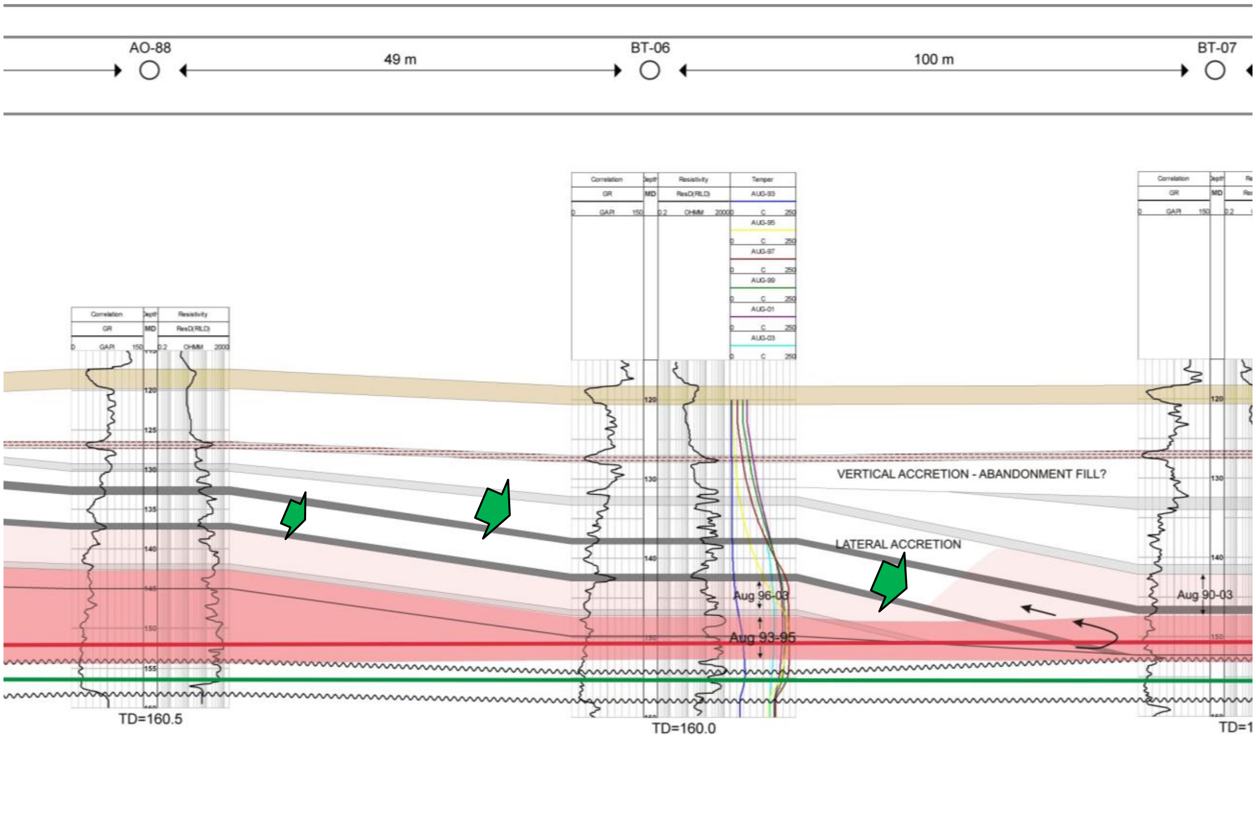

Figure 3. UTF Phase B. Steam rise data from August 1993 to August 2003 is illustrated as mudstone-dominated IHS intervals which delayed steam rise in initial production and continued to act as a barrier to steam from August 1993 to August 2003. The red and green horizontal lines represent the injector and producer wells, respectively. Red and pink shaded intervals indicate where the reservoir achieved steam conditions and associated classic steam chamber production. Green arrows indicate downward flow of conductively heated bitumen from portions of the reservoir not accessed by steam (modified after Strobl 2012).

Conductively Heated Production

Conductive heating occurs above, below and adjacent to the steam chamber, and conductive heating is maximized when the chamber is stalled for extended periods of time at a barrier. In the vertical direction, typical rates of conductive heating are 1.0 to 2.0 m/year to temperatures of 80^{C} to 100^{C} as demonstrated by the observation well in the middle of Figure 3. In post-steam core, conductively heated residual oil saturations vary; 10% to 40% oil saturation by volume is commonly observed where original oil saturations are estimated to range from 65 -75%. A shadow effect is commonly observed immediately above a barrier where we believe bitumen flowing down-slope from upper intervals re-saturates the basal interval. Immediately below the barrier, steam is commonly observed to have a high sweep efficiency resulting in a residual oil saturation of 5-15% compared to original saturations on the order of 75-85% (Figure 4).

