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Kerr (43) **Pub. Date: Jun. 19, 2014**

(54) **USE OF STEAM-ASSISTED GRAVITY DRAINAGE WITH OXYGEN ("SAGDOX") IN THE RECOVERY OF BITUMEN IN LEAN ZONES ("LZ-SAGDOX")**

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(72) Inventor: **Richard Kelso Kerr**, Calgary (CA)

(73) Assignee: **NEXEN ENERGY ULC**, Calgary (CA)

(21) Appl. No.: **14/078,983**

(22) Filed: **Nov. 13, 2013**

Related U.S. Application Data

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(60) Provisional application No. 61/726,239, filed on Nov. 14, 2012, provisional application No. 61/717,267, filed on Oct. 23, 2012, provisional application No. 61/507,196, filed on Jul. 13, 2011, provisional application No. 61/549,770, filed on Oct. 21, 2011, provisional application No. 61/550,479, filed on Oct. 24, 2011, provisional application No. 61/647,153, filed on May 15, 2012, provisional application No. 61/643,538, filed on May 7, 2012, provisional application No. 61/666,116, filed on Jun. 29, 2012.

Publication Classification

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E21B 43/243 (2006.01)

(52) **U.S. Cl.**

CPC ***E21B 43/2408*** (2013.01); ***E21B 43/243*** (2013.01)

USPC **166/261**; 166/256; 166/52

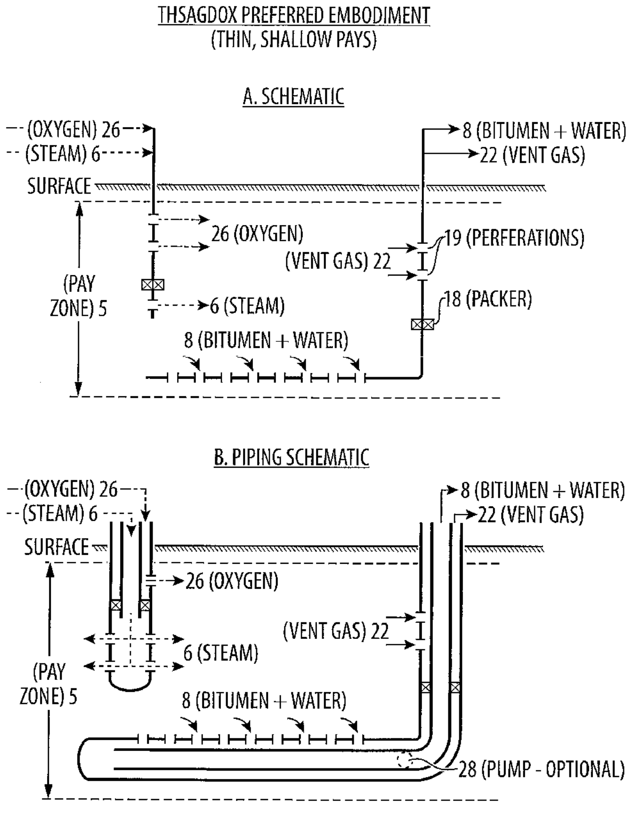
(57) **ABSTRACT**

A process to recover hydrocarbons from a reservoir having at least one lean zone, wherein said lean zone has an initial bitumen saturation level less than about 0.6, said process including:

i) Initially injecting of oxygen into said reservoir;

ii) Allowing for combustion of said oxygen to vaporize connate water in said at least one lean zone; and

iii) Recovering said hydrocarbons from said reservoir.



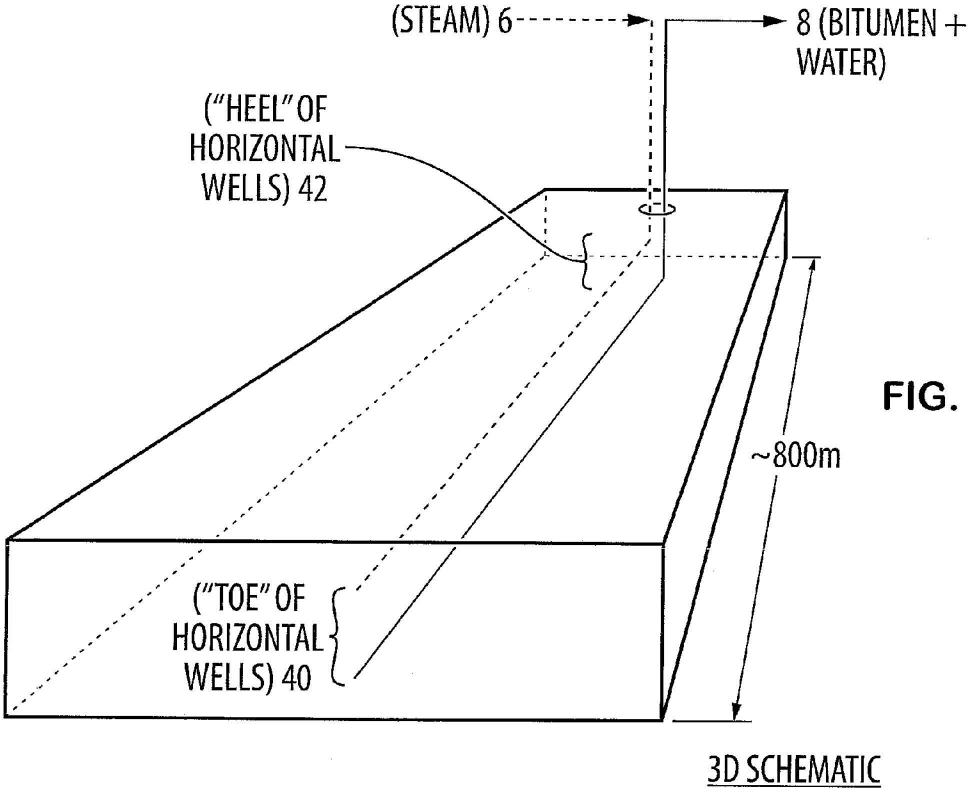
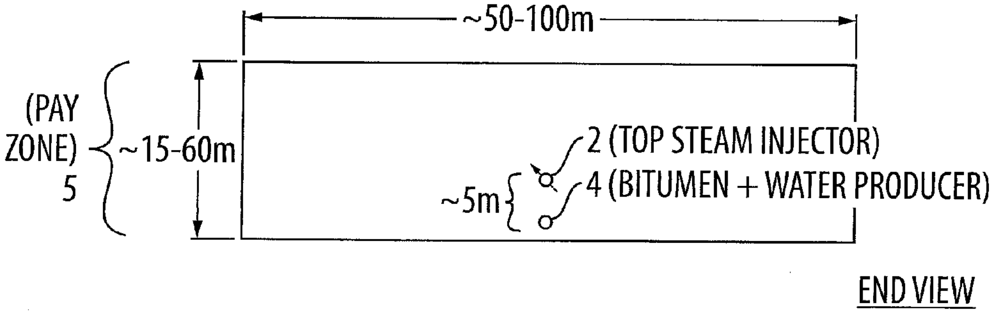


FIG. 1A



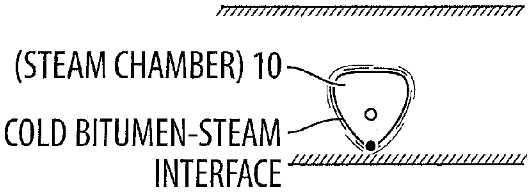
TRADITIONAL SAGD GEOMETRY

FIG. 1B

PRIOR ART

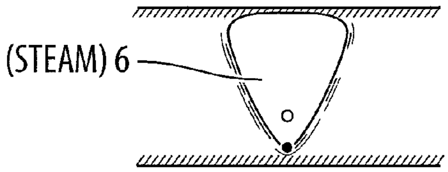
SAGD LIFECYCLE

SAGD PATTERN END VIEW



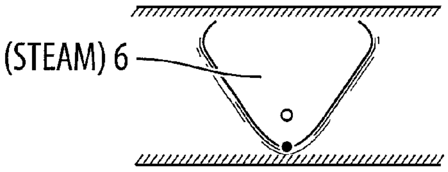
Early Stages
- Small steam chamber

FIG. 2A



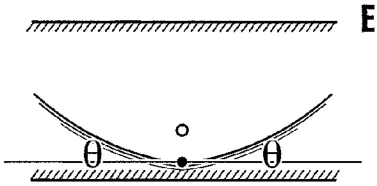
Optimum Productivity
- GD chamber reaches ceiling

FIG. 2B



Maturing/Aging
- Productivity declines

FIG. 2C



End of Life
- drainage angle is smallest
- shut down when bitumen netback = opex
- θ = end-of-life drainage angle

PRIOR ART

FIG. 2D

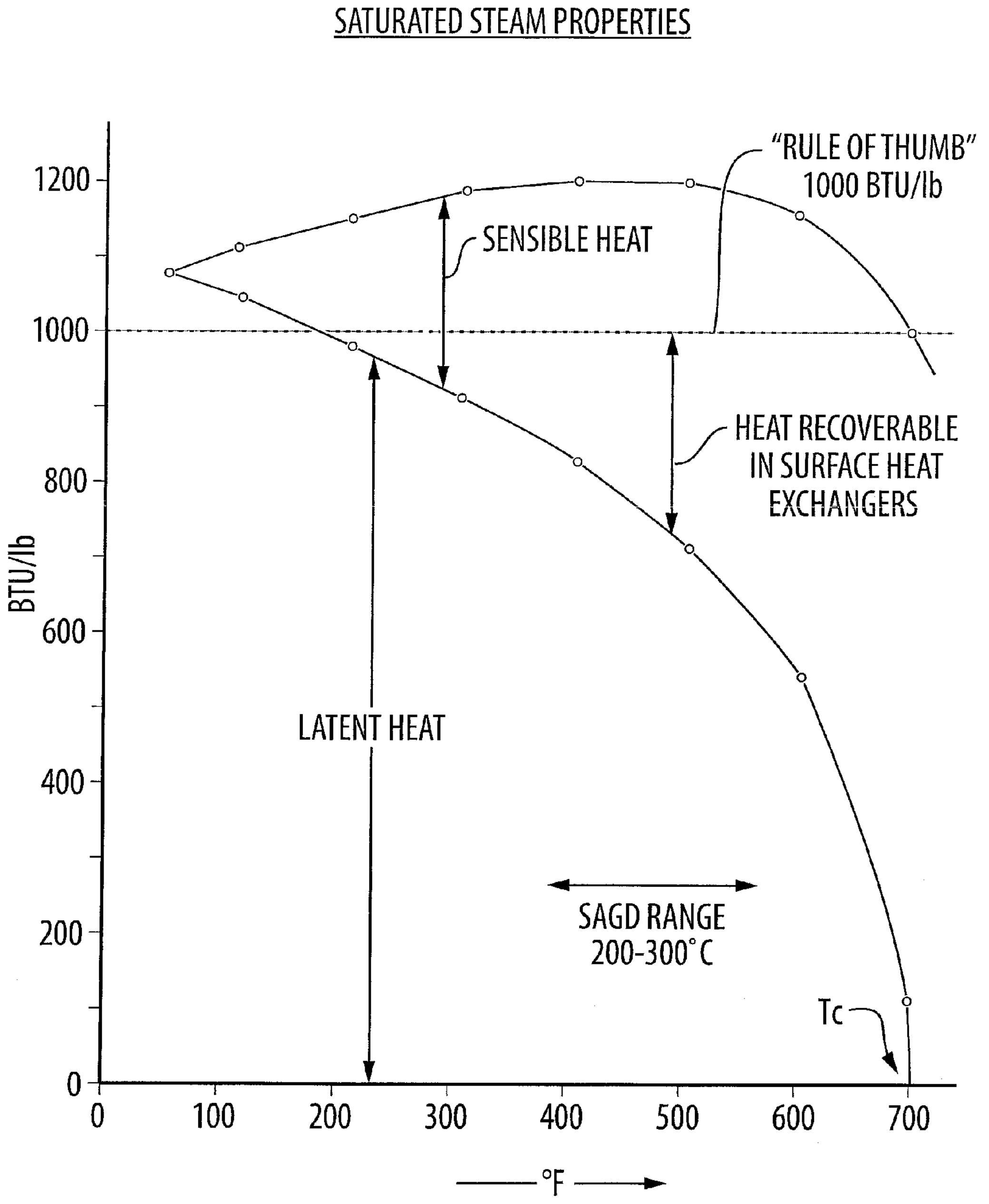


FIG.3

PRIOR ART

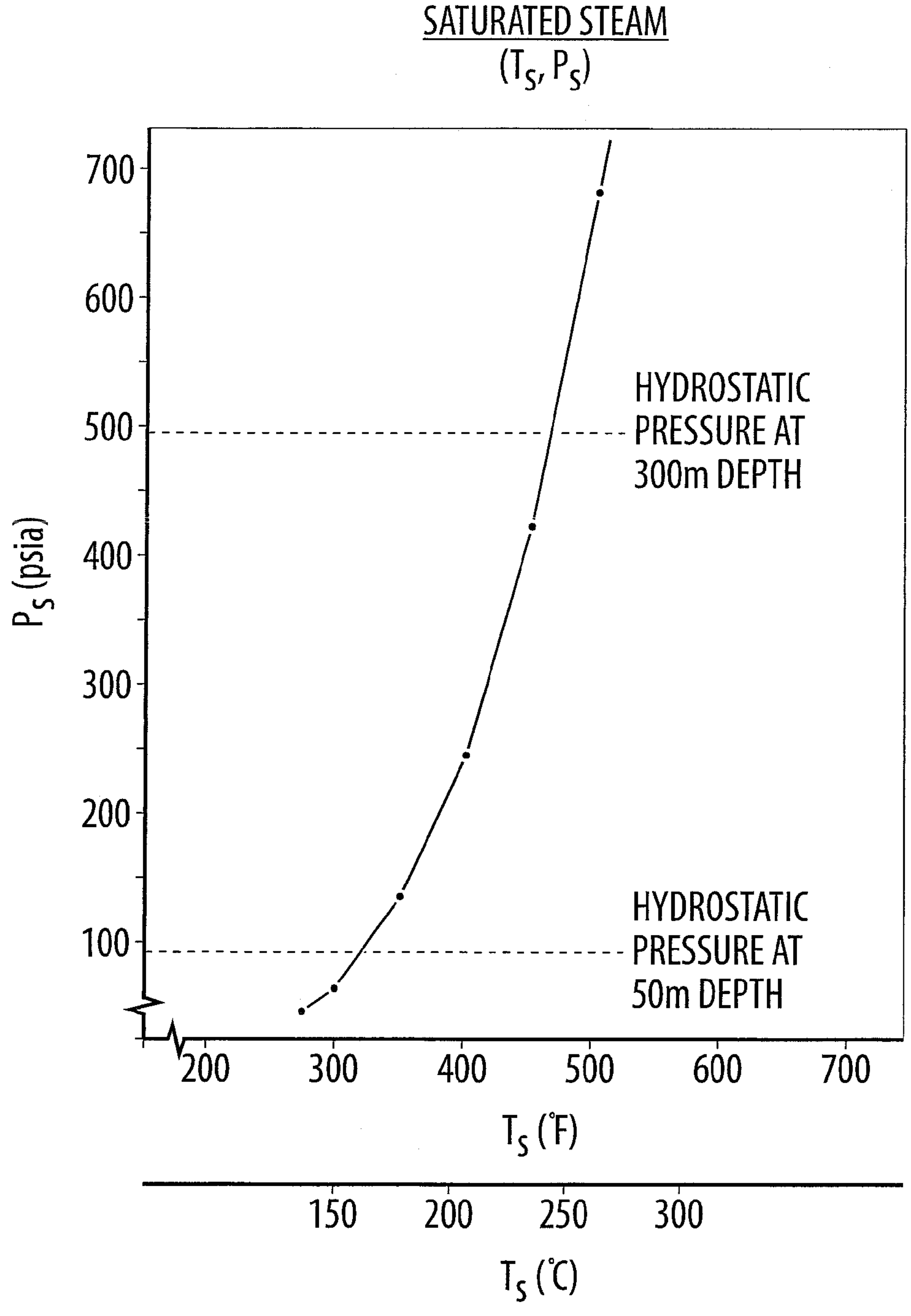


FIG.4

PRIOR ART

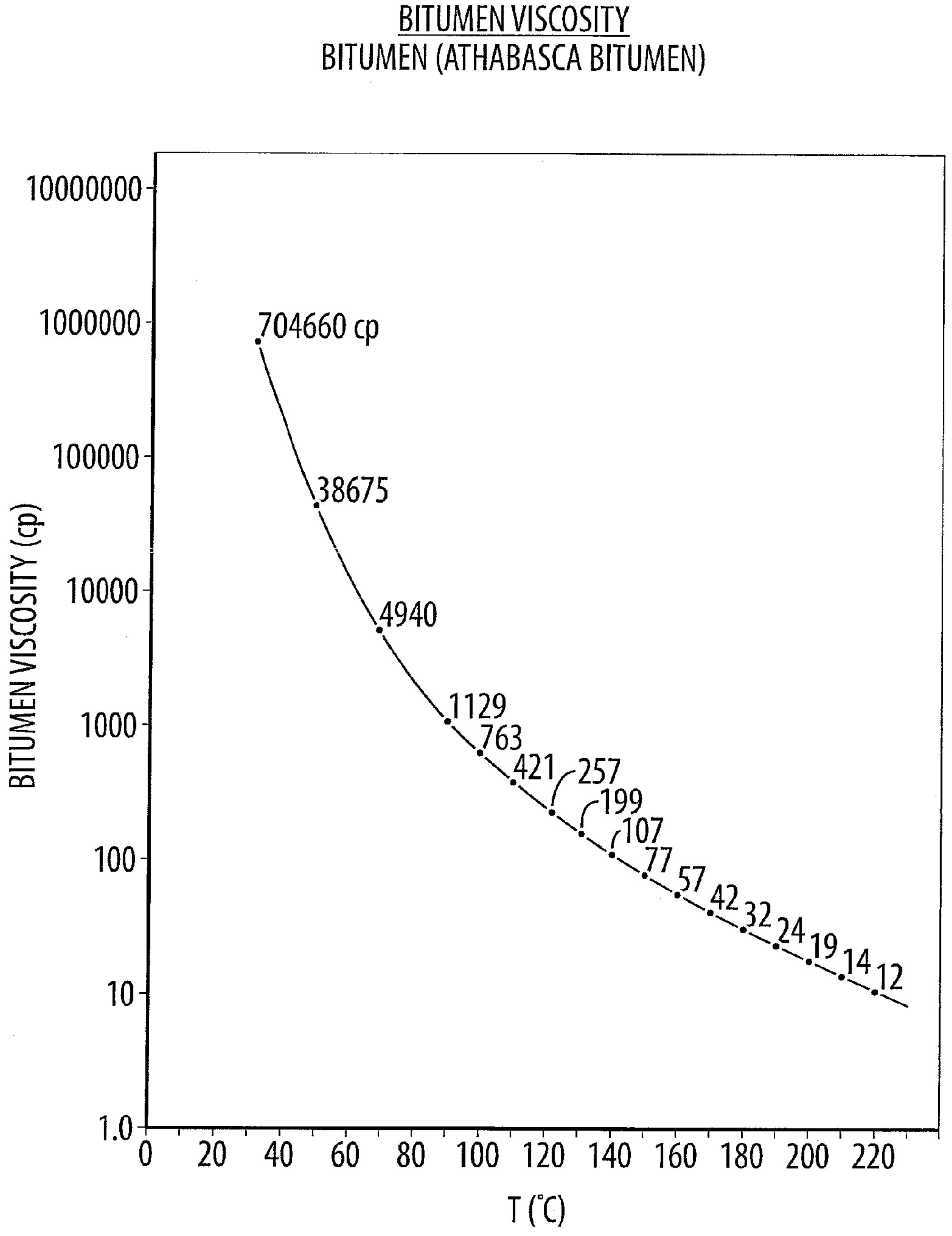

BITUMEN VISCOSITY
BITUMEN (ATHABASCA BITUMEN)
BITUMEN VISCOSITY (cp)
10000000
1000000
100000
10000
1000
100
10
1.0
T (°C)
0
20
40
60
80
100
120
140
160
180
200
220
704660 cp
38675
4940
1129
763
421
257
199
107
77
57
42
32
24
19
14
12

FIG.5

THE GRAVDRAIN EQUATION FOR SAGD BITUMEN PRODUCTIVITY

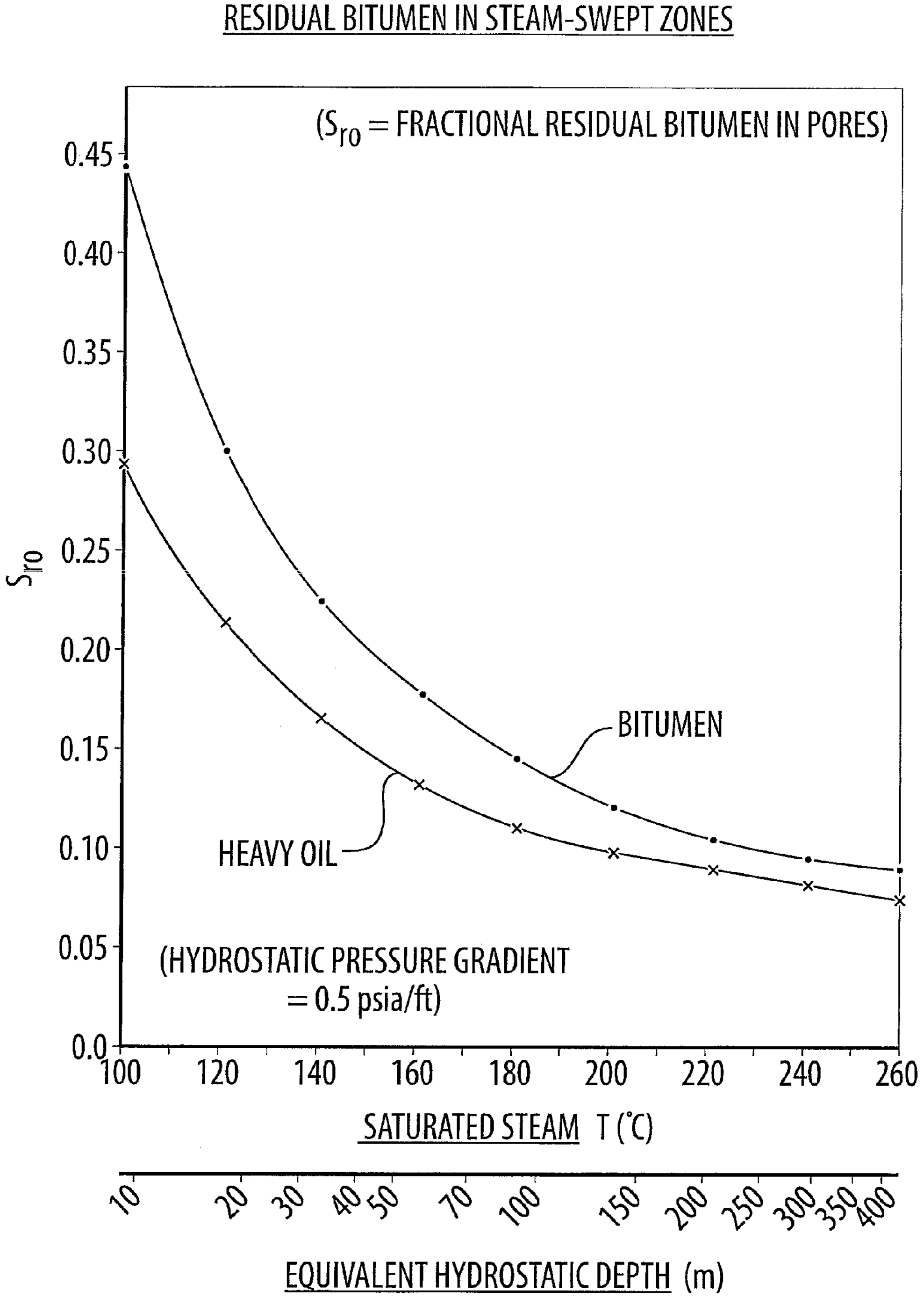
$$q = 2\sqrt{\frac{2\,\Phi\,\Delta S_0\,kg\alpha h}{m\,\mu_S}}$$

q = BITUMEN PRODUCTIVITY PER UNIT WELL LENGTH
Φ = FRACTIONAL POROSITY
ΔS_0 = CHANGE IN OIL SATURATION (STEAM T_S to RESERVOIR T_R)
k = PERMEABILITY (VERTICAL)
g = ACCELERATION DUE TO GRAVITY
μ_S = BITUMEN VISCOSITY AT STEAM T
h = RESEVOIR HEIGHT (GD CHAMBER HEIGHT)
α = THERMAL DIFFUSIVITY
m = DIMENSIONLESS PARAMETER RELATED TO BITUMEN VISCOSITY CURVE SLOPE BETWEEN T_R AND T_S. FOR ATHABASCA BITUMEN $m = 4.1$ FOR $T_R = 13°C$, $T_S = 200°C$
FOR T_S BETWEEN 180° AND 220°C, m VARIES FROM 4.3 TO 3.9

