Air Injection to Improve Oil Recovery from Mature Light Oil Field

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Content

Air injection past experience

Air injection process

Why air injection can compete with other IOR strategies to produce mature light oil reservoirs?

Evaluation of air injection applicability and potential

Definitions

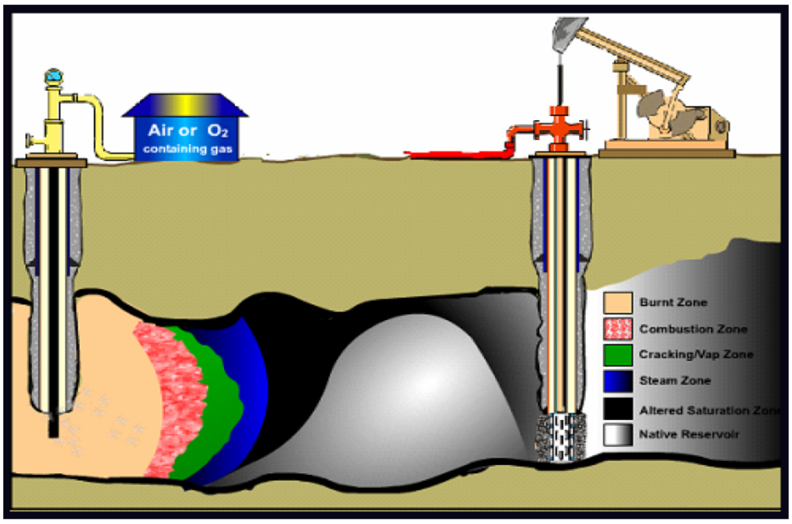
- **In Situ Combustion (ISC):** Air Injection applied to heavy oil reservoirs and oil sands.
- **High Pressure Air Injection (HPAI) or Light Oil Air Injection (LOAI):** Air Injection applied to light oil reservoirs.

Both processes involve oxidation reactions between air (or oxygen-containing gas) and oil. They can simply be referred to as *Firefloods.*

Definitions – Combustion Parameters

- ***Fuel*****:** Oil consumed during the combustion reactions
- ***Fuel requirement*****:** Equivalent oil consumed per unit volume of reservoir (kg/m^3)
- ***Air requirement:*** Volume of air required to burn a unit volume of bulk reservoir ($m^3(ST)/m^3$)
- ***Air flux:*** Volumetric flow rate of air divided by the cross-sectional area over which it is flowing ($m^3(ST)/m^2h$)
- ***Minimum flux*****:** Minimum air flux required to sustain combustion
- ***Enriched air*****:** Feed gas with O_2 content is greater than normal air (i.e. >21% O_2)

In Situ Combustion Classic Schematic



After Szeoke, 2004 (PhD Thesis, University of Calgary)

ISC past experience

In the 1960s and 1970s approximately 40 air injection heavy oil full field or pilot projects were undertaken throughout the world, mostly in the North America.

California, USA

- The State of California has an estimated 3.5 billion barrels of oil reserves. 76% of those reserves are heavy oil (API gravity 10 to 20).
- These deposits were discovered early, between 1880 and 1920.
- A a wide range of thermal techniques have been applied to producing this large resource.
- 61 - 69% of the original oil still remains in place.
- Air Injection held promise in the 1960s and 1970s but did not live up to expectations.

California, USA

- Full field air injection projects in the heavy oil fields of California, in the San Joaquin Valley.
- The largest was the West Newport field, which at one time was producing 3,000 barrels/day from 100 producers.
- Others projects included:
  - Lost Hills, producing 800 b/d from 40 producers
  - Midway Sunset – Potter, producing 1,200 b/d.
- While some of the projects were clearly successful, recovering up to 50% of the original oil in place, overall the results did not live up to expectations.

California, USA

The ISC problems that occurred and caused less than optimal recovery:

- emulsions,
- subsurface scale,
- corrosion and gas buildup at producers,
- the failure to ignite or control the flame front,
- gravity segregation.

Alberta, Canada

- Canada has an estimated 2.5 - 3 trillion barrels of heavy oil and bitumen deposits, 175 billion barrels of which is proved.
- Most of these deposits are in Alberta.
- At one time, there were 16 air injection projects in Alberta and Saskatchewan.
- More failures, than successes.
- Problems:
  - sand production, corrosion, gas locking and difficult emulsions.

