Toe-To-Heel Air Injection (THAI) Process

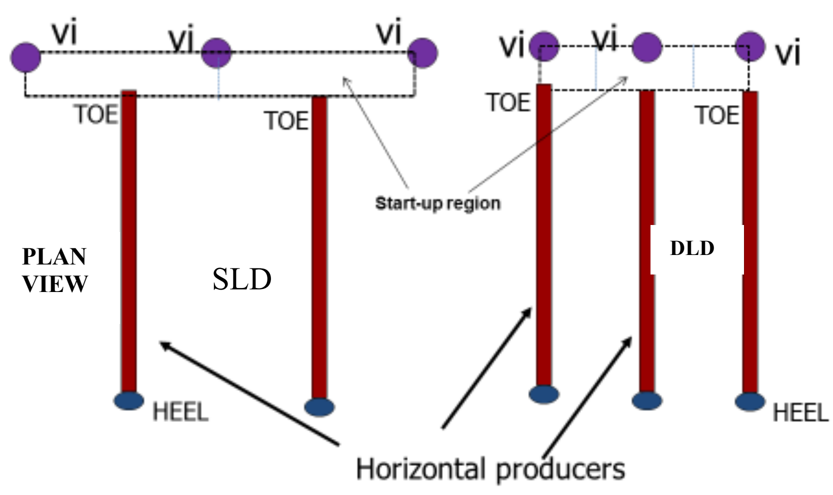
A pseudo-gravity stable displacement in-situ combustion process operating over a short reservoir distance. It has a proven record of producing partially upgraded oil in case of extra-heavy oil reservoirs and oil sands.

Toe-To-Heel Air Injection (THAI)* is a new **i**n-**s**itu **c**ombustion (ISC) technology for the recovery of partially upgraded oil from heavy oil reservoirs.

In the conventional ISC process, which uses vertical injectors and producers, the volumetric sweep is very limited due to pronounced channeling and/or over-running. These deficiencies are overcome by using horizontal producers placed at the bottom of the oil zone so that a special **t**oe-**t**o-**h**eel configuration enables a controlled flow pattern to develop in the reservoir.

The new technology can be applied in two well configurations: either **d**irect **l**ine **d**rive (DLD), where the vertical injector is placed in front of the toe of the horizontal producer, or in a **s**taggered **l**ine **d**rive (SLD), where the toe of the horizontal producer is located close to the line of vertical injectors, but is laterally off-set (Fig. 1). THAI consists of at least one vertical air or air/water injector, perforated in the upper part of the oil layer, and a horizontal producer placed at the lowest possible part of the oil layer, with its toe facing the injector (Fig. 2). It is a pseudo-gravity stable, **s**hort-**d**istance **o**il **d**isplacement (SDOD) process. The advantage of SDOD is that in situ upgrading of heavy oil occurring within the ISC process (the so-called first upgrading) is preserved and some hydrogen is produced. There may be a coke-like plug traveling with the ISC front (Fig. 2). Laboratory tests and field scale simulations have shown that this occurrence provides for localized blocking, in or around the horizontal well and constitutes one of the self-healing features of the process; the second self-healing feature is the controlled over-ridding of the ISC front. Due to these two effects, any potential oxygen short-circuiting is eliminated.

CAPRI (**CA**talytic upgrading **PR**ocess **I**n-situ) is an add-on process to the THAI process, in which the horizontal section of the horizontal producer is surrounded by a catalyst-activated gravel packing (not-pictured) or something similar. CAPRI is therefore a catalytic version of THAI**. All of the physical phenomena (thermal, hydrodynamic, etc) are the same as in THAI, the only difference is that a *secondary upgrading* occurs when the partially upgraded THAI oil flows into the horizontal producer. In laboratory testing, the CAPRI process was able to achieve upgrading of up to 14 API degrees. However, compared to THAI, the CAPRI process is much less developed; theoretically, it has a high potential.