WHERE
- SOURCE, Butler (1991)
- INFINITE PATTERN (NO BOUNDARIES)
- NO HEAT LOSSES
- HOMOGENEOUS RESERVOIR
- CONTAINED GD CHAMBER (NO LEAKS)

FIG.6

PRIOR ART



(Butler, CIM97, 1997)

FIG.7

SAGD HYDRAULIC LIMITATIONS

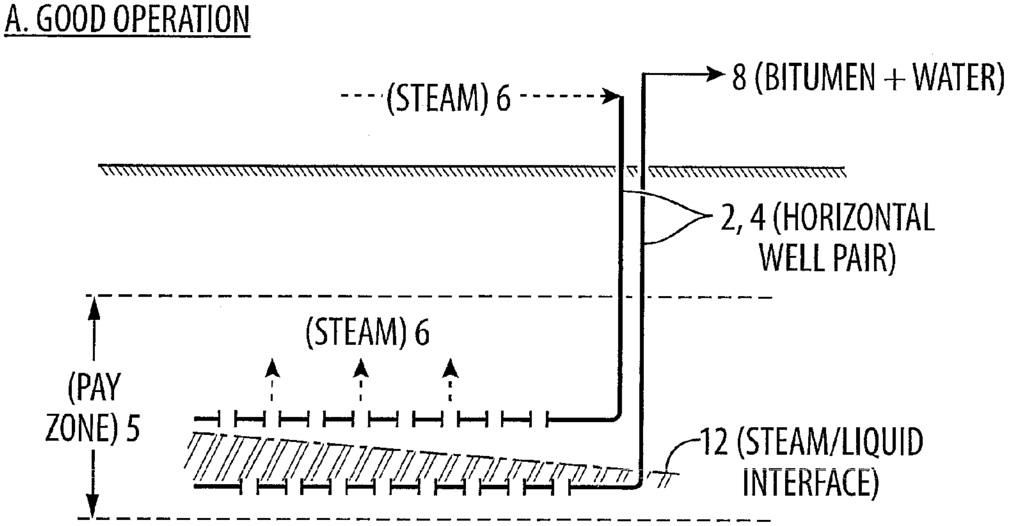


FIG. 8A

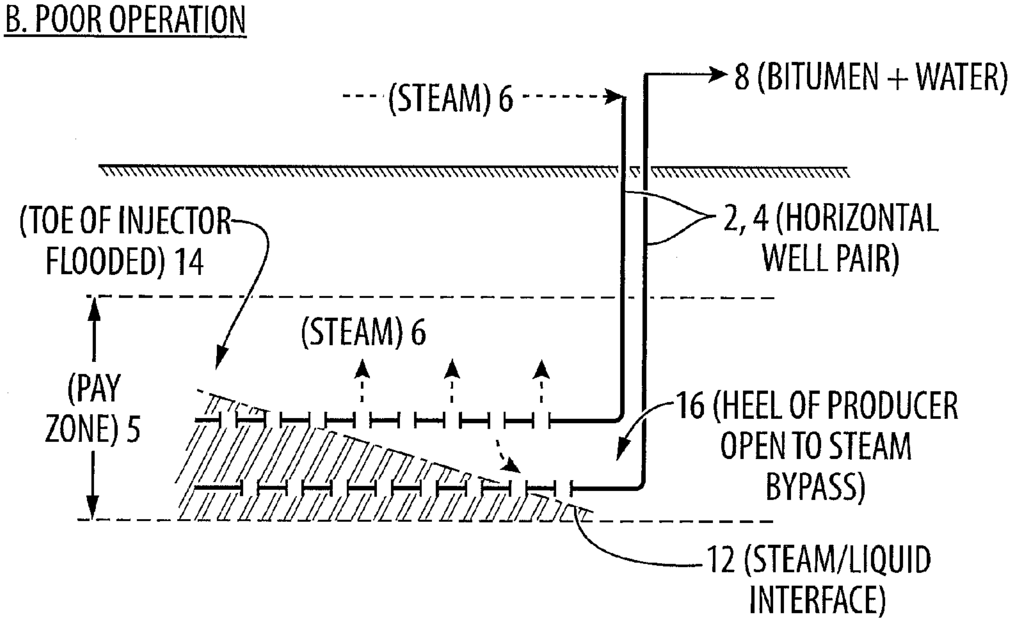


FIG. 8B

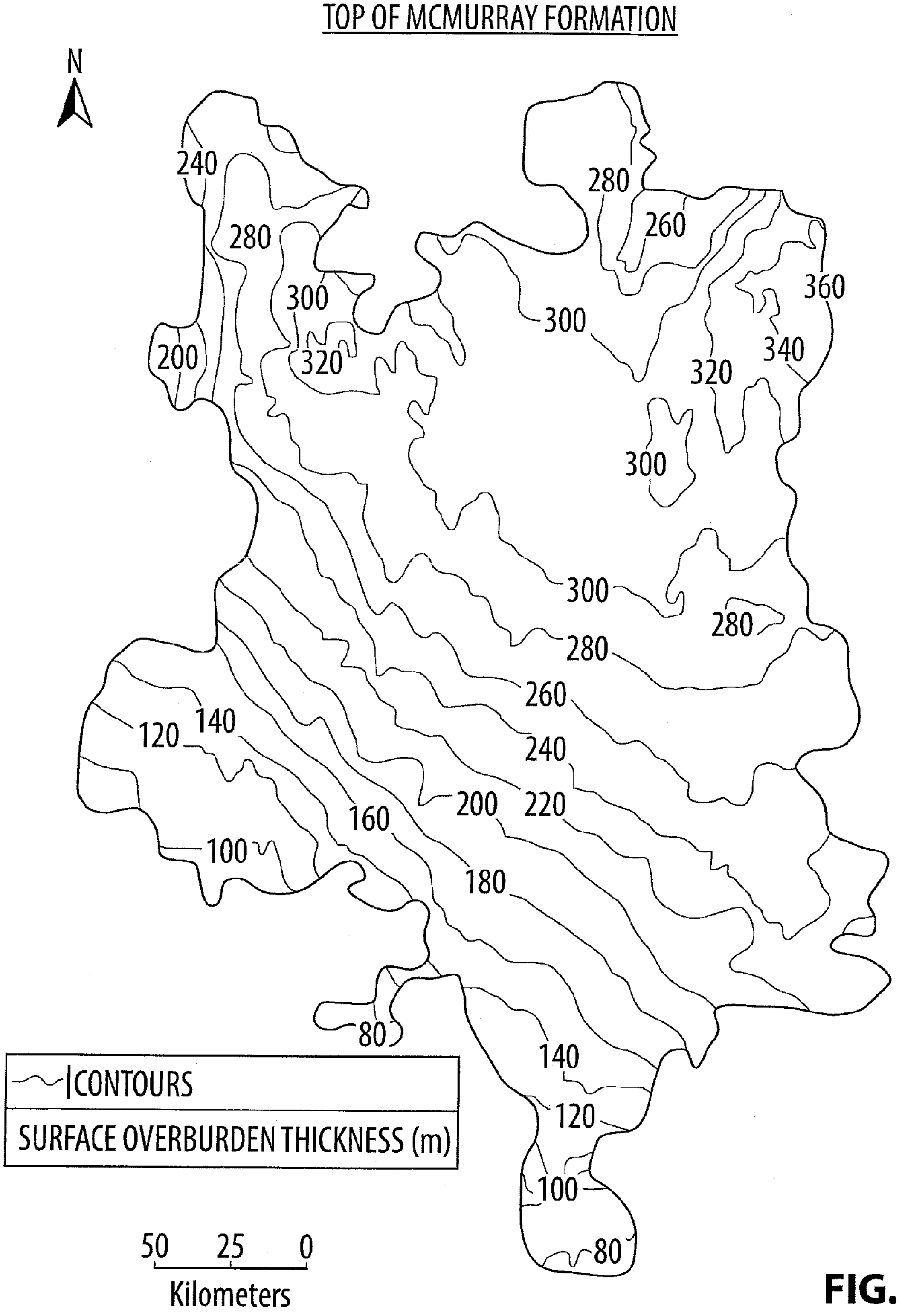

TOP OF MCMURRAY FORMATION
N
240
280
300
320
200
280
260
300
360
340
320
300
300
280
280
260
240
220
200
180
160
140
120
100
80
140
120
100
80
CONTOURS
SURFACE OVERBURDEN THICKNESS (m)
50
25
0
Kilometers

FIG.9

MCMURRAY FORMATION - FORMATION THICKNESS

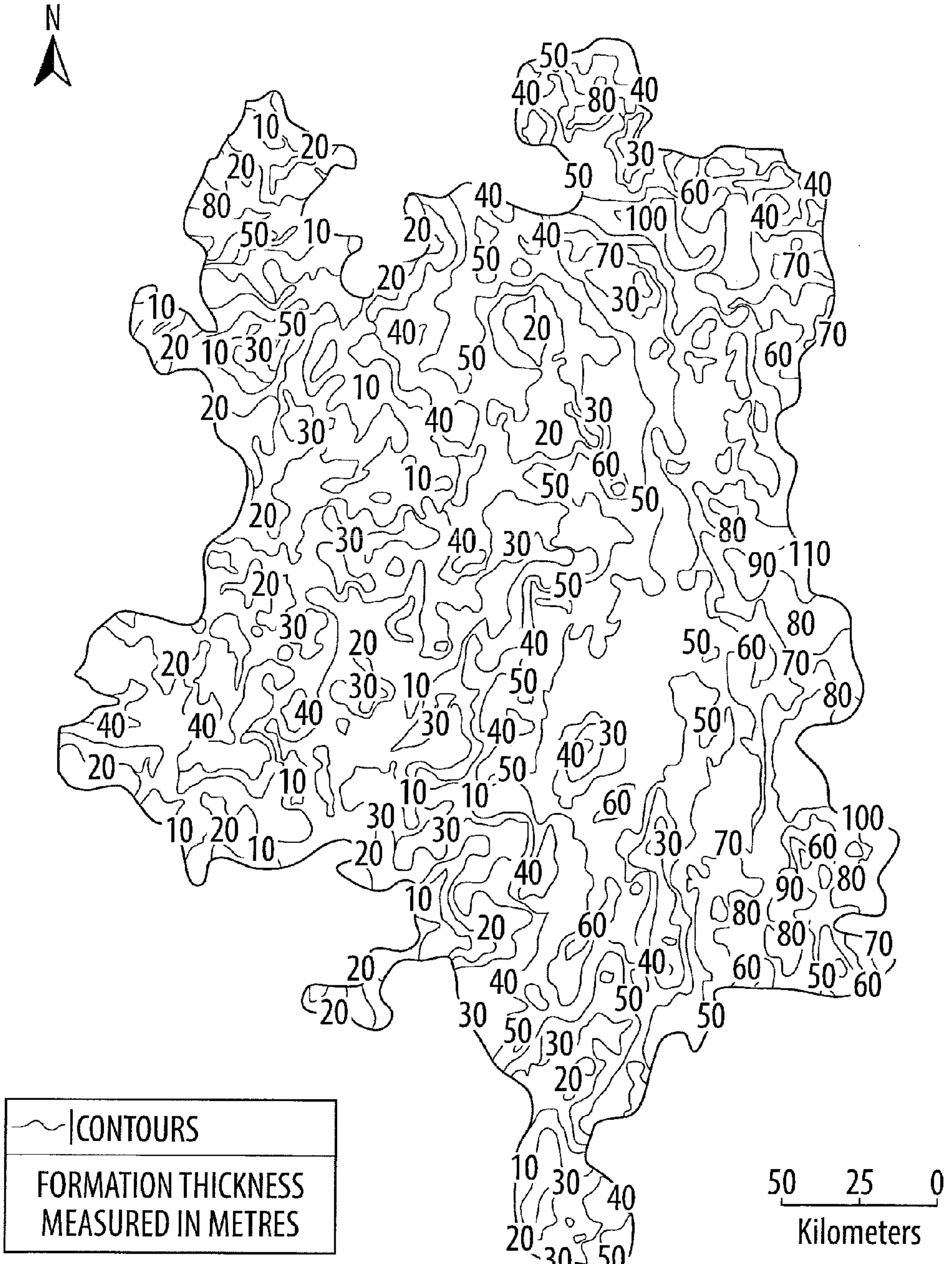


FIG.10

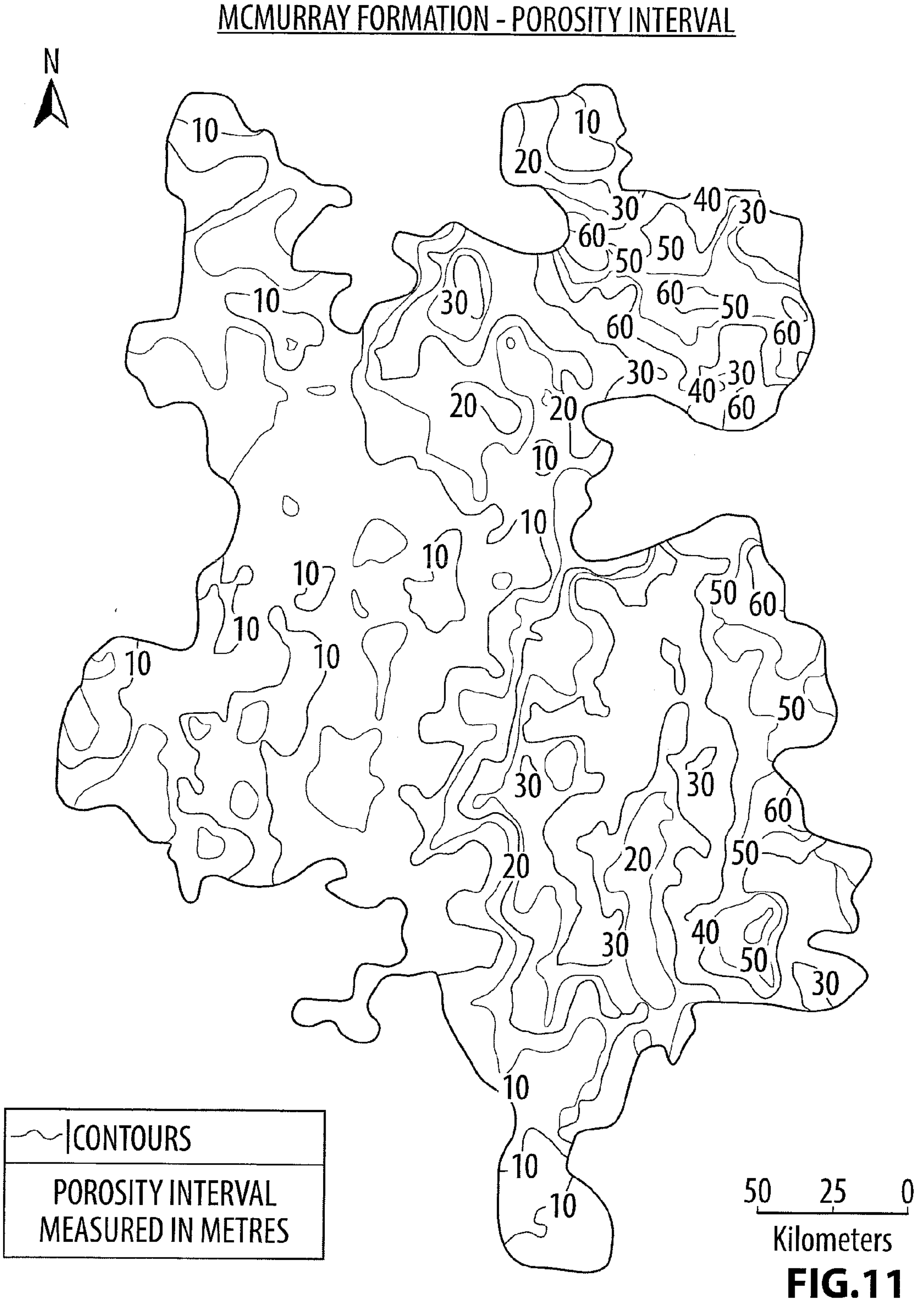

MCMURRAY FORMATION - POROSITY INTERVAL
N
10
20
30
40
50
60
CONTOURS
POROSITY INTERVAL MEASURED IN METRES
50 25 0
Kilometers

FIG.11

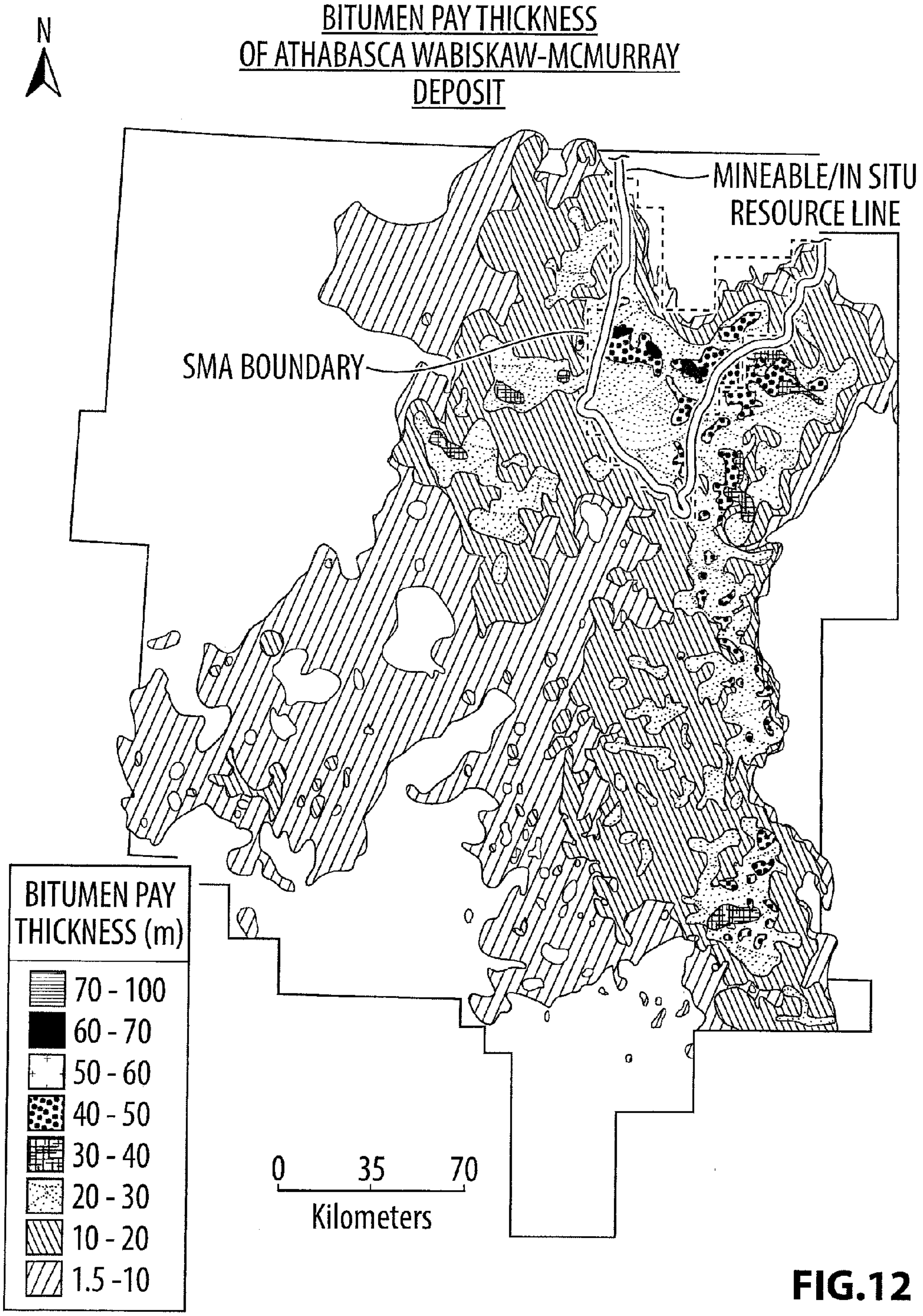
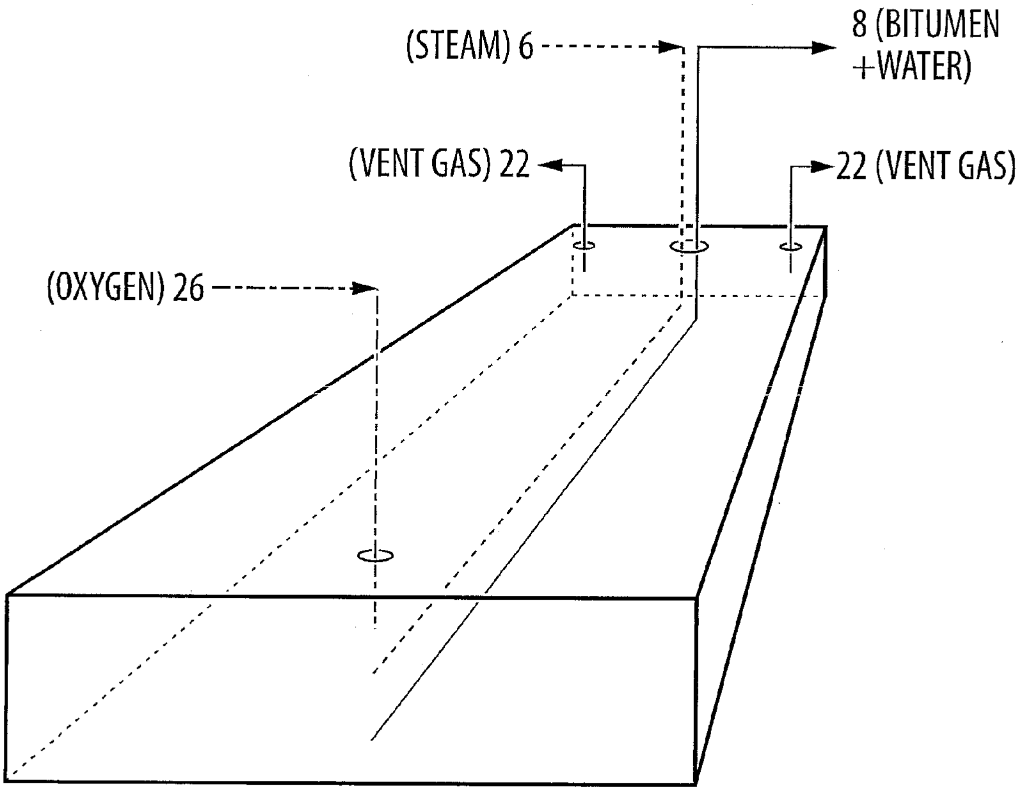

