Manual

Bitumen Thermal EOR Model

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Forward:

' Originality is the art of concealing your source' (F.P. Jones)

A few years ago, I became frustrated that detailed FEA kinetic models of reservoir processes had difficulty modelling hybrid steam and combustion processes. Either the results were nonsensical or the run length was too protracted to be useful. As a result of frustration, I developed a simple way (zone calculations) to model a hybrid process and predict performance parameters that are useful. I also realized that this technique predicted when processes wouldn't work (well) and why. It explains why traditional in situ combustion won't work for most bitumen reservoirs. Initially the calculations were performed by hand, and were protracted and tedious. Since my retirement in 2014, working with my son David, we have computerized the technique and extended the method to model several in situ bitumen EOR processes, herein.

Rich Kerr

1. Background

' There are no eternal facts; there are no absolute truths' (Nietzche)

1.1 Introduction – What is the model?

- The model is a 'partial', mathematical representation of several thermal EOR processes that can recover bitumen.
- The model is 'partial' because no kinetics are included.
- In its simplest form, the model can be considered as a single element in a finite element analysis (FEA) model.
- In its most complex form, the model can be considered as four elements in a FEA model.
- The model predicts performance for a homogeneous reservoir and it is not specific to any well geometry.
- The model predicts useful performance factors, including unit costs, energy use, emissions, water use and other diagnostics (3.3).
- If an existing field project is modelled, heat losses can be determined (3.4).
- The model has some unique features, including a zone analysis for processes with an ISC component (2.1), representations of hybrid processes (4.5) and representations of proprietary process (4.3, 4.5).
- The model issues output WARNINGS when processes may not work and input ALERTS when inputs may not be representative.
- The model is useful for process screening for a reservoir type (E.18), for reservoir screening for a certain process type (3.4)
- This manual is inexpensive, easy to use and fast to run.
- This manual is structured in 4 sections:
    - Section 1 - gives a background overview to prospective model users
    - Section 2 - describes how a zone calculation works and provides key assumptions for the model structure
    - Section 3 - describes input and output of the model
    - Section 4 - describes how the model can be applied to various processes, presents some process outputs and derives some insights from the output examples.

1.2 Users – Who should use this model?

'Art is "I". Science is "we"' (C. Bernard)

- This model can be useful to anyone conducting the following assessments:

  (i) Process screening – the potential performance of EOR process alternatives for a specific reservoir type
  (ii) Reservoir screening – the potential performance of a specific EOR process for various reservoir types
  (iii) Debottlenecking/Optimization – after calibration of an existing EOR project, the impacts of changes in operating conditions (eg. pressure change) or the impacts of process changes (eg. 4.2, SAGP)
  (iv) Troubleshooting – the impacts of reservoir inhomogeneities (eg. lean zones) or change in conditions (eg. heat losses) for and existing EOR project.
  (v) Stability – sustainability and/or attainability for EOR process with an ISC component (eg. 4.4, 4.5)
  (vi) Exploration/Acquisition – what kind of reservoirs to look for?

- In view of the above functionality, the model is useful for engineers (reservoir, project, simulators, operations), technicians (reservoir, project, simulation, operations), management, R&D staff, project analysts, business development and explorationists. The model has a broader use base than detailed FEA simulations.

1.3 Motivations – Why buy this model?

'Learning and teaching are the only routes to job security' (T. Peters)

- This model is quick and flexible and can simulate a wide variety of processes
- The model is actually 15 models of 15 processes.
- The model predicts key performance indicators – cost, ETOR, SOR… (3.3)
- The model will inform the user whether or not the process simulated will work; and ; if not, why not and what remedies are available (3.3)
- The model can simulate complex and unique processes
- The model can simulate and predict the impacts of process changes for operating projects
- The user can use his/her own cost estimates for energy inputs (3.1) and estimates for indirect $C0_2$ emissions (The model can be tailored for individuals or companies expectations
- The model can provide unique insight for users. It can empower users to make good decisions
- The model is a working, debugged system that is inexpensive and user friendly. It has a larger user base than other simulation models.

1.4 Novelty – What is unique about this model?

'We're launching this innovation for the first time' (NYC mayor J. Walker)

- A zone analysis for processes with an ISC component (2.1)
- Predictions of process stability (ie. sustainability) for processes with an ISC component (3.5)
- The ability to easily conduct process screening for a certain reservoir type and/or reservoir screening for a certain process type
- The issuance of output WARNINGS when the process may not work (3.5)
- Provision of remedies to potentially overcome the issues flagged by the WARNING notices (3.5)
- The issuance of input ALERTS (3.3)
- Models of a family of hybrid processes (ISC & steam) that are difficult to model using FEA models (4.5)
- Models of a unique, proprietary family of hybrid processes (Nexen, pat. pend.) combining ISC (O_2) + steam (4.5, SAGDOX)
- Model of a unique, proprietary (Nexen, pat. pend.) ISR process using electricity to generate/reflux steam (4.3)
- The use of the model to optimize/debottleneck an existing EOR project
- The calculations for the ISC component (2.6) have unique features including:
    - (i) Combustion T_c is assumed to be independent of injection gas composition (ie. N_2, O_2, steam). (This has been verified by lab tests.) Knowledge of T_c is sufficient to run the model, without knowing coke/fuel lay down rates.
    - (ii) Combustion heat release is taken as 480 BTU/SCF oxygen for HTO combustion, independent of gas injectant composition, fuel composition (ie. χ in E.1) or combustion product composition (ie. r in E.1)
    - (iii) Fuel consumption is calculated as a bitumen-equivalent at 6MMBTU/bblB (39.84 GJ/M^3B). WARNINGS are issued if there is not (or may not be) enough fuel to sustain HTO combustion (3.3)
- Based on calibration of an existing project, using heat loss as an input variable (3.1), the model can determine field heat losses as a percentage of input energy at the wellhead. (This is similar to history matching for FEA models.) The calibrated heat losses can be used as input to evaluate and optimize potential process alterations.

2. The Model

'The first step to knowledge is to know that we are ignorant' (D. Cecil)

2.1. Zones – What is a zone analysis?

- For the purposes herein, a zone is a reservoir volume where a defined process element takes place (eg. steam condensation), preferably in a steady state process. Zone boundaries are well-defined by process conditions. Fluids flow in/out of the zone. Zones can grow or shrink, depending on process conditions.
- ISC and hybrid processes with an ISC component can be traditionally broken into 3 or 4 zones, depending on water injection to scavenge heat and produce in situ steam. Exhibit 3 shows a block schematic for process groups.
- Starting at the upstream fluid injection site (for steam, air, oxygen or water injection) and finishing downstream at the cold bitumen interface, fluids flow from the wet zone (WZ), to a combustion-swept zone (CSZ), to combustion zone (CZ) and finally to a steam zone (SZ). For a dry process, where water is not injected, the WZ is not present. Under certain conditions, the steam zone is also absent.
- For a point-source injector in a homogeneous reservoir, in 2D, the zone fronts are concentric circles. In 3D, the zone fronts are concentric spheres. In real reservoirs with non point-source injectors, the zone front geometry is much more complex and usually asymmetrical.
- In order from fluid injection (upstream) to cold bitumen interface (downstream), zones (WZ, CSZ, CZ, ECZ, SZ) can be characterized as follows:
  (i) For wet processes, a wet zone (WZ) is formed near the injection site where water has not yet vaporized to produce in situ steam (E.3). Water can be injected separately or it can be the condensed phase of saturated steam, produced by heat losses in the injection well. The leading (downstream) edge of the zone is where water is all vaporized by contacting and extracting heat from the hot reservoir matrix (in the CSZ), produced by downstream combustion (in the CZ). The trailing (upstream) edge of the zone is at the fluid injection site. The WZ grows as water cools the CSZ rock matrix, prior to vaporization. Fluids entering the zone can include water, saturated steam, air or oxygen. Fluids leaving the WZ are steam, air or oxygen.

(ii) A combustion-swept zone (CSZ) is formed directly downstream of the WZ and contains hot reservoir rock and gases (steam, O_2, N_2) with no residual liquids or fuel (coke) (E.3). Created by downstream combustion, the leading (downstream) edge of the zone is at/near the beginning of the combustion front. The trailing (upstream) edge of the zone is the water vaporization front at the WZ leading edge. Upstream fluids, in the zone, are steam, oxygen and/or air. Downstream fluids are superheated steam and hot oxygen and/or air. At the leading edge, the CSZ grows as combustion produces hot rock matrix. At the trailing edge, the CSZ shrinks from WZ growth.

(iii) A combustion zone (CZ) is formed downstream of the CSZ (E.3). The CZ is complex (E.3) and contains several subzones, including:

- a combustion front, where oxygen reacts with 'fuel' to release heat and produce hot combustion gases,
- a pyrolysis zone, where residual bitumen is heated, fractionated and pyrolyzed to produce 'coke' fuel,
- a hot bitumen bank, where residual bitumen is pushed ('bulldozed') by the hot combustion gases. Some bitumen can drain to a production well , and
- a superheated steam zone, where hot combustion gases and steam cool to preheat the reservoir matrix and to vaporize connate water.

Upstream fluids entering the extended CZ are superheated steam and non-condensible oxidant gases (air or oxygen). Downstream fluids leaving the zone are saturated steam and noncondensible flue gases (N_2, CO_2, CO). No liquid water drains from this zone, but bitumen can drain from the zone. The leading (downstream) edge of the CZ is defined as where steam first condenses. The trailing (upstream) edge of the CZ is the start (onset) of the combustion front. The CZ grows at the leading edge as steam condensation moves forward into the SZ. The CZ shrinks at the trailing edge as the combustion front moves forward.

- Under certain conditions a steam zone (SZ) is formed downstream of the CZ, where steam condenses to supply latent heat (and sensible heat) and hot combustion gases (N_2, CO_2, CO) supply sensible heat to/near the bitumen interface and the cold, virgin reservoir (E.3). For steam processes and steam + oxygen hybrids, the SZ temperature is close to the saturated steam T_s at the trailing edge of the SZ. If steam is diluted with noncondensible gases, condensation follows a dew point curve, with T dropping as noncondensible gas concentration increases. Eventually, the steam + nc gas mixture is assumed removed as vent gas at T_v ($T_v<T_s$). Heat provided to the SZ is a combinaction of latent heat from steam condensation and sensible heat when gases cool from T_s to T_v.

Condensed water from steam and some connate water (Siw-Srw) drain from the zone and are collected in a production well. Some heated bitumen (Sib-Srb) is also produced at/near T_s. The leading (downstream) edge of the SZ is at the cold bitumen interface. The trailing (upstream) edge of the SZ is where steam first condenses at T_s. The leading edge of the SZ grows as the heated zone penetrates the reservoir. The trailing edge of the SZ shrinks as the steam condensation front moves forward.

- If the combustion zone grows at a faster rate than the SZ (R, <1), the CZ will overrun the SZ and form an <u>extended CZ (ECZ)</u> with blended features of both zones (E.3). Heat for ECZ growth is provided both from steam condensation and combustion. But, steam condensation cannot be segregated, spatially from the CZ. The downstream edge of the zone is the cold bitumen interface, where heat transfer may be dominated by hot noncondensible gas cooling, not by steam condensation. (This may be undesirable (2.2)).
- Each of these zones contains defined process steps with defined, measurable boundary points. The zones may be different sizes (volumes) and grow at different rates. Steady-state (constant, equal growth rates) is not necessary for stability.
- The choice of zone boundaries, as defined herein, allows for simple energy and material balance calculations for incremental zone growth elements (2.6).
- Assuming that hot gases from the combustion zone are the sole source of heat for the steam zone, the relative growth rates for the CZ and the SZ can be calculated.
- An instability is created when the CZ growth rate exceeds the SZ growth rate. This is undesirable because the heat transfer to the cold bitumen interface may no longer be dominated by steam condensation (2.2).
- Another instability is created when the growth rate of the WZ exceeds the growth rate of the CSZ. If so, the WZ will encroach into the CZ and HTO can revert to LTO or super-wet combustion. Super-wet combustion is undesirable because it leaves behind unburned fuel (coke) and it accelerates the CZ growth rates to increase the risk of SZ instability. This risk is exacerbated by the potential of water channeling (2.2)
- Dry ISC, most wet ISC processes and some hybrid processes, have unstable steam zones and process performance must be analysed using ECZ analysis (E.3). Processes using ECZ's are expected to have reduced productivity compared with processes with stable SZ's. Output WARNINGS (3.5) can flag these conditions and other factors.

2.2 Stability – Why is zone stability important?

'Everyone is a genius at least once a year' (G.C. Lichtenberg)

- For processes with a combustion component and multiple process zones (ie. processes III to XIV, inclusive), integrity of the zones is an important factor. Steam heat transfer at the leading edge of the process is necessary for good productivity. A healthy combustion zone is necessary to maintain good heat release by HTO oxidation.
- When compared to heat transfer by hot combustion gases, condensing steam heat transfer is much more effective and faster. For example, if the SZ is near 200°C at the bitumen interface, the heat available from cooling noncondensible gases from 500 to 200°C is about 16 BTU/SCF. The same volume of saturated steam at 200°C contains 39 BTU/SCF (E.37) of latent heat, more than double the energy content of noncondensible gases.
- Also, when steam condenses it produces a transient low pressure that draws in more steam – heat pump, without the plumbing. When hot noncondensible gases cool, near the bitumen interface, to deliver heat, the residual gas is a good insulator. If it is not quickly removed, the gas can retard further heat transfer. The heat conductivity of noncondensible gas is about 0.31m W/cmK. The heat conductivity of liquid water (from condensed steam) is about 6.8m W/cmK – a factor of more than 20 times better.
- Heat transfer rates at/near the bitumen interface are also proportional to the effective contact area between bitumen and the heat transfer fluid (steam or gas). For lighter oils, with some in situ mobility, especially with pressure gradients, the effective oil/gas interface area can be significantly enhanced by gas fingering. The immobility of bitumen creates sharp interfaces with little fingering.
- Thus, the expectation for the bitumen interface is that steam condensation heat transfer will be much more effective than noncondensible gas heat transfer, by an order of magnitude or more. Preservation of a healthy steam zone is important for good productivity.
- Physical combustion-tube tests do not model the SZ or the bitumen interface, because of preheat requirements to attain gas injectivity. Other 3D models are also preheated. (However, lab combustion tests are good predictors of T_c and fuel lay-down rates.)
- The stability of the CZ is also important for wet processes, where water is injected. If the WZ grows faster than the CSZ, the WZ can overtake the combustion front and dE.stabilize combustion, causing HTO to revert to LTO, loss of ignition or reversion to superwet combustion – all undesirable outcomes.

- Depending on geometry and reservoir inhomogeneities, the WZ can become unstable if water channels/fingers to the combustion zone or to the production well(s). To account for this additional risk, the growth rate of the CSZ should be a multiple of the growth rate of the WZ. This multiple (safety) factor can be dependent on well geometry and actual reservoir homogeneity.

2.3 Performance – What will the model do?

'If you don't recognize that you got what you set out to get, then you didn't get it' (C. Ferguson)

- The model predicts performance, diagnostic and risk factors for several (15) process types. (E.6)
- The model predicts unit cost performance ($/bbl or $/m^3 bitumen) based on input (or default) unit cost data. The user can input his/her own cost data.
- The model predicts energy use for all processes. ETOR (MMBTU/bblB or GJ/m^{3}B) is an energy factor that allows energy performance comparisons between processes. ETOR is based on total energy input at the wellhead.
- The model also calculates other key diagnostic factors – SOR, PWOR, WRR, MUW, T_s, µs, CO_2 emissions, R_1 and R_2 (stability factors), oxygen/air use, fuel use, vent gas production and vent gas steam losses, depending on the process modelled (E.23).
- The model also diagnoses input values and flags a set of input ALERTS (3.3):(E.22)
    - ALERT 1 – there is no SZ
    - ALERT 2 – heat loss ≥ heat input
    - ALERT 3 – excessive liquid saturation
    - ALERT 4 – gas void
    - ALERT 5 – excessive Srw
- Another unique feature is that the model predicts when/why the process won't work or when performance has some significant risks by flagging output WARNINGS (3.5):(E.22)
    - WARNING 1 – the SZ is unstable
    - WARNING 2 – the CZ is unstable
    - WARNING 3 – there is not enough fuel
    - WARNING 4 – there may not be enough fuel
    - WARNING 5 – fluids may leak in/out process zone
    - WARNING 6 – bitumen productivity may be poor
    - WARNING 7 – the fuel is too light
- The model defines 2 stability factors for zone growth rates. R_1 is the ratio of SZ/CZ growth rates. R_2 is the ratio of CSZ/WZ growth rates (see 2.6). R_1 and R_2 are defined so that 'bigger is better'. Stability increases as R_1 and R_2 increase.
- The R_1 factor ($R_1 \leq 1$) automatically triggers a transition from a zone model containing separate CZ and SZ to a model with no SZ and an extended CZ (ECZ) (see E.2). The analysis of the process is based on an ECZ, without a segregated SZ.

- Using heat loss as an input value, the model allows for calibration (history matching of existing project operation). This can be considered as an on-line estimate of heat losses (heat loss is a combination of heat lost to zones outside of the reservoir and to non-productive zones inside the reservoir).
- If lean zones or other inhomogeneities are considered as the total reservoir type for the model, the impact of such zones can be predicted.
- The model can balance the stability of ISC+steam hybrid processes (types VII, VIII, IX, X, in E.6)
- The model will evaluate process performance for a fixed-reservoir type – ie process screening (E.22)
- The model will also evaluate different reservoir types for a specific process – ie reservoir screening (eg E.16)

2.4 Limitations – What won't the model do?

'*The art of being wise is knowing what to overlook' (W. James)*

A. All Processes Modelled

- The model will not predict performance vs time. There are no kinetic limitations in the model. [However, the model will issue productivity WARNINGS (3.5)]
- The model will not predict absolute productivity (eg. bblB/d). [But, it will predict production per unit energy injected.]
- The model does not predict heat losses. [But, heat loss estimates (inputs) can calibrate operating projects. (3.4)]
- The model will not accommodate fluid losses/fluid ingress to/from the process. The processes are assumed to be confined. [But, WARNINGS of fluid loss risk are issued and remedies are suggested.]
- The model is generic and is not tied to specific well geometries.
- The model is also not tied to specific recovery mechanisms. [However, the assumption of low pressure gradients (2.5) may imply that gravity drainage is a key mechanism.]
- The model is based on bitumen, with no in situ mobility. [However, it may be applied to heavy/medium oils where gravity drainage is an important mechanism. Some WARNINGS (eg. R_1<1) may not be important for heavy oil reservoirs.]
- The model predicts performance for mature processes. It does not predict start-up or wind-down (non-steady-state) performance. [But, some later life performance can be simulated by increasing heat loss inputs (3.1)]
- The model will not accommodate limited shale barriers, lean zones, bottom/top water, mudstones…..etc. [However, if these zones (eg. lean zones) are considered as a full homogeneous zone, the model can predict incremental performance impacts of such zones.]
- The model cannot predict sweep efficiency or ultimate recovery. [But, it does predict recovery within the swept zones.]

B. Processes with an ISC component

- The model assumes that vent gas is removed separately and efficiently at a temperature T_v, usually less than T_s. The model is not strictly valid if vent gas is removed with produced liquids (eg. THAI) or if vent gas is retained in the reservoir and impedes heat transfer. [see 4.4 for THAI discussion]

- The model will still run if there is insufficient fuel. [But, a WARNING is triggered].
- ISC oxidant gas is oxygen or air. No enriched air (EAir) is considered. [But, an estimate of EAir performance can be obtained as a linear interpolation of air and oxygen performance.]
- For processes with an ISC component, the model calculations will automatically revert to an ECZ scheme (E.2) if R_1<1. A 'snapshot' of transient performance with a 'temporary' SZ is not available.
- The model predicts snapshot performance for ISC processes with water injection, even if water injection exceeds it stability limits (ie. R_2<2). [But, a WARNING of instability will be issued by the model.]

C. <u>Other Processes</u>

- The model does not explicitly include non-thermal process elements (eg. solvents). [But, the performance of non-condensible gas additives (eg. SAGD) can be modelled as a reduction in heat losses (4.2)]. Solvent EOR may be included in future model updates?
- The model doesn't include potential electric + steam (except for ISR), electric + ISC, electric + steam + combustion, or steam + solvent hybrid processes. [But, these alternatives may be included in future model updates?]

2.5 Assumptions – What are the key assumptions?

'A skeptic is a person who would ask God for his ID card' (E. A. Shoatt)

A. Reservoir

- Homogeneous reservoir, no barriers, no shale streaks, no lean zones, no mudstone zones, no bottom/top water
- No initial gas saturation, no solution gas
- Contained process zone, no fluid leaks in/out of zone.

B. Process (general)

- No calculated heat losses, unless explicitly assumed as input
- Homogeneous, constant process P, no significant pressure gradients (may imply that gravity drainage is a key production mechanism?)
- Instant production of heated bitumen that is available for production, no kinetic or flow path limitations
- All energy cost inputs (steam, oxygen, air, electricity) are at a well head location.

C. Steam EOR (4.2)

- No subcool for produced fluids (bitumen + water). Produced fluids are assumed to be at T_S.
- For steam, heat losses are separated into 3 terms/components
  - Steam Qwh, at wellhead
  - Steam Qsf, at sandface
  - Heat losses (L_R) in the reservoir

Make up water (MUW) is calculated as SOR-PWORx.9, assuming a 90% yield from water treatment to produce BFW. (note, Qsf includes losses at wh)

D. Dry ISC (4.4)

- Simple combustion stoichiometry (E.1), no sulphur compounds, no hydrogen or H_2S produced. There is no oxygen in the vent gas. All oxygen is consumed by HTO combustion.
- Good autoignition to HTO combustion. No LTO.

- Combustion heat release is 480 BTU/SCF oxygen (17884.7 KJ/m^3), independent of fuel type, χ, r, Ø, Srb, Sib, Srw, Siw, rock type, oxidant gas, or steam content of injected gases (for Hybrid processes or wet ISC).

- In an oxidizing environment like the earth's atmosphere, it is appropriate to categorize fuels based on their heat release during combustion (BTU/lb fuel). In a reducing environment like a hydrocarbon reservoir, it is appropriate to focus on specific oxygen heat release (BTU/SCF oxygen) during combustion. In earth's atmosphere, the fuel is costly and oxygen is 'free'. In a reservoir, the oxygen is costly and the fuel (consumed by ISC) is 'free'.

- Exhibit 36 shows specific oxygen heat releases for various fuel types that may be combusted during the ISC process, based on ultimate (ash-free) analysis of the fuel and measured heats of combustion (HHV) for complete combustion. The assumption of 480 BTU/SCF oxygen is appropriate for bitumens, heavy oils and/or coke/pitch that might be formed and combusted during the ISC process. The combustion of sulfur components will lower specific oxygen heat releases; the combustion of light fuels will increase the values.

- Bitumen – equivalent fuel value = 6 MMBTU/bbl (39.84 GJ/m^3B)
- The oxidant gas is compressed (dry)air or oxygen gas (no EAir)
- Any CO produced by combustion (E.1) is assumed to be produced in the vent gas. The water-gas-shift reaction ($CO + H_2O \rightarrow CO_2 + H_2$ + heat) is assumed not to occur. Vent gas emissions include CO as a CO_2-equivalent.
- Process geometry (well locations) is assumed such that all nc gas produced or injected is vented (ie. no gas build up to inhibit injectivity). Vent gas is produced separately from liquids and it is saturated with steam at T_v.
- Combustion Tc (preferably measured in a lab combustion test) is assumed independent of P or oxidant gas composition (demonstrated in lab tests). All bitumen in the CZ is heated to T_c and is either produced as hot bitumen or consumed as a fuel. Fuel consumption is estimated as a bitumen-equivalent fuel volume. There is no provision to account for upgraded bitumen nor for cracked pyrolysis gas production (except for χ in E.1).
- Heat losses to the reservoir (or outside the reservoir) (ie L_R) are an input value as a fraction of input heat at the well head. Heat loss fractions (L_R) are applied equally to the CZ and the SZ.
- There is no allowance for CO_2 (or other gases) dissolution into reservoir or production fluids. All CO_2 is produced in the vent gas. Gases are assumed to be well-mixed in all zones, with no nc gas segregation/removal, except in vent gas.
- For residual (connate) water (Srw) entering the CZ from the SZ, it is only necessary to supply latent heat at T_s to produce steam. The steam produced is swept (with combustion gases) back into the SZ at T_s.
- Liquids produced from the SZ or the ECZ (bitumen + water) are assumed produced at an average T of $T_{s,}$ even though there may be a temperature gradient (dew point curve from T_s to T_v) in the SZ due to noncondensible gas dilution. No reflux steam is produced using heat from hot CZ bitumen draining to the production well (this appears to be negligible, even without heat losses prior to drainage.
- If R_1<1, the CZ no longer exists and the CZ and SZ are replaced with an ECZ (2.2) that includes interactions and heat transfer at the cold bitumen interface. Liquids produced from the ECZ are produced at T_s for water and for bitumen, even though there is a temperature gradient in the zone. Assuming produced liquids are mixed as they drain to a production well, they will be at the same temperature (Ts).
- Zone description (WZ, CSZ, CZ, SZ, ECZ) is useful and fruitful.

E. Wet ISC (4.4)

- All assumptions from Dry ISC apply to Wet ISC.
- Zone description for Wet ISC adds a wet zone (WZ) upstream of the Dry ISC zones (E.3). A healthy CSZ is necessary for stability, otherwise the CZ will be quenched by water breakthrough. R_2 (CSZ/WZ growth rate ratio) is used as a measure of CSZ stability. As R_2 increases, stability increases.
- Combustion T_c is assumed independent of steam content in injectant gases. (Steam is produced by water injection scavenging heat from the CSZ). This has been demonstrated in lab combustion tests.
- All water injection passes through the CSZ, CZ and SZ as steam. Water is totally vaporized. There is no channeling, fingering or bypassing.
- No heat losses are applied to the CSZ for the R_2 stability factor calculation. Any potential heat loss is assumed covered by the safety margin for R_2 targets (ie. $R_2 \geq 2$).

F. Hybrid (ISC+steam) Processes (4.5)

- All assumptions for Dry ISC and steam EOR above apply.
- If the hybrid includes a wet ISC component, the assumptions for wet ISC also apply.
- All steam injection passes through the (WZ), CSZ, CZ and SZ. Any condensate in the injected steam is totally vaporized, by scavenging heat from the CSZ, without affecting energy demands in the CZ and/or SZ.
- Reservoir heat losses (L_R) are applied proportionately to the SZ and the CZ.
- There is sufficient steam-swept zone to support combustion for $R_1 \geq 1$.
- Similarly, for wet ISC hybrids, there is sufficient CSZ to support water vaporization, at least temporarily, even if $R_2 \leq 2$.

G. The ISR process (4.3)

- ISR is a 'special' EEOR process where electric resistance heaters in the horizontal well bore are used to reflux steam. Steam is used as a heat transfer fluid (E.15). No steam is injected from surface boilers.
- From the standpoint of the interior of the reservoir, the process is similar to steam EOR with many of the steam EOR assumptions, as above.
- Conversion of electricity to heat in the resistance heaters is assumed to be without losses.

- There are no energy losses in the vertical section of the well bore.
- Heat losses to the reservoir (L_R) are treated as a single input.
- No fouling, scaling on the resistance heaters to seriously inhibit heat transfer.
- No productivity losses from complex flow patterns around the production well (4.3).
- MakE.up water (MUW) is calculated as bitumen voidage replacement (as steam) less any water produced from connate water (Siw-Srw). A negative MUW = water surplus. No treatment losses are assumed.

H. <u>EEOR Processes (4.6)</u>

- Electricity costs are at the wellhead.
- Produced fluids are at T_s (sat.steam T at process P).
- No heat/radiation losses in the vertical section of the well bore.
- EEOR process heat losses are separated/reflected in 3 factors
    - Conversion loss (electricity to EM radiation)
    - Loss to areas outside the pay zone (eg. over/under burden)
    - Loss to inside the pay zone (eg. areas that are not productive)
- All water leaving the growth element (S_{iw}-S_{rw}) is vaporized to steam.
- All water leaving the growth element is produced as water.

