Appendix 8

Technical Paper – Advanced Solvent-Additive Processes via Genetic Optimization
Advanced Solvent-Additive Processes via Genetic Optimization

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Introduction

The addition of light hydrocarbon solvents to steam has long been regarded as the simplest and most important potential increase in SAGD performance. Recently, at least two commercial implementations of such processes have begun operation. In the current economic environment, advances with in situ technology are all the more important.

Solvent Addition Goals

The perceived benefits of solvent addition to SAGD include:

- reduced SOR
- increased well productivity
- reduced capital intensity to startup
- increased recovery via reduced SOR
- increased recovery via higher (economic) volumetric sweep

In addition to the above, EnCana has recently indicated that their solvent-assisted process (SAP) allows for greater well spacing than with steam alone.

There are as yet no published analyses of the detailed transport mechanisms for the increased oil rates observed with solvents. In general, solvent vapor accumulates ahead of the steam front, where it mobilizes and drains oil from regions that may be considerably cooler than the steam zone. Thus, the average temperature of the drained volume is much less than for the same recovery by steam, accounting for the SOR improvement. The oil rate increase is qualitatively explained by lower oil phase viscosities in the drainage zone.
Solvent Addition Challenges

The principal challenge of hydrocarbon solvent addition is the cost of solvent retained in the reservoir either dynamically, as a running inventory, or ultimately, after final solvent scavenging. The practical solvent candidates are propane, butane, and pentanes plus; all of these are priced as fuels, with varying premiums over the energy-equivalent light oil or gas price. Table 1 indicates the volume of steam that could be raised by burning one liquid barrel each of propane, butane, and pentane. Equivalents are given on an energy basis as well as an equivalent-cost basis. The latter uses current forward strip pricing and considers solvent premiums relative to natural gas. The table illustrates that rather small solvent retentions must be maintained, if the use of solvents is to improve the cash flow per barrel, relative to steam alone.

Table 1 suggests that there should be a strong preference for the use of propane, as the most cost effective diluent. However, propane tends to actually reduce the oil rate when added to steam, presumably because it is too volatile to condense anywhere near steam temperature and therefore acts more like a non-condensable gas. This illustrates a second important challenge, which is that there is no available theory to guide the choice and dosage of solvent.

This in turn raises the third major challenge in the engineering of solvent addition processes, which is the large number of possible recipes, combined with the poorly understood and hence unpredictable nature of solvent effects. Even though numerical simulation is thought to closely predict the performance change in SAGD with solvent, there are a very large number of possible simulations that could be run. In other words, there are too many choices to fully explore in a reasonable time, especially in an operating environment. There may be a period of years available to polish a scheme design, but inevitably the operation will depart from the plan. The operation must then be adapted to actual history and new realities, and this must be done much more quickly than the original design. Thus the complexity of solvent addition increases the risk of failing to adapt to changing circumstances (e.g., a shortage of the chosen solvent) in a timely and effective manor.

A Selective History

The following is not in any way a review of the extensive literature on solvents for bitumen. Instead it highlights certain previous developments, which have anticipated various aspects of the particular process recipe described below.

N-Solv (Hatch)

Nenninger has described a thermal solvent process, N-Solv, which does not use steam. Instead it uses pure propane vapor, as with the well-known Vapex, but at pressures that are elevated with respect to the saturation pressure of the solvent at initial reservoir pressure. This means that solvent is condensed in order to (slightly) heat the reservoir, as the front expands. Nenninger has shown that the elevated temperatures greatly accelerate drainage rates compared with Vapex, to the point of exceeding SAGD rates.

The most important disadvantage of N-Solv in the context of this paper is the high dynamic retention of solvent that follows from using solvent to raise and maintain the temperature. Heat losses will ensure that condensing conditions will persist in most of the chamber until final blowdown, so that liquid solvent saturations in the depleted zone remain elevated, above the oil phase residual.

Solvent-additive SAGD might be thought of as N-Solv with added steam. Having a steam front behind the solvent condensation front, maintains temperatures in the depleted zone high enough to prevent accumulation of liquid solvent. Furthermore the solvent:oil ratio may be kept low because solvent condensation is not required to heat the reservoir.

SAP (EnCana)

Gupta has pioneered the study and testing of butane addition to SAGD, termed Solvent Assisted Process or SAS. Field tests have been reported at Senlac, Saskatchewan and Christina Lake, Alberta.