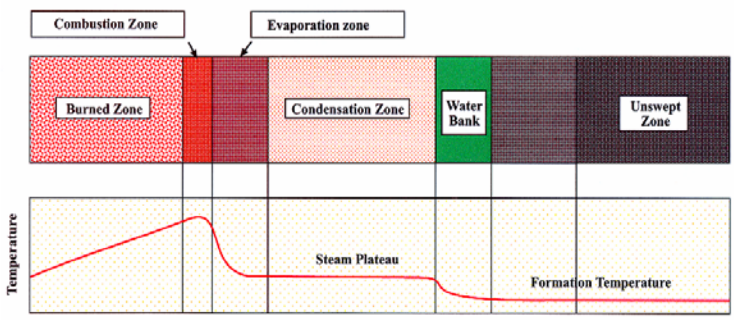
Other ongoing heavy oil ISC applications

- **Romania**
  - Suplacu de Barcau field, Petrom
- **India**
  - Balol and Santhal fields, ONGC
- **Russia, Tartar Republic**
  - Mardovo-Karmalskoye field

Air injection

- Proven IOR process for heavy oil fields
- More than 50 years history
- Secondary and tertiary applications
- Emphasis on light oil mature fields applications due to price and process advantages

7-9% of the contacted oil is consumed to maintain propagation of the in-situ oxidation process



Recovery Mechanisms: Light Oils vs. Heavy Oils

- **Thermal effects are the main recovery mechanism in heavy oils and bitumen (i.e. steam/hot water displacement, combustion front displacement).**
- **Flue gas drive (i.e. pressure maintenance, gasflood, oil stripping, oil swelling , etc.) is the main driving mechanism in light oils at earlier times.**
- **For light oils, thermal effects become important later in the life (i.e. after 1 PV of air injected). Thermal effects provide displacement of residual oil (to gas and steam) and mobility control effects.**

Chemical reactions in situ

- Bond Scission Reactions (Oxidation Reaction)
- Oxygen Addition Reactions (Oxidation Reaction)
- Pyrolisis Reactions (Thermal Cracking)

Bond Scission Reactions

$$\text{Hydrocarbon} + O_2 \rightarrow \text{Carbon oxides} + \text{Water} + \text{Energy}$$

Oxidation Reaction

Heavy oil - dominant at temperatures above 350^{o}C

Light oil – dominant at oil temperatures

Oxygen Addition Reactions

$$\text{Hydrocarbon} + O_2 \rightarrow \text{Oxygenated compounds} + \text{Energy}$$

Oxidation Reaction

Heavy oil - dominant at temperatures below 300^{o}C

Light oil – dominant at temperatures below 150^{o}C

Oxygenated compounds:

Aldehydes, alcolos, ketons, hydroperoxides

Ineffective in mobilizing oil

Formation of stable emulsions with water

Pyrolisis Reactions

$$\text{Hydrocarbon}_{(\text{liquid})} \xrightarrow{\text{Energy}} \text{HC}_{(\text{liquid and / or solid})} + \text{HC}_{(\text{gas})}$$

Thermal Cracking – endothermic reactions

Three overlapping stages:

- ***Distillation (light and part medium fractions lost, gas produced)***
- ***Visbreaking and coking (oil cracks into semisolid residue rich in carbon, gas produced)***

Heavy oil:

important, coke is source of fuel for bond scission reaction

Light oil:

Not important, coke is rarely produced

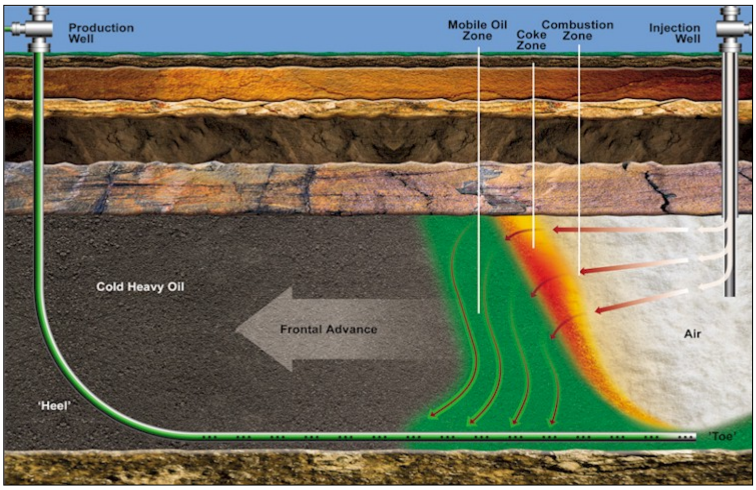
Process Variations (1)

- ***Dry Combustion:*** Only air or enriched air is injected
- ***Wet Combustion:*** Water is injected along with air to create steam and provide additional heat transport and oil displacement
- **Steam-Oxygen Co-injection:** Air-Assisted Steam Injection
- ***Cyclic Combustion:*** CSS but injecting air or steam-air mixtures
- ***COFCAW*:** Combination of Forward Combustion and Waterflooding
- ***Pressure Cycling Combustion:*** Pressure up-Blow down process

Process Variations (2)