N
BITUMEN PAY THICKNESS
OF ATHABASCA WABISKAW-MCMURRAY
DEPOSIT
MINEABLE/IN SITU
RESOURCE LINE
SMA BOUNDARY
BITUMEN PAY
THICKNESS (m)
70 - 100
60 - 70
50 - 60
40 - 50
30 - 40
20 - 30
10 - 20
1.5 -10
0
35
70
Kilometers

FIG.12



SAGDOX

FIG.13

THSAGDOX PREFERRED EMBODIMENT
(THIN, SHALLOW PAYS)

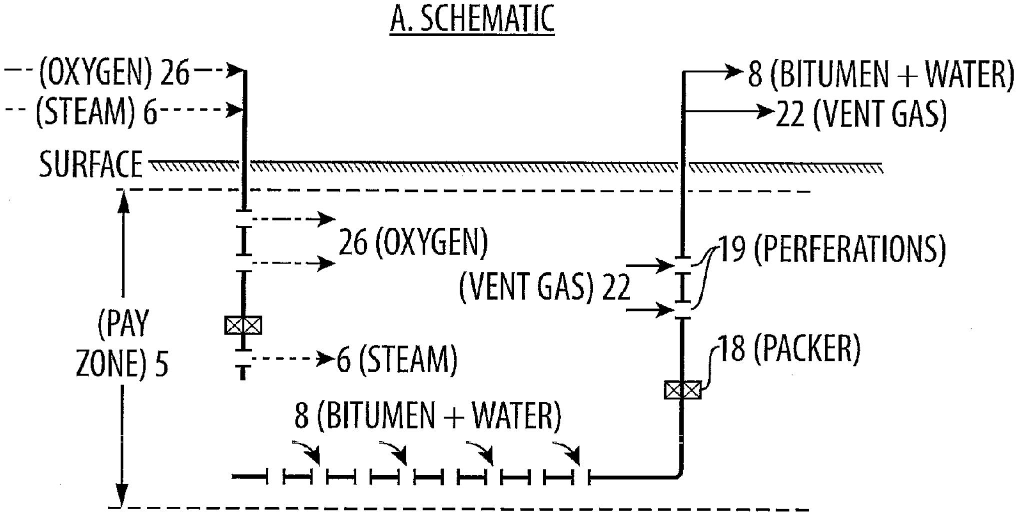


FIG. 14A

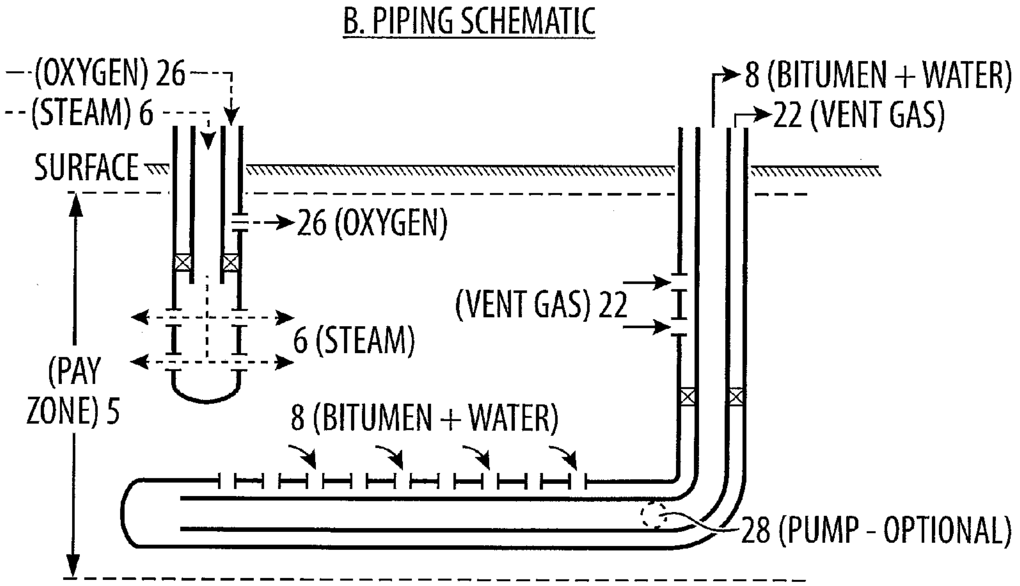


FIG. 14B

SWSAGDOX

A. SCHEMATIC

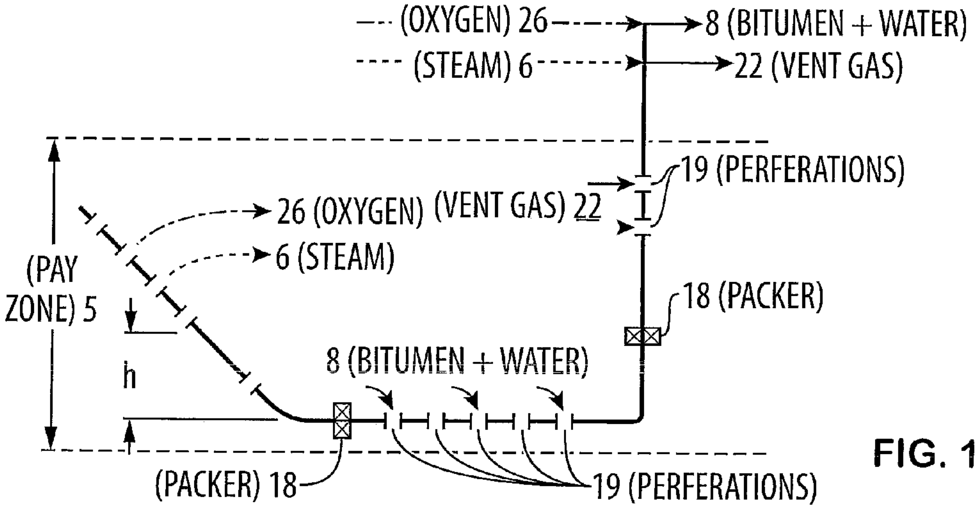


FIG. 15A

B. PIPING SCHEMATIC

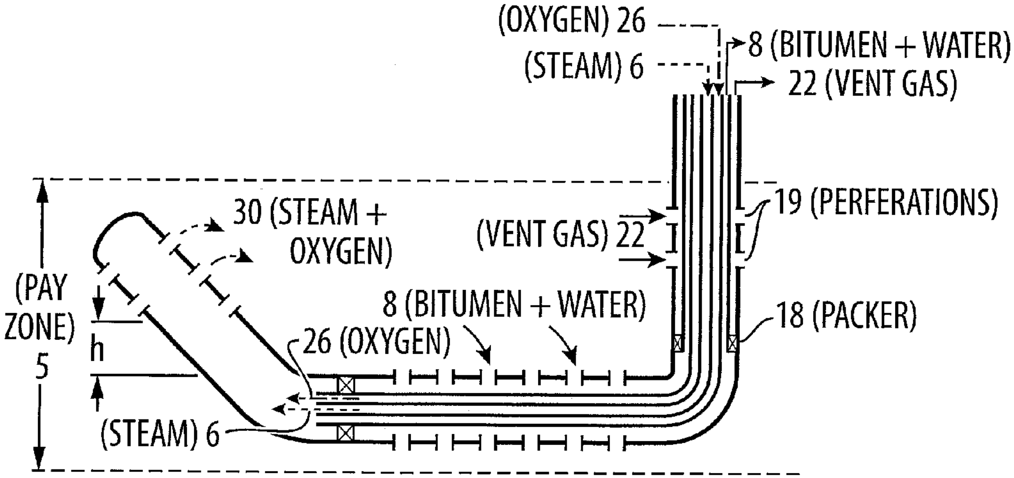
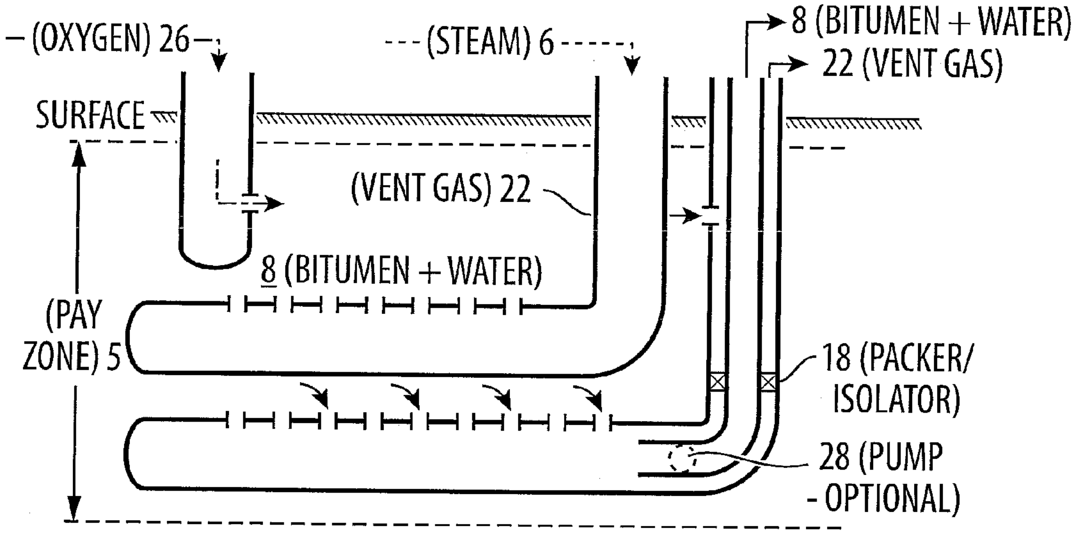


FIG. 15B

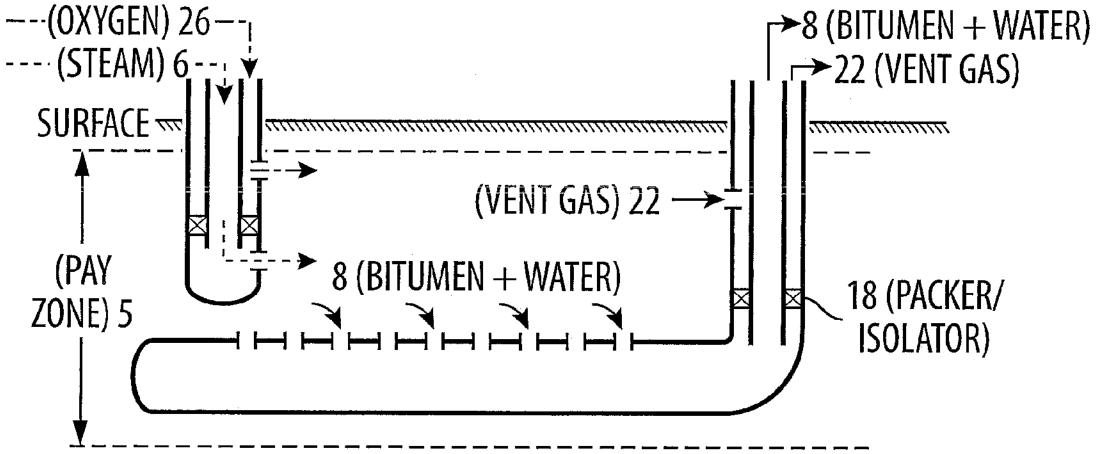
PREFERRED SAGDOX GEOMETRY



A. SAGDOX

FIG. 16A

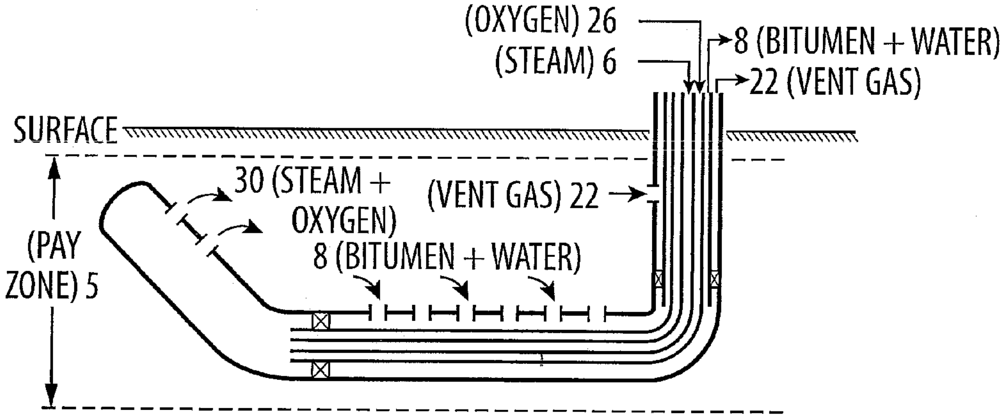
PREFERRED THSAGDOX GEOMETRY



B. THSAGDOX

FIG. 16B

PREFERRED SWSAGDOX GEOMETRY



C. SWSAGDOX

FIG. 16C

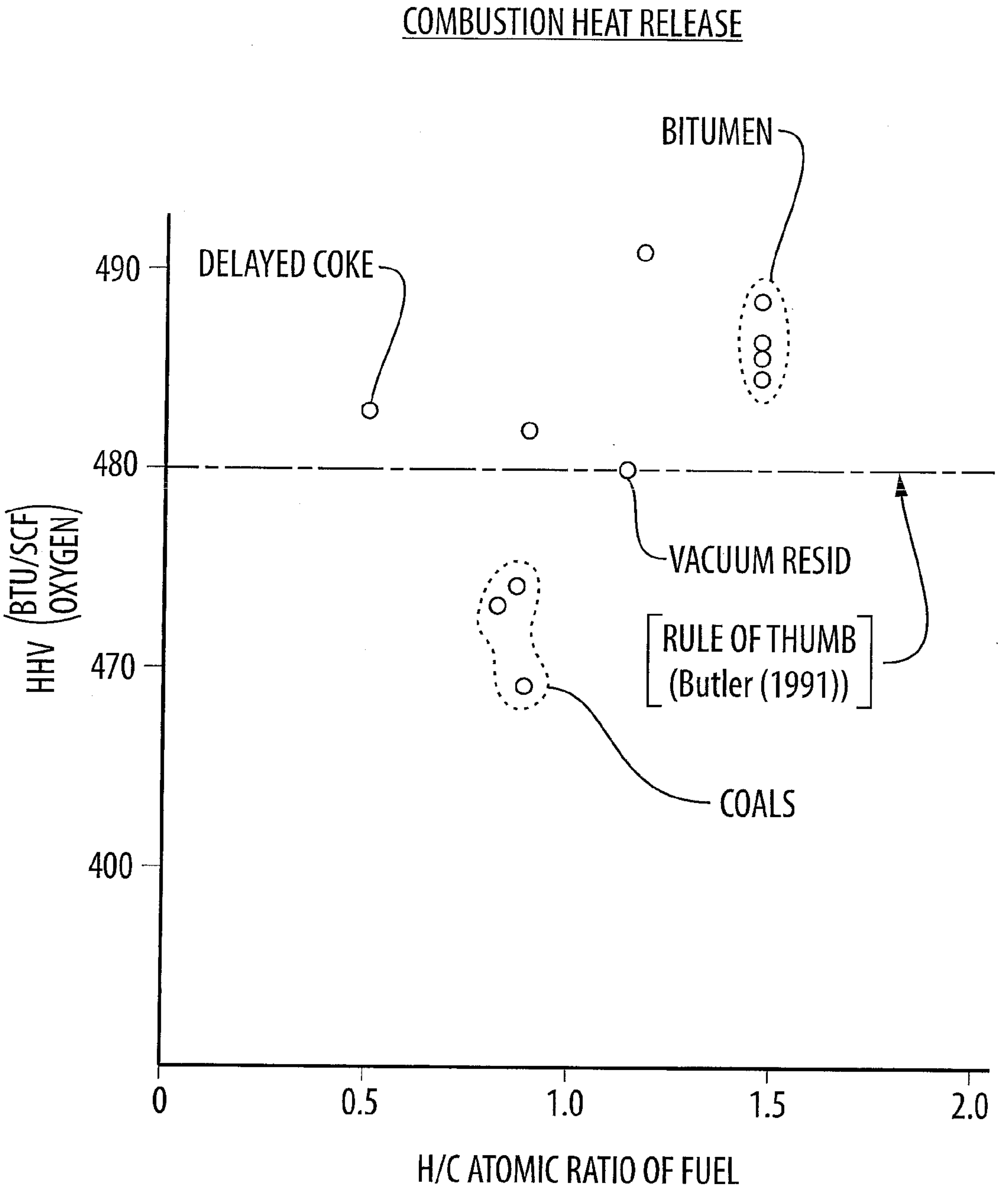
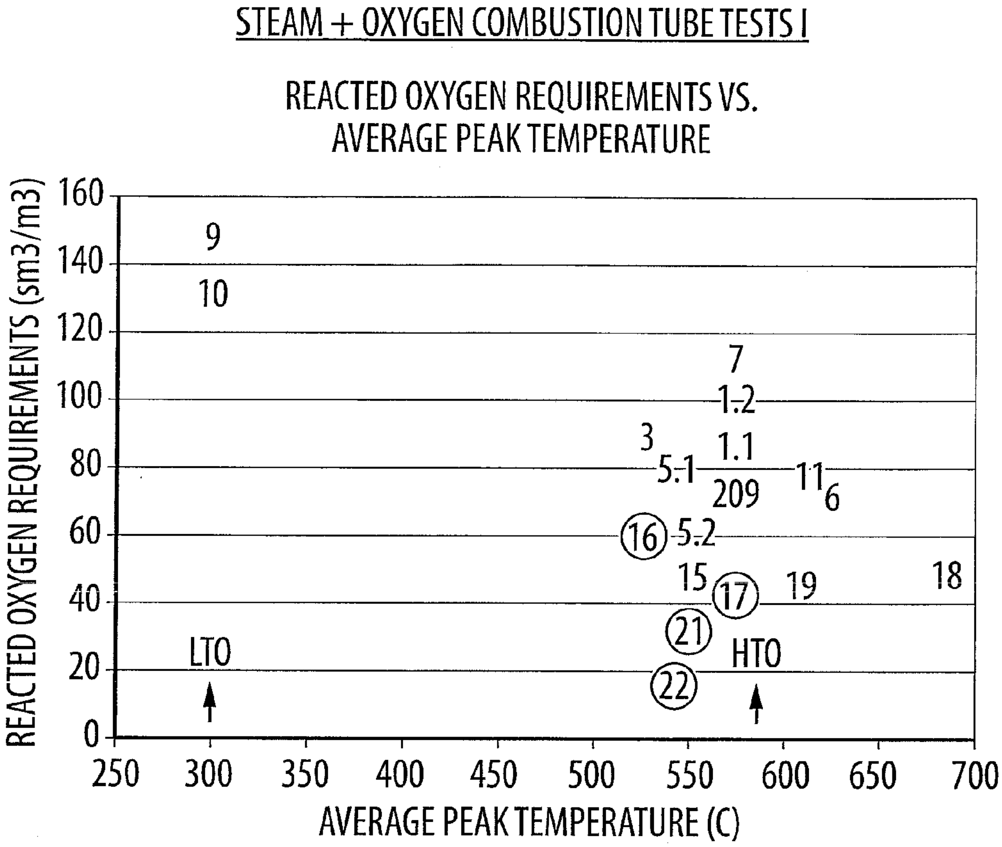

COMBUSTION HEAT RELEASE
BITUMEN
DELAYED COKE
VACUUM RESID
RULE OF THUMB (Butler (1991))
COALS
490
480
470
400
HHV (BTU/SCF OXYGEN)
0
0.5
1.0
1.5
2.0
H/C ATOMIC RATIO OF FUEL

FIG.17



(Moore et al, 1994)

- STEAM + OXYGEN → TEST ⑯ ⑰ ㉑ ㉒
- (OTHER TESTS ARE AIR, OR AIR + WATER, OR OXYGEN + WATER)

	% OXYGEN IN STEAM + O_2 MIX (v/v)
⑯	14.9
⑰	6.6
㉑	6.5
㉒	2.3

FIG.18

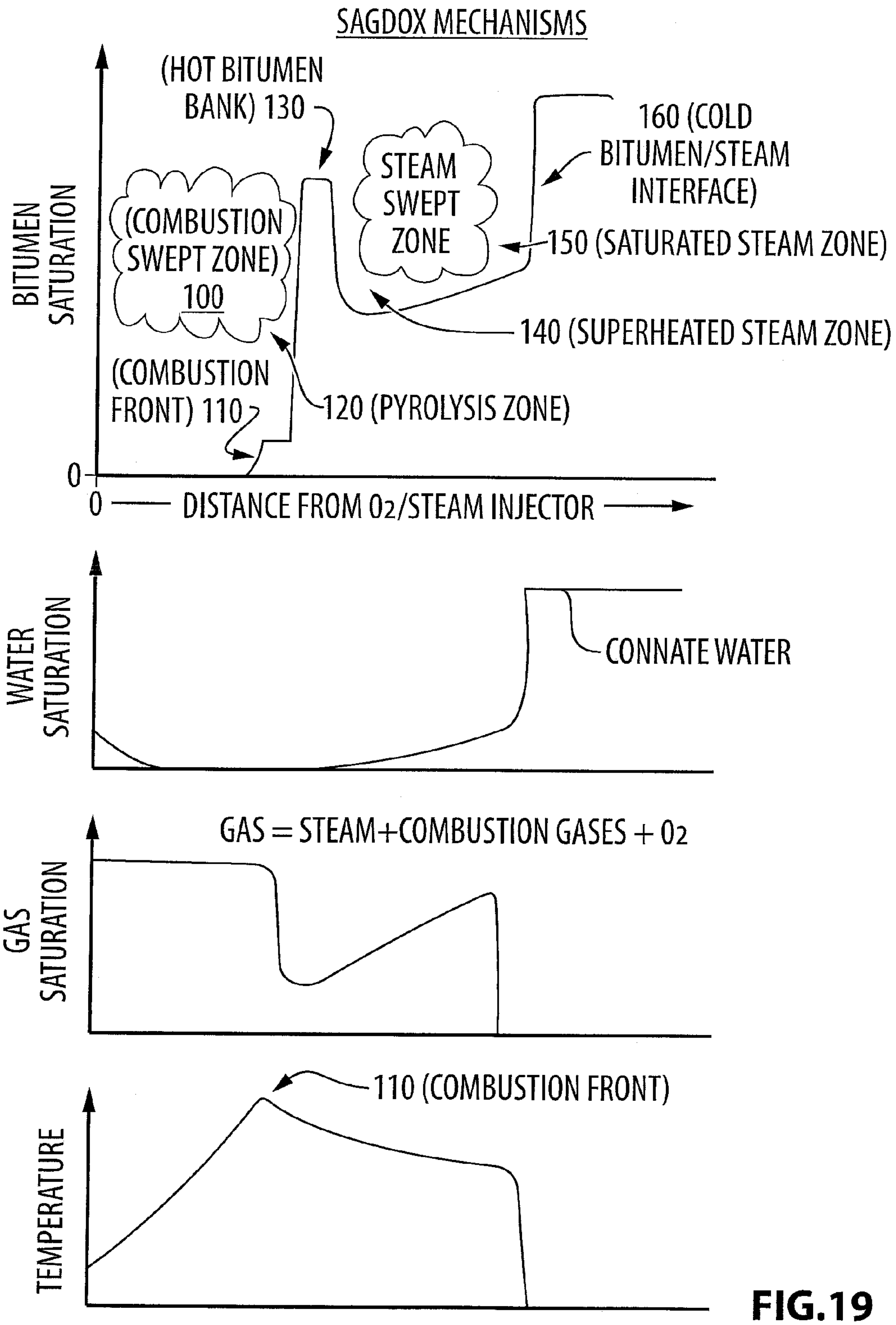

SAGDOX MECHANISMS
BITUMEN SATURATION
(HOT BITUMEN BANK) 130
(COMBUSTION SWEPT ZONE) 100
STEAM SWEPT ZONE
160 (COLD BITUMEN/STEAM INTERFACE)
150 (SATURATED STEAM ZONE)
140 (SUPERHEATED STEAM ZONE)
(COMBUSTION FRONT) 110
120 (PYROLYSIS ZONE)
0
0
DISTANCE FROM O2/STEAM INJECTOR
WATER SATURATION
CONNATE WATER
GAS = STEAM+COMBUSTION GASES + O2
GAS SATURATION
110 (COMBUSTION FRONT)
TEMPERATURE