* US patent: 6,167,966 and Canadian patent: 2,246,461; the US patent expired in 2015, while Canadian patent expired in 2016.
** US patent: 6,412,557/2002 and Canadian patent: 2,255,071/2003; both expired a few years ago

Fig 1: **S**taggered **l**ine **d**rive (SLD) and **d**irect **l**ine **d**rive (DLD) THAI schematics. Legend: VI=Vertical injector

Benefits

- Increased control over the ISC front propagation, compared to conventional ISC process; in general, ISC front break-through occurs at the toe region and then progressively advances towards the heel
- Relatively less sensitive to rock heterogeneity (mainly to stratification)
- Easier to implement when heavy oil has some mobility at reservoir conditions, otherwise initial hot communication has to be developed
- More resilient to thermal production operations (if the damage of the producer occurs it is progressive from toe to heel)

- Easy to implement using existing facilities and **h**orizontal **w**ells (HW); especially if HWs are placed near the bottom of the oil layer
- Same routine laboratory tests are required as for conventional ISC
- Produces in-situ upgraded oil and hydrogen

Laboratory and Simulation Results

Over 100 3-D model (box style 60cm*40cm* 20cm) laboratory investigations have been carried out at the University of Bath (U of B), UK over 12 consecutive years. Generally, the volumetric sweep efficiency and oil recovery were better using an SLD well configuration. In all the laboratory tests, intensive heating of the entrance face/start-up region was performed, before and during the ignition. The U of B results were confirmed by several other organizations using similar 3D combustion cells.

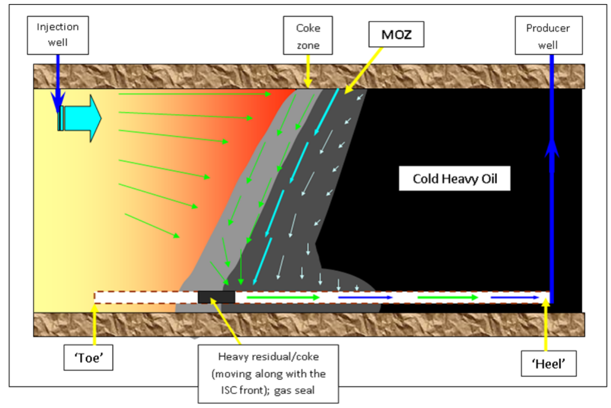


Fig. 2: THAI schematics; cross-section

The upgrading obtained during a laboratory test with Wolf Lake oil (viscosity 44,000 mPa.s) was very substantial; 4-5 points oil upgrading and 44-fold oil viscosity decrease.

Figure 3a shows the temperature isotherms from a 3D combustion cell test on Wolf Lake oil conducted in an SLD configuration, while Fig. 3b shows a CMG-STARS simulation of the same test; both are shown at 8 hours since the initiation of the test. STARS simulations have been also conducted for some field situations.