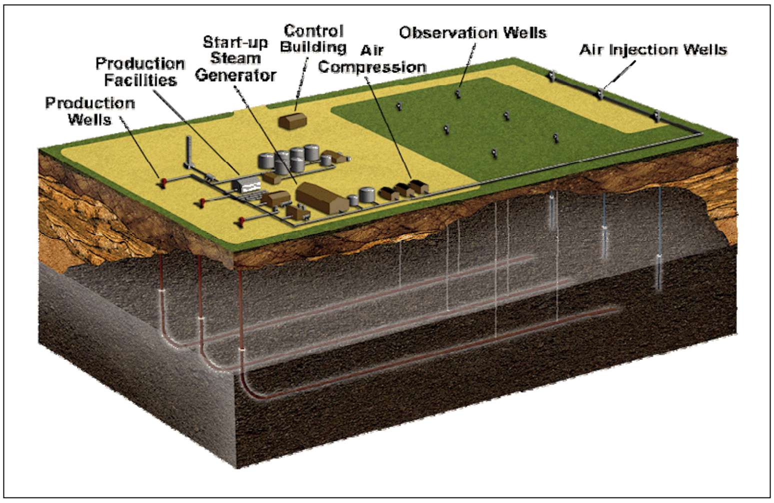
- ***THAI*****:** Toe-to-Heel Air Injection
- ***THAI-CAPRI:*** Catalytic version of THAI
- ***EnCAID*****:** EnCana Air Injection and Displacement process
- ***COSH*****:** Combustion Override Split production Horizontal well process

THAI



www.petrobank.com

Proposed Layout for THAI



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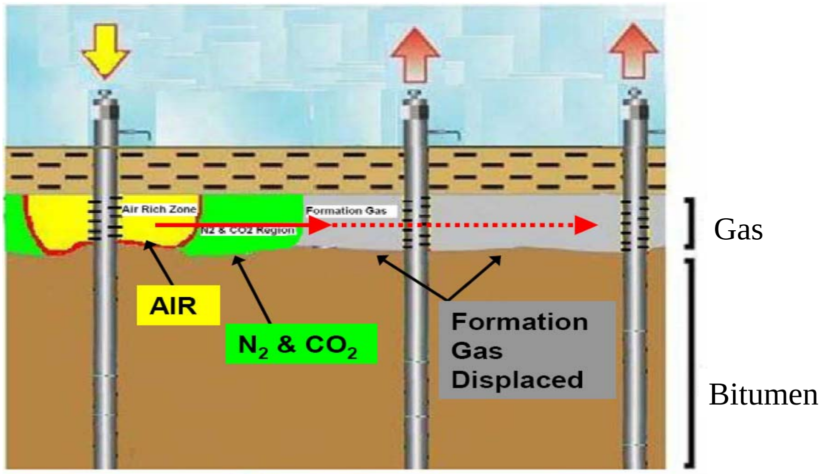
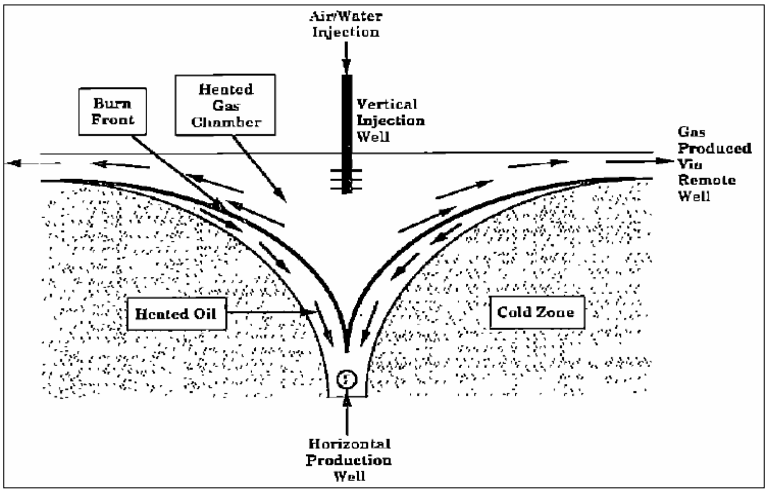
EnCAID



After Freeman, et al. WHOC, paper 2008-497

Schematic COSH Process Diagram



After Kisman and Lau. JCPT 1994.