2.6 Method – How are the calculations performed?

'Logic is the art of going wrong with confidence' (J. W. Krutch)

- The model relies on published algorithms for key data, including rock matrix enthalpy (separate algorithms for sandstone and carbonate matrices), steam/water properties (enthalpy, latent heat, sensible heat, saturate T_s, P_s), bitumen enthalpy and noncondensible gas enthalpy (N_2, Co_2, CO).
- Combustion stoichiometry is based on simple, HTO combustion (E.1) with no oxygen breakthrough, autoignition and no sulphur gases (no SO_2, H_2S…etc.) User inputs include χ (the atomic H/C ratio of fuel), r (the fraction of carbon oxidized to CO), and T_c (the reservoir, steady-state combustion T).
- If we model a process containing all 4 process zones (WZ, CSZ, CZ, SZ) most of the calculation steps will be similar to other processes. Wet ISC (Air) is the example chosen. The calculation proceeds as follows:
    - (i) <u>CZ heat demand</u> is the first step. For a $1m^3$ growth element at the leading edge of the CZ, the rock matrix and the residual bitumen is heated from T_s (the temperature where steam is first condensed, at the CZ leading edge or the SZ trailing edge (E.2)) to T_c (the combustion T). The residual connate water (S_{rw}) in the growth element need only be supplied with latent heat (at T_s) to vaporize the water. The steam produced is swept with the CZ gases back into the SZ. The energy required to supply this heat (rock+bitumen+water) is calculated using enthalpy algorithms for each component. Total heat demand is increased to include heat losses from the zone. At this point, T_s is an unknown value.
    - (ii) <u>CZ heat supply</u> is the second step, for the $1m^3$ growth element of the CZ. Oxygen (or oxygen in air) is assumed to provide 480 MMBTU/SCF oxygen of total heat supply. The oxygen supply is calculated to satisfy the total heat demand above (i). Combustion gas volumes are calculated assuming stoichiometry as in E.1 and input values for χ and r. Steam production in the CZ, per m^3 of growth, is calculated as the sum of steam produced by combustion, steam produced by vaporization of residual connate water, steam injected (zero for this example) and steam produced in the WZ+CSZ by vaporization of injected water by scavenging heat in the CSZ. Using the combustion stoichiometry in E.1, the composition of gases produced by combustion is calculated at the CZ leading edge. The partial pressure of steam is also calculated. At this point, T_s is still an unknown value.

(iii) Calculation of Ts (the steam dewpoint) is the third step. The partial pressure of steam is calculated as above, using combustion stoichiometry and a material balance in the CZ. The saturated steam partial pressure can also be calculated using steam algorithms and T_s. T_s is adjusted (iterated) until these two separate calculations of steam partial pressure are equal. This may require several (computer) iterations. When gases from the CZ cool to this T_s, it defines the exit of the CZ and the start of the SZ (E.3).

(iv) Calculation of the SZ heat demand is the fourth step. For a $1m^3$ growth element of the SZ, heat demand is the energy needed to heat the rock matrix, the bitumen (Sib) and connate water (Siw) from Ti (initial reservoir T) to T_s. Produced liquids are assumed to be at T_s, even though there may be a temperature gradient in the SZ (2.5). Some of the heated bitumen (Sib-Srb) and some of the heated connate water (Siw-Srw) are produced immediately when heated. SZ heat demand is modified to include heat losses from the zone (input).

(v) SZ heat supply is the fifth step. Heat is provided by gases from the CZ (steam+hot noncondensible gases). Energy supply is the enthalpy difference between the noncondensible gases (N_2, CO_2, CO) and steam as the gases cool from T_s to T_v, plus the latent heat released by some steam that condenses in the SZ. The vent gas is assumed to be saturated with steam at T_v and total pressure P. The fraction of steam condensing is also calculated.

(vi) The growth/stability ratio R_1 (SZ/CZ growth ratio) is then calculated, assuming an energy balance between CZ and SZ.

- R_1 = [(heat available to SZ from gases from $1m^3$ CZ growth)/(heat demand for $1m^3$ SZ growth)]
- If $R_1<1$, the CZ is growing faster than the SZ and it will overtake and destabilize the SZ. Noncondensible combustion gases will inhibit heat transfer. As R_1 increases, SZ stability increases, the SZ grows faster than the CZ.
- If $R_1<1$, the calculation automatically reverts to a ECZ scheme as shown in E.3. A material and energy balance in the ECZ zone is sufficient to calculate all performance factors.

(vii) The growth/stability ratio R_2 (CSZ/WZ growth ratio) is then calculated, assuming an energy balance between the WZ and the CSZ. Energy demand is the heat needed to heat up injected water, in a $1m^3$ growth element of the WZ, from Twi (injected temperature) to T_s^1 (saturated steam T at full process pressure P) and to vaporize all the water to produce steam. Energy supply is the heat contained in a $1m^3$ growth element of the CSZ, in the rock matrix heated by upstream combustion. The method assumes a homogeneous wet zone, with no water channeling, override or fingering at the WZ boundary. If this were to occur a target value for R_2 stability would be $R_2 \geq 1$. But, to account for the risk of water channeling a target $R_2 \geq 2$ is used. (R_2 is also an input value for some processes, so the model user can input an additional safety factor, or not, as desired). As R_2 increases, CZ and CSZ stability improves.

(viii) R_1 and R_2 are defined so that 'bigger is better'. Process stability increses as R_1 and/or R_2 increase beyond their balance points (R_1=1, R_2=2).

(ix) <u>Various unit performance factors</u> are next calculated, including cost, ETOR, PWOR, WRR, MUW, air demand, vent gas production, recovery factors and direct/indirect CO_2 emissions (E.13).

- <u>EEOR processes</u> (4.6) provide heat transfer by electricity (or EM radiation), not steam. But, some connate water is vaporized and a process pressure (P) is still established. The production zone is assumed similar to a SZ but without steam injection. Heat losses are segregated into (i) losses in electricity conversion to radiation, (ii) losses to zones outside the reservoir, and (iii) losses to reservoir areas that are not productive. Calculations use steps (iv), (v), and (viii) above.
- <u>ISR process</u> (4.3) is similar to steam, where steam is used for heat transfer. But, because only the latent heat need to provided by an electric in situ reflux heater system, ISR energy demands are less than SAGD (E.12). Calculations are performed using steps (iv), (v) and (viii) (viii) above.
- <u>ISC and Hybrid processes</u> (4.4, 4.5) contain similar steps as in the above example.

(x) The model user is offered 2 options for Hybrid processes (ISC+Steam). Option 1 (processes VII to X) balances the processes using input R_{1T} and R_{2T} target values ($R_1 \geq 1$) and calculates input water and/or steam injection rates (W_{IR} and S_{IR}). Option 2 (processes XI to XIV) uses input water and/or steam injection rates, and calculates the stability factors R_1 and R_2 . This option may result in an unstable process and revert to the merged SZ+CZ (ECZ) calculation.

3. Input/Output

'Invention is the mother of necessity' (T. Veblen)

3.1 Input – What input is required?

- A common input (E.5) is required, describing the reservoir properties (Q, Siw, Sib, Pi, Ti, d, ρ_B, µi), cost factors (C_S, C_E, CO_2, $C_{AIR,}$ C_{CO2}) and indirect CO_2 omission factors. The user can also select to preserve values as defaults for the next run.
- A second input (E.6) allows the user to choose the process to be modelled.
- A third input is used for the process chosen, to specify process conditions (E.7).
- If the user doesn't input each option in the input sheets, the model will default to preset values (E.8). Default values are for a fictitious shallow reservoir and arbitrary process conditions. There is no implication that default values are 'recommended' and consequently, the user should not rely on defaults as 'representative'.
- All default values are numerical except Siw, which defaults to (I-Sib). This ensures that for Sib sensitivity runs E.10), the pore space is initially filled with liquid (ie. no gas saturation). By overriding this default by entering Siw and Sib separately (ie. (Sib+Siw)<1), it is possible to model a reservoir with some initial gas saturation. The model will treat the gas as a vacuum and ALERT will be raised (3.2).
- Some inputs have multiple units. The user need only input the value for 1 unit. The model will calculate other equivalent unit values and assume the input value is correct.
- Most of the inputs are self-explanatory, but some may need a further explanation, as follows:
  - (i) Indirect CO_2 emissions (E.5) are CO_2 emitted on surface – on site or at a remote site, producing the energy needed for EOR (eg. steam, electricity, oxygen gas or compressed air, or CO_2 produced in vent gas treating. (eg. incineration))
  - (ii) For the balanced hybrid process (VII, VIII, IX, X, E.6), input include target balance conditions for R_{1T} and R_{2T}. The user can deem the process 'balanced' for the growth ratio SZ/CZ = R_{1T} and/or the growth ratio CSZ/WZ = R_{2T}. The user may input extra safety factors beyond default assumptions (R_1=1, R_2=2) for each value, as desired. Higher values for R_{1T} and R_{2T} increase process stability.
  - (iii) Cost factors are also an input value (E.5). Care should be taken so that comparisons are on an applE.to-apple basis. For example, electricity costs from the grid include capital (demand) charges as well as opex. A convenient standard is a third party utility with over-thE.fence, takE.or-pay charges for energy. For steam (C_s in E.5) costs would include energy

costs to produce steam, plus a capital charge for the cost of boilers and steam distribution. Likewise for oxygen or compressed air, costs would include capex and opex charges. For some processes, only the major/dominant cost factor is considered (eg. for SAGD, only steam costs are considered). Cost factors include steam, oxygen, air compression, electricity and vent gas treating. The default cost factors (E.8) include both opex and capex cost components. Carbon taxes are also included as a cost factor.

(iv) Reservoir heat losses (L_R in E.7) can be used to 'calibrate' operating field projects, using ETOR (or SOR) as a calibration factor. Losses are taken as a fraction of input energy at the wellhead. The definition of 'loss' is taken in the most general sense, as heat that is not productive, either the heat is lost to the under/over burden or to nonproductive zones in the reservoir.

(v) For processes with multiple energy inputs and/or zones (eg. hybrid processes), heat loss is distributed proportionately to each energy type and/or to each zone.

(vi) For EEOR, heat losses are separated into 3 types (4.6)

(vii) For processes with a combustion component (III to XIV, E.6), one input value is T_c, the in situ combustion T. This is a predominant property of the reservoir matrix and reservoir fluids. It does not depend (strongly) on the oxidant gas used nor the amount of steam or water injected (as long as the process is stable, $R_1 \geq 1$, $R_2 \geq 2$). The combustion temperature can be estimated based on operator experience or it can be determined by laboratory combustion tests (default value $T_c = 550°C$).

(viii) For processes that potentially can have a steam zone (SZ), Srb and Srw are the average residual bitumen and residual water saturations that pass from a SZ to a CZ or remain in the SZ. (Siw-Srw) and (Sib-Srb) respectively represent water and bitumen produced from the SZ.

- Each process also has an input sheet (section) that allows the user to choose sensitivity graphs (E.10). The program plots the graphs chosen, including a title chosen in the process condition sheet (E.7). The original input data is assumed to define a 'base case' and the sensitivity graphs show the impact of deviations from the base case, plotting key performance factors on the y axis (eg. ETOR). Sensitivity graphs can be plotted using either English or metric units (E.10).

3.2 Defaults – What are the bases for default input values?

'*If you come to a fork in the road, take it' (Yogi Berra)*

- Default input values for reservoir properties and other inputs are included in the model. If the user doesn't input a specific value the program will automatically default to a preset value (E.8).
- Default values are for a ficticious shallow reservoir and arbitrary process conditions. There is no implication that default values are 'recommended' nor are they necessarily 'representative'.
- The analysis herein (section 4) is based mostly on default values.
- Default reservoir values (E.8) are based on a typical shallow bitumen reservoir in the Athabasca region of Alberta.
- All default values are numerical except Siw, which defaults to (I-Sib). By overriding this default by entering Siw and Sib so that (Sib+Siw) <1, it is possible to model a reservoir with some initial gas saturation. The model will treat the 'gas' as a void and an ALERT will be raised (3.3).
- The default cost factors (E.8) include both opex and capex charges. Default electricity costs are for a combined-cycle gas power plant. Default steam costs are for an on-site gas-fired boiler, with an on-site water-treatment plant for water recycle and some heat recovery (costs can potentially be lowered with an on-site cogen plant). Default air compression costs are for electric-drive compressors. Default oxygen costs are for a large central cryogenic air separation plant. Default vent gas treating costs (for processes with an ISC component) are for incineration (if desulfurization is required, costs can be higher).
- Default values for indirect CO_2 emissions are also part of the model. Default values for indirect CO_2 related to electricity consumed (I_E in E.8) are based on an on-site (or remote) gas-fired, combined-cycle power plant. Indirect CO_2 from steam (I_S) is based on a gas-fired, on-site boiler. Indirect CO_2 from oxygen used (I_O) is based on a large central cryogenic oxygen plant. Indirect CO_2 from compressed air (I_a) is based on electric-drive compressors.
- Indirect CO_2 from electricity can be reduced (compared to defaults) by using a cogen plant, using renewable energy (e.g. wind), using hydro power or using nuclear power. Indirect CO_2 from electricity can be increased (compared to default values) by using a coal fired power plant, using grid power with a coal component, using a simple gas-fired plant or using an oil or distillatE.fired power plant.

3.3 ALERTS – What input ALERTS are flagged?

'We made too many wrong mistakes' (Yogi Berra)

The model will automatically flag 5 potential input ALERTS (E.22). The model will still run and produce output even if there is one or more ALERTS. (Sometimes an input ALERT will be deliberate – see section 4).

- ALERT 1 – "Heat losses ≥ Heat input", triggered when ($L_R + Q_{wh} – Q_{sf}$) ≥ 1, for processes with a steam component, or when (f_{EH} > 1) or (f_{HR} > 1)(f_{RD} > 1) for the EEOR process XV. For a viable process, the cumulative heat losses should not be greater than or equal to the heat input. The remedy is to reduce the heat loss input values or change the process.
- ALERT 2 – "Excessive Liquid Saturation", triggered when (Siw + Sib) > 1. The initial bitumen saturation plus the initial water saturation should not exceed 1. The remedy is to correct the input values.
- ALERT 3 – "Input Gas Void", triggered when (Siw + Sib) < 1. If this occurs, the model will still run and treat the initial pore volume increment (1 – Sib-Siw) as a vacuum. This may be intentional (see 4.4D).
- ALERT 4 – "The fuel may be too light", triggered when χ>1.5. For processes with a combustion component, χ is the input fuel H/C atomic ratio. This can be determined from experience, from lab combustion tube tests or by analyzing vent gas constituents from an operating ISC process. The default value in the model is χ=0.5, representing coke. For χ=1 the fuel is mostly asphaltenes. If χ>1.5 either light pyrolysis gases or upgraded bitumen is the combustion fuel. Either may be considered undesirable. Potential remedies are to inject more steam (in a hybrid process) or to change the process.
- ALERT 5 – "Excessive Srw". If Srw > Siw the growth element will act as a sink for injected water/steam and water performance measures (E.27) will be non-representative.

3.4 Output – What output is produced by the model?

'Nothing in life is to be feared. It is only to be understood' (M. Curie)

A. The model has 3 generic groups of output – a reiteration of input data and process conditions; a table (E.13) showing performance factors, energy use factors, diagnostic factors, and; one (or more) sensitivity graphs (E.4).

B. The key performance factors (measured at the well head) include – cost ($\$/_{M}{}^{3}{}_{B}$) based on energy performance and unit cost inputs for steam, oxygen, air or electricity; ETOR ($GJ/_{M}{}^{3}{}_{B}$) – the total energy input per unit bitumen production, allowing direct energy comparisons between processes. The water injection rate (W_{IR}) and the steam injection rate ($S_{IR)}$ are also calculated for hybrid processes (VIII to X). CO_2 taxes are also included.

C. Energy use factors (E.26) – include steam use (SOR-$_{M}{}^{3}$ steam as water/$_{M}{}^{3}{}_{B}$) (the traditional SAGD performance indicator); O_2 use ($_{M}{}^{3}/_{M}{}^{3}{}_{B}$); Air use ($_{M}{}^{3}/_{M}{}^{3}{}_{B}$); and electricity use (Kwh/$_{M}{}^{3}{}_{B}$)

D. Environmental factors (E.13) – include makE.up water (MUW, $_{M}{}^{3}/_{M}{}^{3}{}_{B}$); water recycle ratio (WRR, $_{M}{}^{3}$ prod. Water/$_{M}{}^{3}$ injected (water + steam)); produced water to oil ratio (PWOR – $_{M}{}^{3}/_{M}{}^{3}{}_{B}$) indirect CO_2 emissions ($_{M}{}^{3}/_{M}{}^{3}{}_{B}$); direct CO_2 emissions ($_{M}{}^{3}/_{M}{}^{3}{}_{B}$) (from vent gases); and; in situ fuel use ($_{M}{}^{3}/_{M}{}^{3}{}_{B}$) (based on bitumen – equivalent fuel at 6MMBTU/bbl.

E. Other diagnostic factors (E.13) – include; a stability factor R_1 = the SZ/CZ growth ratio; a stability factor R_2 = the CSZ/WZ growth ratio; the T where steam first condenses (Ts, for steam processes this is saturated steam T); the fraction of SZ steam lost to vent gas (Rs); and, the viscosity of bitumen at Ts (μs).

- Because of the nature of individual processes, not all of the above output is produced for every process.

3.5 WARNINGS – What output WARNINGS are flagged?

'Truth will sooner come out of error than confusion' (F. Bacon)

The model will automatically flag 7 output WARNINGS (E.22) with several potential remedies and trigger conditions. Similar to the input ALERTS, the model will still run and produce output with one or more WARNINGS. Sometimes a WARNING condition will be deliberate – see section 4.

- WARNING 1 – "The SZ is unstable", triggered when R_1<1, for processes containing a combustion component. If the CZ grows faster than the SZ, the SZ can become unstable. If this occurs, either productivity will drop significantly (an order of magnitude) or combustion will destabilize. The potential remedies are to switch from air to oxygen, to increase steam injection (hybrid process), to increase the residual water (Srw) in the SZ, to decrease process pressure (P) to increase Siw, to increase Ø, to increase χ, to decrease T_v or to otherwise change the process. The model will automatically revert to an ECZ model (E.3).
- WARNING 2 – "The CZ may be unstable", triggered when R2<2 or R2< an input target. For processes with a wet ISC component, the WZ can grow faster than the CSZ. Including a safety factor to account for water channeling, if this occurs, the WZ can overtake the combustion front and quench combustion or cause LTO to occur. The potential remedies are to decrease water injection rates, to alter well geometry to reduce the risk of water channeling, to increase the temperature of injected water (Tiw), to increase steam quality, to decrease Ø, or to change the process.
- WARNING 3 – "There is not enough fuel", triggered when the bitumen-equivalent fuel demand, expressed as a fraction of the pore volume, is greater than or equal to the residual bitumen saturation carried over from the SZ (ie. Srb). If this occurs, the CZ will overtake the SZ or combustion will destabilize. The potential remedies are to reduce Ts (so that Srb increases), to increase Srb, to switch from oxygen to air (or enriched air), to reduce Tc, to reduce P, to increase Sib, to increase Ø or to change the process.
- WARNING 4 – "There may not be enough fuel", triggered when the bitumen-equivalent fuel demand, expressed as a fraction of the pore volume, is greater than half of the residual bitumen saturation (Srb) carried over from the SZ. Some of the bitumen is drained from the CZ prior to the pyrolysis and combustion sub zones (E.3). The potential remedies are similar to WARNING 3.
- WARNING 5 – "Fluids may leak in/out of the process zone", triggered when the process pressure is too low or too high (see E.43). The transition for significant leakage is taken as a 20 percent variation to the initial reservoir pressure (Pi) divided by the hydrostatic

pressure (P_H). The remedies are to alter the process pressure or do nothing if the process is deemed to be well contained by reservoir geology.

- WARNING 6 – "Bitumen productivity may be poor", triggered when μs≥30 cp. Field experience (eg. SAGD) has shown that for good bitumen productivity, at Ts, bitumen viscosity must be less than about 30cp. The model estimates μs using algorithms for bitumen (or heavy oil viscosity, based on initial (in situ) viscosity and steam Ts. Potential remedies are to increase Ts, to switch from air to oxygen (hybrid processes), to increase P or to change the process.
- WARNING 7 – "There is no steam zone", triggered when Tv≥Ts. For processes with a combustion component, if the vent gas is at a higher Tv than the steam Ts, steam will not condense and there will be no steam zone. Potential remedies are to reduce Tv (eg. change well geometry) or to increase Ts (eg. use oxygen not air).
- The remedies for some WARNINGS (and the remedies for some ALERTS) may cause other WARNINGS (or ALERTS) to occur.

4. Processes

'Genius is the ability to reduce the complicated to the simple' (C.W. Ceram)

4.1 Overview – What processes can be modelled?

- The purpose of this section is to discuss and assess process types, including some daughter processes, to show examples of process model outputs and of insights available from the analyses.
- The model explicitly includes 5 generic process types – (i) steam (eg. SAGD), (ii) electric (eg. ISR, EEOR), (iii) ISC (eg. dry ISC (air)), (iv) balanced hybrids (eg. SAGDOX) and (v) unbalanced hybrids (eg. ISC + steam).
- The model is designed to apply to bitumen reservoirs, but it can also apply to heavy oil or medium oil reservoirs where gas saturation is low and the in situ oil has some mobility.
- All processes involve thermal EOR as the primary process component. There is no explicit consideration of solvent processes or solvent components. (This will be a future model update).
- ISC is a family of combustion processes (dry ISC(O2), wet ISC(O2), dry ISC(air), wet ISC(air). Depending on whether or not water is injected to scavenge heat (wet processes) or whether oxygen or air is used as the oxidant gas, the process may have 3 or 4 process zones (WZ, CSZ, CZ, SZ, ECZ). (E.3, section 4.4)
- Steam is the simplest model (4.2). ISR is a proprietary process (Nexen, pat.pend.) using electricity as the energy source and steam as the heat transfer medium (4.3)
- A series of balanced ISC + steam hybrid processes are also considered (4.5)
- A series unbalanced ISC + steam processes are also considered. These processes may be unstable.
- EEOR is a family of electrical EOR processes where electricity is the energy source and the heat transfer medium (4.6).
- In total there are 15 different process types modelled (E.6). Within each process type there may be several daughter processes that can also be represented by the model, as described herein.

4.2 Steam – How does the model apply to steam EOR processes?

'Discussion is an exchange of knowledge; argument is an exchange of ignorance; (R. Quillen)

- The model for steam EOR is simple, with only a single process zone (SZ) and with steam injected directly into the zone. Heat demand is the energy needed to increase the temperature of a growth element (eg. 1m^3 virgin reservoir) from Ti to Ts, including the rock matrix and the pore fluids. Net heat supply is the latent heat of condensation, assuming steam is condensed at/near the bitumen interface and produced fluids are at/near saturated steam Ts. Although the model is generic and not tied to any specific process, the assumption of near-constant P implies that gravity drainage is a key production mechanism.
- Using heat loss (L_R) and sand-face steam quality (Qsf) as input variables, an operating SAGD process can be calibrated to match ETOR (or SOR) equivalent to FEA history matching). The calibrated model can then be used to predict the impact of process changes or reservoir quality changes. The model may be useful for other steam EOR processes where gravity drainage is an important factor (eg. SF or CSS) or where the process is gravity-stabilized (eg. THSF)
- The lower limit (least severe) for SAGD (and other steam processes) can be determined by the upper limit for bitumen viscosity to provide satisfactory productivity. The default value for the model is µs<30cp; but the limit is somewhat arbitrary and sensitive. Lower limits of 30 and 20cp have the following implications:

µs	<30cp	<20cp
Ts	>155°C (311°F)	>175°C (347°F)
Ps	>545 KPa (79 psia)	>896 KPa (130 psia)
ds	>48.3m (160 ft)	>79.4m (260 ft)

where Ps and ds are hydrostatic pressure and hydrostatic depth at saturated steam (Ts (E.19). It is unlikely that shallow bitumen reservoirs can be over pressured due to the risk of surface breakthrough.

- For lower limits to SAGD, for some shallow reservoirs, mining also becomes an option for bitumen recovery. If this is economic, this may supersede lower limits on SAGD, depending on overburden and reservoir thickness.

- The upper limit (most severe) for SAGD can be determined by heat losses in the vertical well bore section. These losses depend on the design and operation of the steam injection well. For uninsulated wells, it is generally acknowledged that for depths beyond about 2500ft (763m) heat losses make SAGD impractical. So using this depth, assuming hydrostatic operations, SAGD upper limits are:

  $Ts < 300.2°C$ (572.3°F)

  $Ps < 8618$ KPa (1250 psia)

  $d < 763m$ (2500ft)

- Using conventional (uninsulated) well design, the range of SAGD (and related process) applicability is for reservoir depths between about 150 and 2500 ft. or with pressures between about 80 and 2500 psia.
- Insulated tubing or special well design to minimize heat losses can extend the upper limits for SAGD. But SAGD is driven by latent heat of water/steam as a heat transfer fluid. Beyond the critical point of water, latent heat is no longer available and this can set an absolute upper limit for SAGD as:

  $Ts < Tc = 374°C$ (705°F)

  $Ps < Pc = 22064$ KPa (3200 psia)

  $d < 1954m$ (6400ft)

- E.23 to 26 compares the performance of SAGD to other processes that are modelled. SAGD costs (E.24) are at the high end of the scale – third highest in the list of IS processes. SAGD energy use (ETOR)(E.26) is in the middle of the pack – eighth highest. Carbon dioxide emissions (E.25) are on the low side – second lowest. But, if ISC(0) vent gas is sequestered (E.25(a)), SAGD is the sixth lowest emitter. Water use is at the top and viscosity (µs) is the lowest.
- But SAGD has good, field-proven productivity. Another way to compare processes is to focus on processes with steam-heat-transfer (SHT) dominating at the cold bitumen interface. These 6 processes, like SAGD should all have good productivity and include – I SAGD, II ISR and the balanced hybrid process (VII to X). Exhibits 29, 30, 31 compare performance of these 6 SHT processes. SAGD has the third highest cost, the second lowest ETOR, the lowest µs and the lowest CO_2 emissions. (But, if the SAGDOX

processes (VIII and X) sequester vent gas CO_2 directly (E.45, 45(a)), SAGD can become one of the higher CO_2 emitters.

- An insightful way to screen reservoir types is to plot process economic limits as a function of the key reservoir properties Ø and Sib). E.33 shows such a plot for the economic limit or operating costs <\$300/m^3B (<\$47.7/bblB) at L_R = 0.5 (ie 50% heat losses in the reservoir). For each value of Ø, there is a single value of Sib that defines the limit. E.33 shows the locus of these points for SAGD as a line plot. One side of the line is 'economic'. The other side is not economic. For the criteria chosen, E.33 shows that SAGD is not economic for reservoirs with Sib < 3.5 nor for Ø < 0.05. The model user can develop his/her own criteria for economic limits using other variables or other processes.
- The cost and CO_2 tax structure of SAGD and other SHT processes is shown in E.29. Costs and taxes are totally dominated by steam production. (Other common costs such as labor, utilities etc., are omitted from the comparisons.) SAGD costs are on the upper side of the comparison.
- The environmental performance factors for SAGD and other SHT processes are shown in E.31. SAGD energy use is dominated by steam production. SAGD has the highest water usage of all SHT processes.
- SAGD is a relatively low CO_2 emitter (E.31, E.23) but vent gas from SAGDOX processes (VIII and X) is relatively pure CO_2 (+CO) and suitable for direct sequestration. If vent gas is sequestered, SAGD CO_2 emissions are in the middle of the SHT pack (E.25(a), E.45, E.45(a)). Also if renewable or nuclear electricity is used for ISR (process II), CO_2 emissions fall to near zero (E.50).
- SAGD performance is sensitive to pressure (E.34). As pressure increases steam temperatures (Ts) increase and the temperature of the heated reservoir also increases. Also as Ts increases, the latent heat of steam drops (E.38). Both factors increase SAGD steam demand and increase costs. At 7000 kPa, SAGD total cost + tax rises to over \$250/m^3B, and CO_2 emissions rise to over 600m^3/m^3B (E.34).
- The model can also be useful for SAGP, and related processes. SAGP adds a small amount of noncondensible (nc) gas, usually CH_4, to injected steam. The gas remains in the reservoir and is not removed by a vent well. Usually, SAGP is initiated at/near the mature stage of a SAGD project. Physical-model lab experiments have shown that the nc gas occupies the produced-bitumen voidage and migrates to the top (ceiling) of the vapour chamber, where most of the heat losses occur. The nc gas establishes a temperature transition zone between the ceiling (at Ti) and the steam zone (at Ts) and it effectively insulates the celing from heat losses (ie. reduces L_R). More importantly, for some reservoirs, the nc gas increases lateral growth rates compared to vertical growth. The nc gas is only a small, almost negligible, portion of steam injected. E.14 is a plot of

the nc gas needed to occupy bitumen voidage as a function of process pressure (P) and the temperature of the voidage nc gas. Because of the temperature gradient created by the nc gas, the average storage T of nc gas can be much less than Ts.