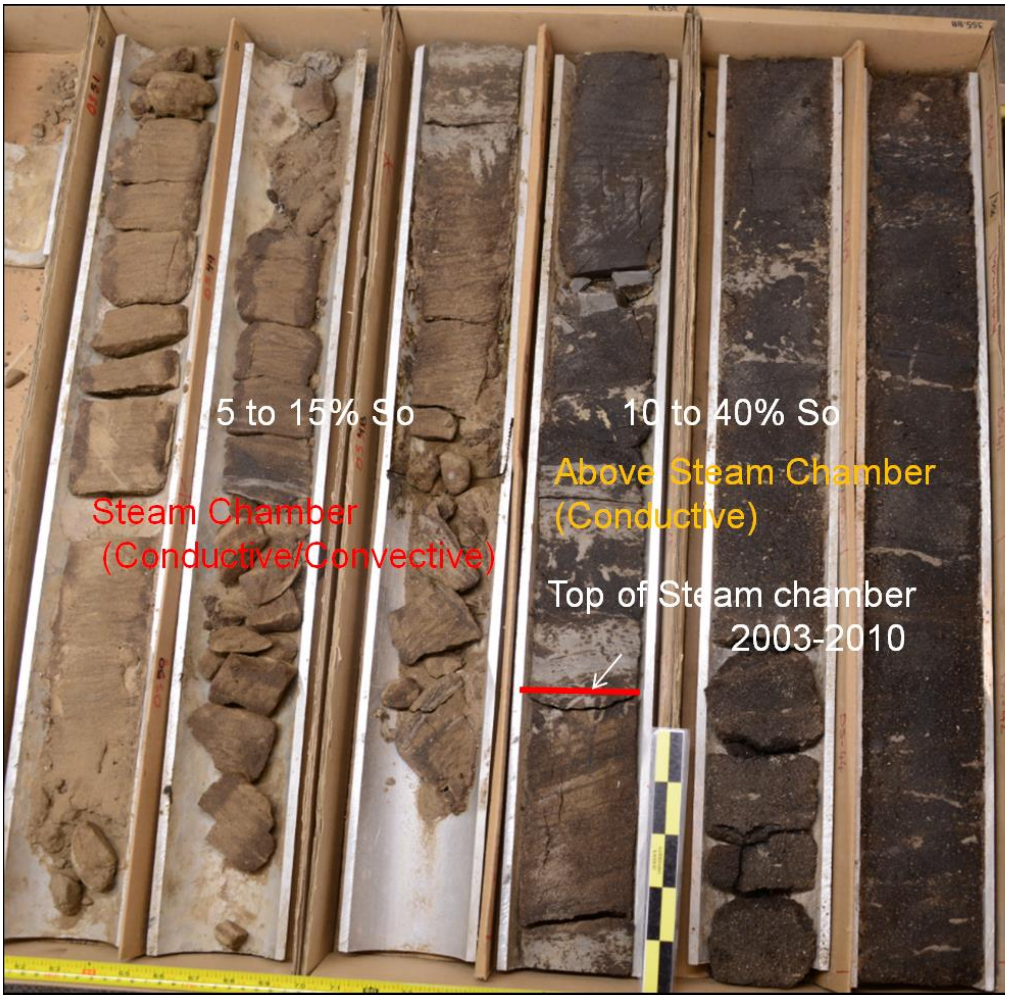

Figure 4. 104/12-16-76-6W4 Cross-bedded oil sands within the steam chamber (tan coloured, low residual oil) and the barrier below the conductively heated portion of the reservoir above the steam chamber in IHS beds (dark coloured, variable oil saturation)

In the post-steam core illustrated in Figure 4, a thin, pervasive mudstone interpreted as a muddy tidal flat Wightman, pers. comm.) separates an estuarine cross bedded sand succession (steam chamber interval) below the mudstone and a sand-dominated I.H.S. succession (conductively heated interval) above the mudstone. This mudstone acts as a vertical barrier to the steam chamber over the entire production history of this well pair (Figure 5). Temperature data from the observation well shows that the conductively heated interval is approximately 12 m thick and reaches temperatures of 80^0C to 100^0C.