Although dynamic retention can be significant when injecting a constant solvent rate, the economic impact is lessened by a shorter pattern life, before final scavenging of the solvent begins.

In SAP field tests, oil rate and hence oil steam ratio increased by more than 30%, at constant steam rate. This response was very close to that predicted by simulation, which is very significant from an engineering viewpoint. It suggests that solvent transport is not a limiting mechanism for the amounts that were injected, and that the physics responsible for this transport are adequately represented in the simulator.

LASER (Imperial Oil)

Leaute and Carey report on the addition of gas condensate, primarily pentanes and hexanes, to the steam in a vertical-well cyclic steam stimulation (CSS) project at Cold Lake. A multi-well pilot, with control wells, was employed to assist with optimization of the dosage and determine retentions. Imperial has been operating 189 wells with the process, called Liquid Addition to Steam for Enhancing Recovery (LASER), on a commercial basis since 2007.

Imperial reports an uplift of 35% on CSS production, using a solvent dosage of 2.4% m³/m³ of steam. The field measured retention is less than 0.02 m³ solvent per m³ of produced oil.

The relevance of a CSS test to SAGD modifications is twofold. In the first place, there is good reason to believe that the basic SAGD mechanism is responsible for the majority of production in the CSS recovery of bitumen. Thus, the effect of solvent additives is probably similar as well. Secondly, the cyclic nature of LASER can be seen as a strategy for optimizing between production rate and retention; each cycle scavenges its own solvent, and can be extended as required.

As in the case of steam, having an injector-producer pair does not rule out cyclic operation, i.e. intermittent steaming.

SAS (Alberta Research Council)

Zhao has made numerical studies of the use of propane with steam. He found that simple addition of propane to the steam was ineffective, resulting in vapor accumulation that was too hot to condense. This acted like a noncondensable gas, resulting in impairment of steam injectivity and oil production relative to the steam-only base case.

Zhao solved this problem by alternating the injection of steam and solvent (called SAS for Steam Alternating Solvent). The startup is the same as SAGD, then after a year or so steam is shut off and the pressure is maintained by injecting propane vapor. Initially oil drainage continues because of the residual heat, and the ability of propane vapor to provide voidage. As the reservoir cools, solvent action becomes increasing important and an N-Solv like phase ensues. When there is not enough heat to sustain drainage with a propane front, propane is replaced by steam and the process repeats.
This appears to be an outstanding concept in terms of SOR reduction, simplicity of concept, and ease of operation and adaptation. Relative to SAGD, Zhao reports a 52% decrease in SOR with an un-optimized process. The one strategic disadvantage of SAS is that propane cannot be used for a year or so, and therefore it has no effect on projects performance during the critical first year. On the other hand, in the second year the project oil production nearly doubles, on the same steam capacity.

Variable Composition

A further recent concept is to use varying solvent compositions with time. See for example, Gupta and Gittins; and Gates and Gutek. In general the idea is to go from heavier to lighter solvents with time. The heavy solvents are used early, because they are most effective at high temperatures and rates. Lighter solvents are used later on. A lighter solvent helps recover the more expensive heavy solvent, and is then easier to recover and less costly to leave behind at the end.

A Complex Problem

The process recipes described above can be considered as members of the class of processes using a SAGD well configuration with arbitrary, time dependant rates for steam and/or one or more solvents. This is a very large field of possibilities (which includes SAGD and Vapex). Suppose we allow 5 different injection rates (one of which is 0) for steam and/or two different solvents, in each quarter of a 5-year pattern life. There are a total of 60 different variables (5x4x3) in the injection schedule, and each can have one of 5 different values. The total number of cases that could be run is then 5^60, which is about 8x10^9. Note this is a simplistic example; in practice we use many more variables, with many more than 5 possible values.

In addition to the truly unimaginable scale of this parameter space, the behavior and performance of the system is highly nonlinear as a function of the inputs. Most solvents display optimum dosages, which may be strongly influenced by the pressure. Both the physical and economic effect of a given solvent will depend on the time it is introduced. 

So on one hand, there are too many steam-solvent possibilities to be adequately surveyed by a shotgun approach. Some kind of intelligent search would seem to be indicated; but this has proven to be a difficult and slow process, for the following reasons:

- Even within a strictly constrained process concept, there are too many different things to try.
- The non-linearities make it very difficult to apply previous lessons to new cases/concepts. What worked in one context may have opposite results when applied to a new situation.
- The mapping from physics to economics, the ultimate objective, applies a further layer of opacity with respect to anticipating the effect of a particular variable. For example, the high cost of solvent retention means that it is easy to increase the oil rate, while simultaneously degrading the economics compared to SAGD.
- We have a poor theoretical understanding of solvent/steam mechanisms, with which to guide our thinking.