- As an example, at P = 2500 KPa and an average storage T of 150°C, for a SAGP process with SOR = 3, the percent v/v) of nc gas in the steam injected is only 0.43 (v/v)% to occupy produced-bitumen voidage. Including consideration of some nc gas losses, some gas dissolution into reservoir fluids and some nc gas in produced fluids, for this example, nc gas injection rates might vary from about 0.5 to 3.0 (v/v)% of steam injected. This is not significant for steam mechanisms in the reservoir. The effect on Ts by gas dilution at the 0.5 to 3.0% level is negligible. But, nc gas injection can reduce heat losses to the ceiling and can stimulate lateral growth of the steam chamber.
- The main beneficial effect of SAGP is to reduce heat losses to the overburden by insulating the ceiling. This can be modelled by reducing heat losses (L_R) in the model. Exhibit 42 shows performance sensitivity to heat losses. If heat losses are reduced from 50% to 30% by injection of a small amount of non-condensible gas with steam, the benefits are as follows:
    - a cost + tax reduction/saving of over \$35/m^{3}B
    - an ETOR reduction of over 2.5 GJ/m^{3}B
    - a water use (MUW) reduction of about 0.1 m^3/m^{3}B
    - a CO2 emission reduction of about 70 m3/m3B

  These potential benefits are substantial. Particularly in the later stages of SAGD, SAGP should be considered as an attractive add-on/alternative to the status quo.
- The model doesn't explicitly account for solvent benefits in a solvent + steam hybrid process (eg. ESSAGD), but some of the benefits of solvent addition to steam can be accounted for as follows:
    (i) One of the major benefits of solvent is to reduce the residual bitumen in the steam-swept zone. This effect can be accommodated by reducing Srb input values. (If solvent is added to a mature SAGD process, a surge in production is expected by solvent scavenging of bitumen in the steam swept zone).
    (ii) Similar to nc gas (SAGP) addition, solvent addition to steam can reduce heat losses by insulating ceiling areas in the steam chamber. This can be accommodated by reducing L_R input values.
    (iii) When gas is mixed with steam, steam partial pressures are reduced, Ts is lowered, bitumen viscosity (μs) is increased and productivity is reduced. On the other hand, solvent dissolution with bitumen reduces mixture viscosity and increases productivity. If these two effects balance each

other, solvent + steam processes can be modelled simply by reducing Srb and L_R input values.

(iv) [Explicit solvent + steam models may be a future addition to this model.]

4.3 ISR – Why is ISR attractive?

- ISR may be considered as a hybrid process, where electricity is the source of energy and steam is heat transfer medium.
- ISR is a Nexen, proprietary process (pat. pend.) where steam is refluxed, in situ, in a single horizontal well, using a series of electrical resistance heaters that are individually controllable (E.15). Produced fluids flow to the well by gravity drainage, water is vaporized/refluxed and bitumen is produced in the well annulus. The reservoir EOR process is similar to SAGD, so SAGD productivity is expected. ISR is one of the SHT processes (E.29, E.30, E.31)
- Despite using high-cost electricity, the ISR process produces steam, at the sand face, at a lower cost than a gas-fired surface SAGD boiler (E.29). Produced fluids (water and bitumen) enter the well at/near Ts, so electrical energy is needed to supply only the latent heat of steam, not the total heat supplied by a surface boiler. ISR steam costs drop with increased pressure/depth (E.12) because steam latent heat also drops with pressure (E.38) and ISR has no well bore heat losses.
- Compared to all other processes (E.23, E.47), ISR is in the middle of the pack for costs and for environmental performance (E.47).
- Compared to other steam-heat-transfer (SHT) processes, ISR is also in the middle of the pack.
- Another key advantage of ISR is that performance doesn't deteriorate rapidly with increased pressure (E.34).
- Exhibits 23 and 24 show a direct comparison of ISR to SAGD, using default values for input. ISR has the following performance:

  (i) a $2.15/m3 modest increase in (cost+tax) at 1724 KPa,

  (ii) a $86.20/m3 reduction in (cost+tax) at 5500 KPa,

  (iii) a 2.52 GJ/m3 (48%) reduction in energy use (ETOR),

  (iv) a 2.7% modest increase in CO_2 emissions (52% reduction at 5500 KPa), and

  (v) a 92.5% reduction in water used

- ISR can potentially be a zero (CO_2) emitter if electricity is sourced from renewable or nuclear sources.

- Other advantages of ISR (compared to SAGD) include:

  (i) longitudinal conformance control using segment heater controls (E.15),
  (ii) reduced fluid flow (no water) in a production well,
  (iii) because of (i) and (ii), the ISR well can be longer (or smaller),
  (iv) reduced capex costs – only a single well,
  (v) with no well-bore heat losses and lower heat demands, ISR can work in deep or off-shore reservoirs, and
  (vi) ISR can work in a pressure-cycle mode similar to CSS.

- A comparison of water use (MUW) between SAGD and ISR is instructive MUW for SAGD (SOR-0.9 PWOR) is mostly due to volume losses in the water-treatment plant to produce BFW. At most, ISR only needs MUW to replace bitumen voidage. If any connate water is produced, it will be vaporized in the ISR well and will provide a surplus of water in the ISR process (ISR MUW = bitumen voidage as steam – connate water production). If ISR requires MUW it can be supplied with a small spaghetti tube in the well annulus (E.15). As an example, an ISR process producing 500 bbl/d bitumen, at default conditions (P=250 psia), bitumen voidage is only 4 bbl/d MUW, with no connate water production. A similar SAGD project operating at SOR = 3, PWOR = 3 requires 150 bbl/d MUW, over 37 times the MUW for ISR. Also for ISR, it is expected that MUW need not be treated prior to injection. Any dissolved salts are expected to be deposited in the reservoir or carried to surface in the produced heated bitumen. Any metallic heat-transfer surfaces will be oil-wet to resist scaling.
- But ISR also has some risks:
  (i) When is situ water is refluxed as steam, dissolved solids will precipitate and may plug the ISR well or coat the resistance heater elements to impede heat transfer or to limit productivity. These risks can be ameliorated if/when the metal surfaces are oil-wet, if the solids are suspended in the produced bitumen or if the reflux heat-transfer site can be moved away from the heater element further into the reservoir where plugging or fouling is less risky.
  (ii) Similarly, coking can foul and impede heat transfer.
  (iii) The flow pattern around the ISR well is complex. Water and bitumen drain towards the well, near where reflux steam is exiting. This flow regime can potentially limit productivity and heat transfer.

4.4 ISC – Why does ISC have difficulty for bitumen EOR?

'The important thing is not to stop questioning'.(A. Einstein)

A. Background

- ISC has been a 'holy grail' for EOR. Combustion is the low cost option to deliver energy to a reservoir (E.12). ISC heat release is substantial and the fuel consumed is a small fraction of the in situ bitumen that would otherwise not be recovered (ie. it is free). Exhibit 12 compares steam, electricity, oxygen and compressed air costs per unit energy delivery at the sand face, for default values in the model. Unit energy costs are compared to hydrostatic depth/pressure, assuming process pressure P is equal to the hydrostatic pressure. Electricity is the high cost option. Oxygen/air is the low cost option. Steam costs escalate rapidly with pressure because of assumed well-bore heat losses in the Exhibit.
- The ISC models are generic, but, because of the assumption of small pressure gradients (2.5), the model is best applied to ISC processes where gravity drainage is a key production mechanism (eg. COSH, COGD, THAI…). But, another assumption of the models is that vent gas is removed separately from produced liquids. This assumption is met by COSH and COGD, but not by THAI, where vent gas and liquids are removed by a common horizontal well. If vent gas is removed at Ts or higher T, there is no steam condensation and no SZ. THAI can be modelled by assuming $Tv \approx Ts$.
- Unlike steam, ISC has no inherent depth limitations and oxygen or air pipes can be much smaller than steam for the same energy delivery rates (E.37). In fact, unlike SAGD, ISC performance is not very sensitive to pressure (eg. E.35) and theoretically ISC can work well at any depth. But, instability is a big issue for ISC. For most ISC processes the SZ or CZ can be unstable and productivity can be very poor (2.2).

B. ISC Process Stability?

There are 2 instability criteria for ISC processes – (i) if $R1<1$, the CZ is growing at a rate faster than the SZ. It will overrun the SZ and destabilize SZ performance. If $R1<1$ the process reverts to one containing an extended combustion zone (ECZ, E.3) with blended elements of both a SZ and a CZ. (ii) if $R2<2$, the WZ grows such that water can/will channel to the CZ and cause the CZ to be unstable.

For default conditions (E.28) all ISC process types are unstable for R1 <1 and for R2<2. ISC stability is improved by heating injection water (recycling hot produced water) (E.32, E.44); by using a wet process (E.28); by reducing vent gas Tv (E.43) or by reducing process pressure, P (E.35). ISC stability is harmed by cold injection water, by using a dry process (E.28), by increasing Tv (E.43) or by increasing process pressure (E.35).

A stable ISC process can be attained for WISC (Air) (process V) by heating injection water or recycling hot produced water (E.44). (But, if pressure is increased only marginally stability can be lost). For the vast majority of ISC types and process conditions, the process will be unstable and steam-heat-transfer will not be dominant heat transfer mechanism at the cold bitumen interface. The zone adjacent to the cold bitumen interface will be a blend of a SZ and a CZ (ie. ECZ).

C. ISC – Air or Oxygen?

- Air injection rather than oxygen gas, results in more non-condensable gases in the reservoir (N_2, CO_2, CO…). Non-condensable gas (mostly nitrogen) is not usually beneficial to ISC processes. Compared to oxygen, N_2 increases piping costs for surface air distribution or for down-hole conveyance. N_2 dilutes steam in the reservoir, reduces steam dew points (Ts) and increases steam losses to vent gas (Rs). (It can also lower heat demands to sustain steam zones which may be of some benefit (eg. process V)).

- Exhibit 28 shows a direct comparison of ISC (O_2) and ISC (Air) processes, for default input values, with the following benefits of using oxygen gas:

	dry ISC	wet ISC
increase Ts (°C)	+39	+22
reduce Rs (%)	-14.7	-4.4
reduce cost ($/m3B)	-14.7	-23.7
decrease µs (cp)	-30	-7.5
reduce vent gas (%)	-82	-91
reduce CO2 emissions (%)	-31	-65

- The cost comparison is both important and clear. The low cost option is to use oxygen gas for a fundamental reason. Oxygen costs are lower than air costs if the cost of vent gas treating is also considered (E.24). Vent gas treating costs (incineration and/or desulfurization) are significant and proportional to vent gas volumes. ISC (O_2) vent gas volumes are less than one fifth the vent gas volumes from ISC (Air) processes (E.1).

- There is actually a double whammy effect of nitrogen dilution – dew points are reduced (20 to 40°C) so it is more difficult for steam to condense, and; vent gas volume is increased by about a factor of S, so vent gas is a more effective sweep gas to remove steam from the process, before it can condense.

- So, there are lessons learned for an ISC operator, including:

  (i) use oxygen rater than compressed air, if practicable,
  (ii) run with Ts as high as possible to minimize produced bitumen μs,
  (iii) remove vent gas at Tv as low as possible, to maximize steam condensation (This reflects both on well pattern design and an operational strategy)
  (iv) remove vent gas separately (and at a lower T) from produced liquids.
  (v) heat water injected or recycle hot produced water

D. <u>ISC – Wet or Dry?</u>

- Wet ISC produces steam, in situ, by scavenging heat from the combustion-swept zone (CSZ) at no additional cost except the cost of water injection. If produced water is recycled, the cost of injection will undoubtedly be more than offset by savings in water disposal. As shown in E.27, all ISC processes (or processes with an ISC component) produce a surplus of water (WRR>1) so no make up water is necessary. Because steam is the most effective heat transfer fluid, wet ISC is a desirable process.

- Exhibit 28 shows a direct comparison of wet and dry ISC processes, for default input values, with the following benefits of water injection:

	ISC (oxygen)	ISC (air)
Increases Ts (°C)	+12	+29
Reduce Rs (%)	-23	-53
Decrease µs (cp)	-3.5	-25.7
Reduce 0_2 use (%)	-63	-26
Decrease ETOR (%)	-63	-26
Increase R_1 (%)	+180	+158

- The cases shown in E28 assume water injection for wet ISC at a default value of Twi = 15°C. Under these conditions for WISC(A), R_2 = 1.80 and for WISC (0), R_2 = 1.88. This would indicate that the WZ-CZ interface is almost stable for both wet processes. For the same conditions WISC(A), R_1 = 1.02 and WISC(0), R_1 = 0.846. This indicates that WISC(0) has an unstable steam zone. There is little room to improve the increase R_1 because increased water injection can reduce R_2<2 and cause WZ-SZ instabilities.

- Exhibit 32 shows the benefits of heating & injection water (or recycling hot produced water, or heating recycled produced water). All ISC processes produce excess water (WRR>1) (E.23, E.28, E.27). Heated injected water frees up capacity for increased water injection and with increased water injection rates, WISC(A) can achieve stability with R_1>1 and R_2>2; WISC(0) only achieves partial stability (R_1>1).

E. Vent Gas Management

Exhibit 43 shows the effects of increasing the temperature of vent gas removal (Tv) for a specific ISC process (V – WISC(Air)). The results can be catastrophic. If Tv reaches Ts, all steam is vented and there is no contribution to heat delivery from steam condensation. Productivity can be expected to be low. Costs are high (a $54/m3B increase compared to the default case). Emissions increase by a factor more than 2 and the process becomes deficient in water (WRR<1) so it is a net water consumer.

Vent gas temperature Tv is mostly dependant on process design. The vent gas well(s) are best if separated from the injection/production wells so that vent gas can cool and some steam can condense in the process zone. (A process like THAI has little chance to reduce Tv; well designs like COSH or COGD have a chance to reduce Tv). If the process has multiple (vertical) vent well (eg. COGD) performance can be optimized by adjusting individual well vent gas removal rates to minimize the temperature of vent gas removal.

In addition to the suggestion in 4.4C, it is suggested that best practices for ISC include:

(i) Inject water (choose a wet process)
(ii) Heat the water as much as possible (or if practical recycle hot produced water)
(iii) Choose a process/well configuration that allows for separate vent gas removal at the lowest possible Tv
(iv) Implement an operation strategy that minimized vent gas Tv

F. ISC – Post Steam

- It has been suggested that ISC can be used as a follow-up process after SAGD has matured (or post steamflood (SF) or post cyclic steam (CSS). A steam zone has already been created, gas injectivity is good, infrastructure is in place, the gas zone has been preheated so autoignition is likely and the residual bitumen (Srb) in the zone may be still significant. But, unless infill wells (eg. wedge wells) are drilled, the bitumen drainage angle is very small and little/no production can be expected from the cold bitumen interface. Almost all secondary ISC bitumen production would be from residual bitumen in the SZ(E.3). On the other hand, instability of the ISC process at the SZ edges (R1<1) is not a particular concern since there is little expectation of production from this area.
- A follow-up ISC process in the steam chamber of a spent SAGD/steam process, without infill wells, can be modelled by assuming the initial reservoir input conditions (E.5) are those for a spent steam chamber and Srw = Siw and Srb = Sib. This will trigger an ALERT (4, 3.3) message because (Siw+Sib) < 1, but this can be ignored for this case. Additionally, since there is no bitumen produced in a SZ, there is no advantage to use a wet ISC (or a hybrid process with a wet ISC component) process for this application. Instability WARNING 1 (3.5) will also be triggered and can also be ignored. Bitumen production is totally due to residual bitumen in the steam zone, less any bitumen needed for ISC fuel.
- If a volatile solvent additive was used during SAGD (eg. ESSAGD), there may not be enough residual bitumen in the steam-swept zone to support ISC as a viable follow-up process.
- For a follow up ISC process in a spent steam chamber, with infill (wedge) wells, there will be some bitumen produced from the leading edge of the process and it will be important to attain/maintain a SZ preceding the CZ. The process can be modelled using the same input as an ISC process applied to a virgin reservoir, with adjustments to L_R (heat losses) to account for preheating the steam zone and for the well geometry. The infill well is the outlet for bitumen produced near the cold interface. In this case, there is an advantage to consider/implement wet ISC (or wet hybrid processes).

G. Post Waterflood ISC

- It has also been suggested that dry ISC can be used as a post waterflood process, where high saturations can be a process advantage if the water is vaporized to steam by hot combustion gases.

- There are 3 cases to consider:

(i) A heavy oil reservoir that was intentionally waterflooded to increase primary production,

(ii) A heavy oil reservoir with an active bottom water where primary production produces a cone or crest zone with high water saturations, and

(iii) A native heavy oil or bitumen reservoir that has a high water saturation from a 'natural' waterflood.

- But, these opportunities may be risky. If the high-water-saturation water is vaporized, a dry ISC process can naturally turn into a more efficient wet ISC process. But, if some water drains to a production well prior to vaporization, the process can be much less effective.
- Exhibit 48 shows an evaluation of ISC of a post waterflood reservoir (Siw = Sib = 0.50). Srw is the pore volume fraction of water that would pass thru a steam zone and be vaporized by combustion. For the study shown unless Srb > 0.4, the combustion process (DISC(0_2)) would not be stabilized. However, stability can be achieved for a wet process (WISC(O_2)). Post waterflood WISC can be a viable and effective process. (E.48 also shows how performance is altered for a leaner, wet reservoir – costs are almost doubled.)

4.5 Hybrid Processes – Why is SAGDOX attractive?

'…the more significant the core competence, the smaller the odds that resident experts will listen to anyone (from outside)' T. Peters

- Hybrid process herein are a combination of ISC and steam that can capture the low cost advantages of ISC and the proven productivity advantage of steam. Steam injection does not harm ISC, it increases the growth rate of the SZ to improve ISC stability and it can attain/retain good bitumen productivity.
- As previously noted (4.4), preferred versions of the ISC component, in the hybrid process include the use of oxygen gas and a well geometry (and operation strategy) that allows water injection to scavenge reservoir heat and produce some in situ steam. Also vent gas temperature should be minimized and water should be injected or recycled so it is hot.
- Hybrid (ISC + steam) processes can be categorized as (i) 'unstable' when insufficient steam/water injection produces a SZ growth rate less than the CZ growth rate (R1<1), or (ii) 'unstable' when water injection is too much and the WZ growth rate exceeds the CZ growth rate (R2<2), or (iii) 'balanced' when R1 = 1 and R2 = 2, or (iv) 'stable' when R1 ≥ 1 and R2 ≥ 2.
- The preferred hybrid choices (wet or dry SAGDOX) are a proprietary Nexen process (pat. pend.) – a subset of the hybrid group – using oxygen gas, where steam/water injection is adjusted so R1 ≥ 1 and R2 ≥ 2 (wet SAGDOX = process VIII (WISC(0) = steam) and dry SAGDOX – process X (DISC(0) + steam)). These processes are stable with steam heat transfer at the bitumen interface (ie. good productivity), they have reduced costs compared to SAGD (E.23), they use less water than SAGD – actually produce a water surplus – (E.31, E.27), and they have less pressure sensitivity than SAGD (E.34, E.35). If SAGDOX vent gas is segregated and sequestered, CO_2 emissions are much less than SAGD (E.45).
- If SAGDOX vent gas is sequestered and electricity is sources from renewable or nuclear power plants, SAGDOX CO_2 emissions are much less than SAGD – 55 to 80 percent lower (E.45(a))
- The wet version of SAGDOX (process VIII, WISC(0) + steam) is preferable (E.29, E.30, E.31)
- In a simple process ranking with equal weightings on economic and environmental performance issues, wet SAGDOX rates as the top-rated process (E.46(a)) comparing processes where steam-heat-transfer at the bitumen interface is dominant (the SHT process group).

- Including SAGDOX versions, there are 2 input options for users of the model. The model user can input R_1 and R_2 (R_{1T} and R_{2T}) and the model will calculate water and/or steam injection rates to attain R_{1T} and R_{2T} target values (processes VII to XIII). Alternately, the model user can input steam (S_{1R}) and water (W_{1R}) injection rates and the model will calculate stability factors R_1 and R_2 (processes XI to XIV).
- All these hybrid processes produce a water surplus (WRR>1)(E.23, E.26, E.27) so no makE.up water is needed. In order to maximize in situ steam production and/or to minimize the WZ growth rate and to reduce the risk of water channeling, it is best to recycle hot produced water and/or to heat injected water to near Ts.
- Oxygen is the preferred oxidant gas (4.4) compared to air.
- SAGDOX may use more wells than SAGD (eg. for oxygen injection or for vent gas removal). But vent gas volumes are less than oxygen injection volumes (E.30) for the SAGDOX processes, and for equal energy deliverability, oxygen volume rates are about one tenth steam volume rates (E.37), so extra SAGDOX wells can be smaller (less costly) compared to SAGD wells. Also, because SAGDOX produces less water (PWOR) than SAGD (E.27), the SAGDOX production well can be smaller (less costly) than an equivalent SAGD well.
- E.29, E.30 and E.31 compare SAGDOX and SAGD performance factors for the same input (default) values. SAGDOX is less costly than SAGD. Wet SAGDOX (VIII) has a total cost (including CO_2 tax) of over \$20/m^3 less than SAGD.
- E.31 shows the environmental performance of SAGDOX compared to other SHT processes. SAGDOX is a net producer of water (WRR>1) and SAGD is a net consumer of water (WRR<1, MUW = 0.2 m^3/m^3B). SAGDOX CO_2 emissions, because of the ISC component are higher than SAGD. But, SAGDOX produces a vent gas that is almost totally CO_2 and it is suitable for direct sequestration. (ISC (air) hybrids produce a vent gas that is more than 5 times the volume (E.28) of ISC (oxygen) versions and the gas is diluted with nitrogen so it is not suitable for direct sequestration). If SAGDOX vent gas is sequestered (E.45), SAGDOX CO_2 production is over 60% less than SAGD. If SAGDOX vent gas is sequestered and electricity is sourced from non-CO_2 emitters (E.45(a)), SAGDOX CO_2 is 80% less than SAGD.
- A feature of some hybrid processes (VII, VIII, XI, XII) including wet SAGDOX (VIII) is simultaneous injection of steam and water (in separate streams?). Exhibit 49 shows that a combined injection stream is equivalent to a ‘crappy’ boiler producing a steam with a quality between about 14 and 50%. Conceptually, such a boiler could use produced water at/near the wellhead to minimize heat losses

and capture sensible heat in the produced water. This scheme may be less costly than water treatment and BFW input to a high-Q boiler.

- Another strategy to produce a low quality steam, is to heat injection water beyond the Ts limitation and to allow the water to flash in the reservoir to produce a low Q steam.

4.6 EEOR – What EEOR processes can be modelled?

'History repeats itself. That's one of the things wrong with history.' C. Darrow

- ISR (4.3) is a special electric EOR process where steam, from refluxed water is used as the reservoir heat transfer agent.
- EEOR processes, herein, use electricity as the primary energy source and heat transfer agent to heat bitumen for EOR. Heat transfer is accomplished by electric currents in the reservoir or by EM radiation penetrating the reservoir.
- At DC or low AC frequencies, individual wells are completed as electrodes, isolated from the steel well bore. DC or AC current travels along connate water or water-zone paths to penetrate the reservoir and provide heat at various sites in reservoir. The heat distribution (ie. conformance) depends on reservoir geology and it is not uniform, nor can it be easily controlled.
- At rf or microwave frequencies, EM radiation from an in-hole antenna can penetrate the reservoir and heat parts of the reservoir where the radiation is absorbed. The antenna can be directional and can focus the radiation toward the bitumen zone. But, heat distribution (ie. conformance) is still not uniform and it is hard to control.
- EEOR calculations are similar to steam – a single process zone, heated to/near saturated steam Ts at process pressures – but there are also significant differences. Saturated steam does not have sufficient energy quality (ie T) to vaporize connate water. Electricity can easily vaporize connate waters. As a default, all water produced from the growth element is assumed to be vaporized.
- The good news for EEOR is that energy injectivity is not limited by fluid injectivity. Heat injection rates can be large, even for virgin bitumen reservoirs.
- The bad news for EEOR is that electricity is the high-cost alternative for energy delivery (E.12), conformance can be poor, energy losses can be extensive, energy can penetrate the reservoir without simultaneously creating a flow path for produced fluids, and energy injection may not be confined to the reservoir zone by an impermeable cap rock.
- To account for these factors, the EEOR process model has separate inputs for the following terms:

  f_{CW} = fraction of connate water in the growth element vaporized by electricity (default value, f_{CW} = 1.0)

  f_{EH} = fraction of electricity ending up as heat in/near the reservoir. For a water conduction process f_{EH} = 1.0. For a radiation process f_{EH} is the conversion efficiency of electricity to radiation. (default value, f_{EH} = 0.8)

f_{HR} = fraction of radiation heat that ends up in the reservoir zone. This may depend on the directional efficiency of the radiation antenna. (default value, f_{HR} = 0.5)

f_{RD} = fraction of heat delivered to the reservoir that results in effective bitumen drainage to a production well. Drainage efficiency can be impaired by lack of flow paths, poor drainage angles or well geometry. (default value, f_{RD} = 0.8)

- Default values are set assuming a radiative EEOR process. For a conductive process $f_{EH} \cong 1.0$ and f_{HR} or f_{RD} may also be changed.
- All water leaving the growth zone (ie. Siw – Srw) is assumed to be vaporized to steam.
- E.23 shows a direct comparison of EEOR to SAGD using the default input values for a shallow, low pressure reservoir (E.8). Compared to SAGD, EEOR has the following performance:
  - (i) Over 350% increase in cost (opex)
  - (ii) Over 100% increase in energy use (ETOR)
  - (iii) Over 350% increase in total CO_2 emissions
  - (iv) 100% decrease in water use

- Because SAGD steam costs increase rapidly with pressure (E.34), increasing pressure favors EEOR.
- Electricity costs and the high opex for EEOR are distinguishing features. But costs can be reduced if an onsite cogen plant is used or if off-peak power is purchased.
- CO_2 emissions are another concern (E.23, E.26). But emissions can be reduced by an onsite cogen plant or eliminated by purchasing power from nuclear or renewable sources.

4.7 Overall comparisons – How can processes be compared?

'Profitability is the sovereign criterion of the enterprise.' (P. Drucker)

- Most comparisons and conclusions herein are based on input default values for a typical, shallow Athabasca reservoir. Because of this, readers/users should be wary of performance predictions and conclusions based on this set of input values. The model user can/should form his/her own conclusions based on specific reservoirs and process conditions.
- Broad comparisons herein are based on the following groupings:
  - (i) Key performance parameters (process cost, CO_2 taxes, SOR, air use, oxygen use, electricity use…)
  - (ii) Diagnostic parameters (R_1, R_2, Rs, WRR, PWOR, Ts…)
  - (iii) Process conditions (P, T, heat losses…)
  - (iv) Environmental parameters (CO_2 emissions, water use, ETOR…)
  - (v) Reservoir factors (Ø, Sib…)

(i) Key performance parameters:

- Cost is the ultimate comparator. The model breaks cost into 2 groups – direct process costs (energy costs + vent gas treating costs) and CO_2 taxes (in jurisdictions where CO_2 taxes may apply). E.23 shows outputs from all processes. E.24 shows a breakdown of cost and CO_2 tax components. The low cost process is WISC (oxygen) (VI) at \$12.90/M^3B (including CO_2 taxes) or \$14.72/M^3B for direct process costs. [But, ISC is an unstable process (R1<1)]. The high cost process is EEOR(XV) at \$50.93/M^3B or \$243.21/M^3B, excluding CO_2 taxes. If we consider just the balanced, stable hybrid processes, SAGD, ISR and EEOR (E.41), the low cost option is [wet ISC(O_2) + steam] (or wSAGDOX process VIII) at \$37.75/M^3B, less than SAGD. If we consider only processes that are stable and have steam-heat-transfer (SHT) as the dominant process at the bitumen interface (E.30, E.29) the low cost option is also process VIII (wSAGDOX).
- <u>Energy usage ETOR</u> is another key performance parameter (E.23, E.24). The lowest energy user is ISR (process II) at ETOR = 3.03GJ/M^3B. This process refluxes steam in situ and only provides latent heat. The highest energy user at ETOR = 10.87 is process XV, EEOR. If we consider only SHT processes (stable steam heat transfer), E.30 shows the lowest energy

user is ISR (II) and the highest user is DISC(A) + S (X) hybrid. Dry hybrid processes are high energy user because the reservoir matrix is heated up to combustion Tc, without any heat scavenging.

