Toe-To-Heel Air Injection (THAI^{TM}) Process

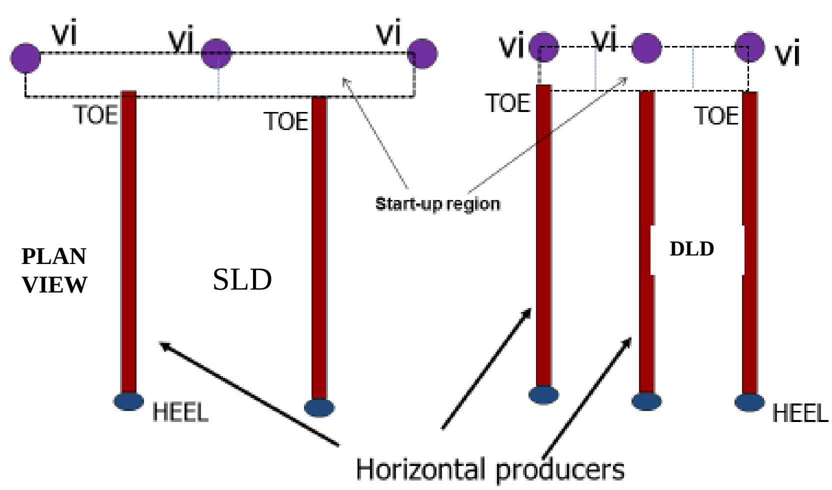
A pseudo-gravity stable displacement in-situ combustion process operating over short reservoir distance. It has a proven record of producing partially upgraded oil in case of extra-heavy oil reservoirs and oil sands.

Toe-To-Heel Air Injection (THAI^{TM})* is a newly developed **i**n-**s**itu **c**ombustion (ISC) technology for recovery of a 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 (TTH) well 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^{TM} 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 vertical injector (Fig. 2). THAI^{TM} is a 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 just ahead of the ISC front is preserved and some hydrogen is produced. There may be a coke-like plug travelling with the ISC front (Fig. 2). Laboratory tests and field scale simulations have shown 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 one is the controlled over-ridding of the ISC front. Due to these two effects, any potential oxygen short-circuiting is totally eliminated.

CAPRI^{TM} 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). 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 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 very 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

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

Benefits

- increased control over the ISC front propagation, compared to conventional ISC process; ISC front break-through always at the toe and progressive advancement 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 is needed
- more resilient to thermal production operations (if damage is occurring 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 required as for conventional ISC

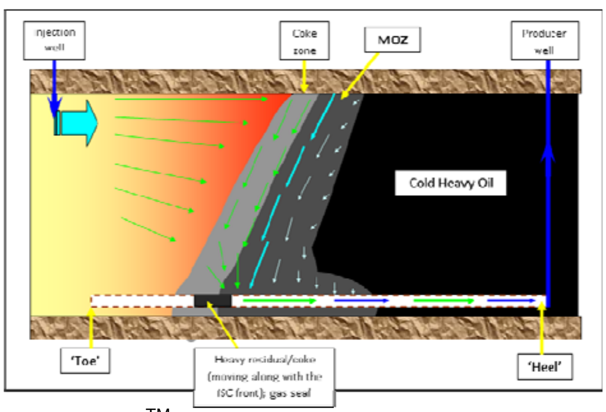


Fig. 2: THAI™ schematics; cross-section.

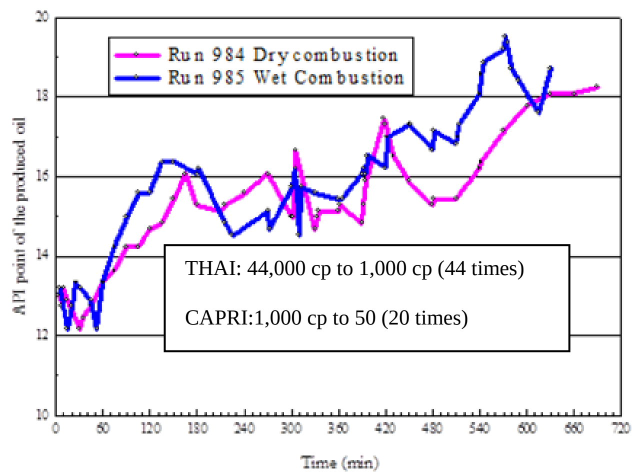


Fig. 3: Upgrading of Wolf Lake heavy oil during dry and wet THAI laboratory tests.