Timely adaptation & risk

These issues are formidable enough in a research environment. They are likely to become critical in an operating situation, where time is always of the essence. Operators need to adapt and reoptimize in the face of market conditions, equipment failures, and other changes. Facility capacity must be allocated and scheduled among an optimized number of well pairs, each of which has unique behavior as a result of variations in geology, completion, and past operation.

Thus, complex solvent projects, i.e. with time varying concentration and composition, could bear a higher risk of sub-par economic performance as a result of the reservoir operation being unable to adapt to new facts in a timely manner. This might argue for seeking concepts that have a restricted number of variables, which is the case for the majority of the approaches described above. A fixed recipe with limited adjustments will result in orderly operations, but will be limited in its the potential to be optimally adapted to changing circumstances, in a timely manner.

The Genetic Solution

Laricina has invested significant effort to apply a genetic algorithm (GA) to the solvent additive problem. A GA is a very simple implementation of some of the basic mechanisms of biological evolution. In Laricina's case, the full algorithm is:

1. Create a 'genome' that defines an arbitrary number of variables to be investigated, each with a finite range and specified number (resolution) of possible values. Such a genome can then be encoded into a string of bits (i.e. boolean values). For example, a variable having 4 different values can be encoded with 2 bits. With reference to the above example, to encode 5 values we need 3 bits for each rate variable, so for 60 variables 180 bits are required.
2. Create a means of automatically preparing a valid simulation input file, which reflects the particular values that are encoded in an arbitrary bit string of the correct length (a 'chromosome' in Laricina terminology).
3. Define an objective function for the overall optimization, e.g. minimize supply cost, or maximize project net present value (NPV). Implement this in a program which can read the necessary simulator output, in order to calculate the 'score' for a particular case.
4. Generate an initial population of chromosomes. A chromosome is represented as an array of bits of the required length. In the initial population, each bit is set randomly (to 0 or 1). Laricina has had satisfactory results with an initial population of 100 chromosomes.
5. Take each chromosome, decode it and produce an input file, and run the simulation. Calculate the score and record it against the chromosome that produced it.
6. When the initial population has been run and scored, sort the chromosomes according to their scores.
7. Generate a number of child chromosomes by mating pairs of parents. Two parent chromosomes are mated, in Laricina's case, by randomly choosing the bit value from one or the other parent, for each equivalent position in the child.
8. For each mating, parents are chosen from the sorted population according to a Gaussian probability distribution. This favors the high scorers, but gives the lesser performers some smaller chance of influencing the next generation. This is intended to maintain and exploit diversity in the population.
9. Randomly and infrequently, any given bit in the child may be subjected to mutation, which consists of flipping the bit to its alternate state.
10. Score all of the new children, and add them to the sorted population.
11. Repeat 7-10 for a number of generations.
In biological terms this algorithm is analogous to adaptation within a single species – there is no way of creating new species, i.e. there is no way for the genome definition itself to evolve. However, the case of dogs bred by humans, shows that an impressively broad range of results can be obtained by encouraging the expression of certain variations in the population over others, via the mating of parents which exhibit the desired qualities.

Laricina has implemented this algorithm in the Java language. Most of the code is common to all problems, except that the engineer must of course define the genome and create a master input file, into which values from particular chromosomes may be written, for example by replacing a keyword in the master file. Depending on what is encoded, some intermediate programming might be needed to go from chromosome values to the actual text in the input file.

In the case presented below, a total of about 5000 simulations were run, optimizing on a single genome. These are run on servers with 16 CPU’s. The multithreading features of Java are used to run 16 (say) simulations in parallel, at a time. As each job finishes it is scored and then notifies the control program that a processor has been freed and a new job should be started.

The time required to evolve a good solution is obviously dependant on the time each run takes, so that some effort is warranted in designing and testing the master file to ensure it will run smoothly for a majority of random chromosomes. Similarly the genome should be designed if possible to maximize the probability that a given random chromosome will encode to a technically reasonable process. For a typical 1-hour completion time, 5000 runs with 16 processors requires just under two weeks of elapsed time. In terms of the full study cycle, the engineering and programming setup usually takes somewhat longer than this, before the run can be started.