- Energy use components (SOR, oxygen use, air use, electricity use) are other key performance parameters. Not surprisingly, the highest steam user is SAGD, at 1.74 m^3/m^3B (E.30) and the lowest user is process VII (WISC(A) + ST) (E.30). (At low P, WISC(A) can be stabilized without any steam injection if injected water is heated (E.44)).

(ii) Diagnostic parameters also can be compared (E.18). Of the processes producing vent gas, the one with the lowest fractional heat/steam lost to the vent gas (Rs) is process XII, WISC(0) + steam with Rs = 0.0648. The process with the highest fractional heat/steam lost is process III, DISC (air) with Rs = 0.2344. For the balanced processes, R1 and R2 are set (default) at 1.0 and 2.0 respectively to ensure that the SZ is stable. The conventional ISC processes are all unstable with R1<1 (E.28, E.18). The wet unbalanced hybrid processes (XI, XII) are stable R1>1 and R2>2. The dry unbalanced processes (XIII, XIV) are unstable (R1<1).

- Steam dew point temperatures (Ts) are also important. Because of dilution, air-based ISC and ISC hybrid processes (III, V, VII, IX, XI, XIII) have steam dew points much lower than other oxygen based hybrids (IV, VI, VIII, X, XII, XIV). Higher dew points are desirable because product liquids are hotter and have lower viscosity (E.18). If we focus on the SHT processes (E.41), the SAGDOX processes (VIII, X), SAGD and ISR have the highest Ts and lowest bitumen viscosities (10-11cp). The conventional ISC processes (E.28) can have low Ts and viscosities above the WARNING trigger point (30cp). Dry ISC (Air) (process III) is the worst culprit (µ = 45cp).

(iii) Process conditions are also important. Pressure is the most sensitive parameter. E.34 and E.35 show the performance variations with pressure for I (SAGD), II (ISR) and VI (WISC(0)). SAGD is particularly sensitive with costs increasing by a factor of about 4.5 as P increases from 1724 KPa (default value) to 7000 KPa. ISR is much less sensitive, because the process only needs to supply latent heat and latent reduces as a fraction of total steam heat as P increases. ISR costs increase only by a factor of only 1.5 from 1724 to 7000 KPa. E.35 shows the behavior for a wet combustion process (VI). Over the same pressure range, costs are stable – this shows a key advantage for including ISC as part of a hybrid process.

- Obviously reservoir heat losses (L_R) can affect all processes in a similar manner. E.42 shows the effect of heat losses on SAGD performance. As L_R increases from 0.1 (default value) to 0.7, process cost escalates by a factor of 3. Similarly CO_2 emissions, MUW, PWOR, SOR and ETOR also escalate.

(iv) Environmental performance is also an important comparator. E.26 shows the environmental performance of all process – CO_2 emission, water issues and energy use. Carbon dioxide emissions can be broken into components as shown in E.25. The lowest emitters are the steam processes (SAGD and ISR). ISR is the lowest emitter at 134 M^3/M^3B. The highest emitter is EEOR at 611 M^3/M^3B – a factor of over 4 times greater. Without CO_2 capture, processes with an ISC component (III to XIV) have high CO_2 emissions. But, processes with an ISC (Oxygen) component produce a vent gas with concentrated CO_2 (ie. IV, VI, VIII, X, XII, XIV). If this CO_2 is captured and sequestered, CO_2 emissions can be less than SAGD or other processes (E.25a) and these processes can be the low-emitter cases (E.50).

- E.31 summarizes environmental performance for the SHT processes including CO_2, water and energy use issues. With CO_2 sequestration of vent gas, SAGDOX (BWISC(0) + S and BDISC(0) + S are the leading environmental processes.
- Water use is another key environmental factor. E.27 compares water use issues for all processes. Processes with an ISC component all produce a water surplus, so no make-up water (MUW) is needed. (If some connate water is produced, ISR can be in a water-surplus position and only SAGD is a consumer of water).

(v) Reservoir factors are another set of comparators. Obviously, all the processes are sensitive to Ø and Sib. Exhibit 33 shows the economic limits for SAGD as a function of Ø and Sib – SAGD is not economic for Ø<0.1 and/or Sib<0.35. Processes with lower costs (hybrid processes, ISC and ISR) can extend these limits to leaner and less porous reservoirs.

- Processes at depth can also pose problems. As pressure (P) increases, ISR, ISC and hybrids become more attractive (E.34, E.35)

(vi) Well-bore heat losses are another important factor. Processes with a steam-injection component (I, VII to XIV) can be sensitive to well-bore heat losses (reduction in steam quality). E.34 shows the effect for SAGD. (ISR has no well-bore heat losses because steam is refluxed in situ.) The hybrid processes (VII) to XIV) can recover from some/all well-bore losses if steam passes through the hot

CSZ and scavenges high-quality heat to revaporize condensed water. This is particularly true for dry hybrid processes (IX, X, XIII, XIV). But, SAGD has no such mechanism and the effect of well-bore heat loss can be devastating on process performance (E.34).

(vii) An overall process ranking is shown in E.47 for all processes and in E.46 for SHT processes. Without any weightings, using 4 criteria – cost, CO2 emissions ETOR and water use – the overall rankings for SHT processes are 1. wSAGDOX (VIII), 2. SAGD (I), 3. WISC (A) + S (VII), 4. ISR (II), 5. + 6. The dry hybrid processes (IX, X).

4.8 Productivity

Productivity is a 'kinetic' parameter. Determination of the rate of bitumen production is predicated on the modeling of a kinetic process that can include several complex steps that occur sequentially (or concurrently). For example, the kinetics of thermal bitumen EOR can include:

(1) Injection of a heat transfer fluid (eg. steam) [or a fluid that can release heat in the reservoir (eg. oxygen)] at the sand face,
(2) Movement of the fluid through the pore structure of the reservoir to reach a position where heat is produced (eg. combustion),
(3) Continued movement of the fluid or (fluids produced by combustion) to reach the bitumen interface,
(4) Transfer of heat to/at the bitumen interface,
(5) Removal of cooled fluids (n.c. gases or water) so as to not impair further heat transfer,
(6) Drainage of the heated bitumen to a production well, and
(7) Conveyance of the heated bitumen to the surface.

Each of these steps can be complex and difficult to model. Some models (eg. FƐA) can represent each step and predict absolute productivity of a thermal EOR process applied to a specific reservoir. But, usually (often) the FƐA model must be 'calibrated' by adjusting input parameters so the model matches the historical productivity profile of the specific reservoir (history matching).

If one of the steps is the slowest in the chain, this step can be termed as the rate limiting-step of the process and the step can dominate the process kinetics. If calibrated, modeling of this step, by itself, can be a good/sufficient model of process kinetics.

The productivity that can be benchmarked is SAGD. SAGD is the only thermal EOR process with proven, good productivity. A rule-of-thumb is that a good SAGD well-pair at/near peak production will produce 1 bbl/d bitumen for each m. of horizontal well length (a 1000m well pair will produce ~ 1000bbl/d of bitumen).

The bitumen EOR model herein does not predict productivity. The assumption of instant heated-bitumen production from the SZ and/or the CZ means that bitumen drainage is not the rate-limiting-step.

At the early (and mid-life) stages of a bitumen EOR process, fluid injectivity (ie. the rate of energy injection) is likely to be the rate-limiting-step for bitumen productivity. As shown in E.12, oxygen gas contains about 10 times the heat content of steam per SCF of fluid injected. SAGDOX (or ISC(0)) processes can potentially have higher productivity than steam (SAGD) at early process stages and with appropriate ISC/SAGDOX geometry to effectively remove non-condensable gases from the reservoir. But, the effective removal of non-condensable gases is not easy and this can limit the productivity of many process types.

Near the end of a project life, bitumen drainage may be expected to dominate process kinetics. Rates for gravity drainage are proportional to $\mu^{-1/2}$ at process temperatures (Ts). Processes with an ISC component dilute steam with non-condensable gases, decrease Ts and increase µs. So at the later stages of a process, steam (and EEOR) can be expected to have better productivity than processes with an ISC component. Processes with an ISC (Air) component can be expected to have poor productivity if bitumen drainage is the dominant kinetic step.

If heat transfer is the ratE.limiting-step or an important kinetic factor, processes with an active steam zone (E.3) can be expected to have good productivity (ie. similar to SAGD). Processes that transfer heat to the bitumen interface, using an extended combustion zone (E.3) can be expected to have bitumen productivity up to about 10 times less than steam (SAGD) processes (2.2).

4.9 Process Management

It may be useful to include an example of how the model can be used to manage the evolution of a field EOR project. Suppose it is intended to develop resource using thermal EOR with a combustion component. The project can proceed in the following stages after drilling and completing wells in a certain geometry.

> Stage 1 – wells are heated (steamed) to establish communication for the EOR process to proceed.
>
> Stage 2 – dry combustion (DISC) is initiated, preferably using oxygen as the oxygen bearing gas. Dry combustion is the necessary starting process, even if wet combustion is better because of the need to establish a robust combustion-swept zone (CSZ) to support wet combustion. The model can be used to calibrate the process and estimate reservoir heat losses L_R. Expect poor productivity and hot vent gases. Costs may be high.
>
> Stage 3 – after a period of time, the process is changed to wet combustion (WISC) by injecting water to scavenge heat from the CSZ and produce steam. Productivity will increase, vent gas temperatures will be reduced, cost is reduced and heat losses are decreased. The model is used and calibrated to predict R1 and R2 stability factors and other performance factors.
>
> Stage 4 – wet combustion is optimized by heating the injected water (or recycling hot produced water) and increasing injection rates so that R_2 is not less than a specified target R_{2T} value. R_2 is a function of fluid flows in the reservoir and the well geometry used in the process. R_{2T} = 2.0 is suggested herein as a good target, but for poor geometries, the target may be further increased to ameliorate risks. The model can now be used and calibrated to field performance to predict R_1 and other factors. If $R_1>1$, a stable steam zone is established and the project may be operated indefinitely with good productivity and low costs. If $R_1<1$ (or $R_1<R_{1T}$), more process modifications may be necessary (ie. Stage 5).
>
> Stage 5 – in addition to water injection, steam is also injected (eg. SAGDOX) to improve steam zone stability and increase productivity. The model can be used to calculate the needed steam volumes to achieve preset R_{1T} target value. This will optimize productivity using a hybrid ISC + steam process.

4.10 Insights – Does the model provide insight?

'I really didn't say everything I said.' Yogi Berra

One definition of insight is – the power of seeing into a situation , that may result in altered strategy or tactics. Based on the analysis herein of bitumen EOR processes, using default input values, the following insights can be developed:

- The model predicts why and when a process won't work (eg. 'unstability'). It issues ALERTS and WARNINGS to focus on problems and it suggests potential remedies to overcome or ameliorate the problems. These insights, as a group, are not provided elsewhere.
- The model groups processes into stable (eg. SHT process group) and unstable (eg. ISC) categories. The potential low-cost process is WISC (Oxygen) (process VI, E.24). But conventional WISC processes are unstable (E.23) (R1<1), (except for WISC(A) and only if injection water is heated or recycled as hot produced water (E.44)). At higher pressures (E.35), or considering other ISC options, the vast majority of ISC processes are unstable. Low productivity is the expectation for conventional ISC processes.
- It is always preferable to use oxygen, rather than air, as the oxidant for processes with an ISC component. When vent gas treating costs are included, oxygen is less costly than air (E.24).
- It is also always preferable to use wet ISC, as a process or as a process component. Water injection can scavenge heat from the CSZ at little/no cost. If water injection is used, it is preferable to recycle hot produced water or to heat injected water up to Ts.
- Steam process (eg. SAGD) have field-proven productivity for bitumen EOR, but steam, by itself, is a costly option (E.23) and costs increase rapidly for higher pressures (E.34).
- The ISR process has obvious attractions (4.3). The reservoir process (steam/water heat transfer), with proven productivity and costs are less than SAGD at higher pressures than default values (E.34).
- Hybrid (ISC + steam) processes can stabilize ISC and potentially capture productivity rates similar to SAGD, with reduced costs and reduced pressure sensitivity due to the ISC component (E.35, E.24). The low cost option for a stable process is WISC (oxygen) + steam (or wet SAGDOX), for default conditions (E.29, 30).

- Electric EOR (EEOR, process XV) is the high-cost option (E.23). EEOR costs can be reduced (compared to the default input case) by purchasing off-peak power or by using an on-site cogen plant.
- Two unique proprietary processes – ISR (process II) and SAGDOX (processes VIII, X, XII, XIV) – may be better than current processes used for bitumen EOR.
- For hybrid processes containing an ISC (oxygen) component (ie. SAGDOX), the vent gas produced is mostly CO2 (ie. concentrated CO2) and it is suitable for direct sequestration with only minor treatment (drying + compression). If SAGDOX vent gas is sequestered, SAGDOX becomes the low CO2 emitter of the SHT group of processes (E.45)(E.50).
- It is also possible to operate a bitumen EOR process with near zero CO2 emissions (direct + indirect) if electricity is provided by renewable or nuclear sources (ISR or EEOR) (E.50).
- For hybrid processes with both steam and water injection, it may be attractive to utilize a 'crappy' boiler that produces low-quality steam rather than injecting steam + water separately (E.49).
- It may also be practical to inject superheated water (T>Ts) and produced flash steam in the reservoir as an alternative to a 'crappy' boiler.
- [These insights may be altered substantially for specific process and/or reservoir conditions different than the default values used herein].

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Exhibit 1

ISC Stoichiometry

1. For ISC Oxygen

$CH\chi + FO_2 \rightarrow (1\text{-}r)CO_2 + r\,CO + \frac{\chi}{2} H_2O + HEAT$

2. For ISC Air

$CH\chi + FO_2 + 3.774\ FN_2^+ \rightarrow (l\text{-}r)\ CO_2 + rCO + \frac{\chi}{2} H2O + 3.774\ FN_2^+ + HEAT$

where: $F = (1 + \frac{r}{2} + \frac{\chi}{4})$; χ = atomic H/C ratio of fuel; r = fraction of C as CO; $N_2^+ = N_2 + Ar$ in air;
HEAT = 480 BTU/SCF O_2; nc = non condensing (gas); Q = (65.789 + 5.483x)

special cases: program default values (χ = 0.5, r = 0.1, F = 1.175, Q = 68.531)
complete combustion, coke fuel (χ = 0.5, r = 0, F = 1.125, Q = 68.531)
complete combustion, light fuel (χ = 2.0, r = 0, F = 1.500, Q = 76.755)

	Generic	Program Default values	Complete Combustion (r=0) (χ = 0.5)	(χ = 2.0)
Steam prod. SCF/SCF O_2	$(^{0.5\chi}/_F)$	0.2128	0.2222	0.6667
CO+CO2 prod. SCF/SCF O_2	$(^1/_F)$	0.8511	0.8889	0.6667
Nc prod. (SCF/SCF O_2)				
ISC(O_2)	$(^1/_F)$	0.8511	0.8889	0.6667
ISC(Air)	$(3.774 + {}^1/_F)$	4.6251	4.6629	4.4407
Fuel consumed:				
(lbs/MMBTU)	$(^Q/_F)$	58.324	60.916	51.170
(BTU/lb)	$(^F/_Q)$	17,146	16,416	19,543

Exhibit 2
Default ISC Stoichiometry

1. For ISC (Oxygen)
   $CH_{0.5} + 1.175O_2 \rightarrow 0.9CO_2 + 0.1CO + 0.25H_2O$ + HEAT

2. For ISC Air
   $CH0_{0.5} + 1.1750_2 + 4.4345FN_2^+ \rightarrow 0.9CO_2 + 0.1CO + 0.25H2O + 4.4345N_2^+$ + HEAT

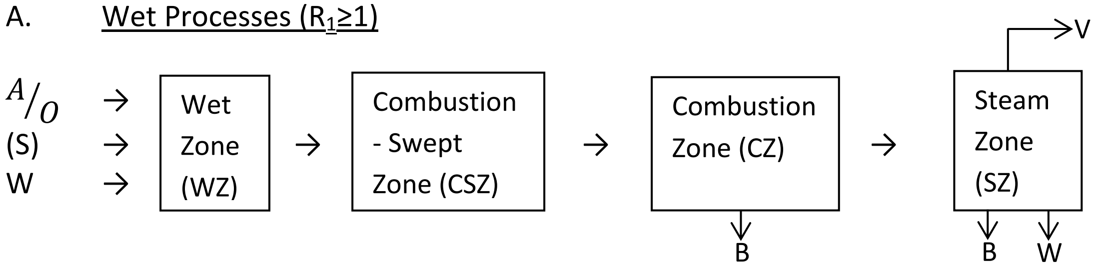
   where: x = 0.5, r = 0.1, F = 1.175, $N_2^+ = N_2 + Ar$; ncg = noncondensable gas; HEAT = 480 BTU/SCF 0_2

   GAS RATIOS

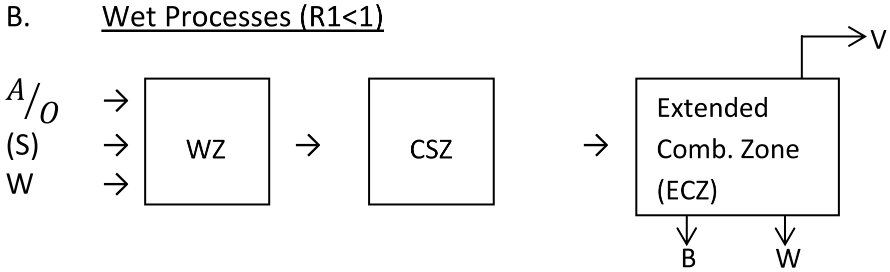
Steam/Ox	=	0.212766
$(CO+CO_2)$/Ox	=	0.85106
N_2^+/Ox	=	3.774
Air/Ox	=	4.774
CO/Ox	=	0.085106
CO_2/Ox	=	0.765957
ncg/Ox=	0.85106 for ISC(Ox)	
	=	1.6763 for ISC(Air)
HEAT	=	17884.7 KJ/m^3 oxygen (480 BTU/SCF oxygen)
	=	3746.3 KJ/m^3 air (100.5 BTU/SCF air)

Exhibit 3
Process Zone Schematics

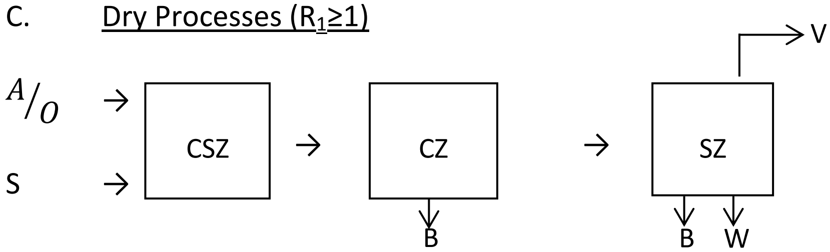
A. Wet Processes ($R_1 \geq 1$)



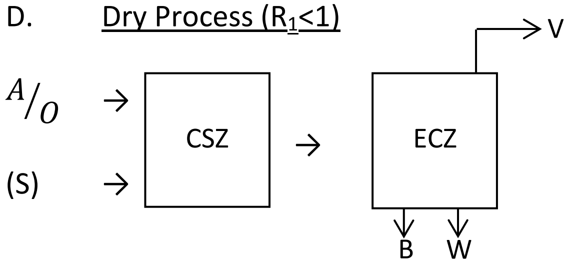
B. Wet Processes (R1<1)



C. Dry Processes ($R_1 \geq 1$)



D. Dry Process ($R_1 < 1$)



where : A = Air; O = Oxygen; W= Water; B = Bitumen; V = Vent gas
: Brackets () indicate optional injectant, depending on process
: A/O = Air or Oxygen gas
: The CZ (or ECZ) contains a combustion front, a pyrolysis zone, a (heated) bitumen bank and a superheated steam zone.
: Left side of schematics = injection site
: Right side of schematics = (cold) Bitumen interface
: R_1 = stability factor = SZ growth rate / CZ growth rate

Exhibit 4

Combustion Zone: Detailed Schematic

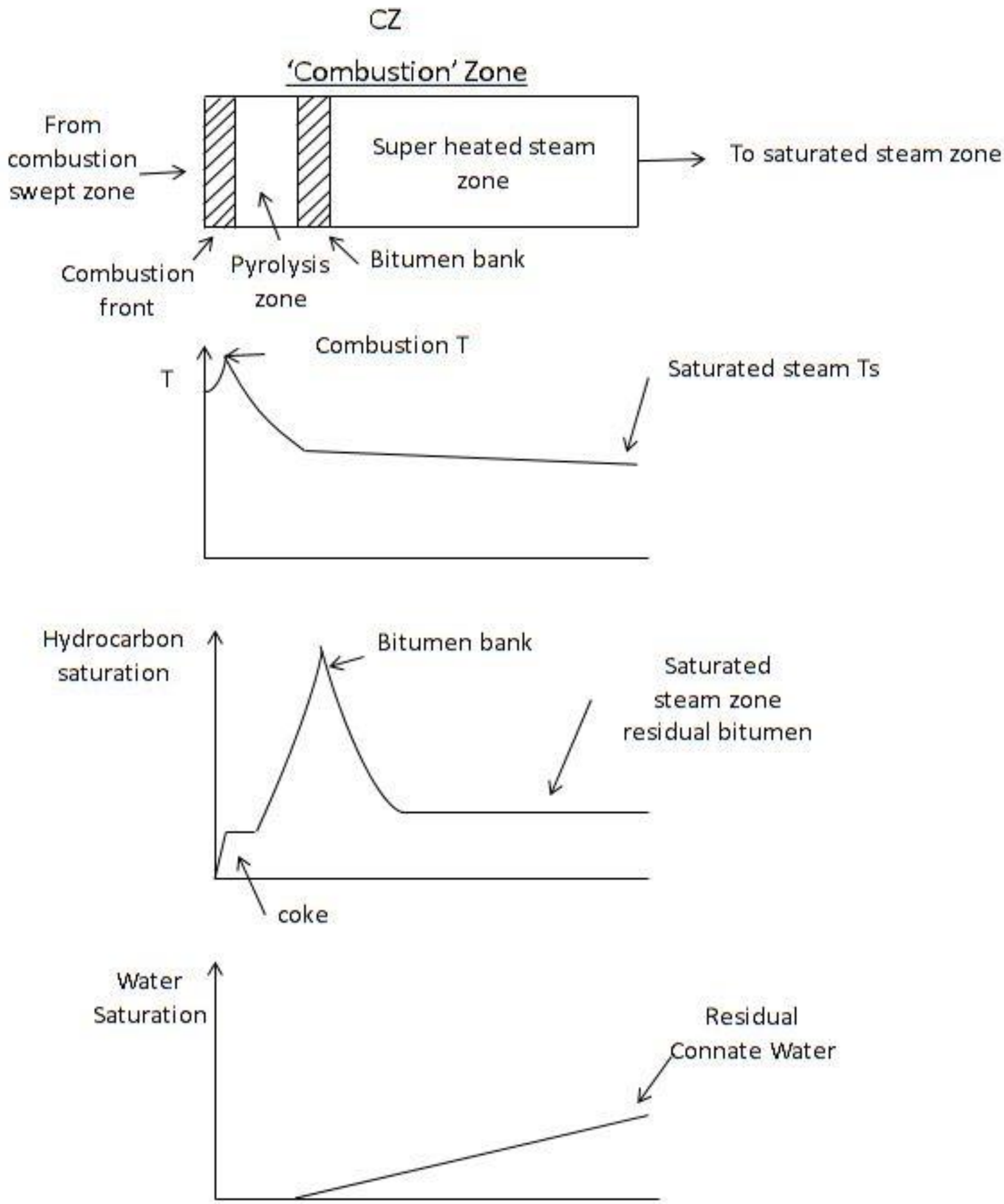


Exhibit 5
Bitumen Thermal EOR Model
Common Inputs

Reservoir Properties	English Units	Metric Units
Rock Type – Sandstone or carbonate		
(Ø) Porosity	fraction	fraction
(Siw) Initial Water Saturation	pore fraction	pore fraction
(Sib) Initial Bitumen Saturation	pore fraction	pore fraction
(Pi) Initial Reservoir Pressure	psia	KPa
(Ti) Initial Reservoir Temperature	°F	°C
(ρb) Bitumen Density	API	kg/m^3
(μi) Initial Bitumen Viscosity	c.p.	c.p.
(d) Depth to top of Reservoir	ft.	m.
Cost Factors		
(Cs) Steam cost	$/bbl	$\$/m^3$(L)
(C_E) Electricity cost	$/kWh	$/kWh
(C_O) Oxygen cost	$/MSCF	$\$/m^3$
(C_A) Air cost	$/MSCF	$\$/m^3$
(C_V) Vent Gas Treating cost ([1])	$/MSCF	$\$/m^3$
(C_{CO2}) Carbon Taxes	$/MSCF	$/m3
Indirect CO2 Emissions		
(Is) CO_2/steam ([2])	SCF/bbl	m^3/m^3
(I_E) CO_2/electricity	SCF/kWh	m^3/kWh
(I_A) CO_2/air compression	SCF/SCF	m^3/m^3
(I_O) CO_2/oxygen	SCF/SCF	m^3/m^3

Other

where (1) vent gas on dry basis
(2) steam measured as condensed liquid (water)

Exhibit 6
Process Choices

	Process		Nomeclature/Acronyms
Steam Processes	I	-	SAGD
	II	-	ISR
Conventional ISC	III	-	dISC (A)
	IV	-	dISC (o)
	V	-	wISC (A)
	VI	-	wISC (o)
Stable Hybrids	VII	-	HB (wISC(A) + s)
	VIII	-	HB (wISC(O) + s)
	IX	-	HB (dISC(A) + s)
	X	-	HB (dISC(O) + s)
Unstable Hybrids	XI	-	HU (wISC(A) + s)
	XII	-	HU (wISC(O) + s)
	XIII	-	HU (dISC(A) + s)
	XIV	-	HU (dISC(O) + s)
Electric	XV	-	EEOR

where SAGD = Steam Assisted Gravity Drainage; ISR = In Situ Reflux;
EEOR = Electric EOR; d = dry; w = wet; ISC = In Situ Combustion;
A = Air; O = Oxygen; S = Steam; H = Hybrid; B = Balanced (Stable);
U = Unbalanced (Unstable)
SAGDOX = w or d (ISC(O) + s)

Exhibit 7
Process Inputs

Input		Processes	Units Metric	English
P	Process pressure	all	kPa	psia
L_R	Reservoir heat losses	I to XIV	frac. of input energy	
Srw	SZ residual water	all	frac. of pore space	
Srb	SZ residual bitumen	all	frac. of pore space	
Tc	Combustion temperature	III to XIV	°C	°F
X	H/C atomic ratio of fuel	III to XIV	ratio	
r	CO production	III to XIV	frac. of fuel carbon	
Tv	vent gas temperature	III to XIV	°C	°F
Tis	air injection temperature	III to XIV odd nos.	°C	°F
Tio	oxygen injection temperature	III to XIV even nos.	°C	°F
Tiw	water injection temperature	wet processes	°C	°F
Qwh	wh steam quality	steam processes	fraction	
Qsf	sf steam quality	steam processes	fraction	
R_1	stability factor	VII to X	SZ/CZ growth ratio	
R_2	stability factor	VII to X wet	CSZ/WZ growth ratio	
Rv	PW recycle ratio	I	ratio	
fw	frac. water refluxed	II	fraction total water	
L_E	elec. to heat conv. losses	II	fraction total energy	
ΔTs	prod. bit. superheat	II	°C	°F
W_{IR}	water injection rate	wet processes	$m3/m3$	$bbl/MMSCF$
S_{IR}	steam injection rate	steam hybrids	$m3/m3$	$bbl/MMSCF$
f_{EH}	elec. conv. to heat	XV	frac. elect.	
f_{HR}	heat to reservoir	XV	frac. total. heat	
f_{RD}	res. heat. to prod. bit	XV	frac. res. heat	
fcw	con. water vaporized	XV	frac. con. water	

Exhibit 8
Input Variable Default Values

Reservoir

Ø = 0.30
Sib = 0.80
Siw = (1-Sib)
Pi = 1724KPa (250psia)
ρ_B= 1014 kg/m^3 (8API)
µi = 3x10^6 cp
d = 152.4m (500ft)
Srw = 0.20
Srb = 0.15
Ti = 15°C (59°F)

Cost Factors

Cs = \$31.46/m^3 (\$5/bbl)
C_E = \$0.07/kWh
C_O = \$O.08475/m^3 (\$2.40/MSCF)
C_A = \$0.01766/m^3 (\$0.50/MSCF)
C_V = \$0.00883/m^3 (\$0.25/MSCF)
C_{CO2} = \$0.01265/m3 (\$0.35815/MSCF)