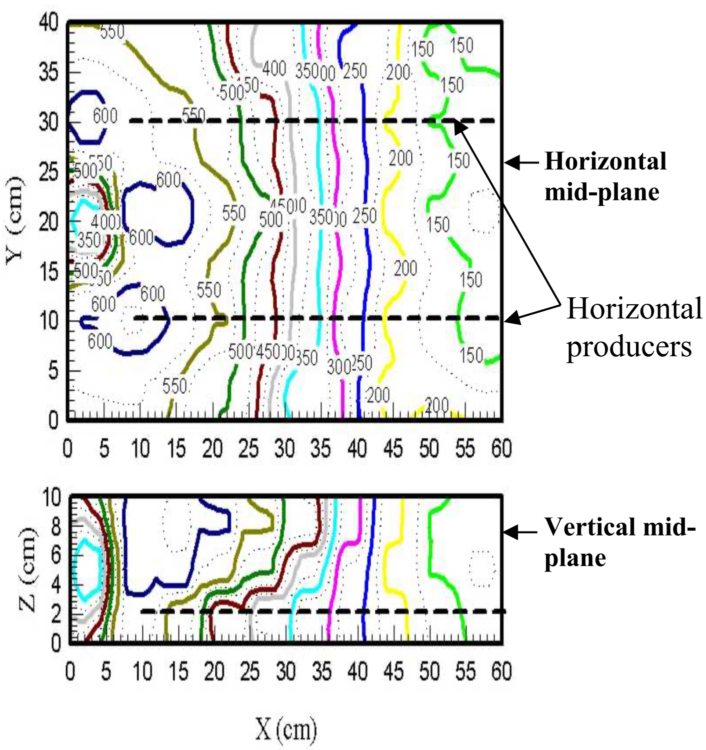


Fig. 3a: Isotherms from the laboratory test

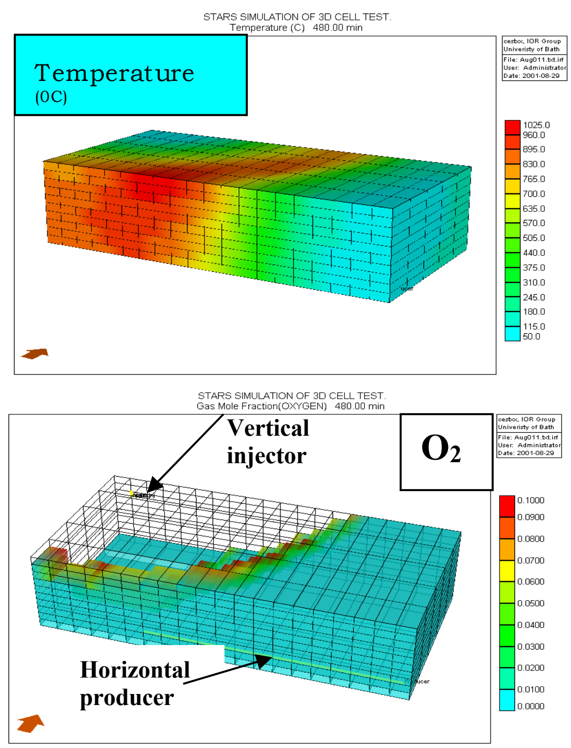


Fig. 3b: Simulated temperature and O_2 distribution

Field Testing

THAI process has been tested in the Athabasca Oil Sands of Alberta (Whitesands Pilot, near Conklin) and also in a conventional heavy oil reservoir (Kerrobert, Saskatchewan). In both of these Canadian projects, the **d**irect **l**ine **d**rive (DLD) configuration was tested. The Whitesands Pilot, which was conducted over 5 years (2006-2011) in the McMurray B formation at a depth of 380m, consisted of three well pairs. The Kerrobert Pilot was conducted in the Waseca Channel (Manville Sand of Lower Cretacic) at a depth of 780m; initially, the project consisted of a two-well pairs, which was expanded in 2011 to 12 well pairs, as a semi-commercial operation. Five more pilots have been conducted outside Canada: in China (starting in 2012) and India (starting in 2016/2017).

Whitesands THAI Pilot: startup was straightforward, and day-to-day operation was robust and easily maintained. Re-starting the process after a long period of air injection interruption, was also easy. Consistent partial in situ upgrading of approximately 4 API points increase was achieved; also, hydrogen production (2-4% in the produced gas) was recorded. The operational performance (Fig. 4) shows a good quality of burning as witnessed by the produced gas composition. Some operational problems occurred, such as sand influx and oil lifting problems, while using PCP for production. For different reasons, horizontal producers were re-drilled; one of them in order to specially complete it for CAPRI testing.