A genetic study therefore represents a significant investment in engineering, elapsed computing time, and the supplementary skills of economics and programming. In Laricina’s experience, this effort has been very well rewarded, as detailed in the following case study.

Robustness & Reverse Engineering

Reverse engineering is the process of translating the raw output of the GA (the winner), into an operable plan for field production. This is largely unexplored yet but will presumably involve things like;

- averaging injection rates and ratios over finite time periods (“periodization”);
- specifying adjustments for varying pay thickness, etc. among patterns;
- transforming times to recoveries;
- corrections for slow downs or shut in periods, e.g. more steam to replace extra heat losses;
- adjustments to changing markets for fuel and solvents.

Robustness refers to the (in)sensitivity of the predicted economic score, to small or moderate variations in the injection schedule, such as those produced by periodization. A lack of robustness, or in other words economics that are very sensitive to small changes in the process, would tend to indicate that a particular process ‘concept’ depends on a precise confluence of favorable factors and timings. Such a process would likely display similar sensitivity to normal variations in geology, and the ever-changing economic environment.

In the limited cases we have explored so far, we have found the recipes produced by GA to be acceptably robust to simplifications like periodization.

Going forward, effective reverse engineering implies the development of a deep understanding of the “reasons” for success of a given GA-produced recipe, in terms of both physics and economics. In the same way that living things have inspired engineering solutions (e.g. birds and aircraft), we have found there is much to be learned about bitumen recovery by studying the results of our artificially-evolved processes.

SC-SAGD Example - Setup

Genome

A class of processes was defined which consisted of various time periods of injection, with separate rates for each of steam, propane, and pentane, in each period. This class was called Solvent-Cyclic SAGD, or SC-SAGD.

The process variables used in this case and their respective ranges were:

- Number of time periods: 17
- Length of each time period: 10–365 days
- Steam rate: 0–220 m^3/d
- Propane rate: 0–60 m^3/d
- Pentane rate: 0–60 m^3/d
- Pattern spacing: 20–250 m

Rates in all time periods were constrained by a constant, maximum injection pressure, so the value in a given case (chromosome) was not necessarily honored exactly.

Reservoir Description

The case presented assumed a Grand Rapids sandstone from the Germain area, 20 m thick and with a porosity of 34%. Conservative permeabilities of 2 Darcies horizontally and 1 Darcy vertically were used. Reservoir original pressure was 1600 KPa and the temperature was 10C. Oil initial saturation is 75% and residual is 15%.

The oil viscosity vs. temperature function was based on lab data and is essentially the same as an 8’ API Athabasca bitumen. In this and most other respects, this reservoir description is fairly comparable to a McMurray reservoir.

Operating Constraints

A normal twin-well SAGD configuration was assumed, with a producer 1.5 m off bottom and the injector 5 m above that. Injection maximum pressure was 3000 KPa. Minimum bottom hole pressure on production side is 1100 KPa. There was a maximum live steam production rate constraint of 2 m^3/d (reservoir volume).

The remaining values, such as steam and solvent rates, were controlled individually as follows.

Objective Function

The scoring function used in this case was NPV per hectare of land (NPV/ha). The economics for a single well pair were calculated by assuming utility prices for steam and solvents. For example, a unit cost for steam was estimated as the price that a third party would be willing to sell it for from a nearby utility, including amortization of capital, labor, etc.

More recently, and not reported here, we have begun using a more elaborate economics calculation that ‘builds’ a complete project from the single-well forecast. This explicitly accounts for the timing and capital cost of the required facilities and wells. It
also allows for a further dimension of optimization in terms of the project size or reserve life.

**SC-SAGD – Results**

**Raw Output**

Case 4958 was the top scorer at the time this study was terminated. Figure 1 shows the optimized steam and solvent injection rates for this case. These are the raw values and time periods from the genome, as modified by the pressure constraint. Figures 2 and 3, and Table 2 summarize production performance and solvent retention.

The (full) spacing between pairs for 4958 was 40 m, about half of what was previously thought to be optimum SAGD spacing. In future work the minimum spacing will be constrained to a larger, more practical minimum, to allow for survey error and to ensure adequate single-pair reserves for a fully-risked recovery factor.

**Robustness to Periodization**

The raw injection schedule (Figure 1) was modified and simplified by calculating the average rates over fixed periods of approximately 3 months and 1 year. Figure 4 compares the oil rates resulting from these cases with the raw forecast, and Table 2 compares the end-of-life performance.