Indirect CO_2 Factors

I_S = 78m^3 CO_2/m^3($_L$) (437.8 SCF/bbl)
I_E = 0.1757m^3/kWh (6.205 SCF/kWh)
I_O = 0.093m^3/m^3O_2 (0.093 SCF/SCF)
I_A = 0.02m^3/m^3air (0.02 SCF/SCF)
I_V = 0.10 m3/m3v (0.1 SCF/SCF)

Process Conditions

P = 1724 KPa (250 psia)
Tc = 550°C (1022°F)
χ = 0.5
r = 0.1
Tv = 100°C (212°F)
Tia = 15°C (59°F)
Tio = 15°C (59°F)
Tiw = 15°C (59°F)
Qwh = 0.95
Qsf = 0.80
R_{1T} = 1.00
R_{2T} = 2.00
L_R = 0.10
R_V = 0.9
f_W = 0.95
L_E = 0.05
ΔTs = 20°C (68°F)
airW_{1R} = 5.6125x$10^{-4}$$m^3$/$m^3$air (100bbls/MMSCF)
oxW_{1R} = 2.806x$10^{-3}$$m^3$/$m^3$ox (500bbls/MMSCF)
S_{1R} = W_{1R}
f_{EH} = 0.80
f_{HR} = 0.50
f_{RD} = 0.80

Exhibit 8(a)
Input Variables Process Applicability

Reservoir (all processes)

Ø	(all processes)
Sib	(all processes)
Siw	(all processes)
Pi	(all processes)
ρB	(all processes)
µi	(all processes)
d	(all processes)
Srw	(all processes)
Srb	(all processes)
Ti	(all processes)

Cost Factors

Cs	(I, VII to XIV)
C_E	(II, XV)
Co	(even nos., IV to XIV)
C_A	(odd nos., III to XIII)
Cv	(III to XIV)
C_{CO2}	(all processes)

Indirect CO_2 Factors

Is	(I, VII to XIV)
I_E	(II, XV)
Io	(even nos., IV to XIV)
I_A	(odd nos., III to XIII)
Iv	(III to XIV)

Process Conditions

P	(all processes)
Tc	(III to XIV)
χ	(III to XIV)
r	(III to XIV)
Tv	(III to XIV)
Tia	(odd nos., III to XIII)
Tio	(even nos., IV to XIV)
Tiw	(V, VI, VII, VIII, XI, XII)
Qwh	(I)
Qsf	(I)
R_{1T}	(VII, X)
R_{2T}	(VII, VIII)
L_R	(I to XIV)
Rv	(I)
fw	(II)
L_E	(II)
ΔTs	(II)
air W_{IR}	(V, XI)
ox W_{IR}	(VI, XII)
air S_{IR}	(XI, XIII)
ox S_{IR}	(XII, XIV)
f_{EH}	(XV)
f_{HR}	(XV)
f_{RD}	(XV)

Exhibit 9
Expected Ranges of Inputs (metric units)

$0.1 \leq Ø \leq 0.4$	(all)	$0 \geq r \leq 0.50$	(CCP)
$0 \leq Siw \leq 0.9$	(all)	$25 \leq Tv \leq 300°C$	(CCP)
$0.1 \leq Sib \leq 1$	(all)	$0 \leq Tia \leq 100°C$	(CCP(A))
$300 \leq Pi \leq 28000$ kPa	(all)	$0 \leq Tio \leq 100°C$	(CCP(O))
$0 \leq Ti \leq 200°C$	(all)	$0 \leq Tiw \leq 350°C$	(wCCP)
$950 \leq \rho b \leq 1100$ kg/m^3	(all)	$0.2 \leq Qwh \leq 1$	(SCP)
$10^3 \leq \mu i \leq 10^7$ cp	(all)	$0.10 \leq Qsf \leq 1$	(SCP)
$50 \leq d \leq 10{,}000$m	(all)	$0 \leq R_1 \leq 20$	(HB)
$300 \leq P \leq 28{,}000$ kPa	(all)	$0 \leq R_2 \leq 20$	(HB)
$0 \leq Srw \leq Siw$	(all)	$0 \leq L_R \leq 0.8$	(SCP + CCP)
$0 \leq Srb \leq Sib$	(all)	$0 \leq R_V \leq 1$	(I)
$1 \leq Cs \leq \$100$/m^3	(SCP)	$0.5 \leq fw \leq 1$	(II)
$0 \leq C_E \leq \$0.30$/kWh	(ECP)	$0 \leq L_E \leq 1$	(II)
$0 \leq C_A \leq \$0.07$/m^3	(CCP(A))	$0 \leq \Delta Ts \leq 100°C$	(II)
$0 \leq C_O \leq \$0.35$/m^3	(CCP(O))	$0 \leq W_{IR} \leq 0.0017$ m^3/m^{3}A	(WCCP(A))
$0 \leq C_V \leq \$0.04$/m^3	(CCP)	$0 \leq W_{IR} \leq 0.08$ m^3/ m^{3}O	(WCCP(O))
$0 \leq I_S \leq 180$ m^3/m^3(L)	(SCP)	$0 \leq S_{IR} \leq 0.0028$ m^{3}L/m^{3}A	(dCCP(A))
$0 \leq I_E \leq 0.5$ m^3/kWh	(ECP)	$0 \leq S_{IR} \leq 0.014$ m^{3}L/m^{3}O	(dCCP(O))
$0 \leq I_A \leq 0.05$ m^3/m^3(A)	(CCP(A))	$0.5 \leq f_{EH} \leq 1$	XV
$0 \leq IO \leq 0.2$ m^3/m^3(O)	(CCP(O))	$0.2 \leq f_{HR} \leq 1$	XV
$300 \leq Tc \leq 700°C$	(CCP)	$0.2 \leq f_{RR} \leq 1$	XV

where:
SCP = Steam Component Process (I, VII to XIV)
ECP = Electric Component Process (II, XV)
CCP = Combustion Component Process (III to XIV)
CCP(A) = CCP Air (CCP odd nos.)
CCP(O) = CCP Oxygen (CCP even nos.)
w = wet process; d = dry process
A = Air, O = oxygen, S = Steam
L = steam as Liquid (water)
H = Hybrid; B = Balanced

Exhibit 10
Bitumen Thermal EOR Model
Input Sheet 3 – Sensitivity Graphs
Process V : Wet ISC (Air)

English □ or Metric □ units (y vs χ plots)

	y		χ	χ
□	Cost	vs	Ø	(range ☐ to ☐, steps of ☐)
□	Cost	vs	Sib	(range ☐ to ☐, steps of ☐)
□	Cost	vs	P	(range ☐ to ☐, steps of ☐)
□	ETOR	vs	Ø	(range ☐ to ☐, steps of ☐)
□	ETOR	vs	Sib	(range ☐ to ☐, steps of ☐)
□	ETOR	vs	P	(range ☐ to ☐, steps of ☐)
□	Ind. CO_2	vs	Ø	(range ☐ to ☐, steps of ☐)
□	Ind. CO_2	vs	Sib	(range ☐ to ☐, steps of ☐)
□	Ind. CO_2	vs	P	(range ☐ to ☐, steps of ☐)
□	Air use	vs	Ø	(range ☐ to ☐, steps of ☐)
□	Air use	vs	Sib	(range ☐ to ☐, steps of ☐)
□	Air use	vs	P	(range ☐ to ☐, steps of ☐)
□	Dir. CO_2	vs	Ø	(range ☐ to ☐, steps of ☐)
□	Dir. CO_2	vs	Sib	(range ☐ to ☐, steps of ☐)
□	Dir. CO_2	vs	P	(range ☐ to ☐, steps of ☐)
□	V. gas vol.	vs	Ø	(range ☐ to ☐, steps of ☐)
□	V. gas vol.	vs	Sib	(range ☐ to ☐, steps of ☐)
□	V. gas vol.	vs	P	(range ☐ to ☐, steps of ☐)
□	R_1	vs	Ø	(range ☐ to ☐, steps of ☐)
□	R_1	vs	Sib	(range ☐ to ☐, steps of ☐)
□	R_1	vs	P	(range ☐ to ☐, steps of ☐)
□				(range ☐ to ☐, steps of ☐)
□				(range ☐ to ☐, steps of ☐)
□				(range ☐ to ☐, steps of ☐)

Exhibit 11
Output Variables

All Processes	Specific (Processes)
Cost ($/volume B)	MUW (I)
ETOR (energy/volume B)	WRR (I, V to XIV)
Ts (steam T)	SOR (I, VII to XIV)
PWOR (prod. wat./bit ratio)	r.f (CZ) (III to XIV)
Ind. CO2 (per volume B)	elec. use (II, XV)
P/P_H (ratio)	O_2 use (III to XIV)
µs (B_{VIS} at Ts)	Air use (III, V, VII, IX, XI, XIII)
r.f. (in SZ)	Fuel use (III to XIV)
	R_1 (III, IV, V, VI, XI, XII, XIII, XIV)
	R_2 (V, VI, XI, XII)
	W_{IR} (VII, VIII, XI, XII)
	S_{IR} (VII, VIII, IX, X, XI, XII)
	Direct CO_2 (III to XIV)
	Vent gas vol. (III to XIV)
	Rs (III to XIV)

where: $R_1 + R_2$ are measures of stability
R_1 = SZ growth/CZ growth
R_2 = CSZ growth/WZ growth
Rs = fraction of SZ inlet steam lost to vent gas

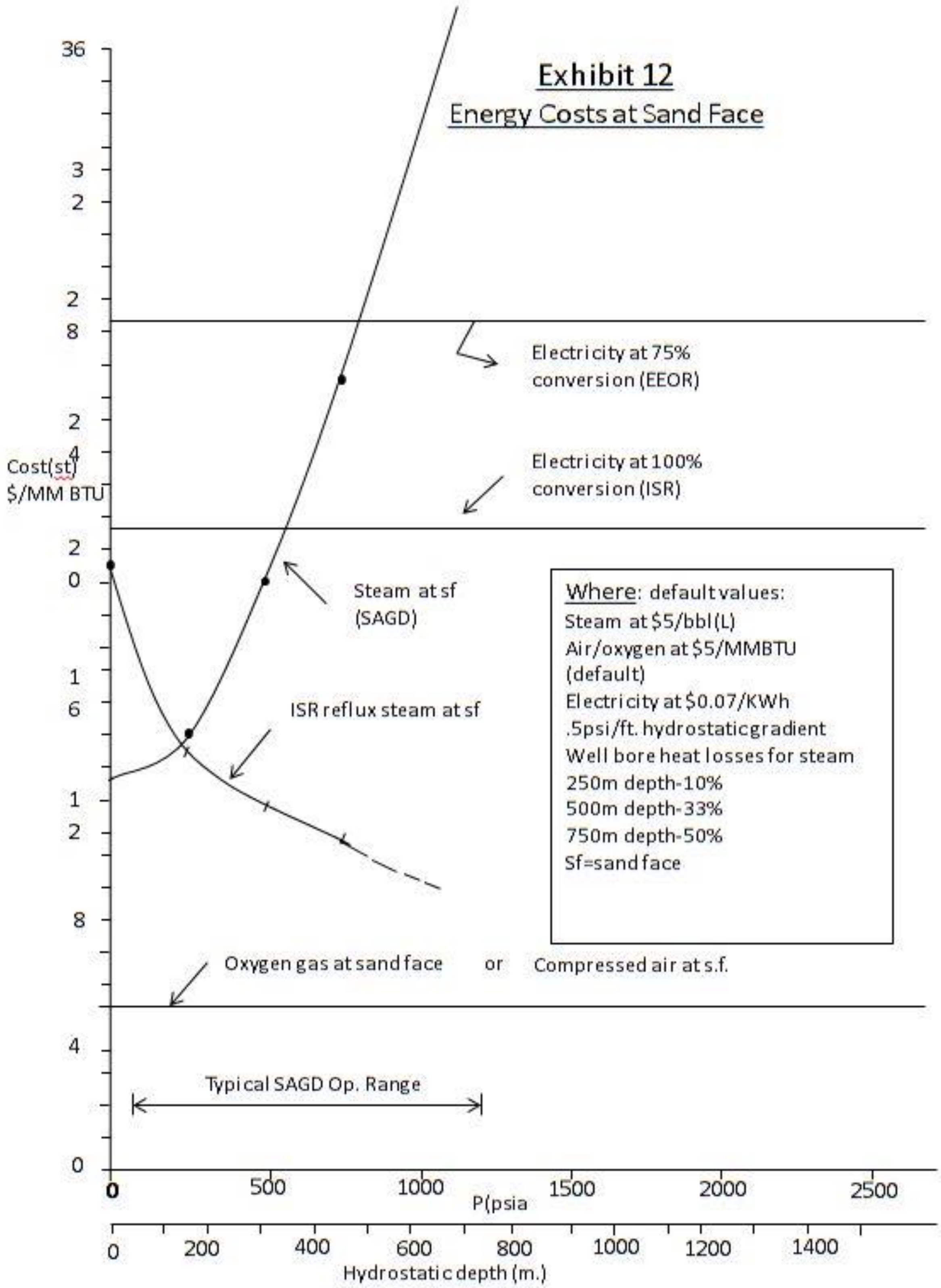


Exhibit 12
Energy Costs at Sand Face
36
3
2
2
8
2
4
Cost(st)
$/MM BTU
2
0
1
6
1
2
8
4
0
Electricity at 75% conversion (EEOR)
Electricity at 100% conversion (ISR)
Steam at sf (SAGD)
ISR reflux steam at sf
Where: default values:
Steam at $5/bbl(L)
Air/oxygen at $5/MMBTU (default)
Electricity at $0.07/KWh
.5psi/ft. hydrostatic gradient
Well bore heat losses for steam
250m depth-10%
500m depth-33%
750m depth-50%
Sf=sand face
Oxygen gas at sand face or Compressed air at s.f.
Typical SAGD Op. Range
0 500 1000 1500 2000 2500
P(psia
0 200 400 600 800 1000 1200 1400
Hydrostatic depth (m.)

Exhibit 13 – Output Values/Units

		Metric units	English units
Performance Factors	Unit Cost[(2)]	($/$m^3$B)	($/bblB)
	ETOR[(2)]	(GJ/m^3B)	(MMBTU/bblB)
Energy Use Factors	SOR[(2)]	(m^3/m^3B)	(bbl/bblB)
	O^2 use	(m^3/m^3B)	(SCF/bblB)
	Air use	(m^3/m^3B)	(SCF/bblB)
	Electricity use[(2)]	(KWh/m^3B)	(KWh/bblB)
Environmental Factors	MUW	(m^3/m^3B)	(bbl/bblB)
	WRR[(3)]	(m^3/m^3)	(bbl/bbl)
	PWOR[(3)]	(m^3/m^3B)	(bbl/bblB)
	ICO_2[(4)]	(m^3/m^3B)	(SCF/bblB)
	DCO_2[(5)]	(m^3/m^3B)	(SCF/bblB)
	Fuel use[(9)]	(m^3/m^3B)	(bbl/bblB)
Diagnostic Factors	R_1	- SZ/CZ growth ratio -	
	R_2	- CSZ/WZ growth ratio –	
	Ts[(6)]	°C	°F
	Fs[(7)]	fraction (vent steam)/(total steam)	
	Vent gas (dry)	(m^3/m^3B)	(SCF/bblB)
	μs	cp	cp
	rf	fractional B recovery	
	Rs	fraction SZ steam lost to vent gas	

where:

(1) I = indirect, D = direct, B = bitumen;
(2) measured at the well head;
(3) excluding water/steam in vent gas;
(4) Indirect CO_2 produced by surface and/or offsite facilities;
(5) Direct CO_2 produced in vent gas;
(6) Ts = temp where steam starts to condense;
(7) Fs = fraction of steam lost to vent gas;
(8) not all processes will have all output values;
(9) bitumen equivalent fuel consumed by ISC component

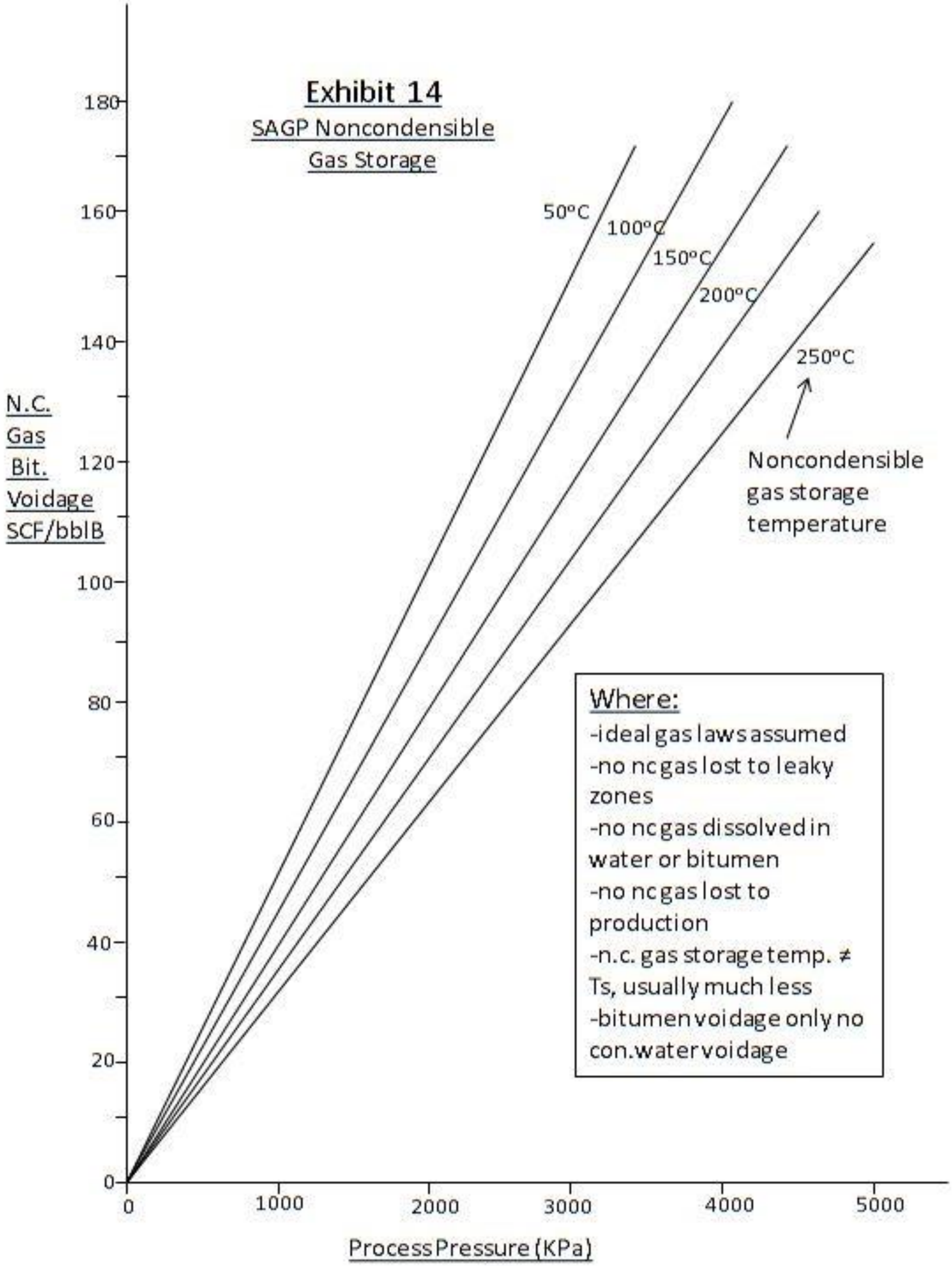


Exhibit 14
SAGP Noncondensible
Gas Storage
N.C.
Gas
Bit.
Voidage
SCF/bblB
0
20
40
60
80
100
120
140
160
180
50ºC
100ºC
150ºC
200ºC
250ºC
Noncondensible
gas storage
temperature
Where:
-ideal gas laws assumed
-no nc gas lost to leaky zones
-no nc gas dissolved in water or bitumen
-no nc gas lost to production
-n.c. gas storage temp. ≠ Ts, usually much less
-bitumen voidage only no con.water voidage
0
1000
2000
3000
4000
5000
Process Pressure (KPa)

Exhibit 15

The ISR Process: Schematic

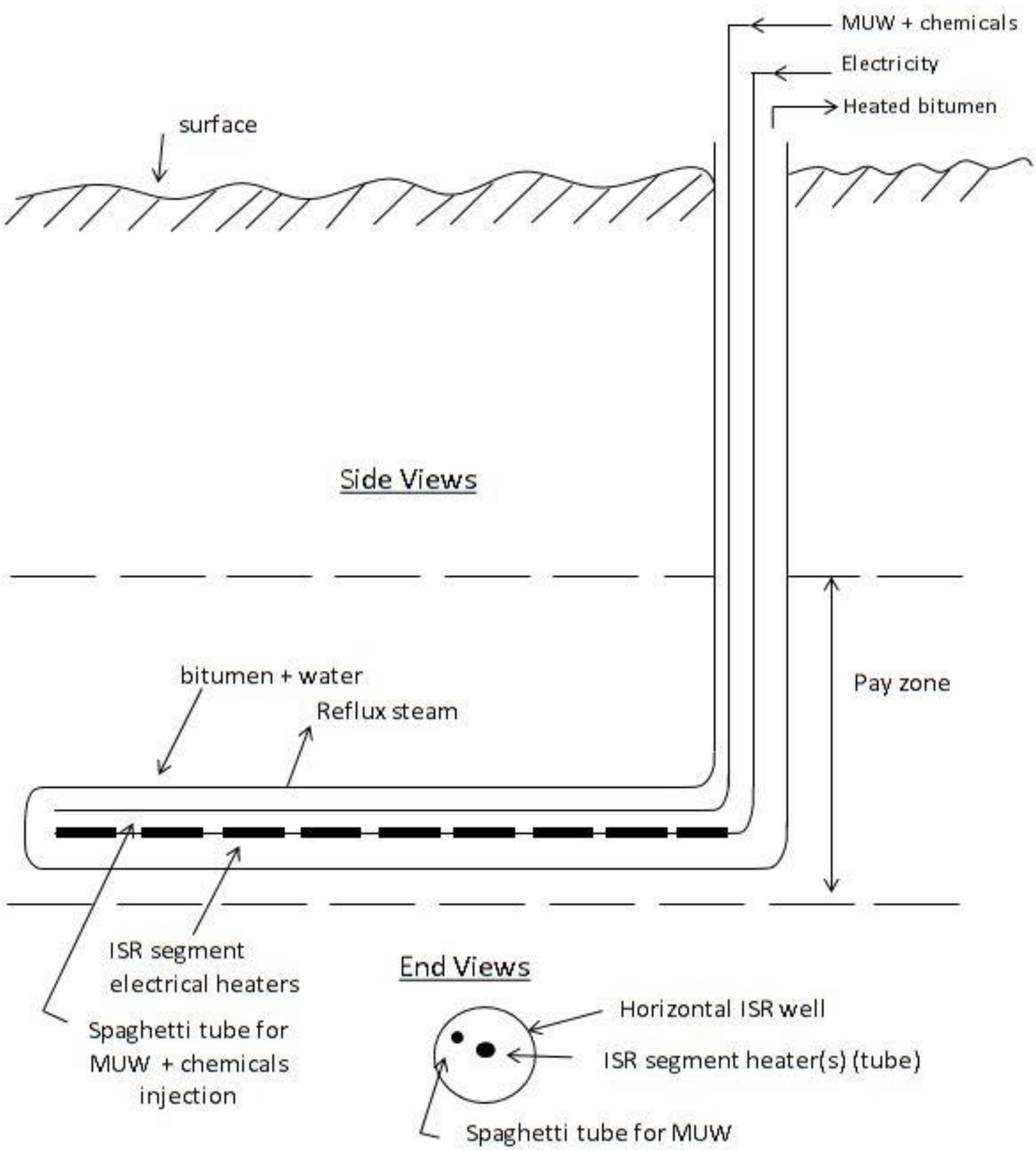


Exhibit 16
Conversion Factors

Parameter	Metric Units	x	Conversion Factor	=	English Units
ETOR	GJ/m^3B		0.1506		MMBTU/bblB
SOR	$m^{3(L)}/m^3B$		1.000		$bbl^{(L)}$ /bblB
Cost	$\$/m^3B$		0.1589		$/bblB
Cost	$\$/m^3gas$		0.28317		$/SCF
Elec. Use	KWh/m^3B		0.1589		KWh/bblB
Gas Use	m^3/m^3B		5.6215		SCF/bblB
CO^2 prod.	m^3/m^3B		5.6125		SCF/bblB
Pressure	KPa		0.14504		psia
Energy	GJ		0.94778		MMBTU
Energy	KWh		3413		BTU
Liquid volume	$m^3(L)$		6.292		bbl
Gas volume	m^3		35.314		SCF
liquid/gas	$m^{3(L)}/m^3$		178174		$bbl^{(L)}$ /MMSCF
heat release	KJ/m^3 gas		0.026839		BTU/SCF

Others: 1 tonne oxygen = 26,173 SCF = 741.14m^3
(kg/m^3B) = (141500)/(API+131.5)
1KWh = 3600 KJ; 1 bbl = 42 USG = 5.611 ft^3
1nM^3 steam = 0.759kg; 1nM^3 CO^2 = 1.855kg; 1nM^3N^2 = 1.1806kg
1nM^3CO = 1.1806kg

Exhibit 17
Key Performance Factors – all processes
Output based on default inputs

Processes	P.Cost $\$/m^3B$	CO2 Tax $\$/m^3B$	ETOR GJ/m^3B	O2 Use m^3/m^3B	SOR m^3L/m^3B	Elec. Use kWh/m^3B	WRR m^3/m^3	TCO2 m^3/m^3B
I SAGD	55.10	1.73	5.2458	-	1.7513	-	0.9927	136.6
II ISR	58.82	1.87	3.0250	-	-	840.3	-	147.6
XV EEOR	211.27	6.71	10.8656	-	-	3018.2	-	530.3
Conv. ISC								
III DISC(A)	49.65	7.07	6.9532	388.8	-	-	-	559.1
IV DISC (O)	31.83	4.49	6.1383	343.2	-	-	-	355.1
V WISC (A)	36.57	5.21	5.1212	286.3	-	-	1.2680	411.8
VI WISC (O)	12.90	1.82	2.4886	139.2	-	-	1.0756	143.9
Hybrids								
VII BWISC (A) + S	38.51	5.31	5.314	289.6	0.0489	-	1.2899	420.2
VIII BWISC (O) + S	34.30	3.70	5.522	259.1	0.318	-	1.2441	292.9
IX BDISC (A) + S	60.48	6.00	7.249	289.1	0.747	-	1.2899	474.7
X BDISC (O) + S	53.52	4.32	7.249	259.1	0.9375	-	1.2441	341.2
XI UWISC (A) + S	61.36	2.22	7.334	289.5	0.776	-	1.1654	476.8
XII UWISC (O) + S	25.31	6.03	3.5959	139.82	0.3923	-	1.2791	175.3
XIII UDISC (A) + S	83.84	8.24	10.011	395.5	1.059	-	1.2680	651.4
XIV UDISC (O) + S	68.69	6.01	9.752	379.5	1.065	-	1.3217	475.7

where: U = unbalanced; B = balanced; W = wet; D = dry; A = air; O = oxygen; S = Steam

Exhibit 18
Diagnostic Factors – all processes
Output based on default inputs

Processes	Ts °C	µs cp	PWOR m^3/m^3B	R1	R2	Rs	Wet Vent Gas m^3/m^3B	BF PV
I SAGD	204.8	10.06	1.7385	-	-	-	-	-
II ISR	204.8	10.06	0	-	-	-	-	-
XV EEOR	204.8	10.06	0	-	-	-	-	-
Conv. ISC								
III DISC (A)	146.2	44.89	0.2722	0.3952	-	0.2363	1911.1	0.1189
IV DISC (O)	185.6	15.05	0.3133	0.2999	-	0.08907	310.4	0.1068
V WISC (A)	175.6	19.12	0.9729	0.9686	1.7995	0.1120	1407.5	0.09116
VI WISC (O)	197.4	11.66	1.0391	0.7705	1.8765	0.06840	253.4	0.08941
Hybrids								
VII BWISC (A) + S	175.1	19.34	0.954	1.000	2.000	0.114	1423	0.092
VIII BWISC (O) + S	198.8	11.31	1.174	1.000	2.000	0.067	234	0.083
IX BDISC (A) + S	175.1	19.34	0.954	1.000	-	0.114	1423	0.092
X BDISC (O) + S	198.8	11.31	1.174	1.000	-	0.067	234	0.083
XI UWISC (A) + S	185.0	15.25	1.711	1.563	1.793	0.090	1423	0.092
XII UWISC (O) + S	200.5	10.93	1.004	1.379	1.703	0.065	126	0.047
XIII UDISC (A) + S	175.6	19.08	1.259	1.022	-	0.112	1944	0.121
XIV UDISC (O) + S	197.8	11.55	1.322	0.846	-	0.068	343	0.117

where: U = unbalanced; B = balanced; W = wet; D = dry; A = air; O = oxygen; S = steam