FIG.19

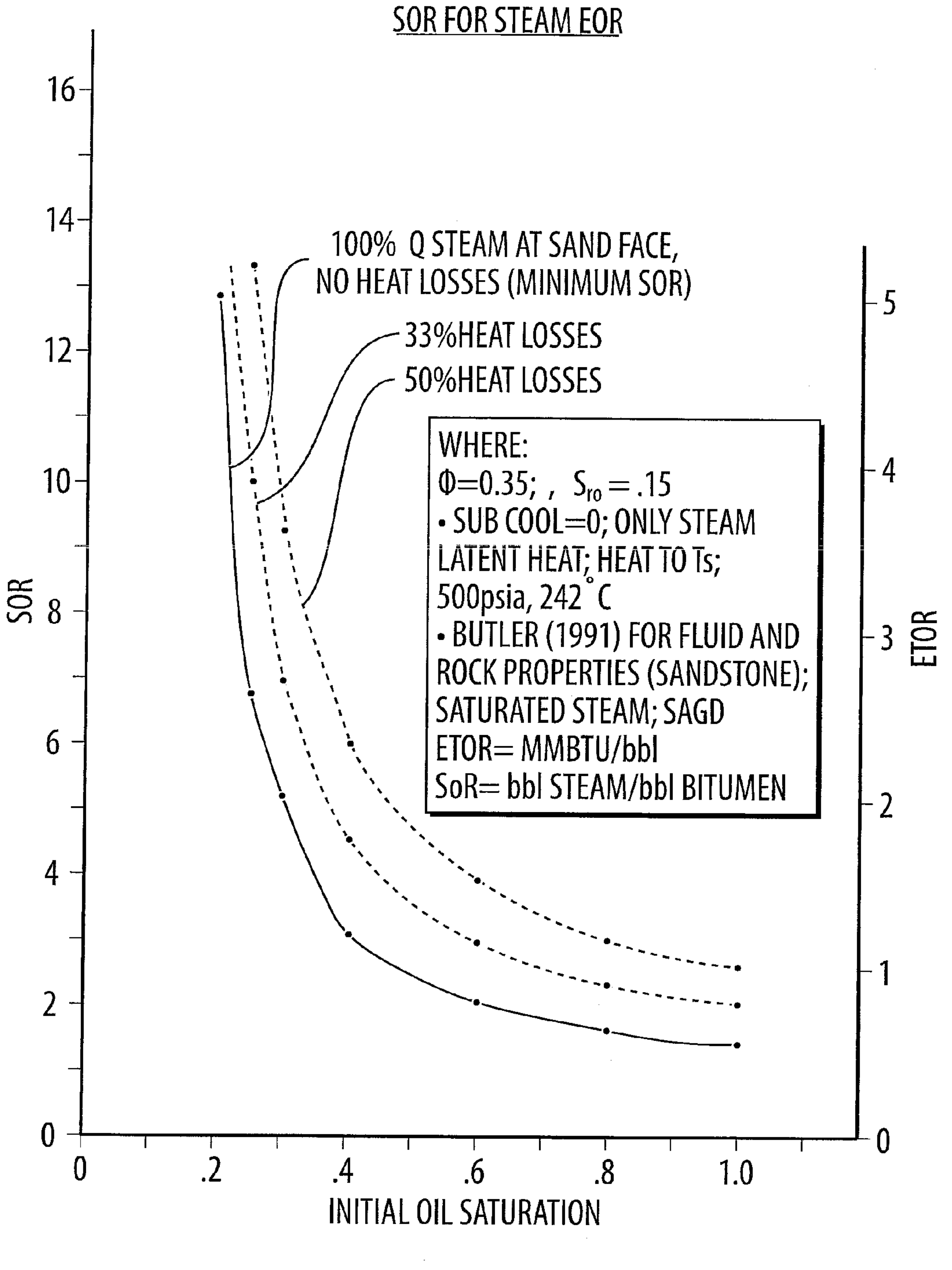

SOR FOR STEAM EOR
SOR
16
14
12
10
8
6
4
2
0
0
.2
.4
.6
.8
1.0
INITIAL OIL SATURATION
ETOR
5
4
3
2
1
0
100% Q STEAM AT SAND FACE, NO HEAT LOSSES (MINIMUM SOR)
33%HEAT LOSSES
50%HEAT LOSSES
WHERE:
Φ=0.35; , S_{ro} = .15
• SUB COOL=0; ONLY STEAM LATENT HEAT; HEAT TO Ts; 500psia, 242°C
• BUTLER (1991) FOR FLUID AND ROCK PROPERTIES (SANDSTONE); SATURATED STEAM; SAGD
ETOR= MMBTU/bbl
SoR= bbl STEAM/bbl BITUMEN

FIG.20

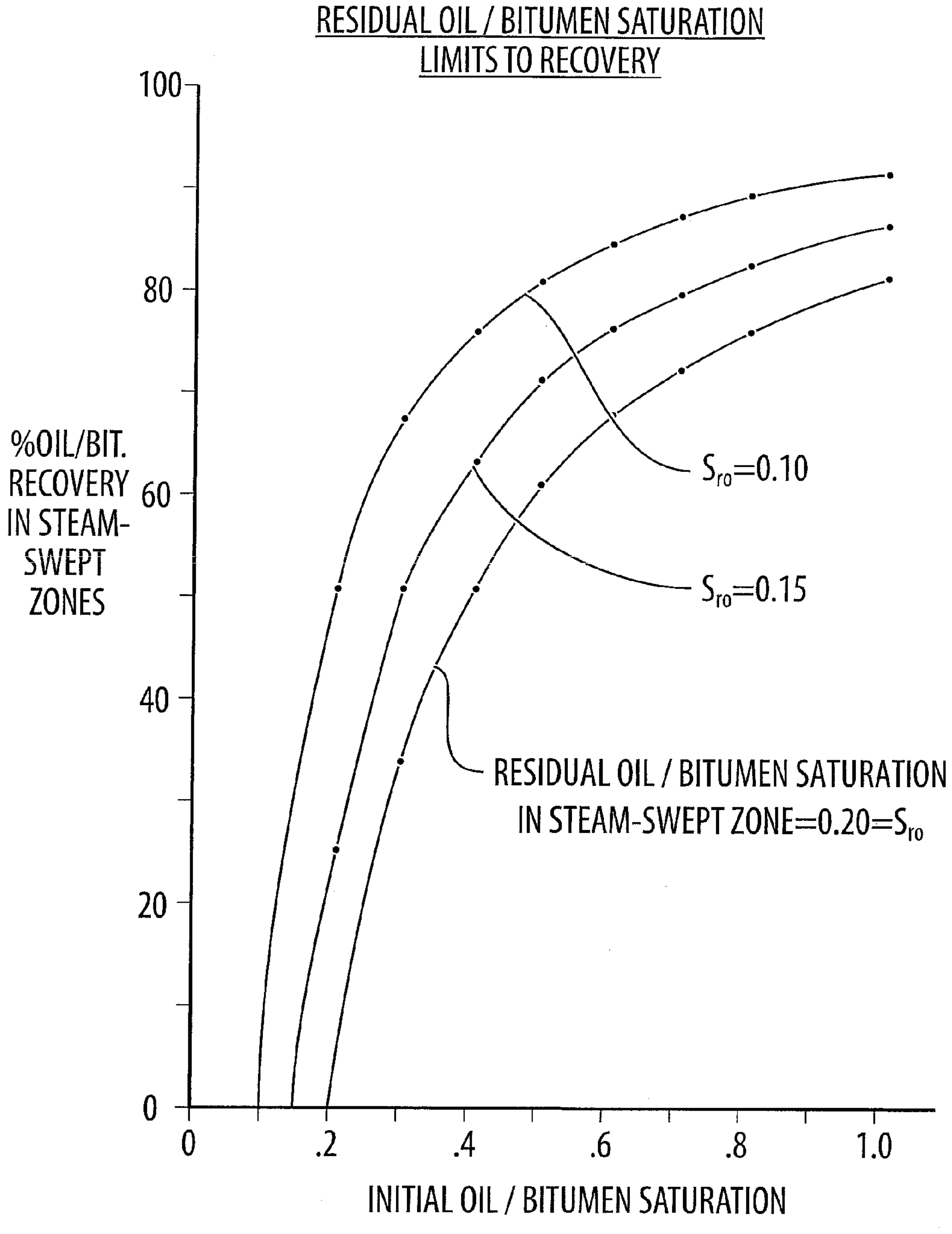

RESIDUAL OIL / BITUMEN SATURATION
LIMITS TO RECOVERY
%OIL/BIT. RECOVERY IN STEAM-SWEPT ZONES
100
80
60
40
20
0
0
.2
.4
.6
.8
1.0
INITIAL OIL / BITUMEN SATURATION
S_{ro}=0.10
S_{ro}=0.15
RESIDUAL OIL / BITUMEN SATURATION
IN STEAM-SWEPT ZONE=0.20=S_{ro}

FIG.21

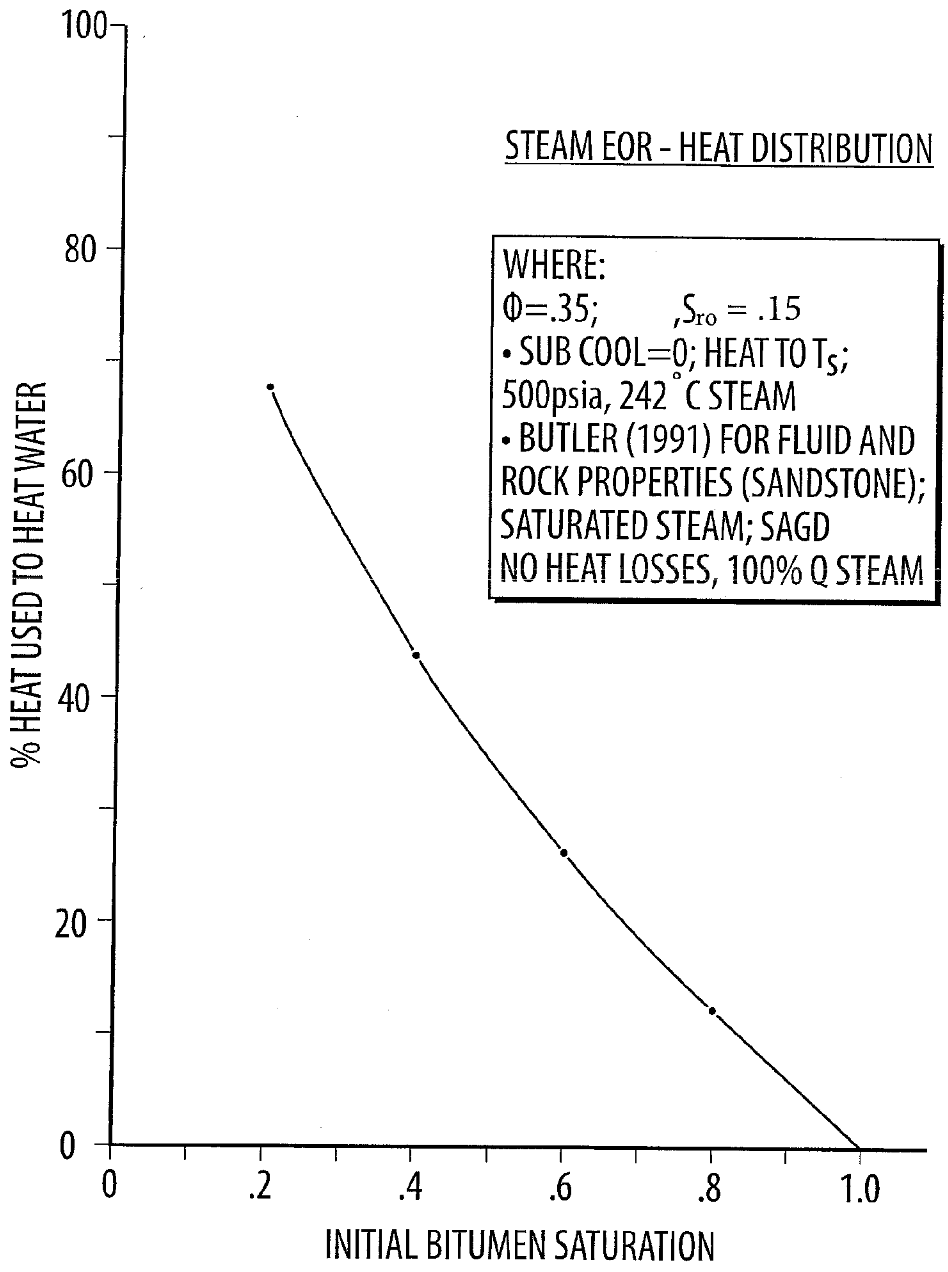

STEAM EOR - HEAT DISTRIBUTION
WHERE:
Φ=.35; ,S_{ro} = .15
• SUB COOL=0; HEAT TO T_S;
500psia, 242°C STEAM
• BUTLER (1991) FOR FLUID AND
ROCK PROPERTIES (SANDSTONE);
SATURATED STEAM; SAGD
NO HEAT LOSSES, 100% Q STEAM
% HEAT USED TO HEAT WATER
100
80
60
40
20
0
0
.2
.4
.6
.8
1.0
INITIAL BITUMEN SATURATION

FIG.22

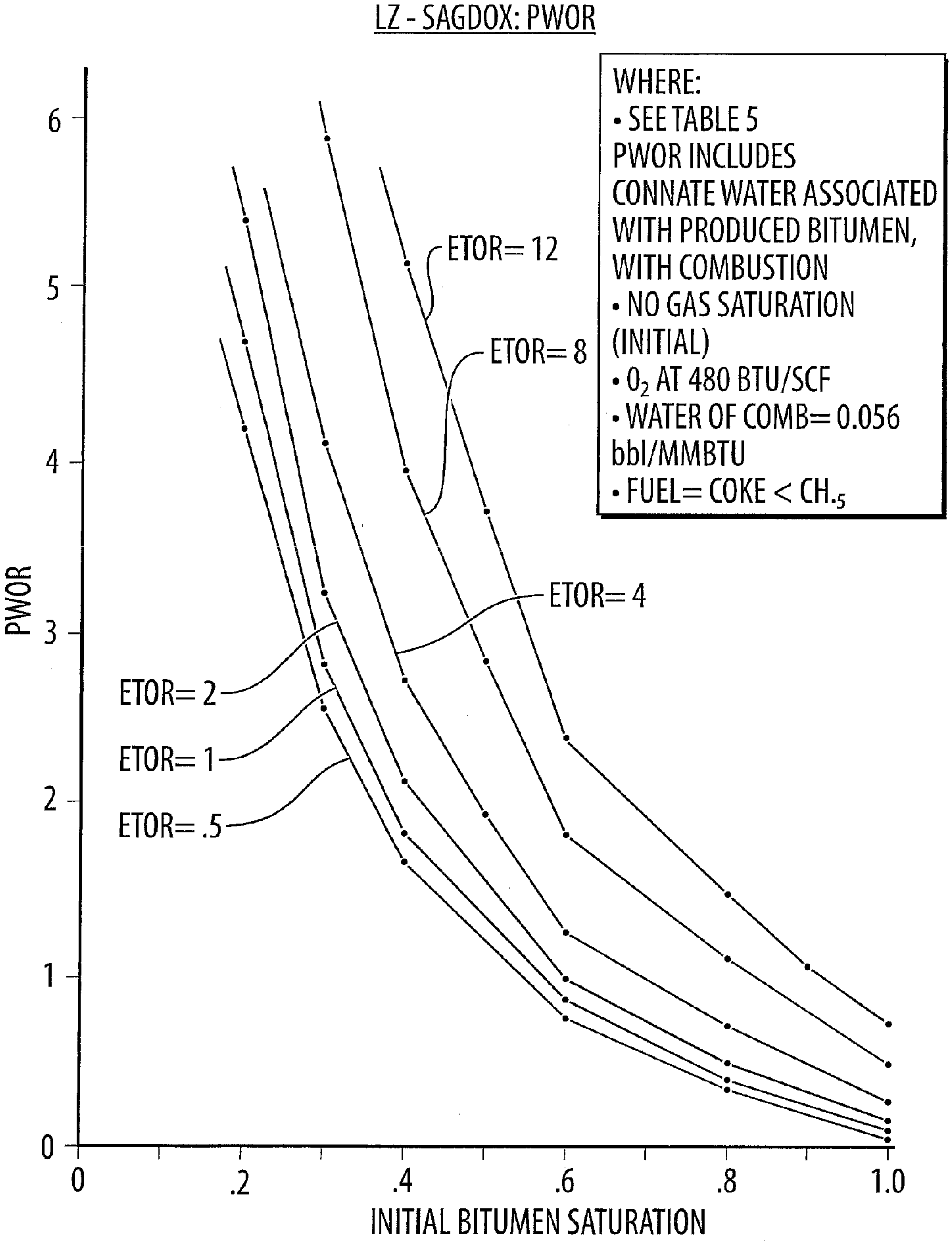

LZ - SAGDOX: PWOR
WHERE:
• SEE TABLE 5
PWOR INCLUDES
CONNATE WATER ASSOCIATED
WITH PRODUCED BITUMEN,
WITH COMBUSTION
• NO GAS SATURATION
(INITIAL)
• O_2 AT 480 BTU/SCF
• WATER OF COMB= 0.056
bbl/MMBTU
• FUEL= COKE < $CH_{.5}$
ETOR= 12
ETOR= 8
ETOR= 4
ETOR= 2
ETOR= 1
ETOR= .5
PWOR
0
1
2
3
4
5
6
0
.2
.4
.6
.8
1.0
INITIAL BITUMEN SATURATION

FIG.23

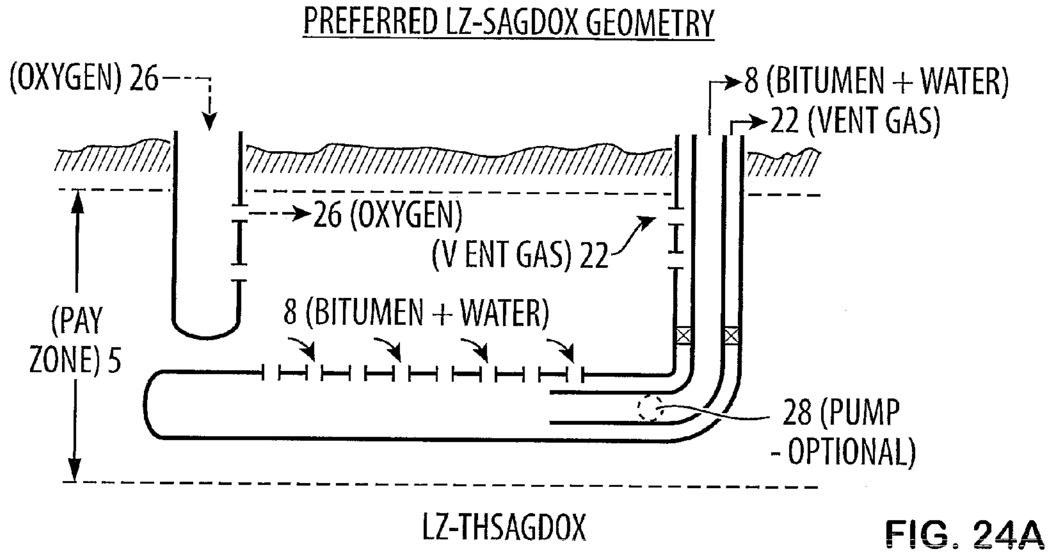


FIG. 24A

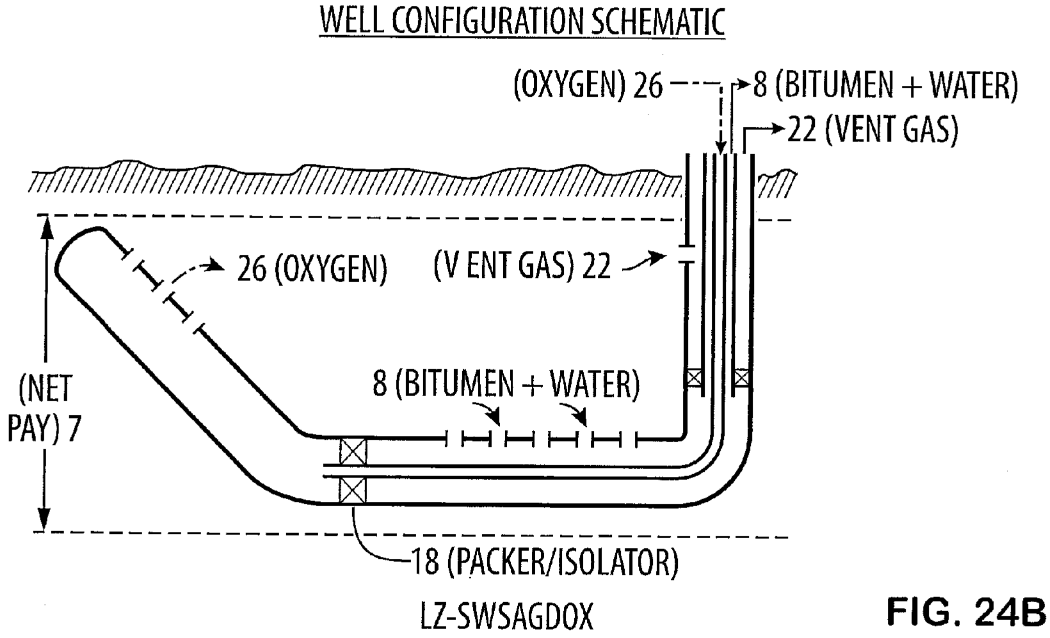
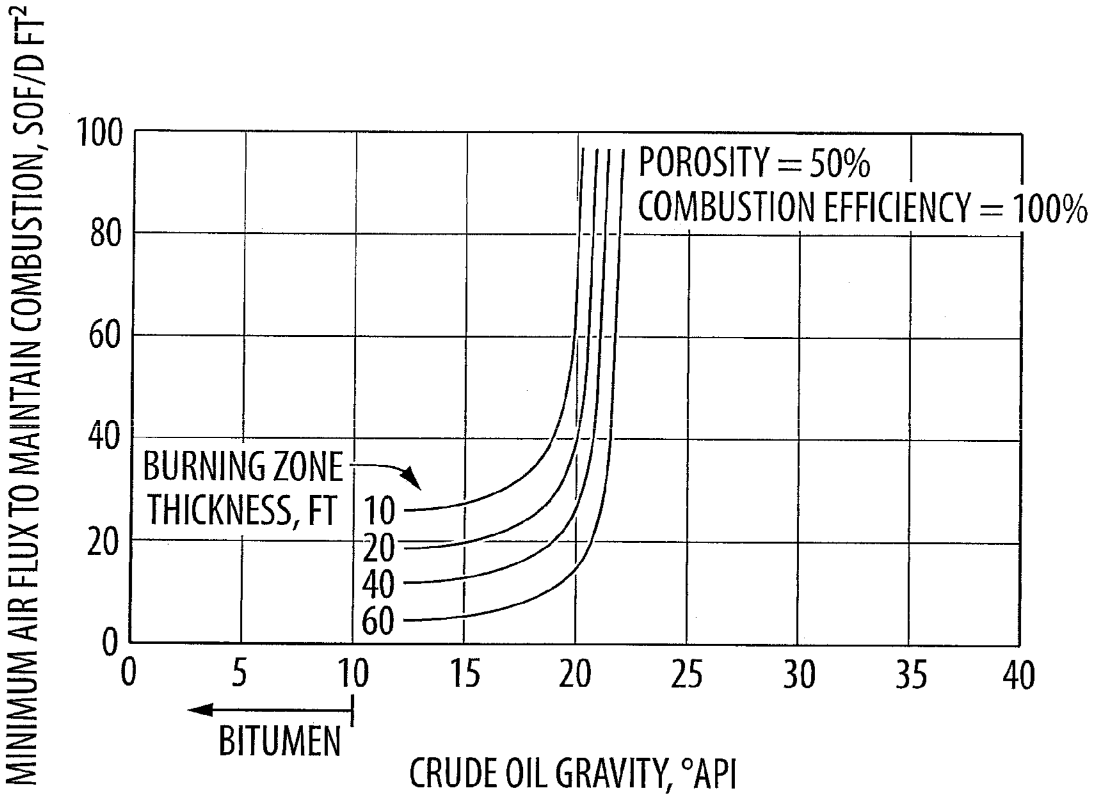