Air injection applications

- Emphasis has shifted from heavy to light oil applications due to price and process advantages
- Approximately 10 000 BOPD produced from light and medium oil reservoirs
- Air injection economics similar to North American new development projects

Air Injection in Light Oil Field Examples

- **BP (Amoco)**
  - Medicine Pole Hills Unit, SPE 35393, 27792
  - Buffalo Red River, SPE 28733, 113254
- **Total**
  - Horse Creek, SPE 49519
  - West Heidelberg Unit, SPE 10247
- **USSR**
  - Gnedintsi, Ukraina, SPE 24162

Air injection - economic parameters

	Heidelberg Mss.	MPHU N.Dakota	Batrum Sask.
Capital cost, $/BO	**3.5**	**2.5**	**2.2**
Operating cost, $/BO	**5.7**	**5.0**	**4.0**
Project size, BOPD	**1000**	**1200**	**7000**

Air Injection in Light Oil
Laboratory and Simulation Studies

- **Norway, CoP, Total, ENI, StatoilHydro**
  - Ekofisk field, North Sea, SPE 97481, 65124
- **UK**
  - Maureen , (PPCoUK, Fina, Agip, BG, Melrose) SPE 3890
- **Argentina**
  - Barrancas field, SPE 49519
- **USA**
  - Coral Creek, SPE 52198
- **Indonesia, Total**
  - Handil field, SPE 54377, 93858
- **Lybia, Total**
  - Haram Field

Air injection in light oil reservoirs

- **Reservoir pressurization, HPHT displacement conditions**
- **Substitution for methane, N2 or CO2**
- **Better mobility ratio. Water at supercritical conditions**
- **Stripping and vaporizing of oil by generated flue gas (85% N2 + 15% CO2)**
- **Swelling of oil by combustion gases and possible miscible effects**
- **Oil banking and improved sweep**
- **Reduction of oil viscosity due to increasing temperature**

Deep light oil reservoirs have usually required conditions for spontaneous ignition

Summary of LOAI Field Experience

- Air injection in light oil, carbonate reservoirs is economically and technically feasible
- Recovery increased by 15-17% of OOIP
- NGL extraction is major contributor to economic success
- Air injection offshore - no field experience documented in open literature
- Air injection in fractured reservoirs - no experience documented in open literature

Key aspects of air injection application

- **Kinetics, activation energy, reactive oil properties**

Differential Thermal Analyser (DTS)- low pressure (up to 100 bar)
Accelerating Rate Calorimeter (ARC) – up to 450 bar
Disc reactor, Ramped Temperature Oxidation (RTO) – res. pressures

- **Oxidation process, quantify performance**

Combustion tube test – res. conditions flow test

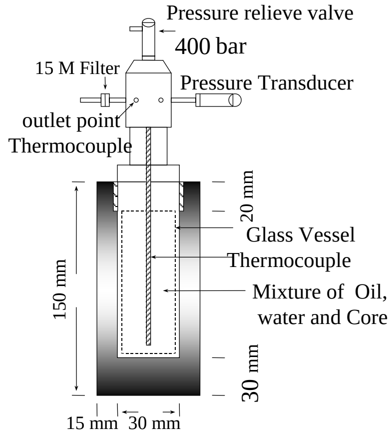
- **Good conformance is critical**

State-of-the-art simulation

Accelerating Rate Calorimeter (ARC) screening of oil

Measurement of kinetic data from exothermic reactions under adiabatic conditions

- Reaction regimes (LTO - HTO)
- Potential for spontaneous ignition
- Ranks oil for combustion tube testing
- Modeling parameters

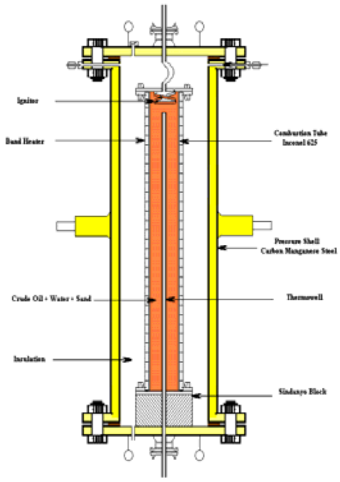


ARC test

- Optimising the amount of reactant into the sample holder and relative air flux
- Screening for air injection (reactivity tests)
- Heat evolved from oxidation reactions
- Oxygen consumption rate and produced carbon oxides
- Distinguish between low (LTO) and high temperature oxidation (HTO) reactions
- Reaction kinetics: Arrhenius model for reaction rate
- Effect of physical parameters e.g. S_o, S_w, pressure, air Influx on exothermicity characteristics

Combustion tube experiment

- Air requirement
- Quantity of fuel deposition
- Fuel molecular weight
- Air / fuel ratio
- Oil and water recovery
- Peak temperature generated
- Potential for combustion front propagation
- Stripping behavior
- Produced gas composition



Modeling in-situ combustion

- Thermal simulator
- K value pseudo-compositional
- Four phases: water, oil, gas, solid
- N - components
- Chemical reactions
- Energy release and temperature modeling

Combustion simulation model

- **Mass transfer reaction example:**

light oil + O2 -> water + inert gas/CO2 + energy

Energy - reaction enthalpy (Hr)