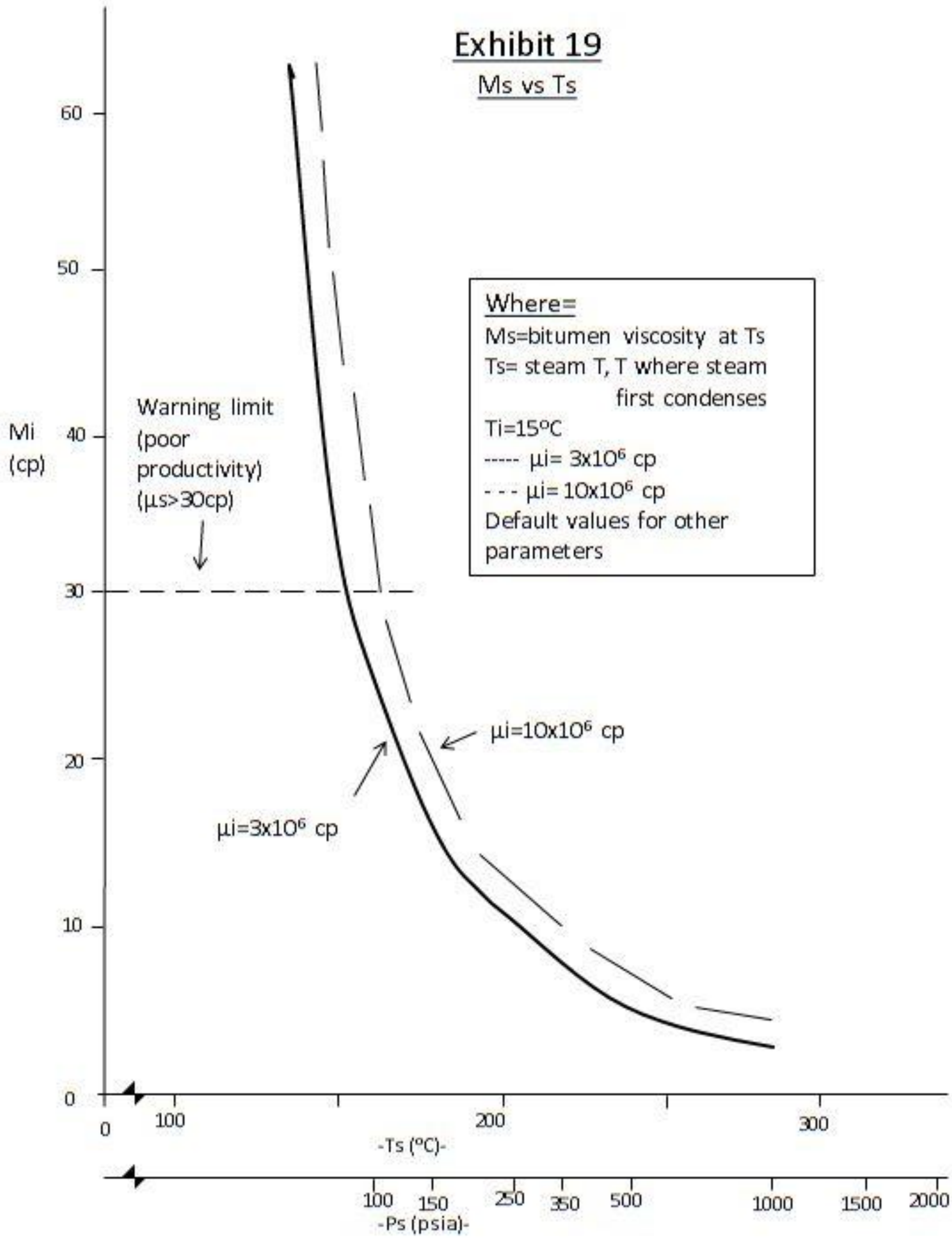


Exhibit 19
Ms vs Ts
Where=
Ms=bitumen viscosity at Ts
Ts= steam T, T where steam first condenses
Ti=15°C
----- μi= 3x10⁶ cp
- - - μi= 10x10⁶ cp
Default values for other parameters
Warning limit (poor productivity) (μs>30cp)
Mi (cp)
μi=10x10⁶ cp
μi=3x10⁶ cp
0 10 20 30 40 50 60
0 100 200 300
-Ts (°C)-
100 150 250 350 500 1000 1500 2000
-Ps (psia)-

Exhibit 20
Input (Default) Indirect CO2 Emission Factors

Factor, Symbol	Metric	English	Process Applicability	Rationale
CO_2/steam, I_S	78 $m^3/m^3_{(L)}$	437.8 SCF/bbl	I, VII to XIV	gas-fired boiler
CO_2/elect., I_E	0.1757 m^3/kWh	6.205 SCF/kWh	II, XV	gas-fired, combined cycle powerplant at 55% efficiency
CO_2/steam, I_O	0.093 m^3/m^3	0.093 SCF/SCF	IV, VI, VIII, X, XII, XIV	large cryogenic plant
CO_2/steam, I_A	0.02 m^3/m^3	0.02 SCF/SCF	III, V, VII, IX, XI, XIII	gas-fired compressors
CO_2 vent gas treating, I_V	0.10 m^3/m^3	0.10 SCF/SCF	III to XIV	gas-fired incineration

Exhibit 21
Input (Default) Cost Factors

Cost Factor, Symbol	**Metric**	**English**	**Process Applicability**	**Rationale**
Steam (Cs)	31.46 $/m3(L)	5.00 ($/bbl)	I, VII to XIV	gas-fired boiler at 85% efficiency
Electricity (C_E)	0.07 $/kWh	0.07 $/kWh	II, XV	industrial costs
Oxygen (Co)	0.08475 $/m3	2.4 $/MCF	IV, VI, VIII, X, XII, XIV	central cryogenic plant at $62.81/tonne. No extra cost for compression – flash liquid O_2 at desirable process P
C. Air (C_A)	0.1766 $/m3	0.5 $/MSCF	III, V, VII, IX, XI, XIII	gas-fired air compressors, no cost escalation for increased P
Vent Treating (Cv)	0.00833 $/m3	0.25 $/MSCF	III to XIV	incineration using $2.5 MSCF methane fuel
CO2 taxes (C_{Co2})	0.01265$/m3	0.35815 $/MSCF	All processes D+I sources	carbon tax at 25 $/tonne

where:

(1) All cost factors are for utility + over-thE.fence supplies and contain capex and opex charges
(2) (L) = liquid
(3) All m3 and SCF/MSCF gas volumes are at standard/normal conditions
(4) Natural gas/fuel costs = 2.5 $/MSCF

Exhibit 22
ALERTS and WARNINGS

Input ALERTS		Triggers	Applicability
ALERT 1 -	"Excessive Heat Losses"	$(L_R + Qwh – Qsf) > 1$	B
		f_{EH} . 1, $f_{HR} > 1$ or $f_{RD} > 1$	XV
ALERT 2 -	"Excessive Liquid Saturation"	$(Siw + Sib) > 1$	A
ALERT 3 -	"Gas Void"	$(Siw + Sib) < 1$	A
ALERT 4 -	"Fuel too light"	$\chi > 1.5$	C
ALERT 5 -	"Excessive Srw"	$Srw > Siw$	A

Output WARNINGS			
WARNING 1 -	"The SZ is unstable"	$R_1 < 1$	C
WARNING 2 -	"The CZ may be unstable"	$R_2 < 2$	D
WARNING 3 -	"There is not enough fuel"	$B_F > Srb$	C
WARNING 4 -	"There may not be enough fuel"	$B_F > 0.5$ Srb	
WARNING 5 -	"Leaky reservoir"	$P < 0.8$ Pi or $0.8 P_H$, or	A
		$P > 1.2$ Pi or $1.2 P_H$	A
WARNING 6 -	"Productivity may be poor"	$\mu s > 50cp$	A
WARNING 7 -	"There is no SZ"	$Tv \leq Ts$	C

Applicability codes

A = All processes (I to XV)
B = processes with a steam component (I, VII to XIV)
C = combustion processes (III to XIV)
D = wet combustion processes (VII, VIII, XI, XII)

Exhibit 23
Comparison – Steam + Electric + Conventional ISC Processes
Outputs based on default inputs

Performance Factors	**I SAGD**	**II ISR**	**XV EEOR**	**III ISC(A)**	**IV ISC(O)**	**V WISC(A)**	**VI WISC(O)**
Process Cost ($/m^{3}B)	55.10	58.82	211.27	49.65	31.83	36.57	12.90
CO_2 tax ($/m^{3}B)	1.73	1.87	6.71	7.07	4.49	5.21	1.82
Total cost + tax ($/m^{3}B)	56.82	60.69	217.98	56.73	36.32	41.78	14.72
ETOR (GJ/m^{3}B)	5.2458	3.0250	10.8656	6.9532	6.1383	5.1212	2.489
PWOR (m^3/m^{3}B)	1.7385	0	0	0.2722	0.3133	0.9729	2.005
WRR (m^3/m^3)	0.9927	0	0	-	-	1.2680	1.076
MUW (m^3/m^{3}B)	0.1867	0.01403	0	-	-	-	-
Ts (°C)	204.8	204.8	204.8	146.2	185.6	175.6	197.8
µs (cp)	10.06	10.06	10.06	44.89	15.05	19.12	11.55
SOR (m^{3}L/m^{3}B)	1.7513	-	-	-	-	-	-
r.f. –	0.8125	0.8125	0.8125	0.8513	0.8664	0.8861	0.9412
Elec. Use (kwh/m^{3}B)	-	840.3	3018.2	-	-	-	-
D CO_2 (m^3/m^{3}B)	0	0	0	330.9	292.1	243.7	118.4
I CO_2 (m^3/m^{3}B)	136.6	147.6	530.3	228.2	63.0	168.1	25.5
T CO_2 (m^3/m^{3}B)	136.6	147.6	530.3	559.1	355.1	411.8	144.0
R_1 –	-	-	-	0.3952	0.2999	0.9686	0.8456
R_2 –	-	-	-	-	-	1.7995	1.7040
Rs –	-	-	-	0.2363	0.08907	0.1120	0.06840
Oxygen use (m^3/m^{3}B)	-	-	-	388.8	343.2	286.3	139.2
Air use (m^3/m^{3}B)	-	-	-	1856.0	-	1367.0	-
Vent gas (wet) (m^3/m^{3}B)	-	-	-	1911.1	310.4	1407.5	125.9
BF PV	-	-	-	0.1189	0.1068	0.09116	0.471
P/PH	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Exhibit 23(a)
ISC + Steam Hybrids : Performance Factors

	Balanced Hybrids				Unbalanced Hybrids			
Performance Factors	**VII WISC (A) + S**	**VIII WISC (O) + S**	**IX DISC (A) + S**	**X DISC (O) + S**	**XI WISC (A) + S**	**XII WISC (O) + S**	**XIII DISC (A) + S**	**XIV DISC (O)**
Process Cost ($/$m^3$B)	38.52	34.04	60.48	53.52	61.36	25.31	83.84	68.69
CO_2 tax ($/$m^3$B)	5.32	3.71	6.01	4.32	6.03	2.22	8.24	6.01
Total cost + tax ($/$m^3$B)	43.84	37.75	66.49	57.84	67.39	27.53	92.08	74.70
Ts (°C)	175.06	198.79	175.06	198.79	184.95	200.48	175.60	197.77
ETOR (GJ/m^3B)	5.3140	5.5216	7.2494	7.2492	7.3335	3.5959	10.0108	9.7575
PWOR (m^3/m^3B)	0.9542	1.1742	0.9542	1.1742	1.7105	1.0037	1.2590	1.3218
SOR (m^3/m^3B)	0.0489	0.3183	0.7471	0.9375	0.7756	0.3923	1.0596	1.0648
WRR (m^3/m^3)	1.2773	1.2525	1.2773	1.2525	1.1027	1.2791	1.1882	1.2413
Oxygen use (m^3/m^3B)	289.55	259.07	289.55	259.07	289.46	139.82	395.48	379.49
Air use (m^3/m^3B)	1382.32	-	1382.32	-	1381.89	-	1888.01	-
Vent gas (wet) (m^3/m^3B)	1423.29	234.33	1423.29	234.33	1422.86	126.47	1943.98	343.25
S_{IR} x 10^4 (m3/m^3 A)	0.3534	-	5.405	-	5.6125*	-	5.6125*	-
S_{IR} x 10^3 (m3/m3 ox.)	-	12.30	-	36.20	-	28.06*	-	28.06*
W_{IR} x 10^4 (m3/m3 air)	5.0511	-	0	-	5.6125*	-	0*	-
W_{IR} x 10^3 (m3/m3 ox.)	-	23.90	-	0	-	28.06*	-	0*
D CO_2 (m^3/m^3B)	246.43	220.48	246.43	220.48	246.35	118.99	336.58	322.97
I CO_2 (m^3/m^3B)	173.79	72.37	228.28	120.69	230.45	56.27	314.85	152.72
T CO_2 (m^3/m^3B)	420.21	292.85	474.70	341.17	476.80	175.27	651.43	475.68
R_1 -	1.000*	1.000*	1.000*	1.000*	1.5629	1.3788	1.0215	0.8455
R_2 -	2.000*	2.000*	-	-	1.7926	1.7025	-	-
R_3 -	0.1135	0.0669	0.1135	0.0669	0.09039	0.06458	0.1121	0.06835
µs (cp)	19.34	11.31	19.34	11.31	15.25	10.93	19.08	11.55
BF (PVF)	0.09206	0.08338	0.09206	0.08338	0.09204	0.04727	0.1207	0.1165
r.f. –	0.8849	0.8958	0.8849	0.8958	0.8850	0.9409	0.8492	0.8544
P/PH -	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

where: * = input values

- Default input values

Exhibit 24
Cost Breakdowns ($/m^{3}B)

←--------------------------Process Costs-------------------------→ ←------------taxes-----------→

Processes	**Steam**	**Air/Ox**	**Elec.**	**Vent Treating**	**Total Process Cost**	**DCO_2 Tax**	**I CO_2 Tax**	**Total Cost & Tax**
I SAGD	55.45	0	0	0	55.45	0	1.74	57.19
II ISR	0	0	53.34	0	53.34	0	1.69	55.03
XV EEOR	0	0	243.21	0	243.21	0	7.72	250.93
Conv. ISC								
III DISC (A)	0	32.80	0	16.89	49.69	4.19	2.89	56.77
IV DISC (O)	0	31.94	0	3.01	34.95	4.06	0.87	39.88
V WISC (A)	0	24.18	0	12.45	36.62	3.09	2.13	41.83
VI WISC (O)	0	11.79	0	1.11	12.90	1.50	0.23	14.72
B. Hybrids								
VII BWISC (A) + S	1.54	24.41	0	12.57	38.51	3.12	2.20	43.82
VIII BWISC (O) + S	10.01	21.96	0	2.07	34.04	2.79	0.92	37.75
IX BDISC (A) + S	23.50	24.41	0	12.57	60.48	3.12	2.89	66.48
X BDISC (O) + S	29.49	21.96	0	2.07	53.52	2.79	1.53	57.84
U.Hybrids								
XI UWISC (A) + S	24.40	24.40	0	12.56	61.36	3.12	2.92	67.39
XII UWISC (O) + S	12.34	11.85	0	1.12	25.31	1.51	0.71	27.53
XIII UDISC (A)+ S	33.34	33.34	0	17.17	83.84	4.26	3.98	92.08
XIV UDISC (O) + S	33.50	32.16	0	3.03	68.69	4.09	1.93	74.70

where: U = unbalanced; B = balanced; W = wet; D = dry; A = Air; O = oxygen; S = steam

Exhibit 25
CO_2 Emission Breakdown (m^3CO_2/m^3B)

←DCO_2→←-------------------- -- --Indirect CO_2---------------------------------→(D + I)

Processes	D CO_2	V. G. Treating	Elec. Prod.	Steam. Prod.	Air Comp.	O2 Prod.	T I CO_2	D + I T CO_2
I SAGD	0	0	0	137.5	0	0	137.5	137.5
II ISR	0	0	133.9	0	0	0	133.9	133.9
XV EEOR	0	0	610.5	0	0	0	610.5	610.5
Conv. ISC								
III DISC (A)	331.2	191.3	0	0	37.2	0	228.5	559.7
IV DISC (O)	320.8	34.1	0	0	0	35.0	69.1	389.9
V WISC (A)	244.0	141.0	0	0	27.4	0	168.4	412.4
VI WISC (O)	118.4	12.6	0	0	0	12.9	25.5	143.9
Balanced Hybrids								
VII BWISC (A) + S	246.4	142.3	0	3.8	27.6	0	173.8	420.2
VIII BWISC (O) + S	220.5	23.4	0	24.8	0	24.1	72.4	292.9
IX BDISC (A) + S	246.4	142.3	0	58.3	27.6	0	228.3	474.7
X BDISC (O) + S	220.5	23.4	0	73.1	0	24.1	120.7	341.2
Unbalanced Hybrids								
XI UWISC (A) + S	246.4	142.3	0	60.5	27.6	0	230.5	476.8
XII UWISC (O) + S	119.0	12.6	0	30.6	0	13.0	56.3	175.3
XIII UDISC (A)+ S	336.6	194.4	0	82.6	37.8	0	314.9	651.4
XIV UDISC (O) + S	323.0	34.3	0	83.1	0	35.3	152.7	475.7

where: DCO_2 – from ISC vent gas (CO_2 + CO), only

D = direct, I = indirect

U = Unbalanced, B = Balanced, W = Wet, D = Dry, A = Air, O = oxygen, S = steam, T = total

V6 = vent gas (from ISC)

Exhibit 25(a)
CO_2 Emission with ISC(O) Vent Gas Sequestered (m^3CO_2/m^3B)

←DCO_2→←-------------------- -- --Indirect CO_2----------------------→(D + I)

Processes	D CO_2	V. G. Treating	Elec. Prod.	Steam. Prod.	Air Comp.	O2 Prod.	T I CO_2	D + I T CO_2
I SAGD	0	0	0	137.5	0	0	137.5	137.5
II ISR	0	0	133.9	0	0	0	133.9	133.9
XV EEOR	0	0	610.5	0	0	0	610.5	610.5
Conv. ISC								
III DISC (A)	331.2	191.3	0	0	37.2	0	228.5	559.7
IV DISC (O)	320.8	34.1	0	0	0	35.0	35.0	35.0
V WISC (A)	244.0	141.0	0	0	27.4	0	168.4	412.4
VI WISC (O)	0	0	0	0	0	12.9	12.9	12.9
Balanced Hybrids								
VII BWISC (A) + S	246.4	142.3	0	3.8	27.6	0	173.8	420.2
VIII BWISC (O) + S	0	0	0	24.8	0	24.1	48.9	48.9
IX BDISC (A) + S	246.4	142.3	0	58.3	27.6	0	228.3	474.7
X BDISC (O) + S	0	0	0	73.1	0	24.1	97.2	97.2
Unbalanced Hybrids								
XI UWISC (A) + S	246.4	142.3	0	60.5	27.6	0	230.5	476.8
XII UWISC (O) + S	0	0	0	30.6	0	13.0	43.6	43.6
XIII UDISC (A)+ S	336.6	194.4	0	82.6	37.8	0	314.9	651.4
XIV UDISC (O) + S	0	0	0	83.1	0	35.3	118.4	118.4

where: DCO_2 – from ISC vent gas (CO_2 + CO), only

D = direct, I = indirect

U = Unbalanced, B = Balanced, W = Wet, D = Dry, A = Air, O = oxygen, S = steam, T = total

V6 = vent gas (from ISC)

Exhibit 26
Environmental Factor Comparisons

	CO2	Water	Resource	Energy Use Factors				
Processes	**Total CO2 (m^3/m^3B)**	**WRR (m^3/m^3)**	**r.f.**	**ETOR (GJ/m^3B)**	**SOR m^3L/m^3B)**	**O2 Use (m^3/m^3B)**	**Elec. Use (KWh/m^3B)**	**Air use (m^3/m^3B)**
I SAGD	137.5	0.993	0.813	4.755	1.762	0	0	0
II ISR	133.9	0	0.813	2.743	0	0	0	0
XV EEOR	610.5	-	0.813	12.508	-	0	3474.5	0
Conv. ISC								
III DISC (A)	559.7	-	0.851	6.960	-	389.2	0	1857.9
IV DISC (O)	389.9	-	0.855	6.740	-	376.9	0	-
V WISC (A)	412.4	1.268	0.886	5.128	-	286.8	0	1368.9
VI WISC (O)	143.9	1.076	0.941	2.489	-	139.2	-	-
Balanced Hybrids								
VII BWISC (A) + S	420.2	1.277	0.885	5.314	0.049	289.6	0	1382.3
VIII BWISC (O) + S	292.9	1.253	0.896	5.522	0.318	259.1	0	-
IX BDISC (A) + S	474.7	1.277	0.885	7.249	0.747	289.6	0	1382.3
X BDISC (O) + S	341.2	1.253	0.896	7.249	0.938	259.1	0	-
Unbalanced Hybrids								
XI UWISC (A) + S	476.8	1.103	0.885	7.334	0.776	289.5	0	1381.9
XII UWISC (O) + S	175.3	1.279	0.941	3.596	0.392	139.8	0	-
XIII UDISC (A)+ S	651.4	1.188	0.849	10.011	1.060	395.5	0	1888.0
XIV UDISC (O) + S	475.7	1.241	0.854	9.758	1.065	379.5	0	-

where: default input values

U = unbalanced, B = balanced, W = wet, D = dry, O = oxygen, S = steam, A = air

Exhibit 27
Water Use Issues
Output based on default inputs

Processes	PWOR (m^3/m^3B)	SOR (m^3/m^3B)	IWOR (m^3/m^3B)	WRR (m^3/m^3)	Rs (fraction)	RWS (m^3/m^3B)	MUW (m^3/m^3B)
I SAGD	1.7496	1.7624	-	0.9927	-	-0.0128	0.2086
II ISR	-	-	-	-	-	-	0.00171
XV EEOR	-	-	-	-	-	-	-
Conv. ISC							
III DISC (A)	0.2723	0	0	0	0.2362	0.2723	-0.2723
IV DISC (O)	0.3216	0	0	0	0.0893	0.3216	-0.3216
V WISC (A)	0.9739	0	0.7683	1.2676	0.1121	0.2056	-0.2056
VI WISC (O)	2.0049	0	1.8640	1.0756	0.0684	0.1409	-0.1409
Balanced Hybrids							
VII BWISC (A) + S	0.9542	0.0489	0.6981	1.2773	0.1135	0.2072	-0.2018
VIII BWISC (O) + S	1.1742	0.3183	0.6192	1.2525	0.0669	0.2367	-0.2013
IX BDISC (A) + S	0.9542	0.7471	0	1.2773	0.1135	0.2071	-0.1241
X BDISC (O) + S	1.1742	0.9375	0	1.2525	0.0669	0.2367	-0.1325
Unbalanced Hybrids							
XI UWISC (A) + S	1.7105	0.7756	0.7756	1.1027	0.0904	0.1593	-0.0731
XII UWISC (O) + S	1.0037	0.3923	0.3924	1.2791	0.0646	0.2190	-0.1754
XIII UDISC (A)+ S	1.2590	1.0596	0	1.1882	0.1121	0.1994	-0.0817
XIV UDISC (O) + S	1.3218	1.0648	0	1.2413	0.0684	0.2570	-0.1387

where: U = unbalanced; B = balanced; W = wet; D = dry; A = Air; O = oxygen; S = steam

IWOR=(PWOR/WRR)-SOR

MUW = steam voidage replacement, otherwise

MUW = (IWOR + $\frac{SOR}{0.9}$) – PWOR, assuming 90% PW recycle

WRR = PWOR/(SOR+IWOR)

RWS = PWOR-(SOR+IWOR)

Negative MUW indicates a water surplus for the process

Exhibit 28
ISC Process Comparisons : Performance Factors

Performance Factors	**III** **Dry ISC (Air)**	**IV** **Dry ISC (O_2)**	**V** **Wet ISC (Air)**	**VI** **Wet ISC (O_2)**
Process Cost $/$m_3$B)	49.69	34.95	36.62	12.90
CO2 Tax $/$m_3$B	7.08	4.93	5.22	1.82
Total Cost + Tax $/$m_3$B	56.77	39.88	41.83	14.72
ETOR GJ/m_3B	6.9601	6.7403	5.1284	2.4886
Ts °C	146.21	185.47	175.58	197.75
PWOR m_3/m_3B	0.2723	0.3216	0.9739	2.0049
WRR m_3/m_3	-	-	1.2676	1.0756
Oxygen Use m_3/m_3B	389.16	376.88	286.75	139.15
Air Use m_3/m_3B	1857.87	-	1368.93	-
Vent Gas (wet) m_3/m_3B	1912.94	340.89	1409.51	125.86
R1 -	0.3966	0.3017	1.0216	0.8456
R2 -	-	-	1.7995	1.7040
Rs -	0.2362	0.0893	0.1121	0.06838
µs cp	44.77	15.07	19.09	11.55
P/P_H -	1.000	1.000	1.000	1.000
BF (PVF)	0.1190	0.1158	0.09127	0.04705
D CO2 m_3/m_3B	331.20	320.75	244.04	118.42
I CO2 m_3/m_3B	228.45	69.14	168.33	25.53
T CO2 m_3/m_3B	559.66	389.88	412.37	143.95
r.f. -	0.8512	0.8552	0.8859	0.9412
$Wi_R \times 10^4$ (m3/m3ox)	0*	0*	-	28.06*
(m3/m3air)	0*	0*	5.6125*	-

Exhibit 29
SHT Process Comparison
Tax + Cost Components ($/m$_3$B)

Cost/Tax Components	**I SAGD**	**II ISR**	**VII WISC(A)+S**	**VIII WISC(O)+S**	**IX DISC(A)+S**	**X DISC(O)+S**
(i) Injectants:						
steam	55.10	-	4.01	10.97	27.71	30.25
air comp.	-	-	26.36	-	26.36	-
oxygen	-	-	-	21.73	-	21.73
electricity	-	58.82	-	-	-	-
(ii) Vent Gas Treating	-	-	12.80	1.93	12.80	1.93
Total Process Costs	55.10	58.82	43.17	34.64	66.87	53.92
(iii) CO_2 Taxes:						
direct emissions (vent)	-	-	3.37	2.76	3.37	2.76
vent gas incineration	-	-	1.94	0.29	1.94	0.29
air compression	-	-	0.38	-	0.38	-
oxygen (ASU) production	-	-	-	0.30	-	0.30
steam production	1.73	-	0.13	0.34	0.87	0.95
electricity production	-	1.87	-	-	-	-
Total CO2 Tax	1.73	1.87	5.81	3.70	6.56	4.30
Total Cost + Tax	56.82	60.69	48.98	38.34	73.43	58.22

where: SAGDOX = VIII or X : SHT = Steam Heat Transfer at leading edge

Exhibit 30
SHT Process Comparison
Key Performance Factors

Balanced Hybrids

Performance Factors	**I SAGD**	**II ISR**	**VII WISC(A)+S**	**VIII WISC(O)+S**	**IX DISC(A)+S**	**X DISC(O)+S**
Process Cost ($/m3B)	55.10	58.82	43.17	34.64	66.87	53.92
CO2 Taxes ($/m3B)	1.73	1.87	5.81	3.70	6.56	4.30
ETOR (GJ/m3B)	5.246	3.025	5.946	5.560	8.035	7.270
SOR (m3L/m3B)	1.739	-	0.127	0.349	0.881	0.962
Air use (m3/m3B)	-	-	1492.8	-	1492.8	-
Oxygen use (m3/m3B)	-	-	312.7	256.4	312.7	256.4
PWOR (m3/m3B)	1.739	0	0.9627	1.1964	0.9627	1.1964
WRR (m3/m3)	0.993	-	1.2899	1.2441	1.2899	1.2441
WIR x 10^3 (m^3L/m^3ox)	-	-	-	2.390	-	-
WIR x 10^4 (m^3L/m^3air)	-	-	5.047	-	-	-
SIR x 10^3 (m^3L/m^3ox)	-	-	-	1.360	-	3.75
SIR x 10^4 (m^3L/m^3air)	-	-	0.853	-	5.900	-
Ts (°C)	204.8	204.8	176.6	199.0	176.6	199.0
µs (cp)	10.06	10.06	18.65	11.28	18.65	11.28
B_F (PV)	-	-	0.0985	0.0826	0.0985	0.0826
D CO2 (m3/m3B)	0	0	266.1	218.2	266.1	218.2
I CO2 (m3/m3B)	136.6	147.6	193.5	74.3	252.3	122.0
Vent Gas (wet) (m3/m3B)	-	-	1537.0	231.9	1537.0	231.9
r.f. -	0.8125	0.8125	0.8769	0.8967	0.8769	0.8967

where: SAGDOX = VIII or X : SHT = Steam Heat Transfer at leading edge

Exhibit 31
SHT Process Comparison
Environmental Factors

Balanced Hybrids

Factors	**I SAGD**	**II ISR**	**VII WISC(A)+S**	**VIII WISC(O)+S**	**IX DISC(A)+S**	**X DISC(O)+S**
(i) Energy (GJ/m3B)						
Steam	5.246	-	0.354	0.974	2.443	2.684
Oxygen/Air	-	-	5.592	4.586	5.592	4.586
Electricity	-	3.025	-	-	-	-
Total ETOR	5.246	3.025	5.946	5.560	8.035	7.270
(ii) Water						
PWOR (m3/m3B)	1.739	0	0.963	1.196	0.963	1.196
WRR (m3/m3)	0.993	0	1.290	1.244	1.290	1.244
MUW (M3/m3)	0.181	0.014	-	-	-	-
(iii) CO2 (m3/m3B)						
Vent gas (CO + CO2)	-	-	266.1	218.2	266.1	218.2
Vent gas incineration	-	-	153.7	23.2	153.7	23.2
Steam production	136.1	-	9.9	27.2	68.7	75.0
Oxygen/air delivery	-	-	29.9	23.8	29.9	23.8
Electricity production	-	147.6	-	-	-	-
Total (D + I) CO2	136.1	147.6	459.6	292.5	518.4	340.3
(iv) Resource Recovery Recovery factor (rf)	0.8125	0.8125	0.8769	0.8967	0.8769	0.8967

where: SAGDOX = VIII or X : SHT = Steam Heat Transfer at leading edge

Exhibit 32
Can WISC be Stabilized by Increasing Rates And Heating Injection Water?