FIG. 24B

ISC MINIMUM AIR FLUX RATES

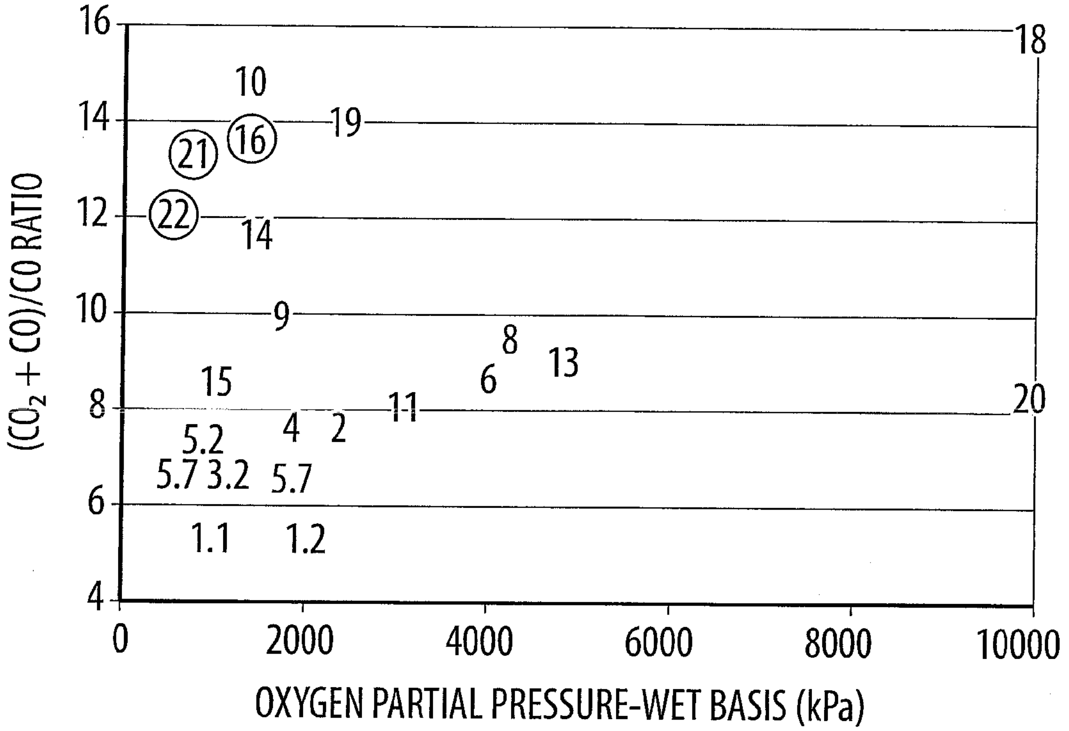


- RELATIONSHIP BETWEEN CRUDE GRAVITY AND REQUIRED AIR FLUX
(Sarathi, DOE, 1999)

FIG.25

STEAM + OXYGEN COMBUSTION TUBE TESTS II

STABILIZED ((CO_2 + CO)/CO) RATIO VS.
OXYGEN PARTIAL PRESSURE ON A WET BASIS

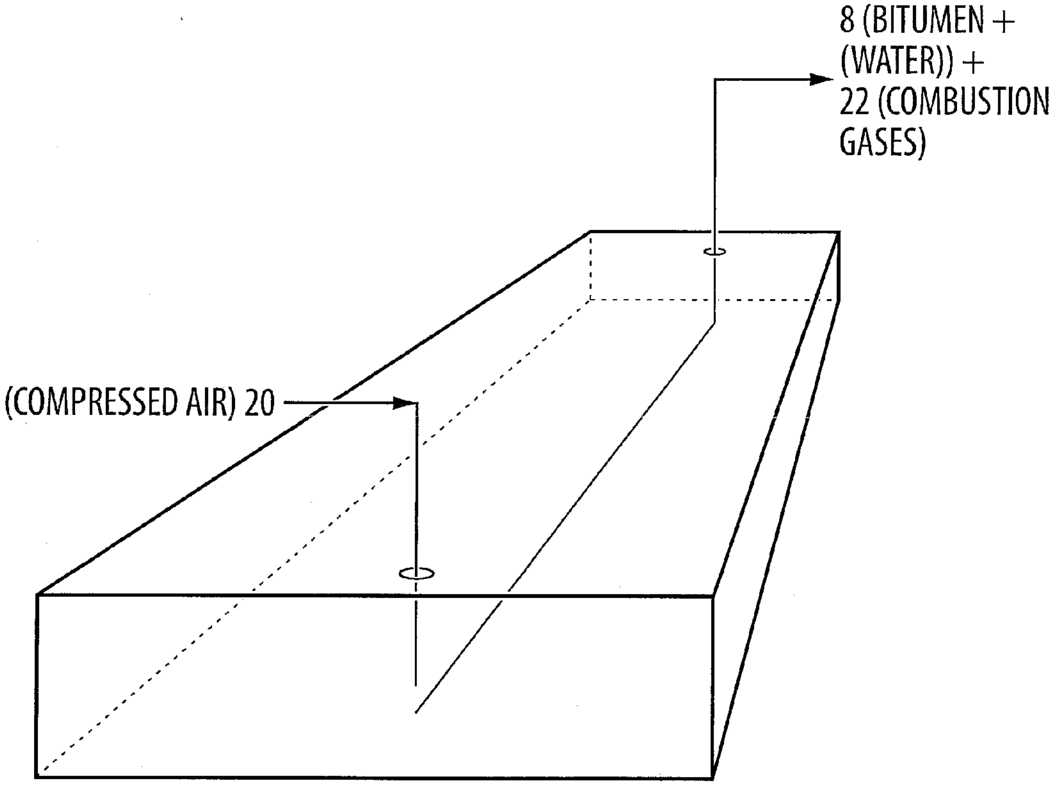


(Moore et al, 1994)

- STEAM + OXYGEN → TEST ⑯ ㉑ ㉒
- (OTHER TESTS ARE AIR, OR AIR + WATER, OR OXYGEN + WATER)

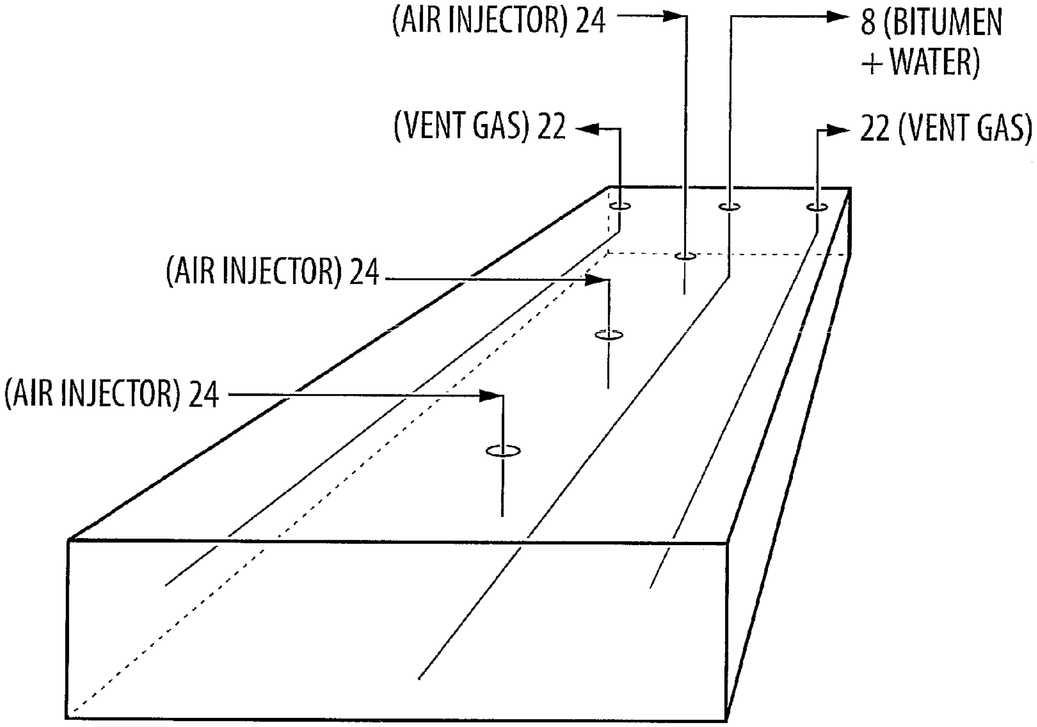
% OXYGEN IN STEAM + O_2 MIX (v/v)	
⑯	14.9
㉑	6.5
㉒	2.3

FIG.26



THE THAI PROCESS (ISC)

FIG.27



THE COGD/COSH PROCESS (ISC)

FIG.28

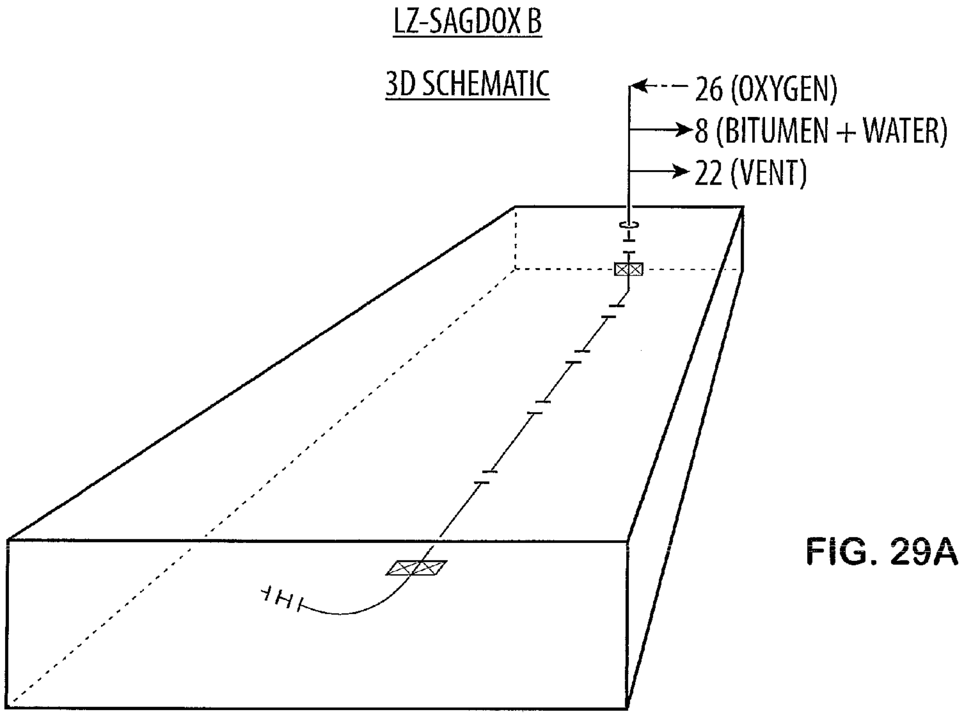


FIG. 29A

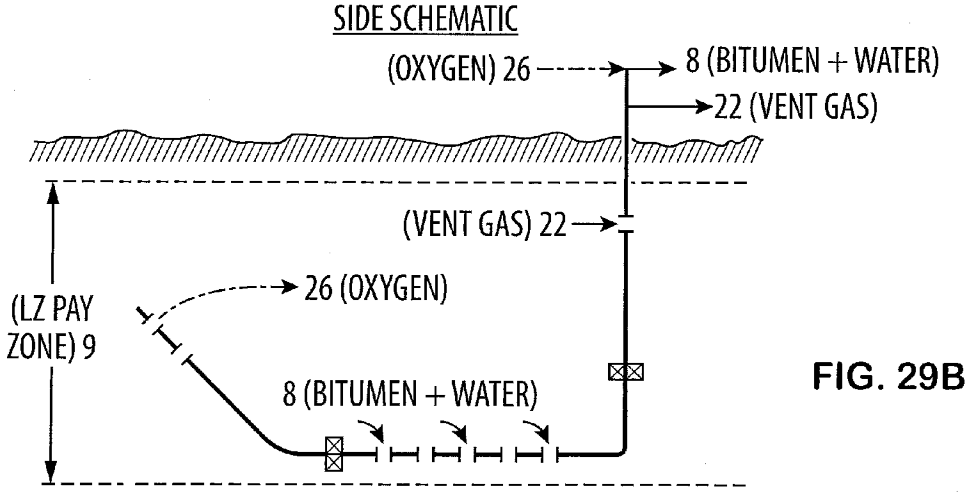


FIG. 29B

LZ-SAGDOX B: WELL SCHEMATIC

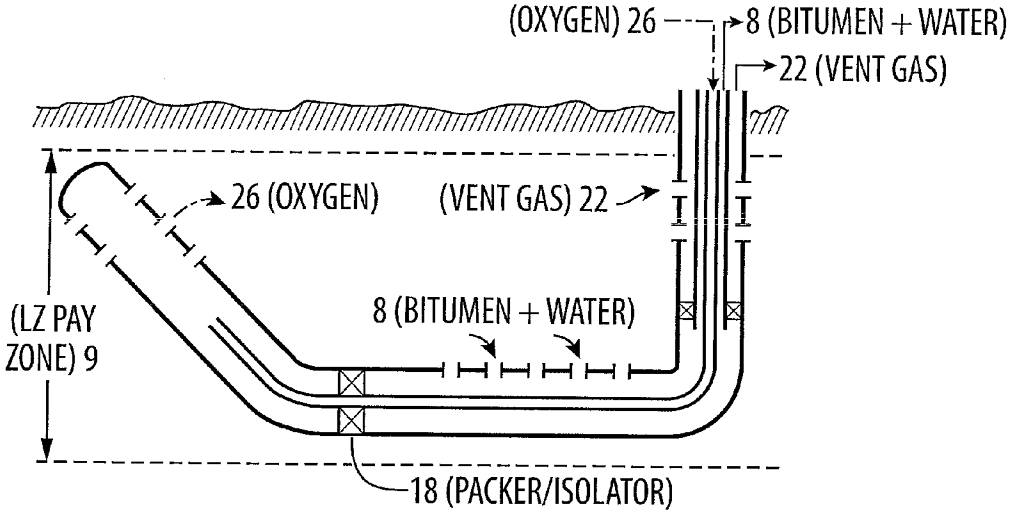


FIG. 30

SWSAGD SCHEMATIC (PACKERS)

3D SCHEMATIC

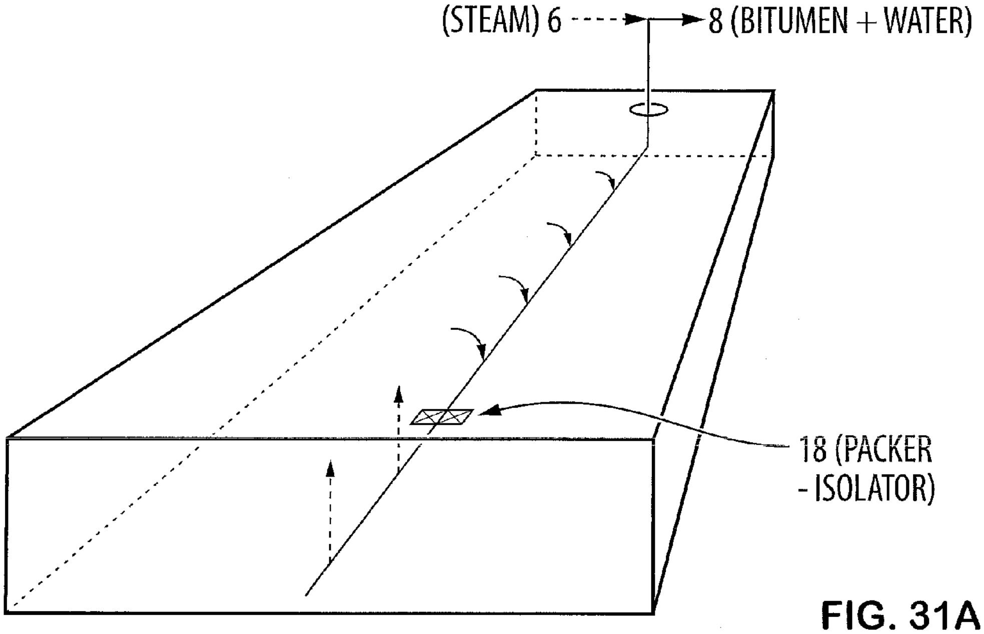


FIG. 31A

WELL CONFIGURATION

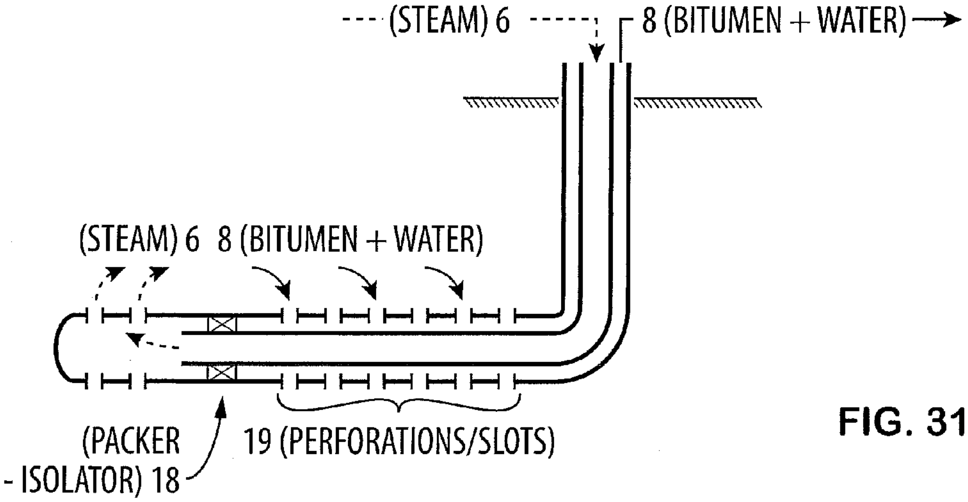
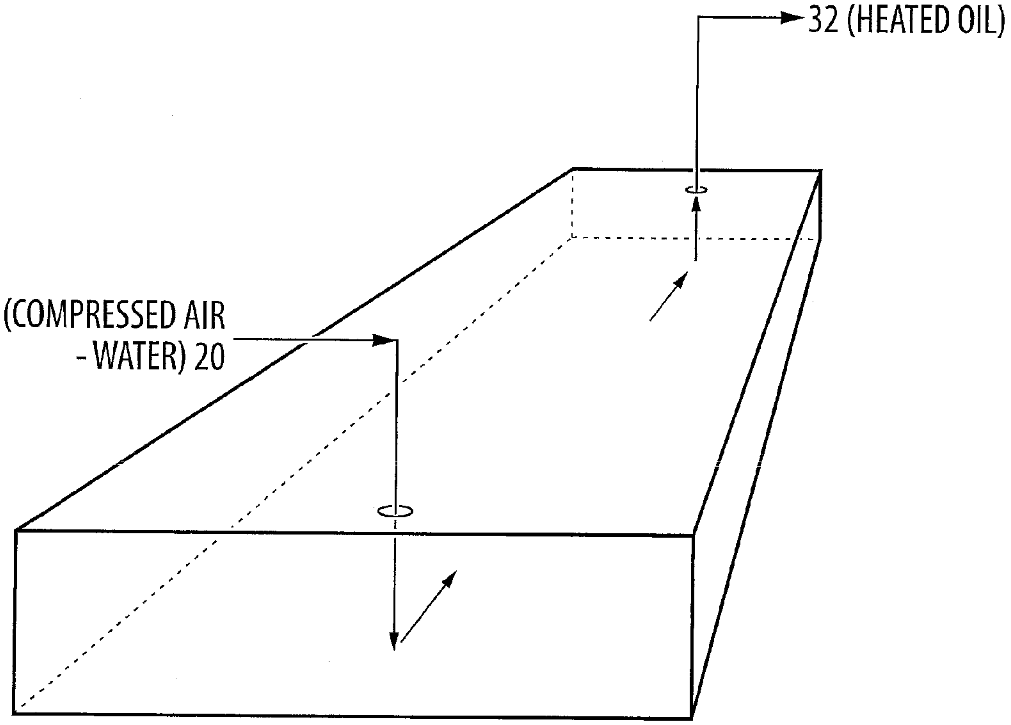


FIG. 31B



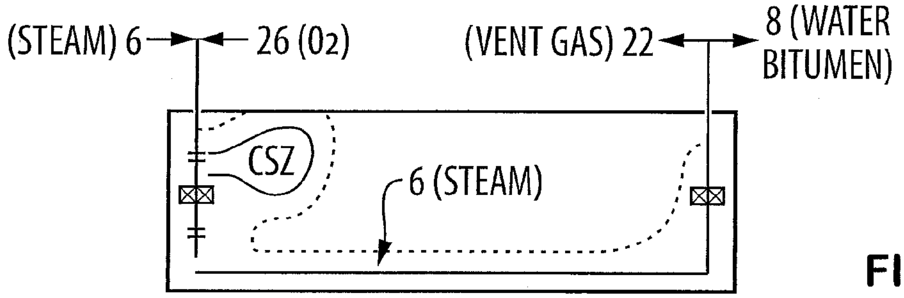
SURFACE WELL PATTERN OF VERTICAL WELLS IS OFTEN IN A GEOMETRIC PATTERN - ie. 5 SPOT, 7 SPOT, 9 SPOT...