- **Kinetic model for reaction:**

Arrhenius model for reaction rate:
R*k*=R*rk* exp(-E*ak*/RT) P Ci

E*ak* - activation energy

Average energy released per fuel consumed

(combustion tube)

Combustion model parameters

- Stoichiometric coefficients of reacting and produced components
- Reaction frequency factor (*freqfac*)
- Activation energy which determines dependence of the reaction rate on grid block temperature (*J/gmol or Btu/lbmol*)
- Reaction enthalpy (*J/gmol or Btu/lbmol*)

Oxidation reactions

Reactant Component + OXYGEN $\rightarrow H_2O + CO_2$ + ENERGY

Input parameters for reaction k:

- mass exchange (stoichiometry)
  - $\longrightarrow$ s_{k,i_C} (reactant stoichiometric coefficent)
  - $\longrightarrow$ s'_{k,i_C} (product stoichiometric coefficent)
- reaction kinetics (reaction rate)

$$r_k = r_{fk} e^{-eact/(T*R)} C_1^{o_{k,1}} \dots C_{nc}^{o_{k,nc}}$$

where C_{i_C} are concentration factors

- reaction enthalpy H_k

Example combustion reactions

Chemical reactions:

1) Cracking of C12-C17 -> coke + C7-C11
2) Cracking of C18+ -> coke + C7-C11
3) Burning of C12-C17 + O2 -> WATER + CO2 + energy
4) Burning of C18 + O2 -> WATER + CO2 + energy
5) Burning of coke + O2 -> WATER + CO2 + energy

Components:

H2O, N2, O2, CO2, C5-C6, C7-C11, C12-C17, C18+
and residual coke (solid component)

Ekofisk chalk field, North Sea

AIROIL - Air injection potential evaluation study (2001 – 2004)

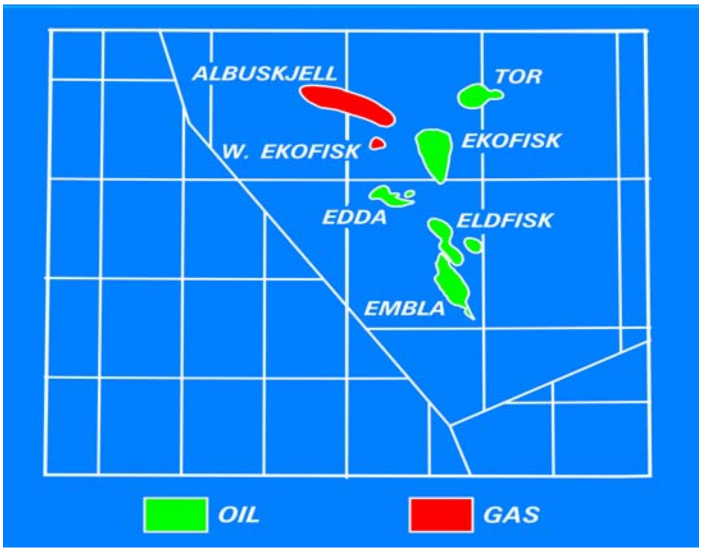
Co-operation partners:

- RF - Rogaland Research (IRIS), co-ordinator
- Phillips Petroleum (CoP)
- Halliburton
- Institut Francais du Petrole
- PETEC
- University of Bath
- TotalFinaElf (Total)

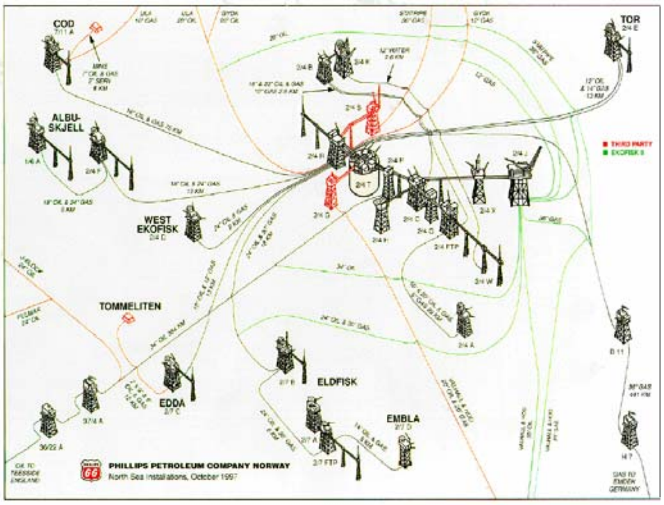
Six work packages:

1. Field pilot screening
2. Supporting experiment
3. AirOil fractured reservoir simulation
4. Downstream processes
5. Field pilot design
6. Field pilot preparation, execution and evaluation