Note that the genome for this study did not incorporate an efficient solvent scavenging step at the end; we believe the final propane retention could be reduced by at least half if scavenging was implemented. It can be seen that the results were not unduly sensitive to most details of the recipe. One final variation is compared with the other cases. It uses 1 year periodization, but the solvent rates have been roughly doubled in most time periods. Figure 4 and Table 2 compare the technical performance of this case with the others. It was found that the economic performance (NPV) was remarkably insensitive to this change.

These observations suggest that case 4958 is a reasonable basis for a field recovery scheme in similar reservoirs.

**Discussion**

**Features & Advantages**

Table 3 summarizes some of the features of the GA product 4958. Note in the right hand column that the process incorporates a number of the best characteristics of thermal-solvent processes, that have been recommended over the years by the leading workers in the field (see A Selective History, above).

The major "innovations" in 4958 appear to be the use of smaller spacing combined with low thermal intensity (steam rates) after the first year or so. Compared to SAGD, smaller spacing is made feasible by the relatively higher recovery factor, resulting from solvent washing of the residual oil.

The steam rates are low enough that the process more resembles a steam-assisted version of N-Solv, than solvent-assisted SAGD. Figure 5 is a visualization of a snapshot in a particular process (not the one reported here) where steam and propane are being injected. The background color represents propane accumulation in the oil phase. The grey mushroom above the injector is effectively the steam zone, where it is too hot for significant propane to enter the residual oil phase.

The arrows in Figure 5 represent propane fluxes in the gas (magenta) and oil (cyan) phases. To the right of the steam zone, there is a significant temperature gradient down to the condensation front, which is at the right hand side of the frame. This gradient drives a thermal convection cell in the main chamber. The gas velocities are such that an outer streamline in the cell might take a month or so to complete one circuit of the (half) chamber. This does not directly impact heat transfer, but it is fast enough to encourage mixing of light and heavy components, that would otherwise tend to segregate.

Propane is condensing at the upper right, and accumulating with mobilized bitumen at lower right. As the mixture flows to the producer, the reverse temperature gradient in encountered, resulting in propane reflux. These phase changes do have a noticeable effect on local temperatures, but it is still secondary compared to thermal conduction from the steam zone.

Note that the genome description that produced 4958 includes N-Solv like processes as a subclass: zero steam rates were valid at all times. But the result always uses enough steam to keep at least the region around the wells hot. There seems to be at least three advantages to using steam with the solvent:

1) it greatly reduces dynamic retention of liquid propane. With N-Solv, external heat losses must be made up with extra solvent condensation. This maintains significant liquid saturations in the depleted chamber. Steam takes up the thermal load and keeps the solvent as vapor until it gets to the front.

2) it drives convection cells like the one seen in Figure 5, and therefore keeps solution methane mixed with the general chamber volume, instead of blanketing the front. It also allows methane to be vented by producing a small stream of vapor along with the oil.

3) although not modelled in this work, the addition of extra heat should allow for minimal asphaltene deposition in the reservoir, by controlling the solvent dose. (While this means the oil is not upgraded very much, in fact deasphalting is usually uneconomic, because the quality premium does not make up for the volume loss.)

**Engineering Leverage: Evolution vs. Intelligent Design**

The elapsed computer (server) time to produce 4958 was about two weeks. Given an efficient software infrastructure (e.g. a general purpose economics package) and some basic programming skills, the engineering time to set a problem up should not be much longer than this.

Remarkably, this GA result has broadly reproduced and combined some of the best ideas that have arisen in the industry, starting about 15 years ago; and then gone on to produce further improvements. We have found evolution to be vastly superior to intelligent design, at least the kind based on human intelligence.

Genetics does not eliminate the need for engineers, but it does tremendously leverage their talent, and allows them to practice the craft on a higher level. It frees us from the constraints of intuition and experience in the search for innovation. It allows us to manage the risks associated with complexity, non-linearity, and path dependence during the design and operation of high-performance thermal solvent processes.
Conclusion

1. The quest for an optimal combination of steam and solvents is made difficult by the large number of possible combinations of injection rates and compositions, and by the non-linear effect of these inputs on the economic performance.

2. A genetic algorithm (GA) has been implemented in Java, and employed to search for an optimal steam-solvent process, based on a given reservoir description, economic objective, and other constraints such as available solvents.

3. A basic GA on a low-end server has demonstrated performance that is much superior to that of expert human engineers, working to optimize the same type of problem.