CONVENTIONAL INSITU COMBUSTION (ISC)
(VERTICAL WELLS)

FIG.32

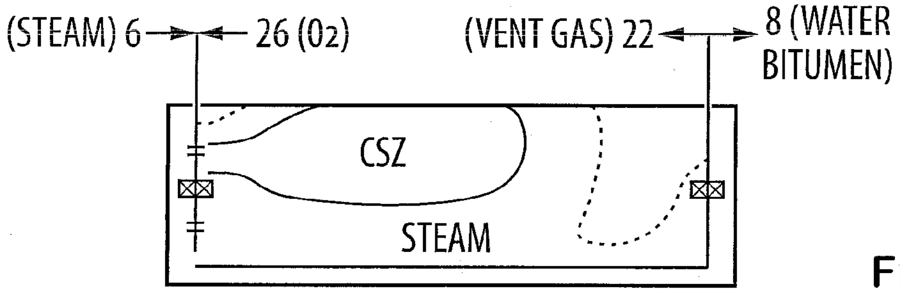
GAS CHAMBER: THSAGDOX

SIDE VIEW OF RECOVERY PATTERN



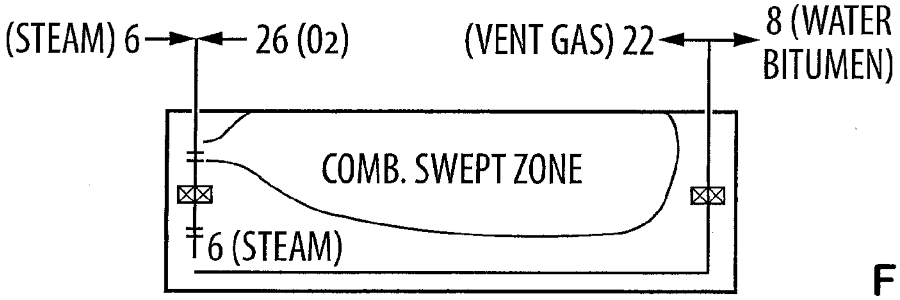
EARLY LIFE

FIG. 33A



MATURE

FIG. 33B



END-OF-LIFE

FIG. 33C

THSAGDOX LIQUID DRAWDOWN

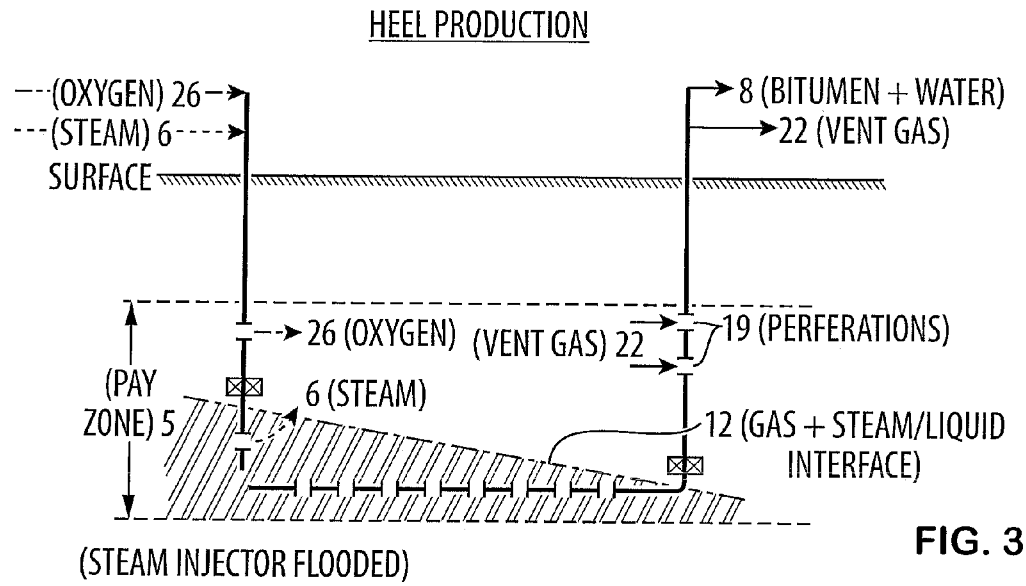


FIG. 34A

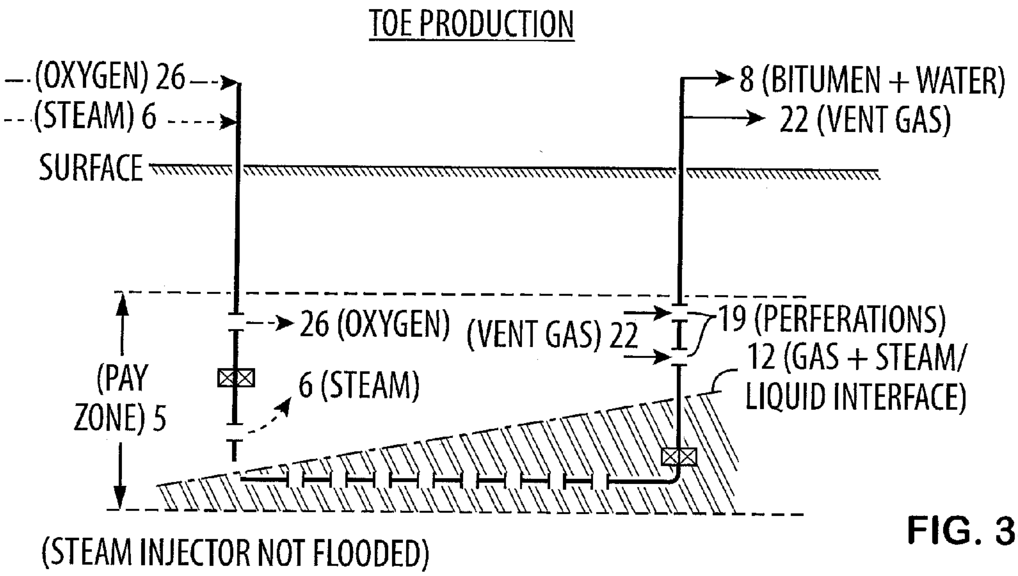


FIG. 34B

SWSAGDOX/SWSAGDOX(U) HYDRAULIC LIMITATIONS
(MATURE OPERATIONS)
(STEADY-STATE)

A. SWSAGDOX

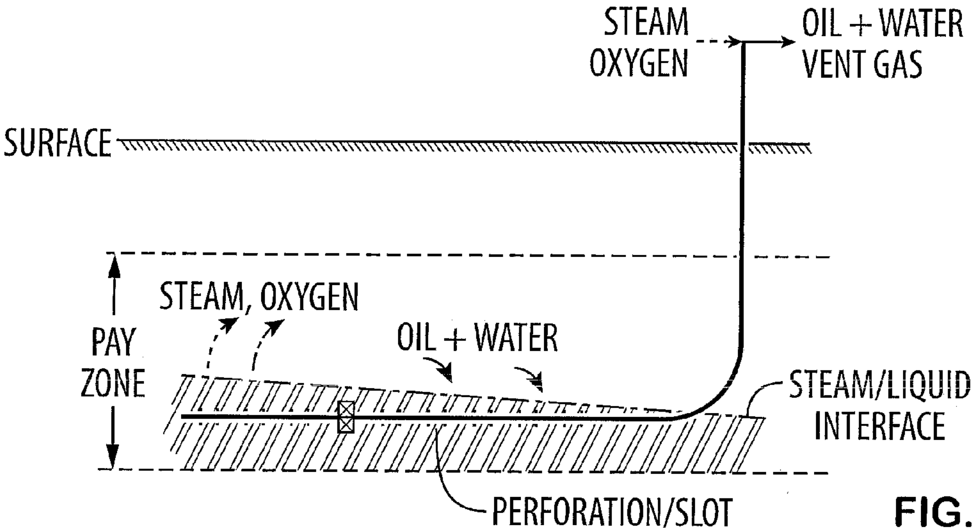


FIG. 35A

B. SWSAGDOX(U)

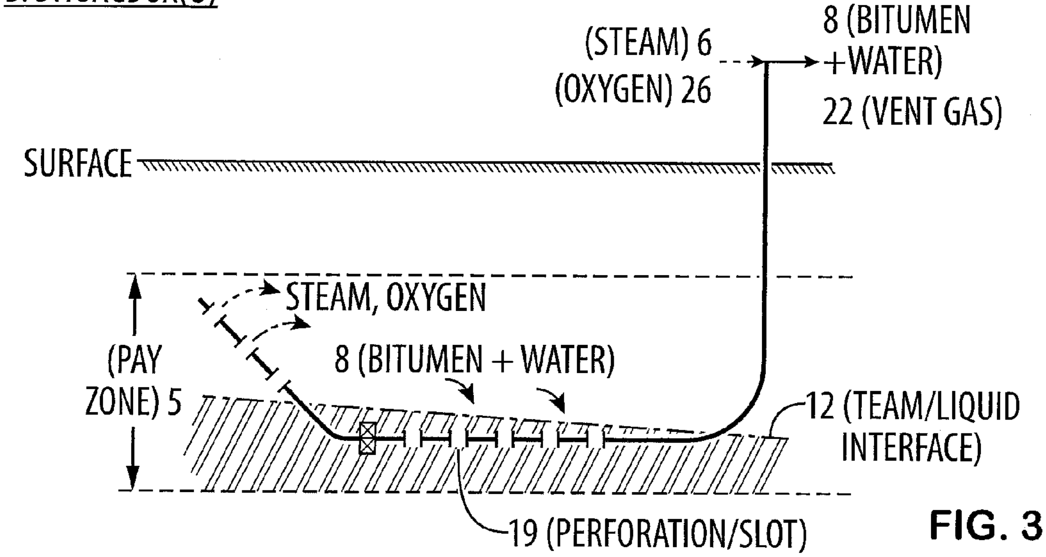


FIG. 35B

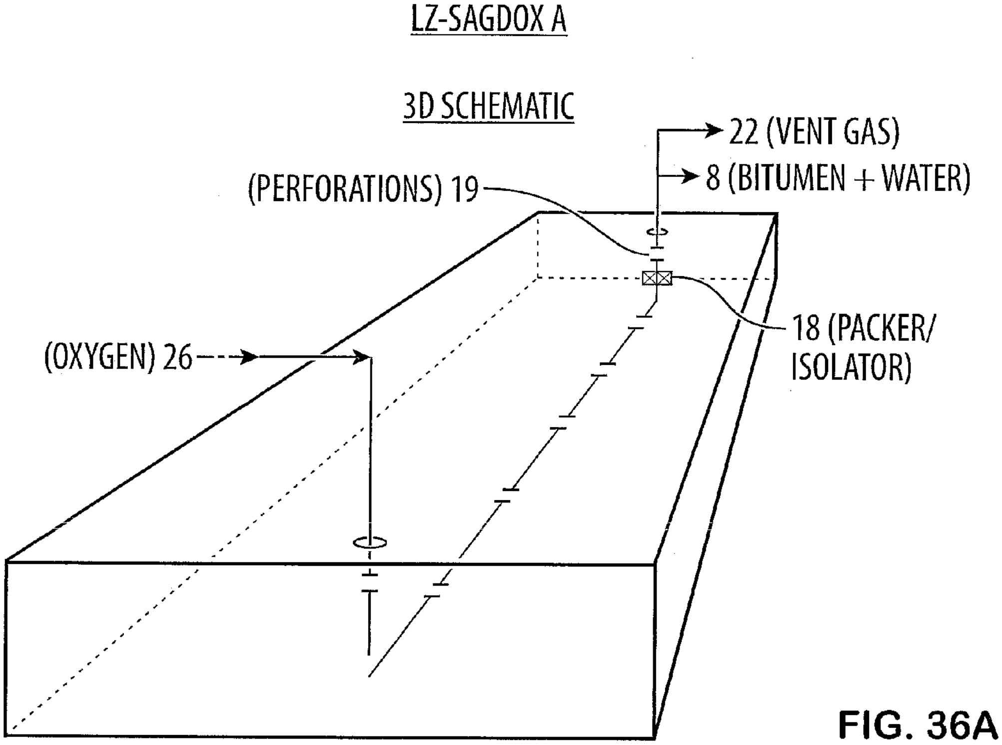


FIG. 36A

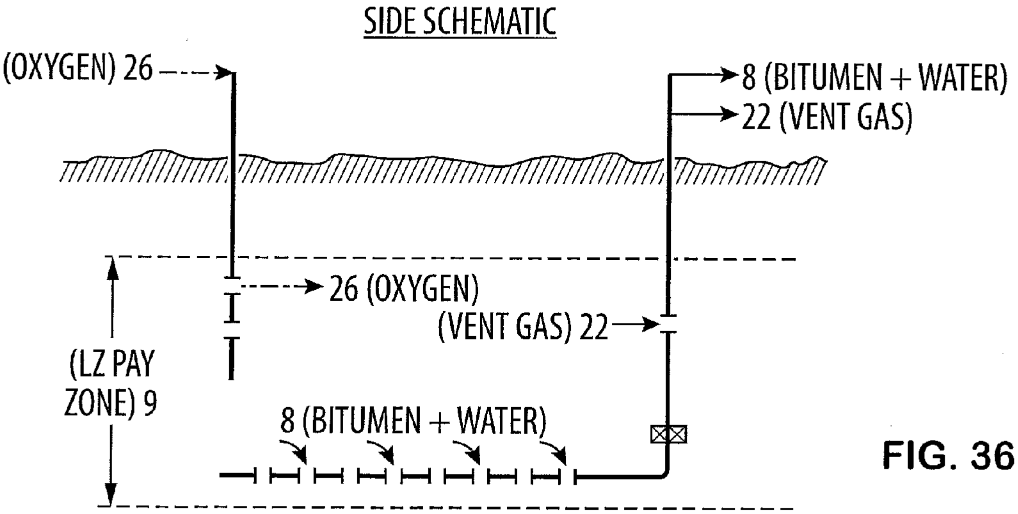


FIG. 36B

LZ-SAGDOX A: WELL SCHEMATIC

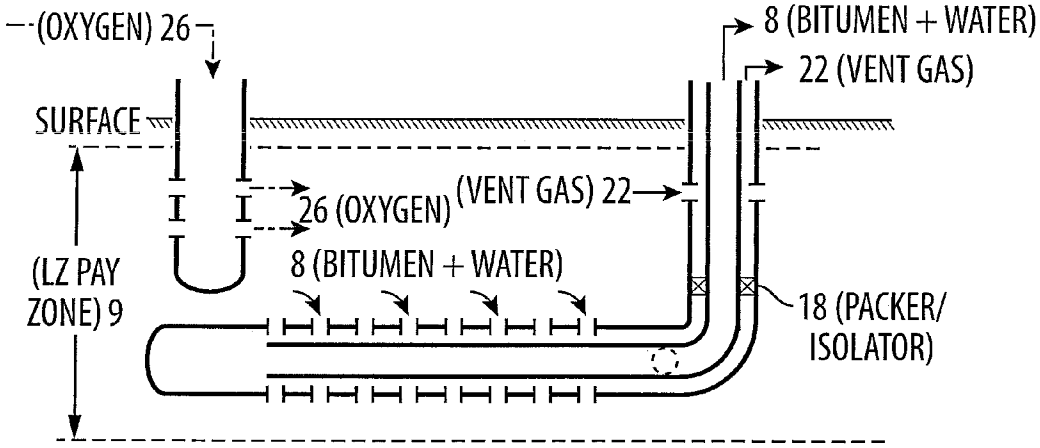


FIG.37

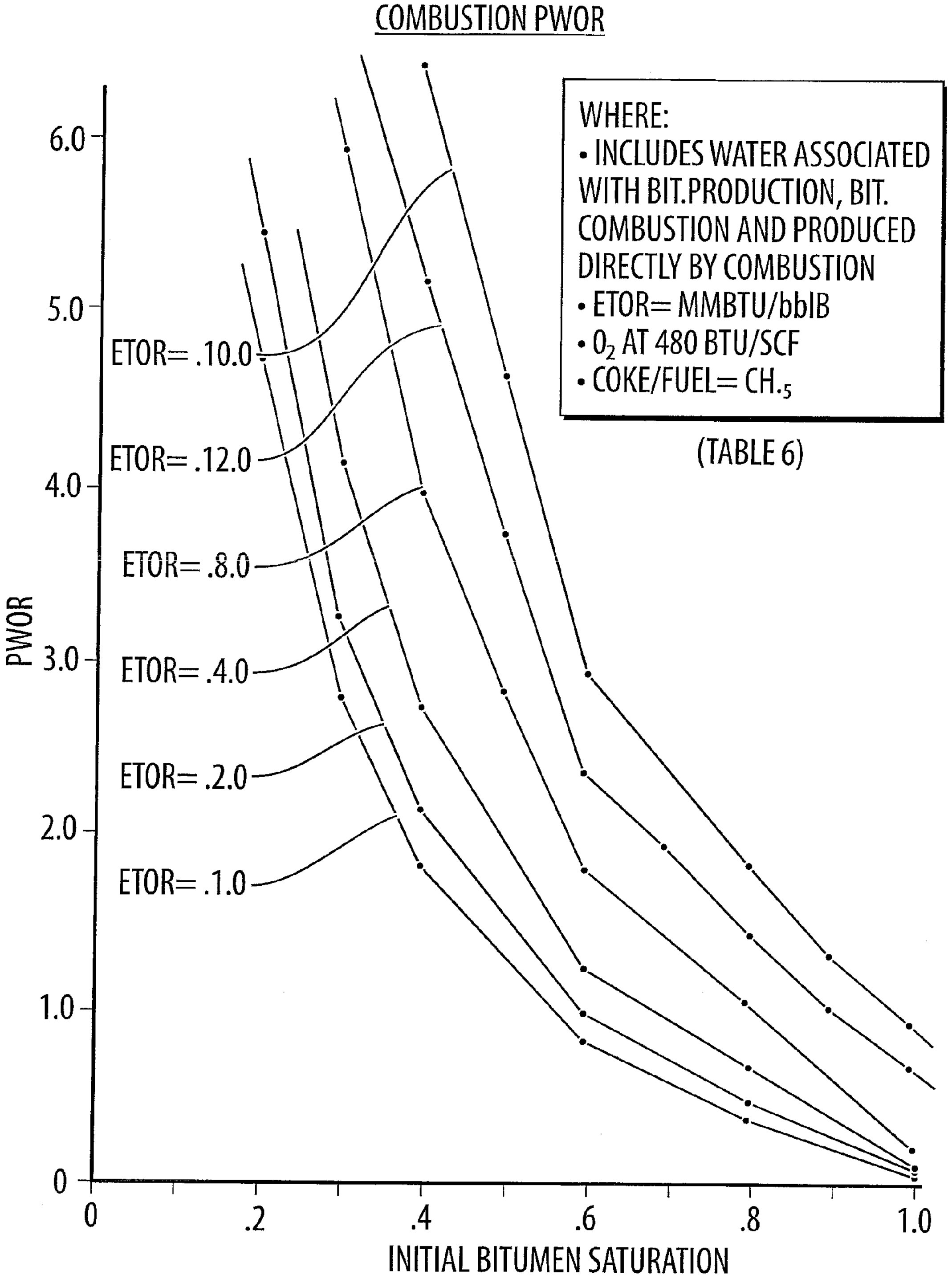

COMBUSTION PWOR
WHERE:
• INCLUDES WATER ASSOCIATED WITH BIT.PRODUCTION, BIT. COMBUSTION AND PRODUCED DIRECTLY BY COMBUSTION
• ETOR= MMBTU/bblB
• 0_2 AT 480 BTU/SCF
• COKE/FUEL= $CH._5$
(TABLE 6)
ETOR= .10.0
ETOR= .12.0
ETOR= .8.0
ETOR= .4.0
ETOR= .2.0
ETOR= .1.0
PWOR
6.0
5.0
4.0
3.0
2.0
1.0
0
0
.2
.4
.6
.8
1.0
INITIAL BITUMEN SATURATION

FIG.38

USE OF STEAM-ASSISTED GRAVITY DRAINAGE WITH OXYGEN ("SAGDOX") IN THE RECOVERY OF BITUMEN IN LEAN ZONES ("LZ-SAGDOX")

BACKGROUND

[0001] Steam Assisted Gravity Drainage (SAGD) is a commercial, thermal enhanced oil recovery ("EOR") process. The SAGD process uses saturated steam injected into a horizontal well, where latent heat is used to heat bitumen in the reservoir. The heating of the bitumen lowers its viscosity, so it drains by gravity to an underlying parallel, twin, horizontal well completed near the reservoir bottom.

[0002] Since the process inception in the early 1980's, SAGD has become the dominant, in situ process to recover bitumen from Alberta's bitumen deposits (Butler, R., "Thermal Recovery of Oil & Bitumen", Prentice-Hall, 1991). Today's SAGD bitumen production in Alberta is about 300 Kbbl/d with installed capacity at about 475 Kbbl/d (Oilsands Review, 2010). SAGD is now the world's leading thermal EOR process.

[0003] FIG. **1** (PRIOR ART) shows the "traditional" SAGD geometry, using twin, parallel horizontal wells **2**,**4** drilled in the same vertical plane. There is a 5-metre spacing between the horizontal wells **2**,**4**, which are about 800 metres long with the lower well 1 to 2 metres above the (horizontal) reservoir floor. Circulating steam **6** in both wells starts the SAGD process. After communication is established, the upper well **2** is used to inject steam **6**, and the lower well **4** produces hot water and hot bitumen **8**. Fluid production is accomplished by natural lift, gas lift, or submersible pump.

[0004] After conversion to "normal" SAGD operations, a steam chamber **10** forms around the injection **2** and production wells **4** where the void space is occupied by steam **6**. Steam **6** condenses at the boundaries of the chamber **10**, releases latent heat (heat of condensation), and heats bitumen, connate water and the reservoir matrix. Heated bitumen and water **8** drain by gravity to the lower production well **4**. The steam chamber **10** grows upward and outward as bitumen is drained.

[0005] FIGS. **2A**-**2D** (PRIOR ART) show how SAGD matures. A "young" steam chamber **10** has bitumen drainage from steep chamber sides and from the chamber ceiling. When the chamber growth hits the top of the reservoir, ceiling drainage stops, bitumen productivity peaks, and the slope of the side walls decreases as lateral growth continues. Heat loss increases (and steam-to-oil ratio ("SOR") increases) as ceiling contact and the "surface area" of the steam chamber increases. Drainage rates slow down as the side wall angle decreases. Eventually, the economic limit is reached, and the end-of-life drainage angle is small) (10-20°.

[0006] Produced fluids are near saturated-steam temperature, so it is only the latent heat of steam that contributes to the process in the reservoir. But, some of the sensible heat can be captured from surface heat exchangers (a greater fraction at higher temperatures), so a useful rule-of-thumb for net heat contribution of steam is 1000 BTU/lb. for the P, T range of most SAGD projects (FIG. **3** PRIOR ART).

[0007] The operational performance of SAGD can be characterized by measurement of the following parameters: 1) saturated steam P, T in the steam chamber (FIG. **4** PRIOR ART); 2) bitumen productivity; 3) SOR, usually at the well head; 4) sub-cool target, the T difference between saturated steam and produced fluids; and 5) Water Recycle Ratio ("WRR"), the ratio of produced water to steam injected.

[0008] During the SAGD process, the SAGD operator has two choices to make: 1) the sub-cool target T difference and 2) the operating pressure in the reservoir. A typical sub-cool of about 10 to 30° C. is meant to ensure no live steam breaks through to the production well. Process pressure and temperature are linked (FIG. **4** PRIOR ART) and relate mostly to bitumen productivity and process efficiency.

[0009] Bitumen viscosity is a strong function of temperature (FIG. **5**). SAGD productivity is proportional to the square root of the inverse viscosity (FIG. **6** PRIOR ART) (Butler (1991)). Conversely if pressure (and T) is increased, the latent heat content of steam drops rapidly (FIG. **3**). More energy is used to heat the rock matrix and is lost to the overburden or other non-productive areas. So, increased pressure increases bitumen productivity but harms process efficiency (increases SOR). Because economic returns can be dominated by bitumen productivity, the SAGD operator usually opts to target operating pressures higher than native or hydrostatic reservoir pressures.

[0010] Despite becoming the dominant thermal EOR process, SAGD has some limitations and detractions. The requirements for a good SAGD project are:

- **[0011]** a horizontal well completed near the bottom of the pay zone to effectively collect and produce hot draining fluids.
- **[0012]** the injected steam, at the sand face, has a high quality (latent heat drives the process)
- **[0013]** the process start up is effective and expedient
- **[0014]** the steam chamber grows smoothly and is contained
- **[0015]** the reservoir matrix is good quality (porosity (ϕ)>0.2);
  - **[0016]** Initial Oil Saturation (S_{io})>0.6; Vertical permeability (k_v)>2D)
- **[0017]** net pay is sufficient (>15 metres)
- **[0018]** proper design and control must achieved to simultaneously; 1) prevent steam breakthrough to the production well and injector flooding; 2) stimulate steam chamber growth to productive zones; and 3) inhibit water inflows to the steam chamber.
- **[0019]** there must be absence of significant reservoir baffles (e.g. lean zones) or barriers (e.g. shale)

[0020] If these conditions are not attained or other limitations are experienced, SAGD can be impaired, as follows:

[0021] (1) The preferred dominant production mechanism is gravity drainage, and the lower production well is horizontal. If the reservoir is slanted, a horizontal production well will strand significant resources.

[0022] (2) The SAGD steam-swept zone has significant residual bitumen content that is not recovered, particularly for heavier bitumens and low pressure steam (FIG. **7**). For example with a 20% residual bitumen (pore saturation) and a 70% initial saturation, the recovery factor is only 71%, not including stranded bitumen below the production well or in the wedge zone between recovery patterns.