Greater Ekofisk Area Reservoirs

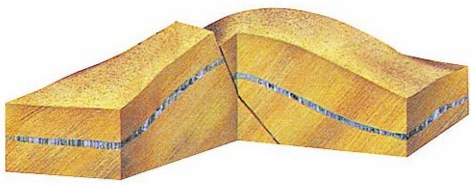


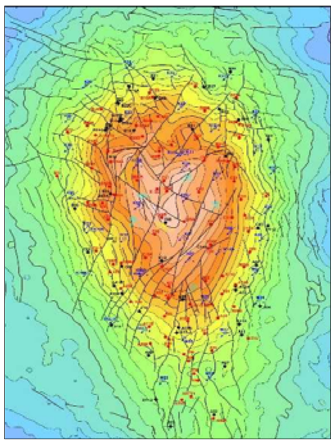
Greater Ekofisk Area Infrastructure



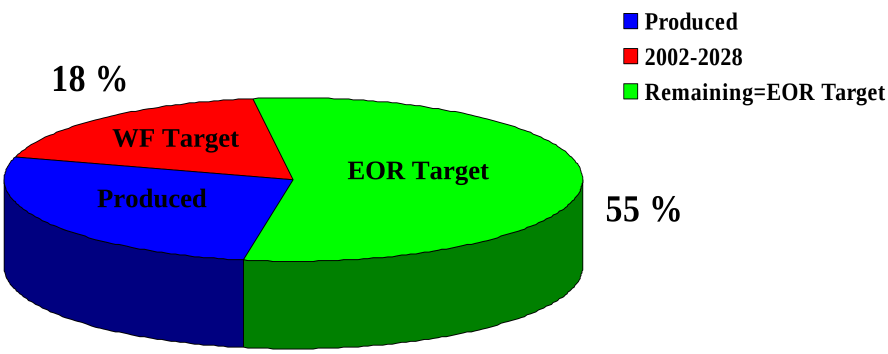
Ekofisk Field Reservoir

- Area 9 x 4,5 kilometers
- Vertical Thickness 300 meters
- Producing From Two Horizons (Ekofisk 70% and Tor 30%)
- Low Productivity Matrix Rock
- High Porosity Matrix Rock (25-48%)
- Initial Oil In Place 6,7 BSTB



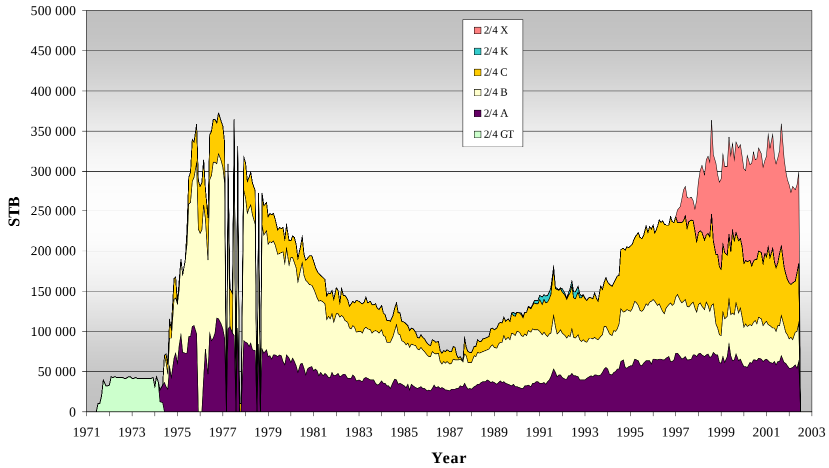


The Ekofisk EOR Target



+1% incremental RF ~ 80 MMBOE

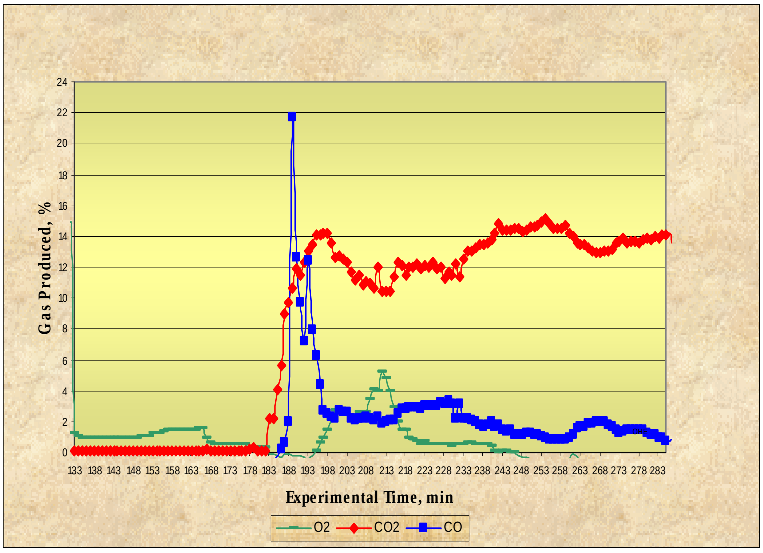
Ekofisk Oil Production History



Simulation of air injection in a chalk reservoir to estimate incremental oil recovery after depletion and waterflooding