	V WISC (A) (default)	**V WISC (A) (heat inj water Increase water**	**VI WISC (O) Default**	**VI WISC (O) (heat water Increase rates)**
T_{IW} (°C) W_{IR} x 10^4 m^3L/m^3 gas	15 5.6125	Ts = 176.6 5.90	15 28.06	Ts = 198.9 36.5
Process cost	36.57	39.17	12.90	10.86
CO2 tax	5.21	5.69	1.82	1.53
Total cost + tax	41.78	44.85	14.72	12.40
ETOR	5.1212	5.5923	2.4886	2.0950
PWOR	0.9729	0.9627	2.0049	2.1680
WRR	1.2680	1.2899	1.0756	1.0622
Oxygen use	286.35	312.68	139.15	117.13
Air use	1367	1492	-	-
Vent gas (wet)	1408	1537	125.86	105.95
D CO^2	243.7	266.1	118.42	99.7
I CO^2	168.1	183.6	25.52	21.5
T CO^2	411.8	449.7	143.94	121.2
Ts	175.6	176.6	197.8	198.9
μs	19.12	18.65	11.55	11.28
B_F	0.09116	0.09851	0.04705	0.03998
R_1	0.9686	1.0455	0.8456	1.006
R_2	1.7995	2.2985	1.7040	1.845
Rs	0.1120	0.1102	0.06838	0.0668
r.f.	0.8861	0.8769	0.9412	0.9500

where: no costs associated with heated inj. water (recycle of hot produced water)

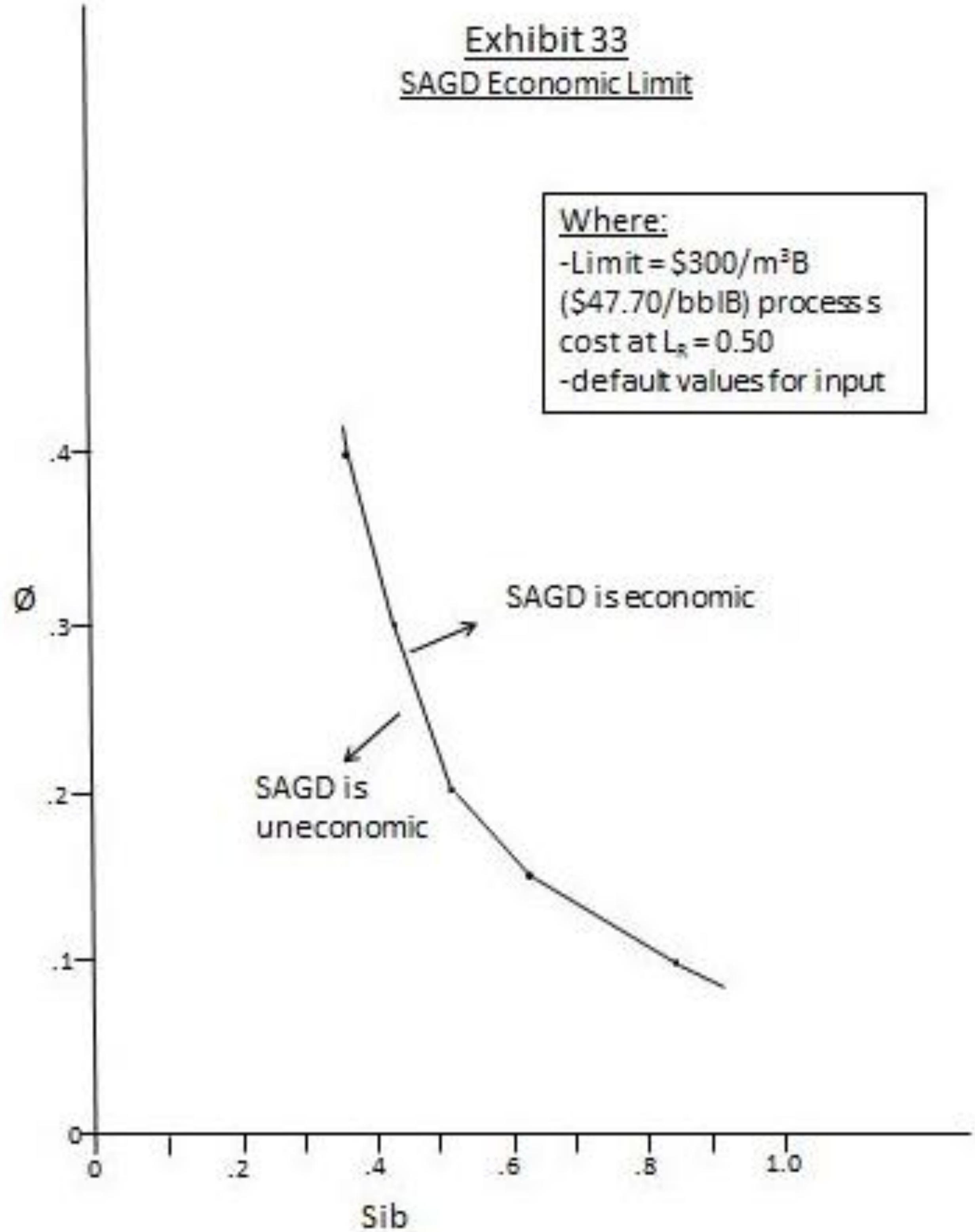


Exhibit 33
SAGD Economic Limit
Where:
-Limit = $300/m³B
($47.70/bblB) process s
cost at L_R = 0.50
-default values for input
SAGD is economic
SAGD is
uneconomic
Ø
.4
.3
.2
.1
0
0
.2
.4
.6
.8
1.0
Sib

Exhibit 34
Pressure Sensitivity – SAGD + ISR

←--------------Process Pressure (kPa)------------→

Performance Factors	Units	1724	2500	3500	4500	5500	7000
Process I = SAGD							
Process Cost	($/$m^3$B)	55.10	74.07	91.27	119.19	157.04	247.34
CO2 Tax	($/$m^3$B)	1.73	2.32	2.86	3.69	4.86	7.64
Total tax + cost	($/$m^3$B)	56.83	76.39	94.13	122.88	161.90	254.98
ETOR	(GJ/m^3B)	5.246	6.377	7.891	10.281	13.526	21.229
SOR	(m^3($_L$)/m^3B)	1.751	2.354	2.901	3.789	4.992	7.862
PWOR	(m3/m3B)	1.739	2.334	2.870	3.743	4.925	7.746
WRR	(m3/m3)	0.9930	0.9915	0.9893	0.9879	0.9867	0.9853
MUW	(m3/m3B)	0.187	0.253	0.318	0.420	0.559	0.890
I CO2	(m3/m3B)	136.60	183.64	226.29	291.94	384.18	604.21
Qsf	Fraction	0.80	0.73	0.65	0.56	0.47	0.34
Hydrostatic depth	(M)	152	221	309	398	486	619
Process II : ISR							
Process Cost	($/m3B)	53.00	57.84	64.66	69.38	73.37	78.43
CO2 tax	($/m3B)	1.68	1.84	2.05	2.20	2.33	2.49
Total tax + cost	($/m3B)	54.68	59.68	66.71	71.58	75.70	80.92
Electricity use	(Kwh/m3B)	757.15	826.34	923.75	991.11	1048.10	1120.44
MUW	(m3/m3B)	0.01403	0.01957	0.02640	0.03298	0.03938	0.04870
I CO2	(m3/m3B)	133.0	145.2	162.3	174.14	184.15	196.86
ETOR	(GJ/m3B)	2.726	2.975	3.326	3.568	3.773	4.034

Where: default case P = 1724 KPa

Except for P, inputs are at default values

For SAGD, Qsf is linearly proportioned to depth (hydrostatic)

(Qsf = 0.950 – 0.0009843d)

MUW for SAGD = SOR – 0.9 PWOR

Hydrostatic depth at 0.5 psia/ft. gradient

Exhibit 35
Pressure Sensitivity – Process VI (WISC(O))

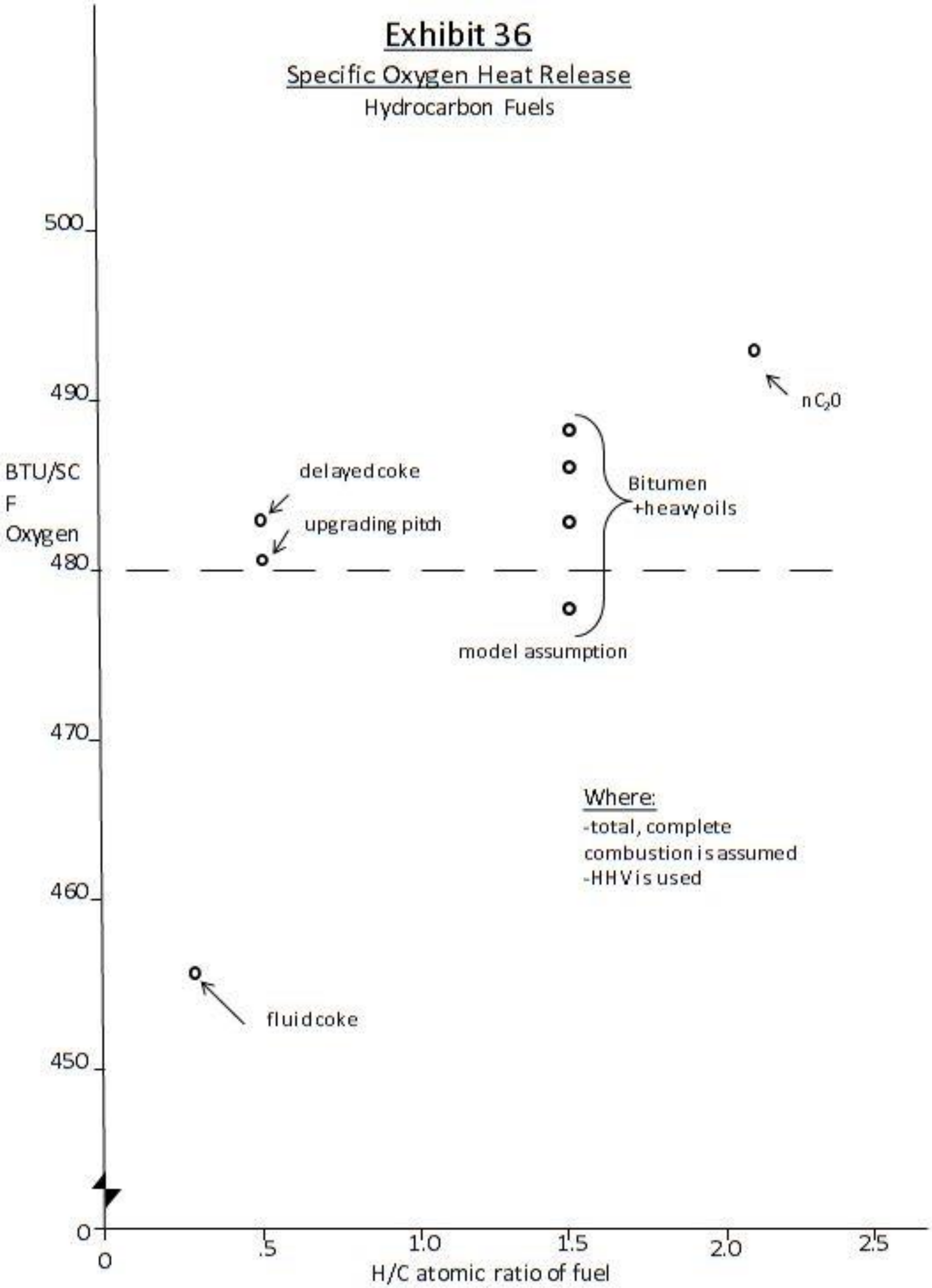
		Process Pressure		
Performance Factors		1724 KPa	3500 KPa	7000 KPa
Process cost	($/$m^3$B)	12.90	13.80	17.81
CO2 tax	($/$m^3$B)	1.82	1.95	2.51
Total cost + tax	($/$m^3$B)	14.72	15.74	20.32
ETOR	(GJ/m^3B)	2.4886	2.6681	3.4472
Oxygen use	(m^3/m^3B)	139.15	149.18	192.75
Vent gas (wet)	(m^3/m^3B)	125.86	130.77	166.46
PWOR	(m^3/m^3B)	2.005	2.212	2.837
WRR	(m^3/m^3)	1.0756	1.1071	1.0986
Ts	°C	197.8	234.37	277.06
R1	-	0.8456	0.6155	0.3138
R2	-	1.7040	1.6918	0.7700
Rs	-	0.06838	0.03355	0.01669
µs	(cp.)	11.55	6.05	3.45
BF	(PVF)	0.04705	0.05024	0.06374
D CO2	(m^3/m^3B)	118.42	126.96	164.04
I CO2	(m^3/m^3B)	25.53	26.95	34.57
T CO2	M^3/m^3B	143.95	153.91	198.61
r.f.	-	0.9412	0.9372	0.9203

Where: default case = 1724 KPa

Exhibit 36

Specific Oxygen Heat Release

Hydrocarbon Fuels



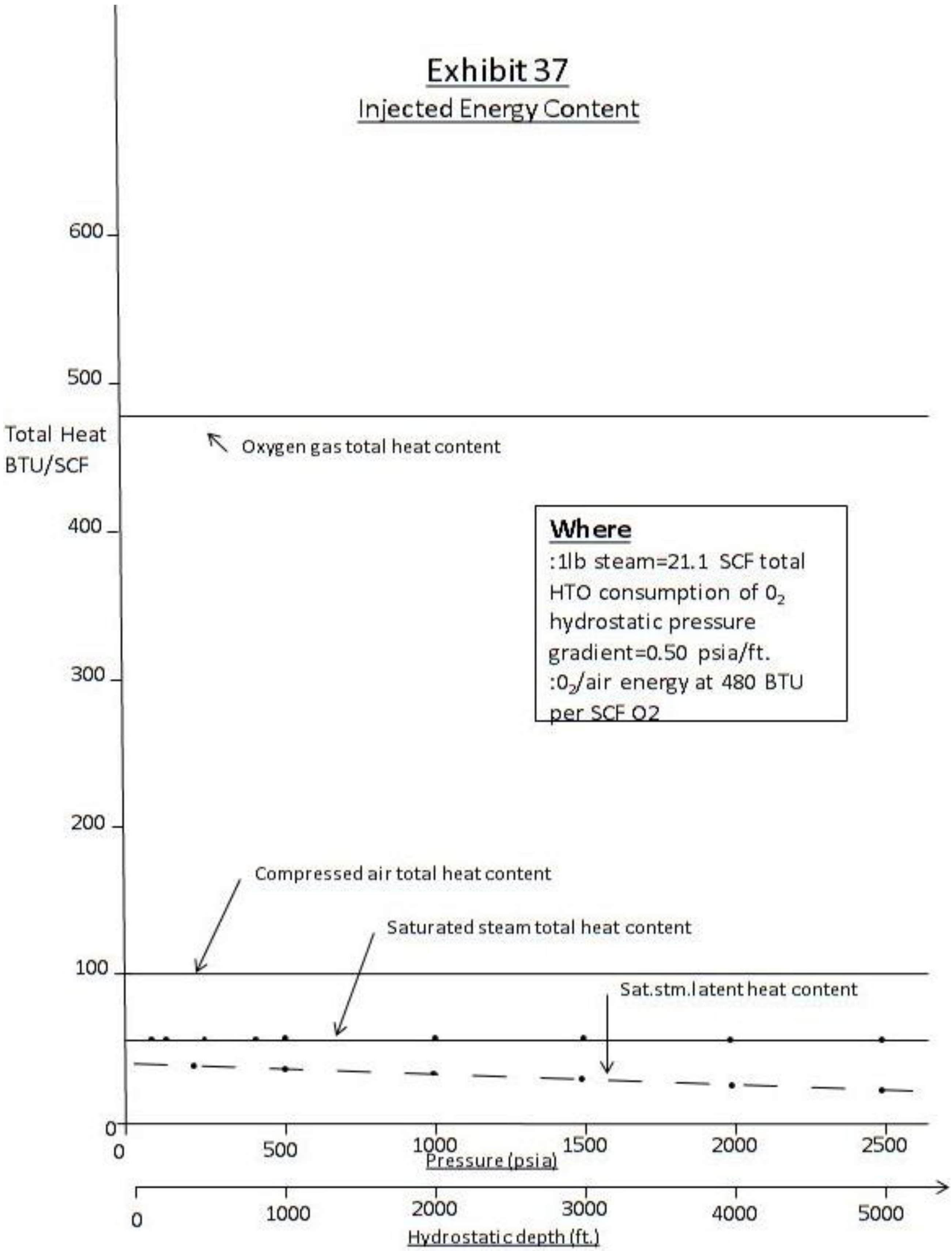


Exhibit 37
Injected Energy Content
600
500
400
300
200
100
0
Total Heat
BTU/SCF
Oxygen gas total heat content
Where
:1lb steam=21.1 SCF total
HTO consumption of O_2
hydrostatic pressure
gradient=0.50 psia/ft.
:O_2/air energy at 480 BTU
per SCF O2
Compressed air total heat content
Saturated steam total heat content
Sat.stm.latent heat content
0
500
1000
1500
2000
2500
Pressure (psia)
0
1000
2000
3000
4000
5000
Hydrostatic depth (ft.)

Exhibit 38

Saturated Steam Properties

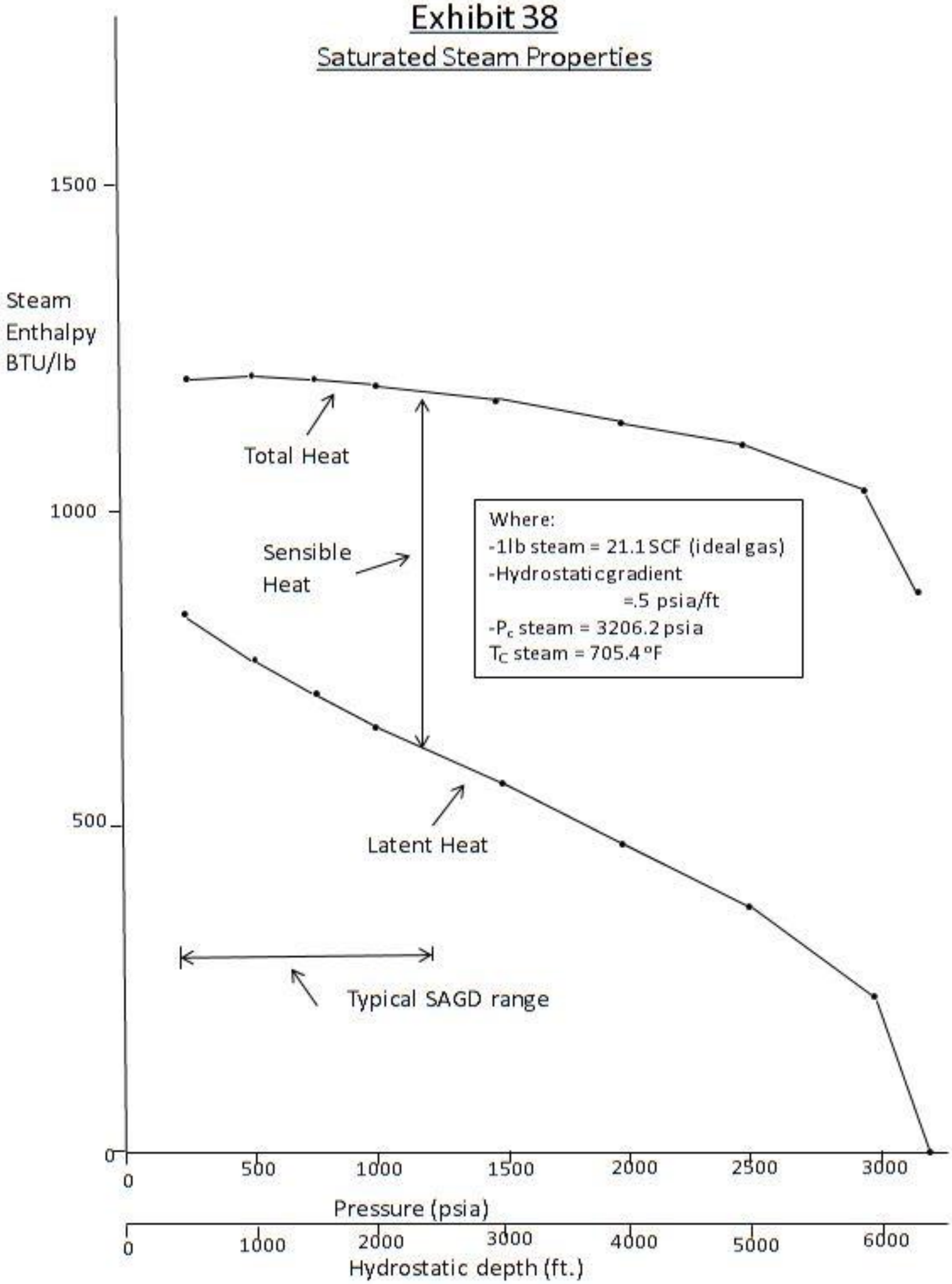


Exhibit 39
ISC + Steam Hybrids : Performance Factors

Balanced Hybrids — Unbalanced Hybrids

Performance Factors	VII WISC (A) + S	VIII WISC (O) + S	IX DISC (A) + S	X DISC (O) + S	XI WISC (A) + S	XII WISC (O) + S	XIII DISC (A) + S	XIV DISC (O)
Process Cost ($/m^{3}B)	38.52	34.04	60.48	53.52	61.36	25.31	83.84	68.69
CO_2 tax ($/m^{3}B)	5.32	3.71	6.01	4.32	6.03	2.22	8.24	6.01
Total cost + tax ($/m^{3}B)	43.84	37.75	66.49	57.84	67.39	27.53	92.08	74.70
Ts (°C)	175.06	198.79	175.06	198.79	184.95	200.48	175.60	197.77
ETOR (GJ/m^{3}B)	5.3140	5.5216	7.2494	7.2492	7.3335	3.5959	10.0108	9.7575
PWOR (m^3/m^{3}B)	0.9542	1.1742	0.9542	1.1742	1.7105	1.0037	1.2590	1.3218
SOR (m^3/m^{3}B)	0.0489	0.3183	0.7471	0.9375	0.7756	0.3923	1.0596	1.0648
WRR (m^3/m^3)	1.2773	1.2525	1.2773	1.2525	1.1027	1.2791	1.1882	1.2413
Oxygen use (m^3/m^{3}B)	289.55	259.07	289.55	259.07	289.46	139.82	395.48	379.49
Air use (m^3/m^{3}B)	1382.32	-	1382.32	-	1381.89	-	1888.01	-
Vent gas (wet) (m^3/m^{3}B)	1423.29	234.33	1423.29	234.33	1422.86	126.47	1943.98	343.25
S_{IR} x 10^4 (m3/m^3 A)	0.3534	-	5.405	-	5.6125*	-	5.6125*	-
S_{IR} x 10^3 (m3/m3 ox.)	-	12.30	-	36.20	-	28.06*	-	28.06*
W_{IR} x 10^4 (m3/m3 air)	5.0511	-	0	-	5.6125*	-	0*	-
W_{IR} x 10^3 (m3/m3 ox.)	-	23.90	-	0	-	28.06*	-	0*
D CO_2 (m^3/m^{3}B)	246.43	220.48	246.43	220.48	246.35	118.99	336.58	322.97
I CO_2 (m^3/m^{3}B)	173.79	72.37	228.28	120.69	230.45	56.27	314.85	152.72
T CO_2 (m^3/m^{3}B)	420.21	292.85	474.70	341.17	476.80	175.27	651.43	475.68
R_1 -	1.000*	1.000*	1.000*	1.000*	1.5629	1.3788	1.0215	0.8455
R_2 -	2.000*	2.000*	-	-	1.7926	1.7025	-	-
R_3 -	0.1135	0.0669	0.1135	0.0669	0.09039	0.06458	0.1121	0.06835
µs (cp)	19.34	11.31	19.34	11.31	15.25	10.93	19.08	11.55
BF (PVF)	0.09206	0.08338	0.09206	0.08338	0.09204	0.04727	0.1207	0.1165
r.f. –	0.8849	0.8958	0.8849	0.8958	0.8850	0.9409	0.8492	0.8544
P/PH -	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Exhibit 40
SAGD, ISR, SWESAGD, EEOR Performance Factors

		SAGD	ISR	EEOR
Performance Factors				
Process Costs	(\$/m^3B)	55.45	53.34	243.21
CO2 Tax	(\$/m^3B)	1.74	1.69	7.72
Cost + Tax	(\$/m^3B)	57.19	55.03	250.93
Ts	(°C)	204.78	204.78	204.78
ETOR	(GJ/m^3B)	4.7545	2.7430	12.5080
PWOR	(m^3/m^3B)	1.7496	0	0
SOR	(m^3/m^3B)	1.7624	-	-
WRR	(m^3/m^3)	0.9927	-	-
MUW	(m^3/m^3B)	0.0878	0.00171	-
D CO2	(m^3/m^3B)	-	-	-
I CO2	(m^3/m^3B)	137.54	133.88	610.49
T CO2	(m^3/m^3B)	137.54	133.88	610.49
Elec. Use.	(KWh/m^3B)	-	761.93	3474.45
P/PH	-	1.000	1.000	1.000
µs	(cp.)	10.04	10.04	10.04
r.f.	-	0.8125	0.8125	0.8125

Where: default inputs

Exhibit 41

Comparison of Stable / Balanced Processes (default input values)