[0023] (3) To contain a SAGD steam chamber, the oil in the reservoir must be relatively immobile. SAGD cannot work on heavy (or light) oils with some mobility at reservoir conditions. Bitumen is the preferred target.

[0024] (4) Saturated steam cannot vaporize connate water. By definition, the heat energy in saturated steam is not high enough quality (temperature) to vaporize water. Field experience also shows that heated connate is not usually mobilized sufficiently to be produced in SAGD. Produced Water-to-Oil Ratio ("PWOR") is similar to SOR. This makes it difficult for SAGD to breach or utilize lean zone resources.

[0025] (5) The existence of an active water zone—either top water, bottom water or an interspersed lean zone within the pay zone—can cause operational difficulties or project failures for SAGD (Nexen Inc., "Second Quarter Results", Aug. 4, 2011) (Vanderklippe, N., "Long LakeProject Hits Sticky Patch", CTV News, 2011). Simulation studies concluded that increasing production well stand-off distances can optimize SAGD performance with active bottom waters, including good pressure control to minimize water influx (Akram, F., "Reservoir Simulation Optimizes SAGD, American Oil and Gas Reporter, September 2010).

[0026] (6) Pressure targets cannot (always) be increased to improve SAGD productivity and SAGD economics. If the reservoir is "leaky", as pressure is increased beyond native or hydrostatic pressures, the SAGD process can lose water or steam to zones outside the SAGD steam chamber. If fluids are lost, the Water Recycle Ratio (WRR) decreases, and the process requires significant water make-up volumes. If steam is also lost, process efficiency drops and SOR increases. Ultimately, if pressures are too high, if the reservoir is shallow, and if the high pressure is retained for too long, a surface breakthrough of steam, sand, and water can occur (Roche, P., "Beyond Steam", New Tech. Mag., September 2011).

[0027] (7) Steam costs are considerable. If steam "costs" are over-the-fence for a utility including capital charges and some profits, the costs for high-quality steam at the sand face is about $10 to 15/MMBTU. High steam costs can reflect on resource quality limits and on ultimate recovery factors.

[0028] (8) Water use is significant. Assuming SOR=3, WRR=1, and a 90% yield of produced water treatment (i.e. recycle), a typical SAGD water use is 0.3 barrels (bbls) of make-up water per barrel (bbl) of bitumen produced.

[0029] (9) SAGD process efficiency is poor, and CO_2 emissions are significant. If SAGD efficiency is defined as [(bitumen energy)−(surface energy used)]/(bitumen energy), where 1) bitumen energy=6 MMBTU/bbl; 2) energy used at sand face=1MMBTU/bbl bitumen (SOR~3); 3) steam is produced in a gas-fired boiler at 85% efficiency; 4) there are heat losses of 10% each in distribution to the well head and delivery from the well head to the sand face; 5) usable steam energy is 1000 BTU/lb (FIG. **3** PRIOR ART); and 6) boiler fuel is methane at 1000 BTU/SCF, then the SAGD process efficiency=75.5% and CO2 emissions=0.077 tonnes/bbl bitumen.

[0030] (10) Practical steam distribution distance is limited to about 10 to 15 km (6 to 9 miles), due to heat losses, pressure losses, and the cost of insulated distribution steam pipes (Finan, A., "Integration of Nuclear Power . . . ", MIT thesis, June 2007), (Energy Alberta Corp., "Nuclear Energy . . . ", Canada Heavy Oil Association, pres., Nov. 2, 2006).

[0031] (11) Lastly, there is a natural hydraulic limit that restricts well lengths or well diameters and can override pressure targets for SAGD operations. FIGS. **8**A and **8**B show what can and has happened. In SAGD, a steam/liquid interface **12** is formed. For a good SAGD operation with sub-cool control, the interface is between the injector **2** and producer wells **4**. The interface is tilted because of the pressure drop in the production well **4** due to fluid flow. There is little/no pressure differential in the steam/gas chamber. If the fluid production rates are too high (or if the production well is too small), the interface can be tilted so that the toe **14** of the steam injector is flooded and/or the heel **16** of the producer is exposed to steam **6** breakthrough (FIGS. **8**A and **8**B). This limitation can occur when the pressure drop in the production well **4** exceeds the hydrostatic head between steam injector **2** and fluid producer **4** (about 8 psi (50 kPa) for a 5 m. spacing).

[0032] As discussed above, SAGD has significant problems, including reduced efficiency (high Steam-to-Oil Ratio), poor productivity, and poor bitumen recovery when dealing with Lean Zones. In particular, SAGD cannot vaporize connate water because it uses saturated steam.

[0033] Lean Zones (LZ) are reservoir zones where hydrocarbon pore saturation is significantly reduced compared to most hydrocarbon reservoirs (<0.6) and where the remaining saturation (>0.4) is mostly water. Lean zones can be interspersed within a reservoir that has higher hydrocarbon saturation. Lean zones can be near the top of a reservoir (transition zone to top water), the bottom of a reservoir (transition zone to bottom water), or the entire pay zone can be classed as a lean zone (<0.6 hydrocarbon saturation). Because of high water saturation, some lean zones can transmit water. The zones can be active (>50 m^3/d water recharge rate) or limited (<50 m^3/d recharge rate). Because bitumen density is near water density (API=10) and because bitumen density changed (rapidly) over time by bacterial degradation, bitumen reservoirs can show multiple LZ's—interspersed, top, bottom or whole reservoir.

[0034] A lean-zone reservoir, or part of a reservoir, has a low original oil (bitumen) saturation (S_{io}) and a corresponding high original water saturation (S_{iw}). For the purposes of this invention, a lean zone is defined as ($S_{io} \leq 0.6$ (i.e. the original oil/bitumen saturation is less than 60 percent of the pore volume).

[0035] A thief zone is defined as an active zone to which fluids are lost.

[0036] For example, FIGS. **9**, **10**, **11**, and **12** characterize the McMurray formation. FIG. **9** shows the depth of the top of the formation—i.e. the overburden thickness. FIG. **10** shows the thickness of the total deposit—both porous and non-porous zones. FIG. **11** shows the porosity internal—the net thickness of the porous portion of the deposit, with a 10% porosity cut off (this portion contains bitumen, water, and gas occupying the pore volume). FIG. **12** shows the bitumen net pay thickness—a portion of the porosity interval. The difference between the porosity interval and the bitumen pay is an indication of impairment zones for EOR processes—gas, top water, bottom water or lean zones. These zones can be within the bitumen net pay or adjacent (top/bottom)

[0037] Industry reports regarding Lean Zones include the following:

> **[0038]** Suncor's Firebag SAGD project and Nexen's Long Lake project each have reported interspersed lean zones that can behave as thief zones when SAGD pressures are too high, forcing the operators to choose SAGD pressures that are lower than desirable (Triangle—"Technical Audit Report, Gas Over Bitumen Technical Solutions", Triangle Three Engineering, December 2010).
>
> **[0039]** Simulation studies of a particular reservoir concluded that a 3 metre standoff (3 metres from the SAGD producer well to the bitumen/water interface) was sufficient to optimize production with bottom water, allowing a 1 metre control for drilling accuracy (Akram (2010)). Allowing for coring/seismic control, the stand-

off may be higher. Nexen and OPTI have reported that interspersed lean zones seriously impede SAGD bitumen productivity and increase SOR beyond original expectations at Long Lake, Alberta (Vanderklippe (2011), (Bouchard, J. et al, "Scratching Below the Surface Issues at Long Lake—Part 2", Raymond James, Feb. 11, 2011), Nexen (2011), (Haggett, J. et al, "Update 3—Long Lake Oilsands Output may lag Targets", Reuters, Feb. 10, 2011).

[0040] Long Lake lean zones have been reported to make up from less than 3 to 5% (v/v) of the reservoir (Vanderklippe (2011), Nexen (2011)).

[0041] Oilsands Quest reported a bitumen reservoir with top lean zones that are "thin to moderate". Some areas had "continuous top thick lean zones" (Oilsands Quest (2011)).

[0042] Connacher Oil and Gas had an oil sands project with a top lean zone (Johnson (2011). The lean zone was reported to differ from an aquifer in two ways—"the lean zone is not charged and is limited size".

[0043] Shell's Peace River Project reportedly had a lean zone, including a "basal lean bitumen zone" (Thimm, H. F. et al, "A Statistical Analysis of the early Peace River Thermal Project Performance," Journal Canadian Petroleum Technology, January 1993). The statistical analysis of the steam soak process (Cyclic Steam Stimulation ("CSS")) showed performance correlated with the geology of the lean zone (i.e. the lean zone quality was the important factor). The process chosen took advantage of lean zone properties, particularly the good steam injectivity in lean zones.

[0044] In-Situ Combustion ("ISC") is the oldest thermal recovery technique. In-situ combustion is basically injection of an oxidizing gas **20** (air or oxygen-enriched air) to generate heat by burning a portion of the residual oil (FIG. **32**). Most of the oil is driven toward the producers by a combination of gas drive (from the combustion gases), steam and water drive. This process is also called fire flooding to describe the movement of a burning front inside the reservoir. Based on the respective directions of front propagation and air flow, the process can be forward, when the combustion front advances in the same direction as the air flow, or reverse, when the front moves against the air flow (Brigham, William, et al. "In-situ Combustion" Chapter 16 Reservoir Engineering).

[0045] The peak production period for ISC was in the 1980s, spurred by government incentives. The peak production was 12 Kbbl/d. In the USA, only 23 of the 1980's ISC projects were deemed economic. In Canada, there has been little focus on bitumen ISC (Butler, 1991). However, Petrobank has been pursuing a toe-to-heel version of ISC called the Toe-to-Heel Air Injection (THAI) process. The THAI process uses a horizontal production well and a vertical air injector completed near the toe of the horizontal well. Field testing of the THAI process started in 2006 but results have been disappointing.

[0046] The Combustion Overhead Split Horizontal (COSH)/Combustion Overhead Gravity Drainage ("COGD") process is another ISC process using a horizontal production well with horizontal vent gas removal wells on the pattern edges, and vertical air injectors are located above the horizontal well. This process was first pursued by Excelsior, but current activity has ceased (New Tech Magazine, "Excelsior Searching . . . COGD Project" Nov. 20, 2009).

[0047] Ramey first suggested the use of oxygen gas, rather than air, for ISC in 1954. Greenwich Oil at Forest Hill, Tex. in 1980 was the first demonstration of successful injection of high concentration oxygen into an oil reservoir; however, other field tests have since been conducted with mixed results (Sarathi, P., "ISC EOR Status", DOE, 1999).

[0048] It is important to note that there have been no specific targets on lean reservoirs using ISC processes.

[0049] SAGDOX is an improved thermal enhanced oil recovery (EOR) process for bitumen recovery. The process can use geometry similar to SAGD (FIG. **13**), but it also has versions with separate vertical wells or segregated sites for oxygen injection and/or non-condensable vent gas removal (FIGS. **14**A, **14**B, **15**A, **15**B, **16**A-**16**C). The process can be considered as a hybrid SAGD+ISC process.

[0050] The objective of SAGDOX is to reduce reservoir energy injection costs, while maintaining good efficiency and productivity. Oxygen combustion produces in situ heat at a rate of about 480 BTU/SCF oxygen, independent of fuel combusted (FIGS. **17**, **18** Butler (1991)). Combustion temperatures are independent of pressure and they are higher than saturated steam temperatures (FIGS. **3**, **18**). The higher temperature from combustion vaporizes connate water and refluxes some steam. Steam delivers EOR energy from latent heat released by condensation with a net value, including surface heat recovery of about 1000 BTU/lb. (FIG. **3**).

[0051] Table 1 compares EOR heat injectant properties of steam and oxidant gases. Table 3 presents thermal properties of steam+oxygen mixtures. Per unit heat delivered to the reservoir, oxygen volumes are ten times less than steam, and oxygen costs including capital charges are one half to one third the cost of steam.

[0052] The recovery mechanisms are more complex for SAGDOX than for SAGD. The combustion zone is contained within the steam-swept zone **170**. Residual bitumen, in the steam-swept zone **170**, is heated, fractionated and pyrolyzed by hot combustion gases to produce coke that is the actual fuel for combustion. A gas chamber is formed containing steam combustion gases, vaporized connate water, and other gases (FIG. **19**). The large gas chamber can be subdivided into a combustion-swept zone **100**, a combustion-zone, a pyrolysis zone **120**, a hot bitumen bank **130**, a superheated steam zone **140** and a saturated steam zone **50** (FIG. **19**). Condensed steam drains from the saturated steam zone **150** and from the ceiling and walls of the gas chamber. Hot bitumen drains from the ceiling and walls of the chamber and from the hot bitumen zone **130** at the edge of the combustion front **110** (FIG. **19**). Condensed water and hot bitumen **8** are collected by the lower horizontal well **4** and conveyed (or pumped) to the surface (FIG. **13**).

[0053] Combustion non-condensable gases are collected and removed by vent gas **22** wells or at segregated vent gas sites (FIGS. **13**, **14**A, **14**B, **15**A, **15**B and **16**A-**16**C). Process pressures can be controlled (partially) by vent gas **22** production, independent of fluid production rates. Vent gas **22** production can also be used to influence direction and rate of gas chamber growth.

[0054] In rich reservoirs, SAGDOX cannot vaporize enough connate water to obviate steam **6** injection.

[0055] To summarize, there is no thermal EOR or ISC technology focused on lean zones to recover bitumen.

[0056] However, lean zones can have some redeeming advantages. They are as follows:

[0057] Connate water can be significant if it can be mobilized and utilized as steam or produced and recycled as steam

[0058] Because of high initial water saturations (>0.4), and possible water channels, lean zones can have some fluid injectivity even if the bitumen fraction is immobile.

[0059] Lean zones with low bitumen saturation (between 0.05-0.20) may provide enough fuel to sustain combustion within the lean zones.

[0060] But for thermal EOR processes using saturated steam, lean zones present the following problems:

[0061] (1) In order to mobilize the oil by heating to steam temperatures, the connate water and the rock matrix also have to be heated. The proportion of heat going to the oil/bitumen drops dramatically as the initial oil saturation drops.

[0062] (2) For a process like SAGD, this is manifested by a rapidly increasing SOR as initial oil saturation drops, as shown in FIG. **20** for a 500 psia saturated steam (242° C.).

[0063] (3) In any steam EOR process, including SAGD, in the steam-swept zone (GD chamber), a residual oil/bitumen is left behind, unrecovered. For bitumen EOR and for a reasonable range of saturated steam temperatures (180° C. to 260° C.), the residual bitumen saturation is in the range of 0.10 to 0.20 (FIG. **7**). This can limit steam EOR recoveries for thermal steam EOR in lean zones, particularly for the lower temperatures and lower initial bitumen saturation levels (FIG. **21**).

[0064] (4) For lean zones with low bitumen (<0.20 initial saturation), there may be zero recovery when steam sweeps the zone.

[0065] (5) As the initial bitumen saturation drops, most of the (steam) heat goes to heating connate water (FIG. **22**).

[0066] (6) Interspersed lean zones can interrupt SAGD steam chamber growth patterns. Interspersed lean zones have to be heated so that GD steam chambers can envelope the zone and continue growth above and around the lean zone blockage.

[0067] (7) An interspersed lean zone has higher heat capacity and higher heat conductivity than a zone with higher bitumen content. Even if an aquifer or bottom/top water zone, does not recharge the lean zone for SAGD, the lean zone will create a thermal penalty as the steam chamber moves through and around the lean zone. For SAGD, bitumen productivity will also suffer as the heated zone moves through (and around) the lean zone.

[0068] (8) If an interspersed lean zone acts as a thief zone, the problems are most severe. The lean zone can channel steam away from the SAGD steam chamber. If the steam condenses prior to removal, the water is lost but some of the heat can be retained. But, if the steam exits the SAGD steam chamber prior to condensing, both the heat and the water are lost to the process. The obvious remedy is to reduce SAGD pressure to minimize the steam/water outflow. But, if this is done, bitumen productivity will be reduced.

[0069] Because of the above problems, lean zones have presented the following disadvantages for thermal EOR:

[0070] The EOR goal is to heat bitumen to reduce its viscosity so it can drain to a production well. But as the oil saturation drops, most of the injected heat goes to heating connate water, particularly for the leanest zones (FIG. **22**).

[0071] Saturated steam is not of sufficient quality to vaporize water, only to heat it to near saturated-steam temperature.

[0072] The residual bitumen in a steam-swept zone can be significant, particularly for heavy bitumens and for cooler thermal EOR processes (FIG. **9**). If the initial bitumen saturation in a lean zone is close to (or below) the residual bitumen in a steam-swept zone, steam EOR can recover little or no bitumen from the lean zone.

[0073] Using a simple model for steam EOR, assuming all bitumen above 0.15 saturation is recovered by heating to 242° C. (500 psia), below an initial bitumen saturation of about 0.4, with modest heat losses, SOR can exceed 5 and steam EOR becomes impractical (FIG. **21**).

[0074] Accordingly, there is a need for an EOR applicable to lean reservoirs. Preferably, a SAGDOX process that is applicable to lean reservoirs.

SUMMARY OF THE INVENTION

[0075] LZ-SAGDOX is a process similar to SAGDOX; however, the process is tailored to lean reservoirs and no steam is injected. LZ-SAGDOX creates steam in the reservoir by two ways: 1) vaporizing connate water and 2) as a chemical production of combustion (water of combustion).

[0076] According to one aspect, there is a provided a process to recover oil from a reservoir having at least one lean zone. Preferably, the lean zone has an initial bitumen saturation (S_{io}) level less than about 0.6. The process comprises an injection of oxygen into the lean zone. The oxygen combustion vaporizes the connate water in the lean zone. The vaporizing of the connate water allows for recovery of oil from the reservoir.

[0077] In one embodiment, the lean zone thickness is less than 25 metres.

[0078] In one embodiment, an initial steam is injected with the oxygen into the reservoir, then the initial steam injection is terminated.

[0079] In one embodiment, combustion occurs at temperatures higher than 400° C.

[0080] In one embodiment, the oxygen has an oxygen content of 95 to 99.9 (v/v) percent.

[0081] In one embodiment, the oxygen is air. In a further embodiment, the air is enriched air with an oxygen containing content of 21 to 95 (v/v) percent.

[0082] In one embodiment, the hydrocarbons are bitumen with an API density less than 10 and in situ viscosity greater than 100,000 cp.

[0083] In one embodiment, the hydrocarbons are heavy oil with an API density greater than 10 but less than 20 and in situ viscosity greater than 1,000 cp.

[0084] According to another aspect of the invention, there is provided a SAGDOX system for recovery of hydrocarbons from a reservoir having at least one lean zone. The lean zone has an initial bitumen saturation level of less than 0.6. The system has a first well, which has a toe and a heel allowing for capture of hydrocarbons from the reservoir. The system has a second well allowing for injection of oxygen into the lean zone containing reservoir. The second well is proximate the toe of the first well. The system further comprises a vent gas means for venting any gas produced in the reservoir.

[0085] In one embodiment, the lean zone thickness is less than 25 metres.

[0086] In one embodiment, the vent gas means is selected from a group consisting of a single substantially vertical well or a plurality of substantially vertical wells.

[0087] In one embodiment, the vent gas means is a segregated annulus section in the heel section of the horizontal well.

[0088] In a further embodiment, the vent gas means is distant said toe of said well.

[0089] In one embodiment, the at least one oxygen injection site is selected from a group consisting of a single substantially vertical well or a plurality of substantially vertical wells.

[0090] According to yet another aspect of the invention, there is provided a SAGDOX system for recovery of hydrocarbons from a reservoir having at least one lean zone. The lean zone has an initial bitumen saturation level of less than 0.6. The system has a well with a toe and a heel, and the well is located within the lean zone containing reservoir. The well further comprises at least one oxygen injection site proximate the toe for injecting oxygen into the reservoir. The well also has a hydrocarbon recovery site for recovery of hydrocarbons from the reservoir. Even further, the well has at least one vent gas site for venting any gas produced in the reservoir.

[0091] In one embodiment, the lean zone thickness is less than 25 metres.

[0092] In one embodiment, the vent gas means is a segregated annulus section in the heel section of the horizontal well.

[0093] In one embodiment, the vent gas means is distant the toe of the well.

[0094] In one embodiment, the oxygen injection site is a segregated toe section of the horizontal well.

[0095] In one embodiment, the toe of the well is at a different level in the reservoir than the heel of the well.

[0096] In one embodiment, the toe of the well is at a higher level in the reservoir than the heel of the well.

BRIEF DESCRIPTION OF THE DRAWINGS

[0097] FIG. **1**A is a perspective view of traditional SAGD well geometry;

[0098] FIG. **1**B is an end elevational view of FIG. **1**A;

[0099] FIG. **2**A is a schematic view of the early stages of the SAGD life cycle;

[0100] FIG. **2**B is a schematic view of optimum productivity of an SAGD well;

[0101] FIG. **2**C is a schematic view of a maturing/aging SAGD well;

[0102] FIG. **2**D is a schematic view of the end of life of an SAGD well;

[0103] FIG. **3** depicts saturated steam properties;

[0104] FIG. **4** depicts the operational performance of an SAGD process;

[0105] FIG. **5** depicts Long Lake bitumen viscosity;

[0106] FIG. **6** depicts the gravdrain equation for SAGD bitumen productivity;

[0107] FIG. **7** depicts residual bitumen in steam-swept zones;

[0108] FIG. **8**A depicts SAGD hydraulic limitations and good operation of an SAGD well;

[0109] FIG. **8**B depicts SAGD hydraulic limitations and poor operation of an SAGD well;

[0110] FIG. **9** depicts the depth of the top of the McCurray deposit;

[0111] FIG. **10** depicts the thickness of the total McCurray deposit;

[0112] FIG. **11** depicts the net thickness of the porous portion of the deposit of the McMurray deposit;

[0113] FIG. **12** shows the bitumen net pay thickness of the McMurray deposit;

[0114] FIG. **13** depicts SAGDOX well geometry;

[0115] FIG. **14**A is a schematic of the preferred embodiment of THSAGDOX;

[0116] FIG. **14**B is a piping schematic of THSAGDOX;

[0117] FIG. **15**A is a schematic of a Single Well SAGDOX well geometry;

[0118] FIG. **15**B is a piping schematic of SWSAGDOX well;

[0119] FIG. **16**A is a schematic of a preferred SAGDOX geometry;

[0120] FIG. **16**B is a schematic of a preferred THSAGDOX geometry;

[0121] FIG. **16**C is a schematic of a preferred SWSAGDOX geometry;

[0122] FIG. **17** depicts combustion heat release;

[0123] FIG. **18** depicts steam and oxygen tube tests 1;

[0124] FIG. **19** depicts SAGDOX mechanisms, including bitumen saturation, water saturation, gas saturation and temperature in relation to distance from an O_2/steam injector;

[0125] FIG. **20** depicts a steam-to-oil ration for Steam EOR;

[0126] FIG. **21** depicts residual oil/bitumen saturation limits to recovery;

[0127] FIG. **22** depicts Steam EOR Heat Distribution;

[0128] FIG. **23** depicts Produced Water-to-Oil Ratio for LZ-SAGDOX;

[0129] FIG. **24**A depicts preferred LZ-SAGDOX geometry;

[0130] FIG. **24**B is a well configuration schematic for LZ-SAGDOX;

[0131] FIG. **25** depicts ISC minimum air flux rates;

[0132] FIG. **26** depicts steam and oxygen combustion tube tests II;

[0133] FIG. **27** depicts THAI process well geometry;

[0134] FIG. **28** depicts COGD/COSH process well geometry;

[0135] FIG. **29**A is a schematic perspective view of LZ-SAGDOX;

[0136] FIG. **29**B is a side schematic of LZ-SAGDOX;

[0137] FIG. **30** is a schematic of LZ-SAGDOX;

[0138] FIG. **31**A is a perspective view of SWSAGD SAGDOX (packers);

[0139] FIG. **31**B is a side elevational schematic of SWSAGD;

[0140] FIG. **32** is a perspective view of conventional In-Situ Combustion;

[0141] FIG. **33**A is a schematic side elevational view of a gas chamber in THSAGDOX in early life;

[0142] FIG. **33**B is a schematic side elevational view of the well of FIG. **33**A at a mature stage;

[0143] FIG. **33**C is a schematic view of the well of FIG. **33**A at end of life;

[0144] FIG. **34**A is a schematic view of THSAGDOX liquid drawdown heel production;

[0145] FIG. **34**B is a schematic view of THSAGDOX liquid drawdown toe production;

[0146] FIG. **35**A is a schematic view of SWSAGDOX during mature operations;

[0147] FIG. **35**B is a schematic view of SWSAGDOX(U) during mature operations;

[0148] FIG. **36**A is a perspective view of LZ-SAGDOX A;

[0149] FIG. **36**B is a side schematic view of the well of FIG. **36**A;

[0150] FIG. **37** is a well schematic of LZ-SAGDOX A; and

[0151] FIG. **38** is a table illustrating combustion PWOR.