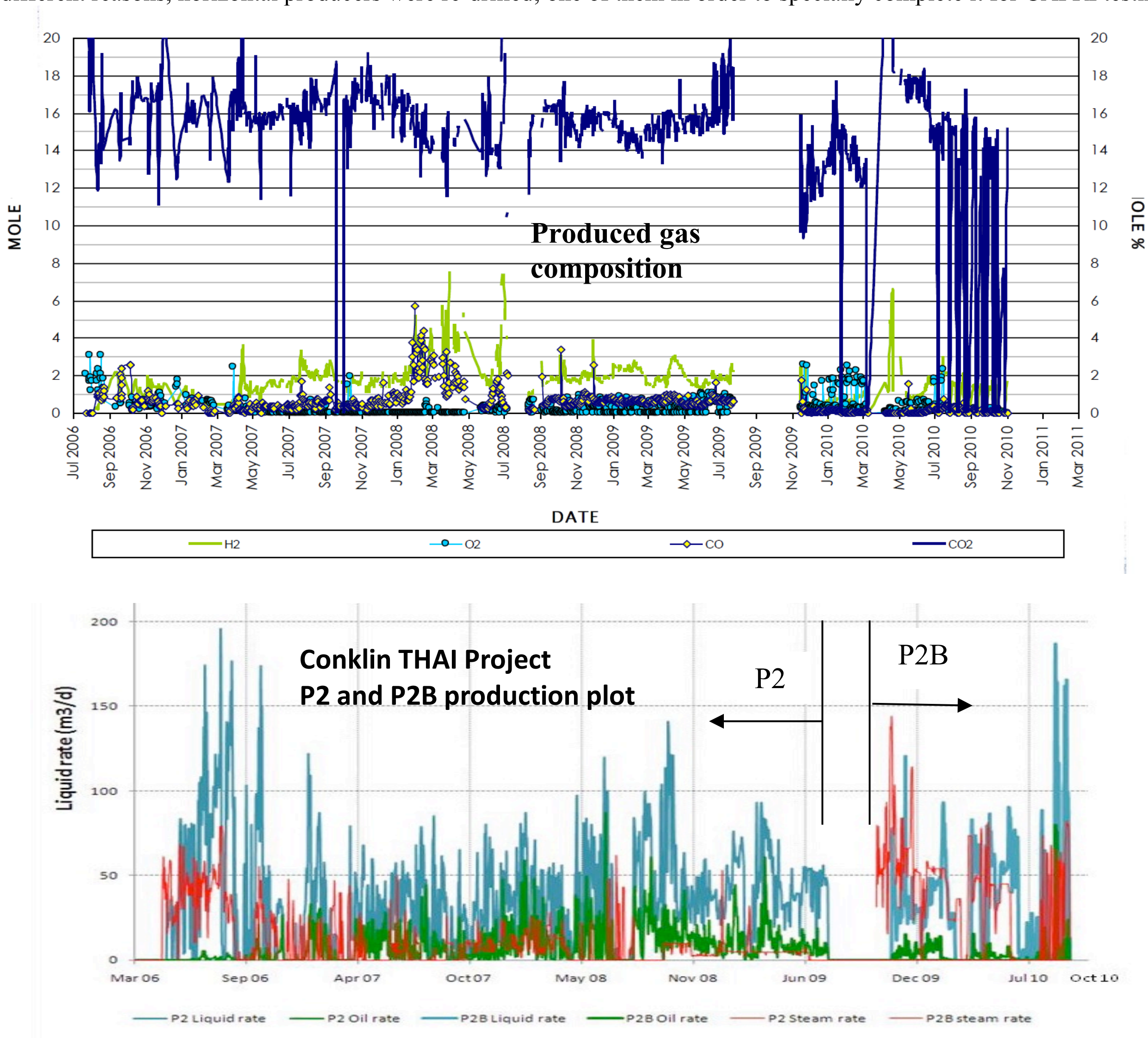
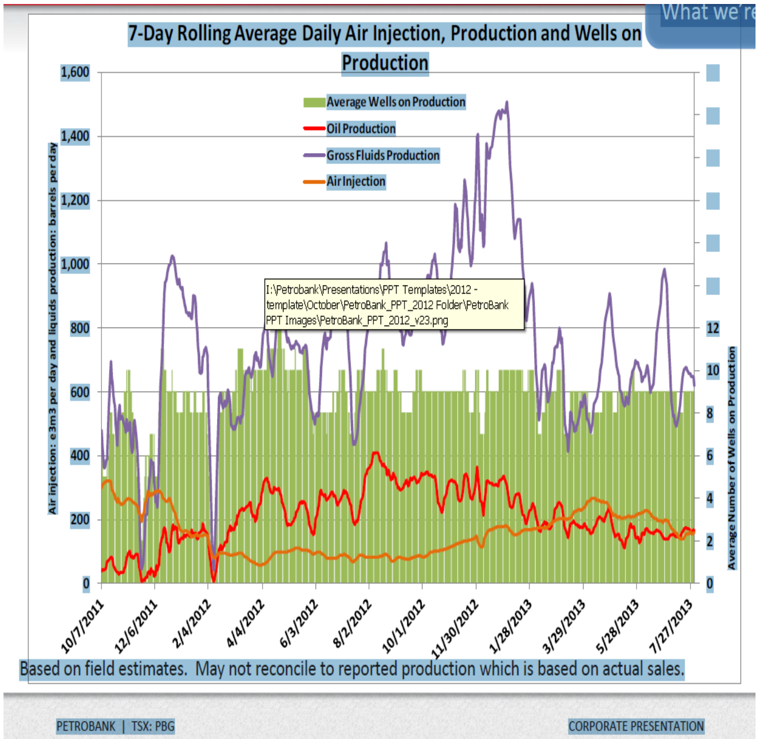


Figure 4: Performance of the Whitesands THAI Pilot, pair A2-P2 (produced gas composition and oil production). Innovative Energy Technology Programs (IETP) Study, 2008. P2B is the replacement well for P2