Conductively heated production is accelerated after non-condensable gas (NCG) co-injection commences. The production mechanism in the conductively heated I.H.S. is considered to be flow from higher reservoir pressures into lower reservoir pressures in the steam chamber. Higher pressures observed in the I.H.S. are due to reservoir confinement where multiple mudstone beds act as boundaries. Pressures continue to increase with thermal expansion and upward migration of solution gas and co-injected gas into confined conductively heated intervals. Viscosity estimated to be 50 to 100 centipoise at 80^0 C in bitumen saturated sand intervals of the I.H.S. allows flow down-slope to an amalgamated steam chamber. Differences in reservoir pressure between the conductively heated interval and the steam chamber helps to explain why bitumen continues to drain and adds production from the I.H.S. while the steam chamber remains stalled, which accounts for the observed recovery in existing wells.

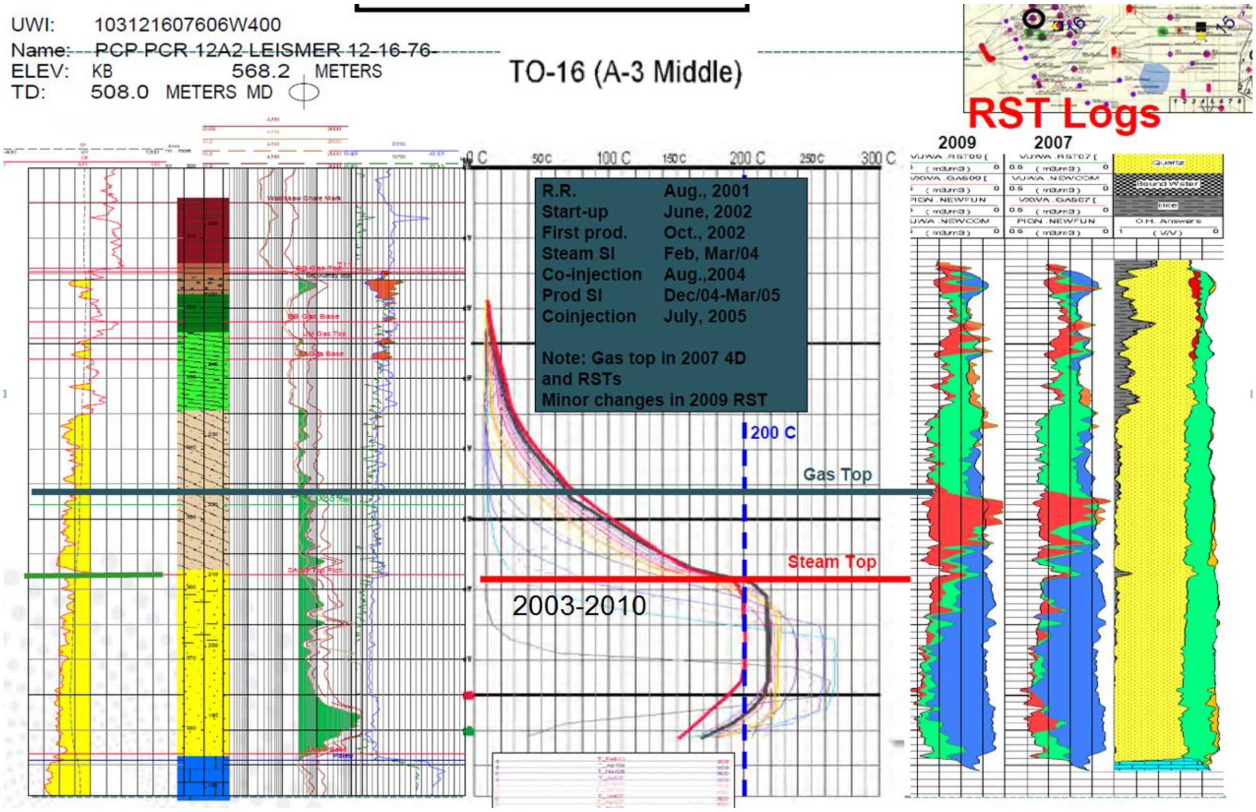

Figure 5. 104/12-16-76-6W4 Temperature curves, RST and representative petrophysical logs. RST logs and core data confirm substantial drainage of I.H.S. beds which did not encounter steam conditions. Approximately 12 m of conductively heated production was achieved with residual oil saturations varying between 10 to 40% within sand beds of the I.H.S. (from Cenovus AER annual report 2011).

In-Fill Wells

In-fill production wells drilled midway between SAGD well pairs access un-drained or partially-drained bitumen from the producer level to the base of the steam chamber. Data from operators indicate potential uplift to the recovery factor on the order of 8% (depending on how recovery is calculated), large incremental production of bitumen with rates of 300-1,800 barrels/day/well, and associated reduction in cumulative steam/oil ratios and associated improvements in economics for the pad.