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 (UB), UK over 12 years. Generally, the volumetric sweep efficiency and oil recovery were better using an SLD well configuration (SLD-THAI process). In all the laboratory tests, intensive heating of the entrance face/start-up region was performed, prior to ignition. The UB results were confirmed by several other organizations using similar 3D combustion cell arrangements. The oil upgrading obtained during a laboratory test with Wolf Lake oil (viscosity 44,000 mPa.s) was substantial; 44-fold permanent decrease of the oil viscosity and 4-5 API points upgrading (Fig. 3). Figure 4a shows the temperature isotherms from a 3D combustion cell test on Wolf Lake crude, while Fig. 4b shows a CMG-STARS simulation of the same test. STARS simulations were also conducted for some simplified field situations.

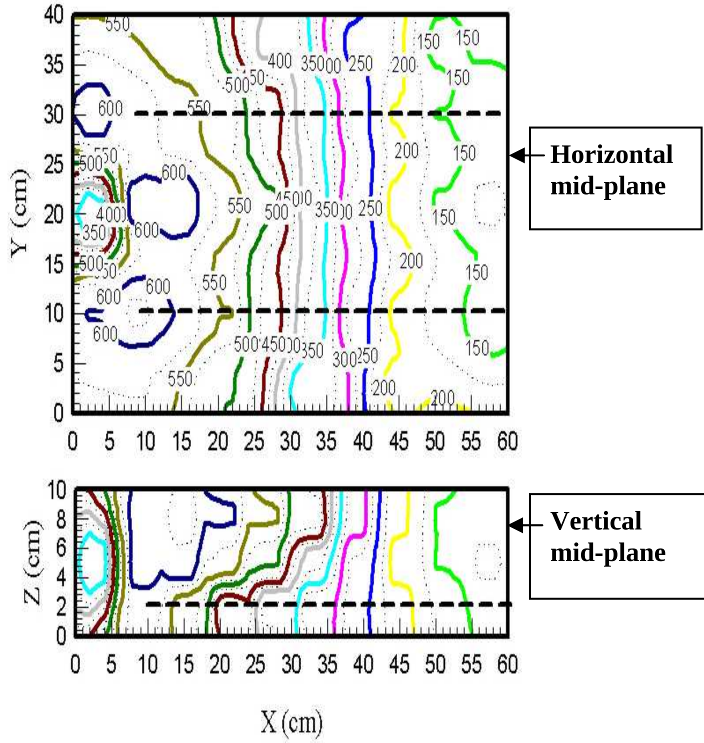


Fig. 4a: Isotherms for a heavy oil (44,000 mPa.s viscosity) laboratory THAI test, after 8 hrs since the initiation of the test.