Kerrobert Project (initiated in 2009): Heavy oil reservoir with **b**ottom **w**ater (BW). The thickness of the BW zone was slightly lower than that of the oil zone (25 m). Generally, there have been fewer operating problems than in Whitesands Pilot, with the main one being the presence of BW, which had a negative effect (high water cuts); BW effects negated the possibility to increase the air rate over a certain value. The project has been operated for more than 12 years and it is still ongoing, as of March 2022. The operational performance (Fig. 5) does not show a proportionality between air injection and oil production. The produced oil from the Kerrobert Pilot/semi-commercial project consistently averaged 14 API to 17 API in-situ upgrading during its entire operation; Fig. 6, shows a 3 to 7 API point increase for the Pilot. The THAI process *provided sustained in-situ upgrading of heavy oil and hydrogen production (1.5-3%); the obtained upgrading is a partial upgrading.*

So far, from both Canadian projects (Whitesands and Kerrobert), over half of million barrels of partially upgraded oil have been produced. However, the oil rate per well was lower than in the steam-assisted gravity drainage (SAGD) process. It was, generally, in the range of 10-30 m^3/day (63-190 bbls/day).



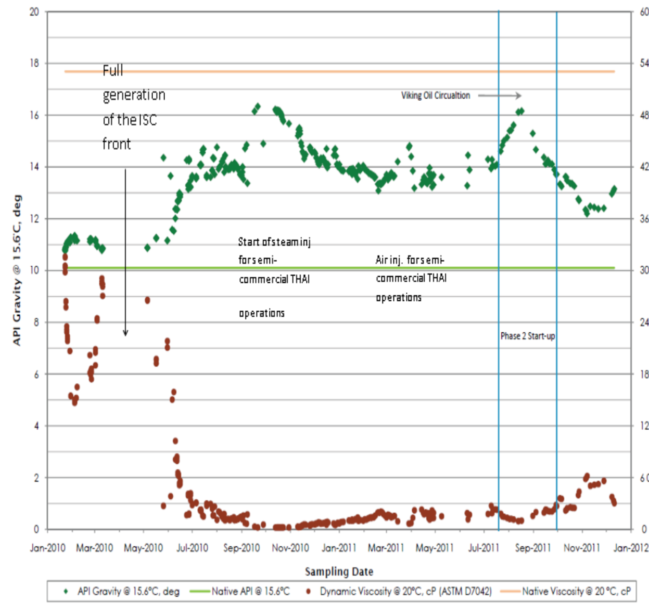


Fig. 6: Produced oil quality during Kerrobert THAI pilot (in-situ upgrading) in the period January 2010-July 2011(Petrobank website)

Figure 5. Performance of the Kerrobert THAI Project (2011-2013). Source: Petrobank presentation, August 2013 (www.petrobank.com)

Outside Canada THAI pilots: There have been three Chinese THAI pilots [one pilot in Shuguang (Liaohe) and two pilots in Fengcheng (Xinjiang Oilfield)] and three THAI applications in India (Balol, Lanwa and Santhal Fields); in Balol field, the pilot consisted of 5 patterns operation, while in Lanwa - in 2 patterns; both were conducted using staggered line drive (SLD) configuration. In Santhal Field, the test started recently. Based on the learnings from the pilots – conducted both inside and outside Canada - it can be concluded that the technical validity of the THAI process is validated. Its economic performance is underway to be validated and this way THAI is going to take its place as a major oil recovery/upgrading technology. So far, the SLD-THAI process has been field-tested only in India, and it showed that it could provide a better practical solution.

Criteria for THAI Application: The following set of screening criteria are based on results from laboratory tests, numerical simulation studies and data from 7 THAI field tests.

The candidate reservoir should meet the following conditions:

- No extensive bottom water (BW); thickness of BW zone less than 70% of that of the oil zone
- No extensive fracturing (natural or induced)
- Formation type: sand or sandstone
- Pay thickness > 6m
- Oil viscosity (reservoir conditions) > 200 mPa.s
- Oil density (surface conditions) > 900 kg/m^3
- Horizontal permeability (K_H) > 200 mD
- K_V/ K_H > 0.25
- Water cut< 70%

The last three screening criteria can be relaxed, if it is known that the permeability is increasing downwards (fluvial deposition); for a final decision about THAI feasibility, reservoir simulation is highly recommended. THAI may be applicable to reservoirs with small gas cap reservoirs, including gas-over-bitumen (GOB) situations; this condition is practically equivalent to a high permeability streak at the top of the formation and the performance will be slightly lower.

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A T EOR Consulting Inc.

Put our expertise to work for you. We offer a full range of services including screening, design/simulation, field implementation, operation/monitoring guidance and evaluation of THAI-related applications.

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