An example from Cenovus Christina Lake is illustrated in Figure 6 where 103/5-15-76-6W4 is a cored well drilled prior to SAGD production, providing baseline oil saturations prior to SAGD and fitted with temperature sensors to serve as a temperature observation well during production at the infill location. A post-steam cored well 104/5-15-7606W4 represents conditions in the reservoir prior to infill well production. During conventional SAGD, the base of steam chamber remained relatively constant until 2011. Rapid changes are observed however, after the infill well was put on production The base of the steam chamber is observed to drop 8m between 2011 to 2012. This data supports the concept of steam drive and a top down production mechanism of a heavy oil (type) reservoir with significant fluid mobility. Production from infill wells vary, but average rates of 60% of associated SAGD well pair peak rates are observed based on data from multiple operators (Figure 8).

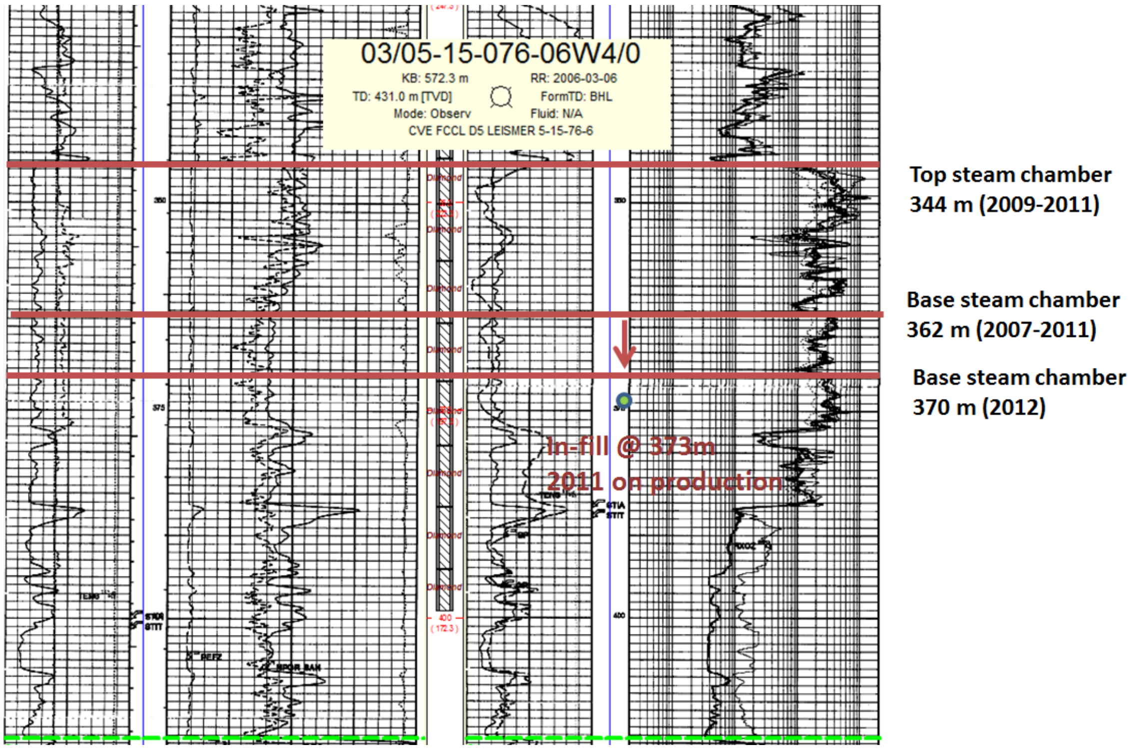

Figure 6. In-fill observation well 03/5-15-76-6W4 providing oil saturations and reservoir data prior to SAGD and used as an observation well to study in-fill production and steam behaviour. Data Source: AER: Cenovus Christina Lake, In-situ Oil Sands Scheme 2010-2011.