DETAILED DESCRIPTION OF THE INVENTION

[0152] The SAGDOX process injects some steam (with oxygen) to improve combustion kinetics and to improve heat transfer (particularly lateral heat transfer) in the reservoir. For high bitumen-saturation reservoirs (0.6 to 1.0 saturation), steam addition to oxygen is necessary to attain minimum steam levels in the reservoir. A measure of this minimum has been suggested as Produced Water-to-Oil Ratio ("PWOR") ≥1.0.

[0153] For lean zones, vaporized connate water can capture these benefits without any steam addition from outside the reservoir. For the purpose of this invention, lean zones are porous rocks defined to contain less than or equal to 60 percent of the pore volume, by volume, bitumen and the remainder of the pore volume is mostly water. A lean zone may occupy all or part of the pay zone.

[0154] As far as the reservoir is concerned, LZ-SAGDOX gas mixtures (steam+oxygen) are similar to SAGDOX. The LZ-SAGDOX process simply injects oxygen gas, with no steam (except for start-up) to achieve a SAGDOX EOR process in a lean zone reservoir. Combustion temperatures are in the 500 to 600° C. range (FIG. **21**), so combustion heat is of sufficient quality to vaporize lean-zone connate water creating and sustaining a good steam inventory in the reservoir.

[0155] If one assumes the following: 1) the connate water associated with bitumen production and bitumen consumed is all vaporized and recovered as product water (e.g. if the initial bitumen saturation is 0.3, the associated connate water is 2.33 bbl/bitumen); and 2) any water created as a chemical product of combustion is also produced, then Table 4 and FIG. **23** show Produced Water-to-Oil Ratio for LZ-SAGDOX processes. As shown in FIG. **23**, for LZ-SAGDOX, PWOR is not a strong function of the energy-to-oil ratio ("ETOR"), but it is a strong function of initial bitumen saturation. For leaner reservoirs (lower initial bitumen saturation) higher ETOR is expected as most of the heat goes to heat matrix and water zones (FIG. **20**).

[0156] An assumption, to attain good water/steam benefits in the reservoir, is that PWOR should equal or exceed 1.0. PWOR is a reflection of steam in the reservoir per bbl of bitumen produced. For LZ-SAGDOX (FIG. **23**) this implies a maximum initial bitumen saturation of 0.6. This sets a preferred limit value for the LZ-SAGDOX process.

[0157] Referring to Tables 2 and 5, one can also see the similarity of the processes (SAGDOX vs. LZ-SAGDOX) from the standpoint of the reservoir and predicted PWOR. SAGDOX, using 35% oxygen (v/v) in steam+oxygen injectants in a reservoir with 0.8 initial bitumen saturation and with ETOR=2.0, has a PWOR of 1.3 (Table 2). LZ-SAGDOX, in a reservoir with 0.6 initial bitumen saturation and with ETOR=4.0, has a PWOR=1.2.

[0158] As long as the initial bitumen saturation in the lean zone is above about 0.05, there is enough combustion energy available from this fuel to vaporize all the water in the lean zone pores (95 (v/v) percent). If bitumen saturation is higher than this, some net bitumen can be recovered. A combustion-swept zone has near-zero residual hydrocarbons (FIG. **19**), so the bitumen in a lean zone will either be mobilized and produced or consumed as a fuel, as the combustion front sweeps through the lean zone.

[0159] FIGS. **24**A, **24**B, **36**A, **36**B and **37** shows the preferred geometry for LZ-SAGDOX, retaining a horizontal production well **4** and vent gas **22** removal using a segregated section (annulus) of the production well **4**. Oxygen **26** is either injected in a separate vertical well or in a segregated, upturned toe section of a single well version of the process. No provision is made for continuous steam **6** injection. Start-up can be accomplished by steam circulation or steam huff-and-puff.

[0160] Preferably, oxygen **26** rather than air is the oxidant injected. If the cost of treating vent gas **22** to remove sulphur components and to recover volatile hydrocarbons is included, even at low pressures the all-in cost of oxygen is less than the cost of compressed air, per unit energy delivered to the reservoir. Further, oxygen occupies about one fifth the volume compared to air for the same energy delivery. Well pipes/tubing are smaller and oxygen can be transported further distances from a central plant site. Another benefit of injecting oxygen is that in-situ combustion using oxygen produces mostly non-condensable CO_2, undiluted with nitrogen. CO_2 can dissolve in bitumen to improve productivity. Dissolution is maximized using oxygen. Also, vent gas, using oxygen, is mostly CO_2, and it may be suitable for sequestration Finally, there is a minimum oxygen flux to sustain high temperature oxidation ("HTO") combustion (FIG. **25**). It is easier to attain/sustain this flux using oxygen.

[0161] Preferably, oxygen **26** injection should be kept at a concentrated site. Because of the minimum O_2 flux constraint for in situ combustion (FIG. **25**), the oxygen **26** injection well (or a segregated section) should have no more than 50 metres of contact with the reservoir.

[0162] Preferably, oxygen **26** and steam **6** injectants are segregated as much as possible prior to injection. Condensed steam **6** (hot water) and oxygen **26** are very corrosive to carbon steel. To minimize corrosion, there are three options: 1) either oxygen **26** and steam **6** are injected separately (FIGS. **13**, **14**A and **14**B); 2) comingled steam and oxygen **30** have limited exposure to a section of pipe that can be a corrosion resistant alloy, the section integrity is not critical to the process (FIGS. **15**A and **15**B); or 3) the entire injection string is a corrosion resistant alloy.

[0163] Preferably, the vent gas **22** well or site is near the top of the reservoir, far from the oxygen **26** injection site and laterally offset from the injection **2**/production **4** wells. Because of steam **6** movement and condensation, non-condensable gas concentrates near the top of the gas chamber. The vent gas **22** well should be far from or distant the oxygen injector to allow time/space for combustion.

[0164] Preferably, vent gas **22** should not be produced with significant oxygen content. To mitigate explosions and to foster good oxygen **6** utilization, any vent gas **22** production with oxygen content greater than 5% (v/v) should be shut in.

[0165] Preferably, a minimum amount of steam **6** in the reservoir is attained or retained.

[0166] Steam **6** is added or injected with oxygen **26** in SAGDOX because steam helps combustion. Steam **6** preheats the reservoir so ignition, for HTO, can be spontaneous. Steam **6** adds OH^- and H^+ radicals to the combustion zone to improve and stabilize combustion (FIGS. **18** and **26**) (Moore, G. et al, "Parametric Study of Steam Assisted ISC, unpublished, February 1994). This is also confirmed by the operation of smokeless flares, where steam is added to improve combustion and reduce smoke (Stone, D. et al, "Flares," Chapter 7, gasflare.org, June 2012), (U.S. Environmental Protection Agency "Industrial Flares," www.EPA.gov, June 2012), (Shore, D. "Making the Flare Safe," Journal of Loss Prevention in the Process Industries, 9, 363, 1996). The process to gasify fuels also adds steam to the partial combustor to minimize soot production (Berkowitz (1997)). Steam also condenses and produces water that "covers" the horizontal production well and isolates it from gas or steam intrusion. Further, steam condensate adds water to the production well to improve flow performance—water/bitumen emulsions—compared to bitumen alone.

[0167] Steam is also a superior heat transfer agent in the reservoir. If we compare hot combustion gases, mostly CO_2 to steam, the heat transfer advantages of steam are evident. For example, if we have a hot gas chamber at about 200° C. at the edges, the heat available from cooling combustion gases from 500 to 200° C. is about 16 BTU/SCF. The same volume of saturated steam contains 39 BTU/SCF of latent heat—more than twice the energy content of combustion gases. In addition, when hot combustion gases cool they become effective insulators, impeding further heat transfer. When steam condenses to deliver latent heat, it creates a transient low-pressure that draws in more steam-a heat pump, without the plumbing. The kinetics also favour steam/water. The heat conductivity of combustion gas is about 0.31 (mW/cmK) compared to the heat conductivity of water of about 6.8 (mW/cmK)—a factor of 20 higher. As a result of these factors, combustion (without steam) has issues of slow heat transfer and poor lateral growth. These issues can be mitigated by steam injection.

[0168] Finally, since one cannot measure the amount of steam in the reservoir, SAGDOX sets a steam minimum by a maximum oxygen/steam (v/v) ratio of 1.0 or alternately 50% (v/v) oxygen in the steam+oxygen mix.

[0169] Preferably, a minimum oxygen injection is attained or exceeded. Below about 5% (v/v) oxygen in the steam+oxygen mix, the combustion-swept zone is small and the cost advantages of oxygen are minimal. At this level, only about a third of the energy injected is due to combustion.

[0170] Preferably, oxygen injection is maximized. Within the constraints of the above preferred embodiments, because per unit energy oxygen is less costly than steam, the lowest-cost option to produce bitumen is to maximize oxygen/steam ratios.

[0171] Preferred SAGDOX geometries should be used. Depending on the individual application, reservoir matrix properties, reservoir fluid properties, depth, net pay, pressure and location factors, there are three preferred geometries for SAGDOX (FIGS. **16**A-**16**C). FIGS. **14**A, **14**B, **16**B Toe-to-Heel SAGDOX ("THSAGDOX") and **16**C (also shown in FIGS. **33**A-**33**C, **34**A and **34**B) Single Well SAGDOX ("SWSAGDOX") (see FIGS. **35**A and **35**B) are best suited to thinner pay resources, with only one horizontal well required. Compared to SAGDOX, THSAGDOX and SWSAGDOX have a reduced well count and lower drilling costs. Also, internal tubulars and packers **18** should be usable for multiple applications.

[0172] Preferably, SAGDOX is controlled or operated by the following:

- **[0173]** i) Sub-cool control on fluid production rates where produced fluid temperature is compared to saturated steam temperature at reservoir pressure. This assumes that gases, immediately above the liquid/gas interface, are predominantly steam.
- **[0174]** ii) Adjust oxygen/steam ratios (v/v) to meet a target ratio, subject to a range limit of 0.05 to 1.00.
- **[0175]** iii) Adjust vent gas removal rates so that the gases are predominantly non-condensable gases; oxygen content is less than 5.0% (v/v); and to attain/maintain pressure targets.
- **[0176]** iv) Adjust steam+oxygen injection rates (subject to (ii) above), along with (iii) above, to attain/maintain pressure targets.

[0177] To summarize, LZ-SAGDOX, as shown in FIGS. **29**A, **29**B and **30**, is superior to SAGDOX in LZ reservoirs for the following reasons:

- **[0178]** LZ-SAGDOX doesn't inject steam (except for start-up). Steam is more costly than oxygen (for combustion), so LZ-SAGDOX operating costs are less than SAGDOX.
- **[0179]** Because of lower operating costs, LZ-SAGDOX can be applied at lower bitumen saturations.
- **[0180]** Also, because of lower operating costs, LZ-SAGDOX will increase reserves compared to SAGDOX.
- **[0181]** LZ-SAGDOX saves one well (or one completion zone) compared to SAGDOX (steam injector).
- **[0182]** Fresh water or make-up water use for LZ-SAGDOX is zero (except for start-up)

[0183] As discussed above, distinctions between LZ-SAGDOX and SAGDOX include the following:

- **[0184]** LZ-SAGDOX has no steam injected; SAGDOX has steam injection;
- **[0185]** LZ-SAGDOX has one less injectant site (well, port), no steam injector;
- **[0186]** LZ-SAGDOX has restricted range for bitumen saturation (5 to 60 percent); SAGDOX doesn't;
- **[0187]** LZ-SAGDOX is a combustion EOR process (based on injectants), SAGDOX is a combined steam and combustion EOR process;
- **[0188]** SAGDOX uses surface water for steam; LZ-SAGDOX uses no water (except for start-up).

[0189] Distinction between Toe-to-Heel Air Injection ("THAI") (FIG. **27**) and LZ-SAGDOX include the following:

- **[0190]** THAI injects air; LZ-SAGDOX prefers oxygen;
- **[0191]** THAI has no explicit restriction on bitumen saturation; LZ-SAGDOX does;
- **[0192]** THAI is field tested with poor results.
- **[0193]** THAI has had problems with lateral growth; no steam added to foster heat transfer; LZ-SAGDOX generates steam from LZ connate water.

[0194] Distinctions between SAGD and LZ-SAGDOX include the following:

- **[0195]** SAGD is a pure steam EOR process; LZ-SAGDOX is a pure combustion EOR process (based on injectants);
- **[0196]** SAGD has no explicit bitumen saturation limits;
- **[0197]** SAGD doesn't perform well on LZ (poor field history).

[0198] Distinctions between LZ-SAGDOX and Combustion Overhead Split Horizontal ("COSH") or Combustion Overhead Gravity Drainage ("COGD") (FIG. **28**) include the following:

- **[0199]** COSH/COGD prefer air injection;
- **[0200]** COSH/COGD get lateral growth from position of vent wells; LZ-SAGDOX gets lateral growth from steam produced in situ;
  - **[0201]** different geometry.

[0202] Distinctions between LZ-SAGDOX and Conventional ISC (FIG. **32**) (neither injects water or steam) include the following:

- **[0203]** ISC uses vertical wells (HZ for LZ-SAGDOX)
- **[0204]** ISC prefers air (O_2 for LZ-SAGDOX)
- **[0205]** no LZ preference for ISC

[0206] Distinctions between LZ-SAGDOX (SW version, FIGS. **29**A, **29**B, **30**) and Single Well SAGD ("SWSAGD") (FIGS. **31**A and **31**B) include the following:

- **[0207]** SWSAGD is a steam process; LZ-SAGDOX is a combustion process
- **[0208]** no LZ preference for SWSAGD

[0209] Distinctions between LZ-SAGDOX and Combination of Forward Combustion and Water ("COFCAW") include the following:

- **[0210]** COFCAW injects water; LZ-SAGDOX has no water (or steam) injection
- **[0211]** COFCAW uses vertical wells and conventional ISC geometry (FIG. **28**)
  - **[0212]** COFCAW uses air injection; LZ-SAGDOX prefers oxygen;
- **[0213]** no LZ preference for COFCAW

[0214] To summarize, the unique Features of LZ-SAGDOX include the following:

- **[0215]** Limitation range of bitumen saturation for process applicability
- **[0216]** ISC process where bitumen saturation is a key factor
- **[0217]** Focus on lean zones; upper bitumen saturation limit
  - **[0218]** Consideration of connate water as a steam source and the importance of steam in a ISC process
- **[0219]** Upturned toe version for SW LZ-SAGDOX process
- **[0220]** Focus/preference for oxygen as oxidant source
- **[0221]** Limitation of oxygen injection contact-zone
- **[0222]** Focus/preference on bitumen
- **[0223]** Removal of vent gas in separate well(s) or locations (vent gas not forced to go to fluid production well)
- **[0224]** No other EOR processes are specifically focused on lean zones
- **[0225]** Need for a minimum amount of connate water for process to be successful
- **[0226]** Preferred LZ-SAGDOX geometries (FIGS. **24**A and **24**B)

TABLE 1

Injectant Heat "Content" for Thermal EOR

	Steam	Oxygen	Air
(BTU/lb.)	1000	5700	1318
(BTU/SCF)	47.4	480	100
(MSCF/MMBTU)	21.1	2.08	10.0

[0227] Where—assumes:

- **[0228]** steam at 1000 BTU/lb. avg.
- **[0229]** oxygen at 480 BTU/SCF avg (Butler, (1991))
- **[0230]** ideal gas laws
- **[0231]** air at 20.9% (v/v) oxygen

TABLE 2

SAGDOX: PWOR

	% O_2 (v/v) in steam and O_2 mixes				
	0	5	35	50	100
ETOR = 1.0					
(1)	3.18	2.07	0.49	0.29	0
(2)	0	0.09	0.21	0.23	0.25
(3)	0	0.01	0.02	0.03	0.03
(4)	0	0.013	.032	.035	.038
PWOR	3.18	2.18	0.75	0.59	0.32
ETOR = 2.0					
(1)	6.36	4.14	0.98	0.58	0
(2)	0	0.09	0.21	0.23	0.25
(3)	0	0.02	0.05	0.05	0.05
(4)	0	0.026	0.064	0.07	0.076
PWOR	6.36	4.28	1.30	0.93	0.38

Where

- **[0232]** (1)=condensed steam
- **[0233]** (2)=water (connate) associated with produced bit from comb.
- **[0234]** (3) =water associated with combusted bitumen
- **[0235]** (4)=water of combustion
  - **[0236]** PWOR=(1)+(2)+(3)+(4) (bbls.water/bblB)
  - **[0237]** S_{io}, =0.8; no gas
  - **[0238]** (2), (3), (4) are pro rated by heat from comb
  - **[0239]** (1) is prorated by heat from steam

TABLE 3

SAGDOX Injection Gases

	% (v/v) O_2 in Steam and O_2 mixes						
	0	5	9	35	50	75	100
% heat from O_2	0	34.8	50.0	84.5	91.0	96.8	100.0
BTU/SCF mix	47.4	69.0	86.3	198.8	263.7	371.9	480.0
MSCF mix/MMBTU	21.1	14.5	11.6	5.0	3.8	2.7	2.1
MSCF O_2/MMBTU	0.0	0.7	1.0	1.8	1.9	2.0	2.1
MSCF Steam/MMBTU	21.1	13.8	10.6	3.3	1.9	0.7	0

[0240] Where:

- **[0241]** (1) Steam at 1000 BTU/lb.
- **[0242]** (2) Oxygen at 480 BTU/SCF

TABLE 4

LZ-SAGDOX: PWOR

	Initial Bitumen Saturation				
	.2	.4	.6	.8	.10
ETOR = 1.0					
(1)	4.00	1.50	0.67	0.25	0.00
(2)	0.67	0.25	0.08	0.04	0.00
(3)	0.06	0.06	0.06	0.06	0.06
PWOR	4.73	1.81	0.81	0.35	0.06
ETOR = 2.0					
(1)	4.00	1.50	0.67	0.25	0.00
(2)	1.34	0.50	0.17	0.08	0.00
(3)	0.11	0.11	0.11	0.11	0.11
PWOR	5.45	2.11	0.95	0.44	0.11
ETOR = 4.0					
(1)	4.00	1.50	0.67	0.25	0.00
(2)	2.68	1.00	0.33	0.17	0.00
(3)	.22	0.22	0.22	0.22	0.22
PWOR	6.90	2.72	1.22	0.64	0.22
ETOR = 8.0					
(1)	4.00	1.50	0.67	0.25	0.00
(2)	5.36	2.00	0.66	0.34	0.00
(3)	0.45	0.45	0.45	0.45	0.45
PWOR	9.81	3.95	1.78	1.04	0.45

Where

[0243] Entries are bbl water/bbl bitumen

[0244] (1)=connate water associated with produced bitumen

[0245] (2)=connate water associated with bitumen combustion

[0246] (3)=water of combustion

[0247] PWOR=(1)+(2)+(3)

[0248] Water of combustion=0.056 bbl/MMBTU

[0249] Fuel=coke ($CH._5$)

TABLE 5

PWOR LZ-SAGDOX
(PWOR bbl water/bblB)

	Initial Bitumen Saturation			
	.2	.4	.6	.8
ETOR = 2: PWOR	5.45	2.11	0.95	0.44
ETOR = 4: PWOR	6.90	2.72	1.22	0.64
ETOR = 8: PWOR	9.81	3.95	1.78	1.04
ETOR = 12: PWOR	12.71	5.17	2.34	1.42
ETOR = 16: PWOR	15.62	6.40	2.90	1.82

Where:

[0250] PWOR=water associated with bitumen produced+bitumen combusted+water of combustion

[0251] fuel =$CH._5$ coke

[0252] comb. Water=0.056 bbl/MMBTU

[0253] complete HTO combustion

[0254] bit. fuel value=6 MMBTU/bbl

[0255] O_2 heat at 480 BTU/SCF

[0256] As many changes therefore may be made to the embodiments of the invention without departing from the scope thereof. It is considered that all matter contained herein be considered illustrative of the invention and not in a limiting sense.

1. A process to recover hydrocarbons from a reservoir having at least one lean zone, wherein said lean zone has an initial bitumen saturation level less than about 0.6, said process comprising:

i) Initially injecting of oxygen into said reservoir;

ii) Allowing for combustion of said oxygen to vaporize connate water in said at least one lean zone; and

iii) Recovering said hydrocarbons from said reservoir.

2. A process according to claim **1** further comprising initial steam injection with oxygen into the reservoir then terminating said steam injection.

3. The process of claim **1** where combustion occurs at temperatures higher than 400° C.

4. The process of claim **1** where the oxygen has an oxygen content of 95 to 99.9 (v/v) percent.

5. The process of claim **1** where the oxygen is air.

6. The process of claim **5** where the air is enriched air with an oxygen containing content of 21 to 95 (v/v) percent.

7. The process of claim **1** where the hydrocarbons are bitumen API density (<10; in situ viscosity>100,000 cp.).

8. The process of claim **1** where the hydrocarbons are heavy oil (10<API<20); in situ viscosity>1000 cp.).

9. A steam assisted gravity drainage with oxygen system for recovery of hydrocarbons from a reservoir having at least one lean zone, wherein said lean zone has an initial bitumen saturation level less than about 0.6, said system comprising:

i) A first well, having a toe and a heel, said first well within said lean zone containing reservoir, for capturing said hydrocarbons;

ii) A second well within said lean zone containing reservoir, for injection of oxygen into said lean zone containing reservoir;

iii) Said second well being located proximate said toe of said first well; and

iv) At least one vent gas means for venting any gas produced in said reservoir.

10. A steam assisted gravity drainage with oxygen system for recovery of hydrocarbons for a reservoir having at least one lean zone, wherein said lean zone has an initial bitumen saturation level less than about 0.6, said system comprising:

i) A well, having a toe and a heel, said well being located within said lean zone containing reservoir; wherein said well further comprises:

  a. At least one oxygen injection site proximate said toe, for injecting oxygen into said reservoir;

  b. A hydrocarbon recovery site for recovery of said hydrocarbons from said reservoir; and

  c. At least one vent gas site for venting any gas produced in said reservoir.

11. The system of claim **9** where the vent gas means is selected from a group consisting of a single substantially vertical well or a plurality of substantially vertical wells.

12. The system of claims **9** and **10** where the vent gas means is a segregated annulus section in the heel section of the horizontal well.

13. The system of claim **9** where the at least one oxygen injection site is selected from a group consisting of a single substantially vertical well or a plurality of substantially vertical wells.

14. The system of claim **10** where the at least one oxygen injection site is a segregated toe section of the horizontal well.

15. The system of claim **10** wherein said toe of said well is at a level in said reservoir different than said heel of said well.

16. The system of claim **10** wherein said toe level is at a level higher in said reservoir than said heel of said well.

17. The system of claims **9** and **10** wherein said at least one vent gas site is distant said toe of said well.

18. A process according to claim **1**, **9** or **10** where the lean zone thickness is less than 25 metres.

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