4. An important concept that was "invented" by the GA, is to look at steam as a driver of a more or less pure solvent front: a steam-assisted solvent process. Thus the winning solution features very small amounts of steam in later years.

5. Thermal-solvent processes give rise to convection cells in the depleted vapor chamber. These are fast enough to affect the mixing of solvent and solution methane, in a helpful way.

Acknowledgements

The authors wish to thank Laricina Energy Ltd. for the opportunity to perform this work and for permission to publish it.

REFERENCES

Table 1.

Volume of Steam Equivalent to 1 Volume of Solvent

<table>
<thead>
<tr>
<th></th>
<th>Energy Equivalent*</th>
<th>Price Equivalent**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propane</td>
<td>10.6</td>
<td>18</td>
</tr>
<tr>
<td>Butane</td>
<td>11.7</td>
<td>22</td>
</tr>
<tr>
<td>Pentane</td>
<td>12.9</td>
<td>28</td>
</tr>
</tbody>
</table>

*Energy Equivalent is bbls of steam that could be raised by burning 1 bbl of solvent (liq).
**Price Equivalent is bbls of steam that could be raised using the amount of natural gas that could be purchased for the cost of 1 bbl of solvent.

Table 2.

Performance Parameters for the GA-produced process after 7 years, and their sensitivity to periodization and solvent intensity

<table>
<thead>
<tr>
<th></th>
<th>Recovery %OIP</th>
<th>CDOR tonnes/d</th>
<th>CSOR</th>
<th>C3 retention mass%*</th>
<th>C5 retention mass%*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw</td>
<td>89.8</td>
<td>56.0</td>
<td>1.03</td>
<td>4.8</td>
<td>0.4</td>
</tr>
<tr>
<td>90-day periods</td>
<td>79.3</td>
<td>49.4</td>
<td>1.14</td>
<td>3.9</td>
<td>1.0</td>
</tr>
<tr>
<td>1-year periods</td>
<td>76.6</td>
<td>47.6</td>
<td>1.17</td>
<td>3.9</td>
<td>1.0</td>
</tr>
<tr>
<td>~2x solvent</td>
<td>88.4</td>
<td>54.2</td>
<td>1.03</td>
<td>4.8</td>
<td>0.8</td>
</tr>
</tbody>
</table>

* retention = mass of solvent (inj-prod) / mass of oil produced
<table>
<thead>
<tr>
<th><strong>Feature</strong></th>
<th><strong>Advantages</strong></th>
</tr>
</thead>
</table>
| Use of NGL solvents w/steam | • Increased recovery factor from low residual oil saturations  
• Major reduction in CSOR  
• Proportional reductions in emissions and water use |
| Well spacing half of SAGD | • Addresses capital/operating imbalance in current designs  
• High economic sweep (recovery) factors  
• Reduce heat loss exposure time by half  
• Scavenge retained solvent after less time |
| Same initial steam rate as SAGD | • 35% (typ.) increase in initial productivity |
| 75% reduction in steam rate after 1st year | • Increase well count by 75% in the second year, etc. – 2x leverage on steam capacity |
| Most use of butanes+ early | • Maximize early production  
• Minimize initial well count  
• Eliminate SAGD solution gas poisoning  
• Leaves time to recover heavy solvents |
| Use of small amounts of propane late with small steam rates | • Propane replaces steam in most of the chamber and continues drainage at lower temperatures (dramatic CSOR reduction)  
• Steam keeps the near-well region hot enough to cause most propane to be reboiled and recycled within the reservoir |
| Mild cycling of steam, solvent rates | • Reduce average drainage temperature (CSOR) further  
• Minimize solvent retention cost |
| Low-risk extension of SAGD | • Standard wells & equipment, in different proportions  
• Use standard gas processing technology for solvent recovery and recycle  
• Field-proven by EnCana (Senlac, Christina), IOL (Cold Lake) |
| Solvent purity not critical | • Avoid expensive pots & pans and associated op. costs |
Figure 1.
Raw steam and solvent injection schedule, 4958

Figure 2.
Oil phase component mass production rates, 4958 (raw)
Figure 3. SOR and Solvent Retention, 4958 (raw)

![Graph showing SOR and Solvent Retention, 4958 (raw)](image)

Figure 4. Comparison of oil rate forecasts for raw and modified process 4958

![Graph showing Comparison of oil rate forecasts for raw and modified process 4958](image)
Figure 5.
Propane fluxes and accumulation, under co-injection with steam