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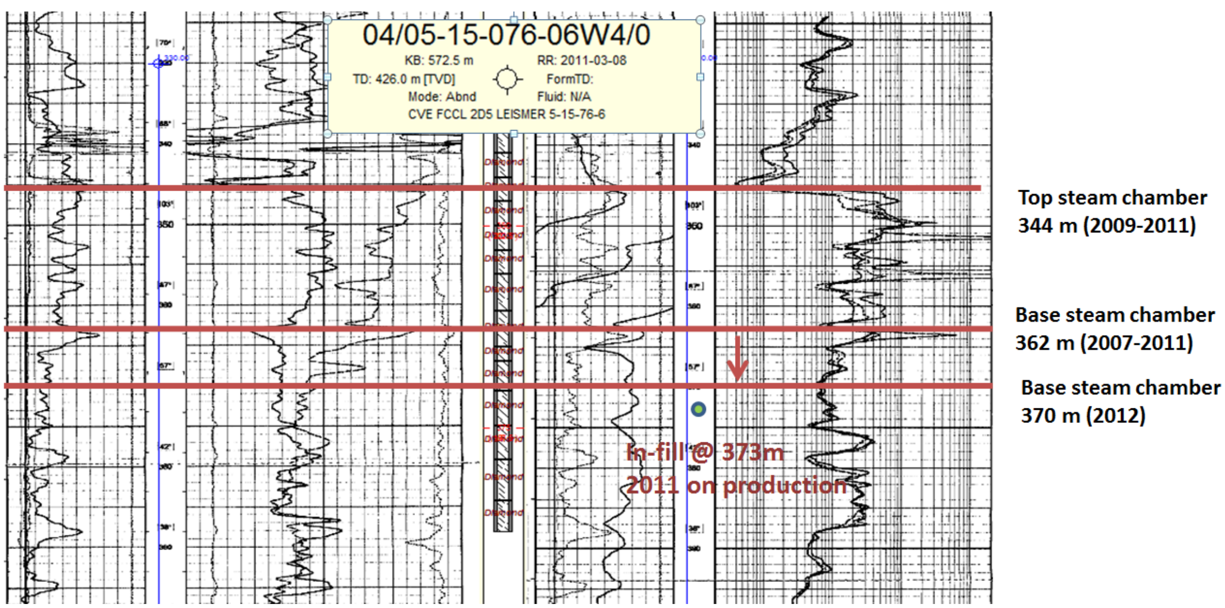

Figure 7. In-fill post-steam 04/5-15-76-6W4 providing data on steam chamber and un-drained portions of the reservoir in the infill location. Data Source: AER: Cenovus Christina Lake, In-situ Oil Sands Scheme 2010-2011.

	Peak Rate SAGD Pair	Peak Rate Infills	Peak Rate Ratio
Suncor Firebag Pad 102N	274	307	1.12
Suncor Firebag Pad 101S	345	323	0.94
Suncor Firebag Pad 102S	222	207	0.93
Nexen Long Lake Pad 7N	191	160	0.84
Connacher Great Divide Pad 102W	78	52	0.66
Cenovus CL Pad B02 (w/oB02-04W,05W)	209	135	0.64
MEG Christina Lake A	131	83	0.63
Suncor Firebag Pad 101N	370	230	0.62
Cenovus Foster Creek Pad D	195	119	0.61
Cenovus Foster Creek Pad Exp/M	108	64	0.59
Cenovus Foster Creek Pad C	180	103	0.57
Cenovus Foster Creek Pad G	164	92	0.56
Cenovus CL Pad B01	262	146	0.56
Cenovus Foster Creek Pad A	177	82	0.46
Cenovus Foster Creek Pad E/K	162	69	0.43
MEG Christina Lake C+D6	229	96	0.42
MEG Christina Lake B+BB+D7	170	67	0.39
Cenovus CL Pad A01+B02-04W,05W	189	73	0.38
Cenovus Foster Creek Pad B/L	133	48	0.36
MEG Christina Lake D	103	35	0.34
ConocoPhillips Surmont Pad 101S	157	47	0.30
Cenovus Foster Creek Pad E24	186	52	0.28
Cenovus Foster Creek Pad F	201	55	0.27
Average including all competitor data	193	115	0.60

Figure 8. Infill production rates and associated peak rates of adjacent well pair production (m^3/d) as of mid-2014 (Source: Craig Flowers, pers. corr.).

Conclusions

Three distinct recovery mechanisms are present in SAGD operations, which are (1) steam chamber (classic SAGD); (2) conductively heated bitumen; and (3) steam drive (heavy oil type) infill production. Bitumen volumes and production life observed from mature SAGD operations cannot be achieved from a steam chamber or classic SAGD mechanism alone.

Each mechanism is unique and each contributes to overall production from the SAGD process on a pad scale, where produced bitumen is accessing reserves from a larger heated volume associated with amalgamated steam chambers and contiguous well pads. Effective operating strategies utilizing these three mechanisms provide reduced steam-oil ratios, stabilized rates, and longer production life. Higher than expected or calculated recovery factors and economics are achieved for both good quality and oil sands reservoirs with significant impairments.

Further studies are recommended to establish criteria which acknowledge individual contributions, and provide optimal timing for infill wells and NCG co-injection in on-going operations given these considerations.

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