←-------------Hybrids------------→

		I SAGD	II ISR	XV EEOR	VIII wSAGDOX	X dSAGDOX	VII WISC(A)+S	IX DISC(A)+S
Key Performance Factors								
Total cost + tax	($/$m^3$B)	56.82	60.69	217.98	38.34	58.22	48.99	73.43
ETOR	(GJ/m^3B)	5.246	3.025	10.866	5.560	7.270	5.946	8.035
SOR	(m^3L/m^3B)	1.751	-	-	0.3488	0.9616	0.1274	0.8807
Oxygen use	(m^3/m^3B)	-	-	-	256.4	256.4	312.7	312.7
Air use	(m^3/m^3B)	-	-	-	-	-	1493	1493
Electricity use	(Kwh/m^3B)	-	840.3	3018	-	-	-	-
Vent gas (wet)	(m^3/m^3B)	-	-	-	231.9	231.9	1537	1537
Key Diagnostic Factors								
Ts	(°C)	204.8	204.8	204.8	199.0	199.0	176.6	176.6
µs	(cp)	10.06	10.06	10.06	11.28	11.28	18.65	18.65
R_1	-	-	-	-	1*	1*	1*	1*
R_2	-	-	-	-	2*	-	2*	-
Rs	-	-	-	-	0.06665	0.06665	0.1102	0.1102
T CO^2 (D+I)	(m^3/m^3B)	136.6	147.6	530.3	292.5	340.3	459.6	518.4
$W_{IR} \times 10^4$	(m^3L/m^3G)	-	-	-	23.90	0	5.047	0
$S_{IR} \times 10^4$	(m^3L/m^3G)	-	-	-	13.60	37.50	0.8534	5.900
r.f.	-	0.8125	0.8125	0.8125	0.8967	0.8967	0.8769	0.8769

Where: * = input / default value

W_{IR} + S_{IR} units are per m^3 oxygen or m^3 air, depending on the process

Exhibit 42
The Effect of Heat Losses on SAGD Performance

←------------Reservoir Heat Loss (L_R)------------→

		0.1	0.3	0.5	0.7
Process Cost	($/$m^3$B)	55.10	70.72	109.04	164.48
CO2 Tax	($/$m^3$B)	1.73	2.22	3.10	5.16
T cost + tax	($/$m^3$B)	56.83	72.94	112.14	169.64
ETOR	(GJ/m^3B)	5.246	6.734	9.408	15.661
SOR	($m^3_{(L)}$/m^3B)	1.751	2.248	3.142	5.228
PWOR	(m^3/m^3B)	1.739	2.235	3.129	5.215
WRR	(m^3/m^3)	0.993	0.994	0.996	0.998
MUW	(m^3/m^3B)	0.187	0.236	0.326	0.534
I CO2	(m^3/m^3B)	136.60	175.35	245.08	407.81
Ts	(°C)	204.8	204.8	204.8	204.8
µs	(cp)	10.06	10.06	10.06	10.06
P/PH	Ratio	1.000	1.000	1.000	1.000

Where: MUW = SOR – 0.9(PWOR) : WRR = (PWOR/SOR) : default L_R = 0.1, other values at default inputs

Exhibit 43
Tv Sensitivity – Process V, WISC (A)
(Default Input Values, except Tv)

Performance Factors		**(Default) Tv = 100°C**	**Tv = 150°C**	**Tv = Ts (175.6°C)**
Process costs	($/m^{3}B)	36.57	47.06	84.77
CO_2 taxes	($/m^{3}B)	5.21	6.71	12.45
Total cost + tax	($/m^{3}B)	41.78	53.77	97.22
ETOR	(GJ/m^{3}B)	5.121	5.978	46.843
Oxygen use	(m^3/m^{3}B)	286.3	334.2	511.2
Air use	(m^3/m^{3}B)	1367.0	1595.6	2440.6
Vent Gas (wet)	(m^3/m^{3}B)	1407.5	2138.7	5002.5
PWOR	(m^3/m^{3}B)	0.9729	0.5868	0
WRR	(m^3/m^3)	1.2680	0.6553	0
Ts	(°C)	175.6	175.6	175.6
R_1	-	0.9686	0.9704	0
R_2	-	1.7995	1.7995	1.7995
µs	(cp)	19.12	19.12	19.12
P/PH	-	1.000	1.000	1.000
BF	(PV)	0.09116	0.1044	0.1494
D CO^2	(m^3/m^{3}B)	243.7	284.4	435.1
I CO^2	(m^3/m^{3}B)	168.1	245.8	549.1
T CO^2	(m^3/m^{3}B)	411.8	530.2	984.1
Rs	-	0.11205	0.5256	1.000
r.f.	-	0.8861	0.8695	0.8133

Exhibit 44
Effect of Heating Injection Water
On Wet Process Performance (R_2)

R_2 values

	Injected Water at 15°C (default)	Injected water at Ts
V WISC(A)	1.7995	2.4123 (+34.1%)
VI WISC(O)	1.7040	2.3950 (+40.6%)
XI WISC(A)+S	2.1141	2.9670 (+40.3%)
XII WISC(O)+S	2.0330	2.8734 (+41.3%)

Where: default values except for Twi

Balanced Hybrid Processed not included, R2 is input value

Other performance factors are not affected by heating injected water (recycling hot produced water). No cast is assigned to water heating.

R2 = growth rate ratio of (CSZ/WZ)

Exhibit 45
SHT Processes – CO2 Emissions / Sequestration
(Default input values) (m^3/m^3B)

CO^2 Emission Components	**I SAGD**	**II ISR**	**VII WISC(A)+S**	**VIII WSAGDOX**	**IX DISC(A)+S**	**X DSAGDOX**
(m^3/m^3B)						
Vent gas	-	-	266.1	0	266.1	0
Vent gas incineration	-	-	153.7	0	153.7	0
Steam production	136.1	-	9.9	27.2	68.7	75.0
Oxygen production	-	-	-	23.8	-	23.8
Air compression	-	-	29.9	-	29.9	-
Electricity production	-	147.6	-	-	-	-
Total (D+I) CO^2	**136.1**	**147.6**	**459.6**	**51.0**	**518.4**	**98.8**
% of SAGD	100.0	108.4	337.7	37.5	380.9	72.6
Rank (6 = best)	4	3	2	6	1	5

Where: vent gas from SAGDOX is directly sequestered (no emissions)

SHT = Steam Heat Transfer (at leading edge)

WSAGDOX = WISC(O) + Steam ; DSAGDOX = DISC(O) + Steam

Exhibit 45(a)
SHT Processes – Low Emission Scenarios
(Default Input Values)

				←------------------Balanced Hybrids------------→			
		I SAGD	II ISR	VII WISC(A)+S	VIII wSAGDOX	IX DISC(A)+S	X DSAGDOX
A. Default Case							
Total CO2 Emissions	(m3/m3B)	136.1	147.6	459.6	292.5	518.4	340.3
CO2 Taxes	($/m3B)	1.73	1.87	5.81	3.70	6.56	4.30
Total cost + tax	($/m3B)	56.82	60.69	48.98	38.34	73.43	58.22
B. Zero Elec. Emissions							
CO2 Emission Savings	(m3/m3B)	0	147.6	29.9	23.8	29.9	23.8
Revised CO2 Emissions	(m3/m3B)	136.1	0	429.7	268.7	488.5	316.5
CO2 Tax Savings	($/m3B)	0	1.87	0.38	0.30	0.38	0.30
Revised tax + cost	($/m3B)	56.82	58.82	48.60	38.04	73.05	57.92
C. Vent Gas Sequestration							
CO2 Emissions Savings	(m3/m3B)	0	0	0	241.4	0	241.4
Revised CO2 Emissions	(m3/m3B)	136.1	147.6	459.6	51.1	518.4	98.9
CO2 Tax Savings	($/m3B)	0	0	0.38	3.05	0	3.05
Revised tax + cost	($/m3B)	56.82	60.69	48.98	35.29	73.43	55.17
D. = B+C Simultaneously							
Revised CO2 Emissions	(m3/m3B)	136.1	0	429.7	27.3	488.5	75.1
Revised tax + cost	($/m3B)	56.82	58.82	48.60	34.99	73.05	54.87

Where: A = default case; gas-fired steam boilers; elec. Drive air compressors + ASU plant; electricity produced in a gas-fired combined cycle power plant

B = Electricity sourced from renewable (hydro, solar, wind) or nuclear plants

C = SAGDOX vent gas is directly sequestered

D = B + C increments, simultaneously

Exhibit 46
SHT Processes – Ranking (Unweighted)
(6 = Best; 1 = Worst)

<----------------Environment----------→

SHT Processes	Cost + Tax	CO2	ETOR	WATER	Totals
I SAGD	4	6	5	1	16
II ISR	2	5	6	2	15
VII Balanced Hybrids	5	2	3	5.5	15.5
VIII Balanced Hybrids	6	4	4	3.5	17.5
IX Balanced Hybrids	1	1	1	5.5	8.5
X Balanced Hybrids	3	3	2	3.5	11.5
Totals	21	21	21	21	84

Where: bigger = better; 6 = best, 1 = worst

Tied score -> split points

Best water use -> highest surplus, worst = highest MUW

Default input values

Hybrids do not sequester CO_2

Electricity from a gas-fired, combined cycle plant

VIII = wet SAGDOX

Exhibit 46(a)
SHT Processes – Ranking
Equal Weights to Cost + Environment Issues

SHT Processes	Cost + Tax	CO2	ETOR	WATER	Totals
I SAGD	12	6	5	1	24
II ISR	6	5	6	2	19
VII (Balanced Hybrids)	15	2	3	5.5	25.5
VIII (Balanced Hybrids)	18	4	4	3.5	29.5
IX (Balanced Hybrids)	3	1	1	5.5	10.5
X (Balanced Hybrids)	9	3	2	3.5	17.5
Totals	63	21	21	21	126

Where: Cost + tax weighting factor = x3

bigger = better

default input values

hybrids do not sequester vent gases

electricity from gas-fired, combined cycle power plant

SAGDOX = VIII or IX

VIII = wet SAGDOX

Exhibit 46(b)
SHT Process Ranking
Low Emission Scenarios
Equal Weights to Cost & Environment

<----------------Environmental---------->

	Cost + Tax	CO2	ETOR	WATER	Totals
I SAGD	9	3	5	1	18
II ISR	6	6	6	2	20
VII WISC(A)+S (Balanced Hybrids)	15	2	3	5.5	25.5
VIII WISC(O)+S (Balanced Hybrids)	18	5	4	3.5	30.5
IX DISC(A)+S (Balanced Hybrids)	3	1	1	5.5	10.5
X DISC(O)+S (Balanced Hybrids)	12	4	2	3.5	21.5
Totals	63	21	21	21	126

Where: electricity sourced from renewable or nuclear sources

Vent gas from ISC(O) processes is directly sequestered

Bigger = better ; tied scores – split points

default input values

VIII = wet SAGDOX

Exhibit 47
Process Ranking – All Processes
(Unweighted)

	Cost + Tax	CO2	ETOR	WATER	Totals
I SAGD	6	15	11	1	33
II ISR	4	14	15	3	36
III DISC(A) (Con. ISC)	7	1	6	14	28
IV DISC(O) (Con. ISC)	14	7	8	15	44
V WISC(A) (Con. ISC)	12	6	13	12	43
VI WISC(O) (Con. ISC)	15	13	14	13	55
VII WISC(A)+S (Balanced Hybrids)	9	5	9	11	34
VIII WISC(O)+S (Balanced Hybrids)	13	12	10	10	45
IX DISC(A)+S (Balanced Hybrids)	2	3	2	2	9
X DISC(O)+S (Balanced Hybrids)	5	9	3	6	23
XI WISC(A)+S (Unbalanced Hybrids)	11	10	12	4	38
XII WISC(O)+S (Unbalanced Hybrids)	10	11	7	8	36
XIII DISC(A)+S (Unbalanced Hybrids)	3	4	4	7	18
XIV DISC(O)+S (Unbalanced Hybrids)	8	8	5	9	30
XV EEOR	1	2	1	5	9
Totals	120	120	120	120	480

Where: = uses default input values
= bigger = better, points 1 to 15; ties split points
= no sequestration of vent gas
= electricity from a gas-fired, combined-cycle power plant
= best water = biggest surplus ; worst water = highest MUW

Exhibit 47(a)
Process Ranking – All Processes
(Weighted)

	Cost + Tax	CO2	ETOR	WATER	Totals
I SAGD	18	15	11	1	45
II ISR	12	14	15	3	44
III DISC(A) (Con. ISC)	21	1	6	14	42
IV DISC(O) (Con. ISC)	42	7	8	15	72
V WISC(A) (Con. ISC)	36	6	13	12	67
VI WISC(O) (Con. ISC)	45	13	14	13	85
VII WISC(A)+S (Balanced Hybrids)	27	5	9	11	52
VIII WISC(O)+S (Balanced Hybrids)	39	12	10	10	71
IX DISC(A)+S (Balanced Hybrids)	6	3	2	2	13
X DISC(O)+S (Balanced Hybrids)	15	9	3	6	33
XI WISC(A)+S (Unbalanced Hybrids)	33	10	12	4	59
XII WISC(O)+S (Unbalanced Hybrids)	30	11	7	8	56
XIII DISC(A)+S (Unbalanced Hybrids)	9	4	4	7	24
XIV DISC(O)+S (Unbalanced Hybrids)	24	8	5	9	46
XV EEOR	3	2	1	5	11
Totals	360	120	120	120	720

Where: = uses default input values
= bigger = better, points 1 to 15; ties split points
= no sequestration of vent gas
= electricity from a gas-fired, combined-cycle power plant
= best water = biggest surplus ; worst water = highest MUW
= equal weighting for cost + environment issues

Exhibit 48
Post Waterflood Reservoir + ISC (Oxygen)
(Default Values except as noted)

			DISC (Ox)		WISC (Ox)	
Selected Performance Factors		Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
Process Cost	($/m3B)	31.83	58.39	58.85	48.22	48.22
ETOR	(GJ/m3B)	6.138	11.262	11.349	9.299	9.299
PWOR	(m3/m3B)	0.313	1.073	1.300	2.711	2.711
WRR	(m3/m3)	-	-	-	1.858	1.858
Oxygen Use	(m3/m3B)	343.2	629.7	634.5	519.9	519.9
Vent Gas (wet)	(m3/m3B)	310.4	569.5	573.9	470.3	470.3
Ts	(°C)	185.6	185.6	192.4	199.0	199.0
R_1	-	0.2999	0.2755	0.4885	1.1204	1.1204
R_2	-	-	-	-	1.4974	2.1102
B_F	(PV)	0.1069	0.1102	0.1109	0.09466	0.09466
r.f.		0.8664	0.7795	0.7782	0.8107	0.8107

Where: scenario : A= default case, Sib = 0.8, Siw = 0.2, Srb = 0.15, Srw = 0.2 (virgin reservoir)

(post waterflood cases)

B – Sib = 0.5, Siw = 0.5, Srb = 0.15, Srw = 0.2 (same water carryover to CZ)

C – Sib = 0.5, Siw = 0.5, Srb = 0.15, Srw = 0.4 (extra water carryover)

D - Sib = 0.5, Siw = 0.5, Srb = 0.15, Srw = 0.4 (WISC process)

E - Sib = 0.5, Siw = 0.5, Srb = 0.15, Srw = 0.4 (WISC process + heat inj. water to Ts)

Exhibit 49
wISC Hybrids – Low Q Steam Injection

Process	**W_{IR} x 10^4 ($m^3{}_L/m^3$Air/ox)**	**SIR x 10^4 (m^3L/m^3 A or O)**	**Combined Steam Q (%)**	**R_1 (ratio)**	**R_2 (ratio)**
Balanced Hybrids					
VII WISC(A) + steam	5.0466	0.8534	14.46	1*	2*
VIII wet SAGDOX	23.897	13.603	36.27	1*	2*
Unbalanced Hybrids					
XI WISC(A)+Steam	5.6125*	5.6125*	50.00	1.5477	2.1141
XII wet SAGDOX	28.06*	28.06*	50.00	1.3773	2.0330

Where: wSAGDOX = WISC(O) + steam

WIR = water injected

SIR = steam injected

* = default input values

Exhibit 50
SHT Processes + Low Emission Scenario
CO_2 Emission Components

←------------------**Balanced Hybrids**------------→

CO^2 Source(m^3/m^3B)	I SAGD	II ISR	VII WISC(A)+S	VIII WISC(O)+S	IX DISC(A)+S	X DISC(O)+S
Direct vent gas	0	-	266.1	0	266.1	0
Vent incineration	-	-	153.7	0	153.7	0
Oxygen production	-	-	0	0	0	0
Air compression	-	-	0	-	0	-
Steam production	136.6	-	9.9	27.2	68.7	75.0
Electricity prod.	-	0	0	0	0	0
Totals (m^3/m^3B)	136.6	0	429.7	27.2	488.5	75.0
% of SAGD	100.0	0.0	314.6	19.9	357.6	54.9
Process cost ($/$m^3B$)	55.10	58.82	43.17	34.64	66.87	53.92
CO2 tax ($/$m^3B$)	1.73	0	5.44	0.34	6.18	0.95
Total cost + tax ($/$m^3B$)	56.83	58.82	48.61	34.98	73.05	54.87
%SAGD	100.0	103.5	85.5	61.6	128.5	96.6

Where: electricity sourced from renewable or nuclear sources

Vent gas from ISC(O) processes (VIII or X)

Oxygen production and air compression based on electric drives

SAGDOX = VIII or X

6. Bookkeeping

6.1 Acronyms Used

AC	=	Alternating Current
B	=	Bitumen
COGD	=	Combustion Overhead Gravity Drainage
COSH	=	Combustion Overhead Split Horizontal
CSS	=	Cyclic Steam Stimulation
CSZ	=	Combustion Swept Zone
CZ	=	Combustion Zone
DC	=	Direct Current
DCO_2	=	Direct (process) CO_2 emissions
DCO_2	=	Direct CO_2 (emissions)
Dry ISC	=	ISC with no water injected
E	=	Exhibit (Table or Graph)
EAir	=	Enriched Air
ECZ	=	Extended Combustion Zone
EEOR	=	Electric EOR
EM	=	Electro – Magnetic
EM	=	Electro Magnetic (radiation)
EOR	=	Enhanced Oil Recovery
ESSAGD	=	Expanding Solvent SAGD
ETOR	=	Energy to Oil (bitumen) ratio
FEA	=	Finite Element Analysis (model)
FG	=	flue (vent) gas
HB	=	Hybrid, Balanced process
HTO	=	High T Oxidation
HU	=	Hybrid, Unbalanced process
ICO_2	=	Indirect CO_2 (emissions)
ICO_2	=	Indirect CO_2 emissions
ISC	=	In Situ Combustion
ISC(air)	=	ISC using air as oxidant gas
ISC(O_2)	=	ISC using oxygen gas as oxidant
ISR	=	In Situ (steam) Reflux Process
LTO	=	Low T Oxidation
MUW	=	make up water needed (bbl/bblB or m^3/m^3B)
nc	=	noncondensible (gas)
PV	=	Pore Volume
PWOR	=	Produced Water to Oil (bitumen) ratio
rf	=	radio frequency
SAGD	=	Steam Assisted Gravity Drainage

SAGDOX	=	SAGD with oxygen
SAGP	=	Steam Assisted Gas Push
sf	=	sand face
SF	=	Steam Flood
SOR	=	Steam to Oil (bitumen) ratio
SZ	=	Steam Zone
THAI	=	Toe to Heel Air Injection
THSF	=	ToE.to-Heel SF
Wet ISC	=	ISC with water injected to scavenge heat
wh	=	well head
WRR	=	Water Recycle Ratio (water produced/(water+steam)) injected
WZ	=	Wet Zone

6.2 Symbols Used

Tc	=	Combustion T
Ts	=	Saturated steam T
Tv	=	T of vent gas removed
T	=	Temperature
Siw	=	Initial water saturation in PV
Srw	=	Residual water saturation in SZ, PV
Sib	=	Initial bitumen saturation in PV
Srb	=	Residual bitumen saturation in SZ, PV
χ	=	Atomic H/C ratio in combustion 'fuel'
r	=	fraction of carbon combusted to CO
Ø	=	porosity
R_1	=	ratio of SZ/CZ growth rates (ISC processes)
R_2	=	ratio of CSZ/WZ growth rates (ISC processes)
P	=	process pressure
Ps	=	saturated steam pressure
PPs	=	partial pressure of steam
P_H	=	hydrostatic pressure (at top of reservoir)
Q	=	steam quality (wh Qwh or at sf Qsf)
L_R	=	fraction of heat last to non-productive areas
d	=	depth of top of reservoir
Pi	=	initial reservoir pressure
Cs	=	unit cost of steam
C_E	=	unit cost of electricity
CO_2	=	unit cost of oxygen
C_{AIR}	=	unit cost of compressed air
Rv	=	surface recycle rate of produced water
Tia	=	T of injected air
Tio_2	=	T of injected O_2
W_{IR}	=	water injection rate
T_{IW}	=	water injection T
ρB	=	bitumen density
Ti	=	initial reservoir T
d	=	reservoir depth
µi	=	initial bitumen viscosity (in situ)
µs	=	bitumen viscosity at Ts
P	=	process pressure
f_{EH}	=	fraction of electricity converted to heat (ie. electrical heat)
f_{HR}	=	fraction of electrical heat delivered to the reservoir
f_{RD}	=	fraction of reservoir heat that causes drainage to a production well
Is	=	indirect CO_2 from steam used
I_E	=	indirect CO_2 from electricity used
Io	=	indirect CO_2 from oxygen used
Ia	=	indirect CO_2 from air used
M^3B	=	m^3 Bitumen
bblB	=	bbl Bitumen

6.3 Glossary

'Balanced' -	a balanced, hybrid or ISC process is one where the growth rate of the steam zone (SZ) equals the growth rate of the combustion zone (CZ). The term 'balanced' may also be applied when the growth rate of the combustion swept zone (CSZ) equals a multiple of the growth rate of the wet zone (WZ). The 'multiple' factor (Rz) is necessary to account for the risk of water channeling.
'Bitumen' -	a liquid hydrocarbon with API ≤ 10 and in situ viscosity $\mu i > 10{,}000$cp.
'Cold Bitumen Interface' -	a region/interface where bitumen is first heated (usually by steam), so its viscosity is reduced so it can flow.
'CZ' -	the extended combustion zone (CZ) includes a combustion front, a pyrolysis zone, a bitumen bank and a superheated steam zone (Exhibit 3).
'CSZ' -	the combustion swept zone (CSZ) is the hot matrix rock produced by downstream combustion. The matrix T is at/near Tc and the matrix pores contain only gases.
'Dry' -	a dry combustion process (dry ISC) injects no separate water stream. Steam may be injected in a dry process.
'ETOR' -	is the Energy to Oil Ratio (GJ/m^3B or MMBTU/bblB), measured at the well head using total energy injected. ETOR is a general term that allows easy energy comparisons between processes or process components.
'Hybrid' -	an EOR process combining 2 or more process components (eg. dry ISC + steam)
'HTO' -	high temperature oxidation or 'good' combustion where the products of oxidation are CO^2, H^2O and CO (Exhibit 1) and steady state Tc is about 400 to 650°C.
'LTO' -	low temperature oxidation or poor, incomplete combustion where the products of oxidation include partially oxidized organic compounds and oxidation temperature is about 150-300°C.
'Model' -	a mathematical representation of a thermal EOR process that recovers bitumen.
'R_1' -	a stability factor = the growth rate ratio of SZ/CZ. If R = 1 (or a preset target), the process is balanced. If $R_1 > 1$ the process is unbalanced and stable. If $R_1 < 1$ the process is unstable.
'R_2' -	a stability factor = the growth rate ratio of CSZ/WZ. If $R_2 = 2$ the process is balanced. If $R_2 > 2$ the process is unbalanced and stable. If $R_2 < 2$ the process is unstable.

'SAGDOX' -	a family of hybrid processes (ISC + steam), using the oxygen as the injectant oxidant gas. The water/steam injection is adjusted so the processes are balanced and/or stable.
'Stable/Unstable' -	$R_1 \geq 1$ and $R_2 \geq 2$, ISC + steam hybrid processes.
'SZ' -	the steam zone is formed when heat transfer to the cold bitumen interface is dominated by steam condensation.
'Steady State' -	ideally the model describes a process that is operating well and can be sustained for an extended time (ie. steady state). But, some processes are unstable and performance cannot be sustained.
'Super-wet' -	super wet combustion injects too much water or water too early in the process so some water overtakes the combustion front. Without totally quenching or destabilizing combustion, super wet combustion advances faster than HTO, leaving behind some uncombusted fuel (coke) in the CSZ. Tc may be reduced and/or CO production increased.
'Ts' -	saturated steam temperature for this model is the temperature where steam first condenses. If the process includes nc gases mixed with steam, Ts is the saturated steam T at the partial pressure of steam.
'Vent Gas' -	or flue gas from combustion consists of the nc gases produced by combustion, saturated with steam at the vent gas temperature Tv.
'Wet' -	wet combustion involves the separate injection of water, used to scavenge heat from the CSZ to produce in situ steam.
'WZ' -	a wet zone is formed when water is injected in a wet ISC process. The zone contains water. At the leading edge water is vaporized using sensible heat from the CSZ.
'Zones' -	a process with a combustion component can be separated into process zones (Exhibit 2). Zones are convenient to describe what is happening in the process.

6.4 Copies – How can model copies be purchased?

The manual is available to copy from our website 'www.bitumeneor.com' at no cost.

Two purchase options are provided – namely

(1) an encrypted flash drive uncopiable version – the purchaser may use the program at an unlimited rate for an indefinite time period. Each purchase includes a flash drive version.

(2) a corporate version that can be installed so that corporate users have unlimited use. The company would have to assure that the model would not be copied indiscriminately.

Multiple purchases can have discounts.

Contacts are:

Prime contact -	David Kerr		all year
Secondary contact -	Rich Kerr	403-241-6977	summer only

6.5 Support – What support is provided?

- Support is not extensive – limited resources
- If there is a 'bug' we will fix it and supply new process versions to all flash drive users.
- If there is a suggestion for an improvement, we may or may not institute the improvement, totally at our discretion
- From time to time, new model versions may be issued. Flash drive users and website users can access the new versions at an additional cost to be determined (less than the cost for new users)

6.6 Resumes

Rich Kerr, Ph.D., P.Eng. (non practicing)

Education	- Queens University, B.Sc. (Engineering Physics), 1967 - U.B.C., Ph.D. (Sold State Physics), 1972 - U of C., E.D. Program (mini MBA), 1985
Work History	- Western Research and Dev. Ltd. (1971-76) - A.E.C. (now Cenovus & Encana) (1976-1991) - Saskoil/Wascana Energy (1991-1997) - Canoxy/Nexen (1997-2014)
Accomplishments	- 43+ years experience in Canada's Oil and Gas sector - Extensive knowledge of Canada's energy R&D infrastructure - Managed several corporate groups – R&D lab, R&D investments, reservoir simulation, petrophysics, reserves, safety, land, insurance, coal mine JV, oilsands JV, engineering, environment - Author of several papers and about 20 patents - Recipient of 1991 Frank Spraggins APPEGA award for integrity, expertise and outstanding accomplishments. - Past member of several not for profit boards and advisory groups – ARC (now Alberta Innovates), PRI, CFER, PTAC, U of C, SAIT, CONRAD - Past member of several industry boards and advisory groups – IPAC, Northwest Dev. Ltd., Syncrude, Moose Jaw Asphalt Inc. - Past member of federal advisory groups including the Energy Minister, NRC, NRCan, NSERC - Author and designer of 2 previous computer simulations involving Claus plant operation and tail gas incineration

Rich is currently retired, spending summers in Calgary, Alberta and winters in Mesa, Arizona.

David Kerr, B. Sc

Education	- University of Regina, B. Sc. (Computer Science), 1995 - Object Oriented Software Development, Certificate (SAIT), 2008
Work History	- Naturally Intelligent Inc. (2006-Present) - Claero Solutions (2008-2013)
Accomplishments	- 20+ years experience in Software Development - Lead Developer of FIRE 5 Field Invoicing Software - Proficiency in 2D and 3D simulations, multiplayer networking, virtual ecosystems, physical simulations, and artificial intelligence - Indie video game designer with successful Kickstarter funding - Author of two science fiction novels

6.7 Disclaimers

I desire what is good. Therefore, everyone who does not agree with me is a traitor. King George III

- The calculations and date herein are engineering estimates. The accuracy of the results is not warranted.
- The default input values are not representative of any particular reservoir and are not meant to imply representitivity for bitumen resources.
- Performance or non performance predictions are not warranted
- Accuracy of many calculations is based on data algorithms accurate to ≤ 1%. Some calculations (eg. high T properties) may be outside the usual range and accuracy may drop to ≤ 5%. Expect most performance predictions to be good to about 3 figures (ie. Engineering accuracy)
- Any costs used herein (eg. E.12) should be considered illustrative and not representative of real costs.
- Conclusions and/or predictions should be considered illustrative and not representative of real costs.
- Conclusions and predictions may not apply to other reservoir types or process conditions. Reader beware!
- User beware. Use results at own risk.