- Segment reservoir model
- Combustion Tube experimental data for light oil
- Accelerating Rate Calorimeter (ARC) experimental data
- Gas diffusion experiments, fracture-matrix
- Rock compaction effects, mechanical strength tests
- Injection / production scenarios
- Thermal in-situ combustion model

Produced Gas Composition



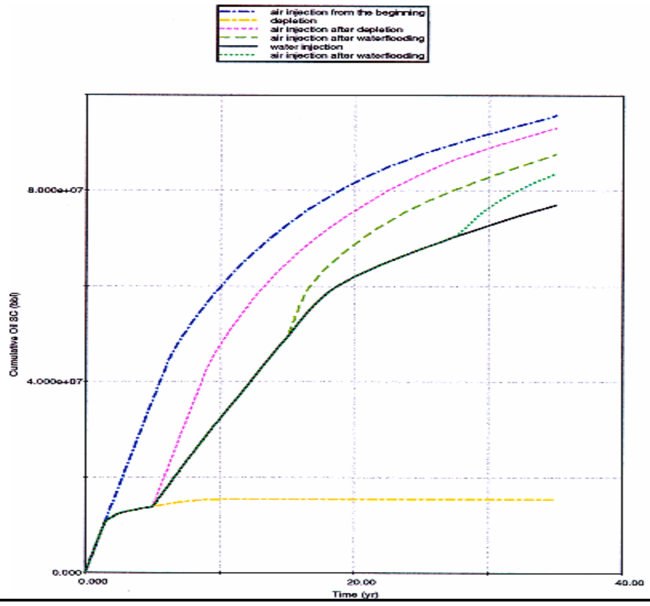
AIROIL simulation models

- Thermal simulators (Stars and Athos)
- Sector reservoir simulation models
- Single and dual porosity
- Gas diffusion modelling

Surguchev, L., Koundin, A., Yannimaras, D.: ”Air Injection: Cost Effective IOR Method to Improve Oil recovery from Depleted and Waterflooded Fields”, SPE 57296, 1999

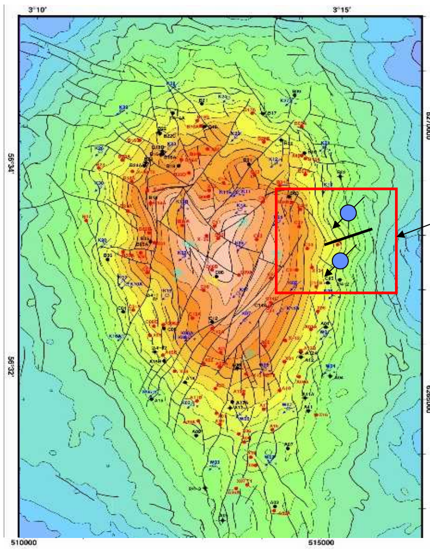
Stokke, S. et al.:”Evaluation of air injection as IOR method for the giant Ekofisk chalk field” SPE 97481, 2005

Air injection - cumulative oil produced



Air injection in light oil Ekofisk reservoir after depletion and waterflooding

Ekofisk Map & Pilot Area



Proposed pilot area

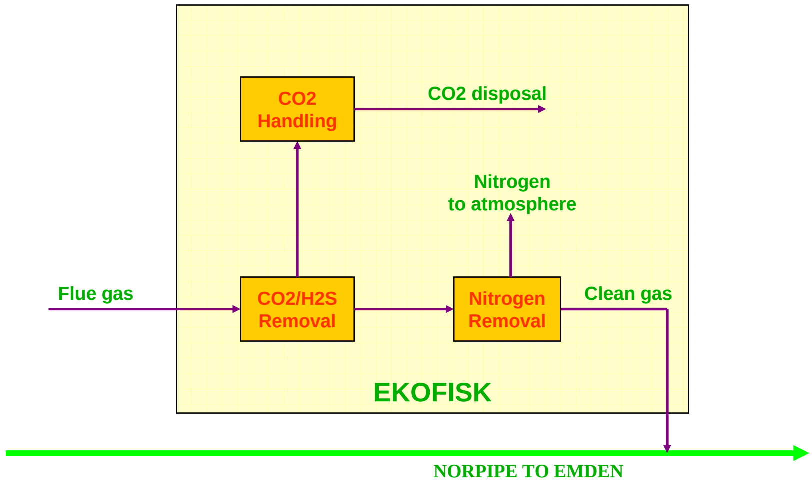
AIROIL Downstream Processing

Options:

1. Gas Cleaning and Gas Processing on EKOFISK
2. Gas Processing onshore
3. Gas Processing offshore and onshore

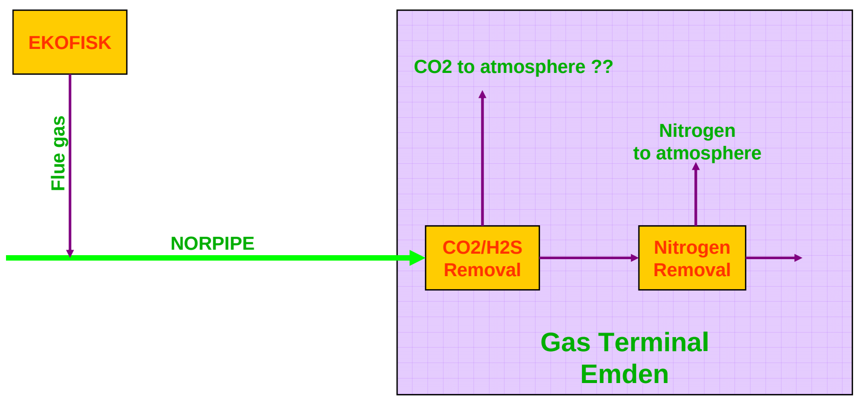
Downstream Processing

Option 1 Gas Cleaning and Gas Processing on EKOFISK



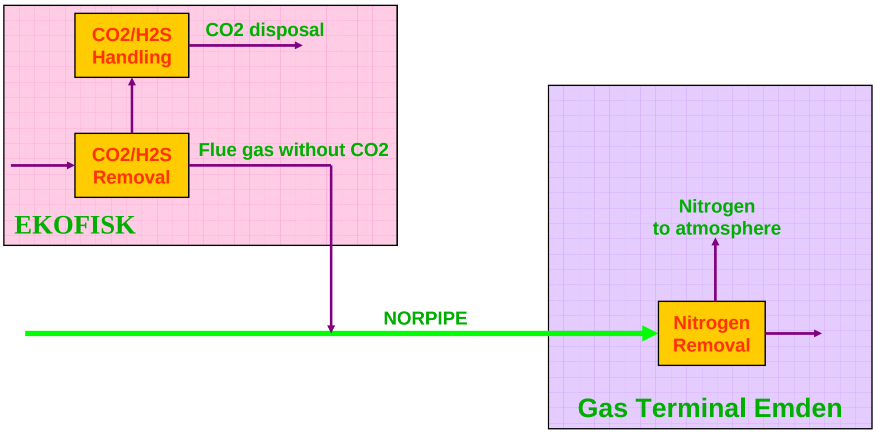
Downstream Processing

Option 2 - Gas Processing onshore



Downstream Processing

Option 3 - Gas Processing offshore and onshore



Shortcomings during Air Injection Processes

- Downstream processing
- Air compression and operation could be expensive
- Complex process: multiphase flow, heat transfer and chemical reactions. It is difficult to model.
- Failures during early ISC projects
- It requires special (non-conventional) laboratory tests
- No offshore experience
- Operationally challenging (i.e. emulsion treatment, risk of explosions, etc.)

Air injection potential risks

INJECTION SIDE:

• Eventual O_2 back production

Measures:
Well bore isolation
No tubing leaks
Second injection line to purge water or N2

PRODUCTION SIDE:

• O_2 breakthrough risk

Measures:
Production monitoring
Down hole gas gauges

Operational and safety issues are not regarded any more as obstacles for field application.

Number of successful field applications.

Why reconsider air injection today? (1)

- Thermally, it is the most efficient oil recovery process
- Availability of air (cheap injection fluid)
- Proven technology in different reservoir settings (shallow heavy oil and deep light oil reservoirs)
- High displacement efficiency
- It can be applied in cases where waterflooding or steam injection are not effective
- It can be applied where other EOR processes (e.g. CO2 injection, chemical injection, etc.)

Why reconsider air injection today? (2)

- Size of the resources
- Better production procedures and equipment
- Better access to the reservoir with horizontal wells
- Better understanding of the process mechanisms, particularly the oxidation kinetics and relative permeability effects of liquid-blocking gas flow.

Light oil air injection advantages

- No commercial value injection agent
- Displacement efficiency 100%. No oil and water left behind the front
- Applicable in low permeable reservoirs
- Reservoir pressurization
- Production response within a short time period
- Consumption of 7 to 10% of oil in place can lead potentially to recovery of all remaining oil
- Air autoignites when injected
- Potential to enhance oil recovery after depletion or waterflooding