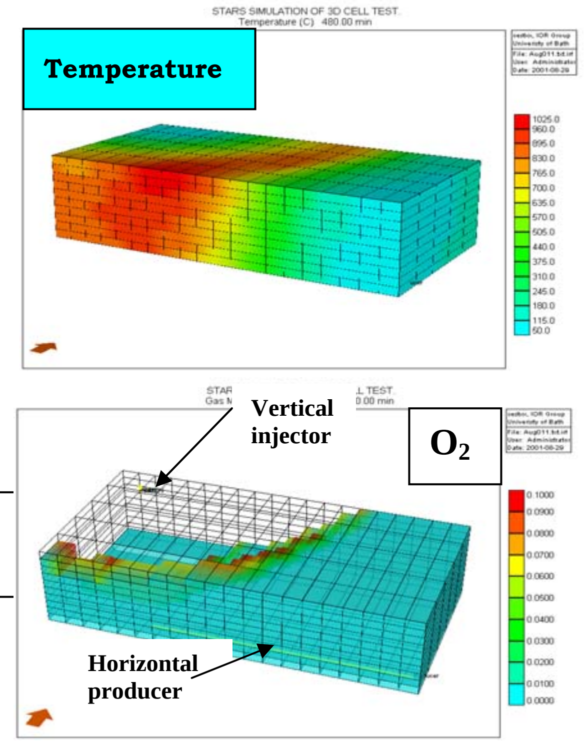
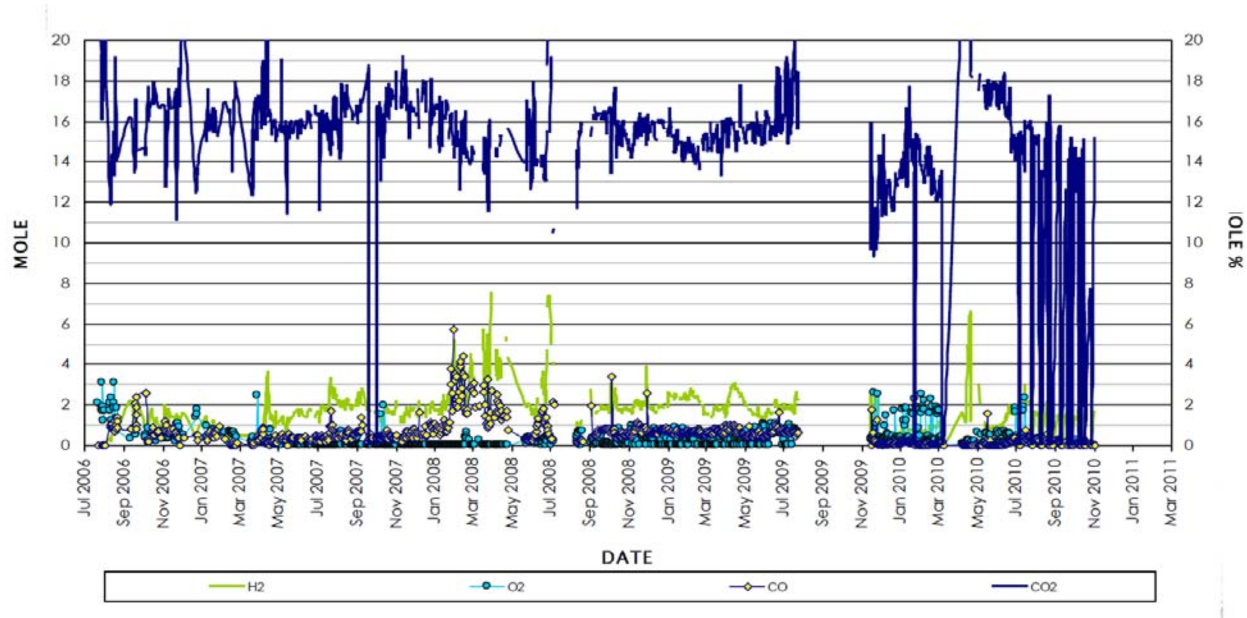


Fig. 4b: Simulated isotherms and O_2 distribution test conducted in an SLD configuration (at 8 hrs since the initiation of the test).

Field Testing

THAI heavy oil technology has been tested in the Athabasca Oil Sands of Alberta (Whitesands Project, near Conklin) and also in a conventional heavy oil reservoir (Kerrobert, Saskatchewan). In both of these Canadian projects only 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 Project was conducted in the Wasseca Channel (Manville Sand of Lower Cretacic) at a depth of 780m; initially, the project consisted of a two-well pairs pilot, which was expanded in 2011 to 12 well pairs, as a semi-commercial operation. Three more pilots have been conducted outside Canda.

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 (up to 16% in the produced gas) was recorded. The operational performance (Fig. 5) shows a good quality of burning as witnessed by produced gas composition. Some operational problems occurred, such as sand influx and oil lifting problems while using PCP for production. All of the horizontal producers were re-drilled. Good results from the first three years of the pilot resulted in a large scale commercial design (May River), which, later on, was cancelled.



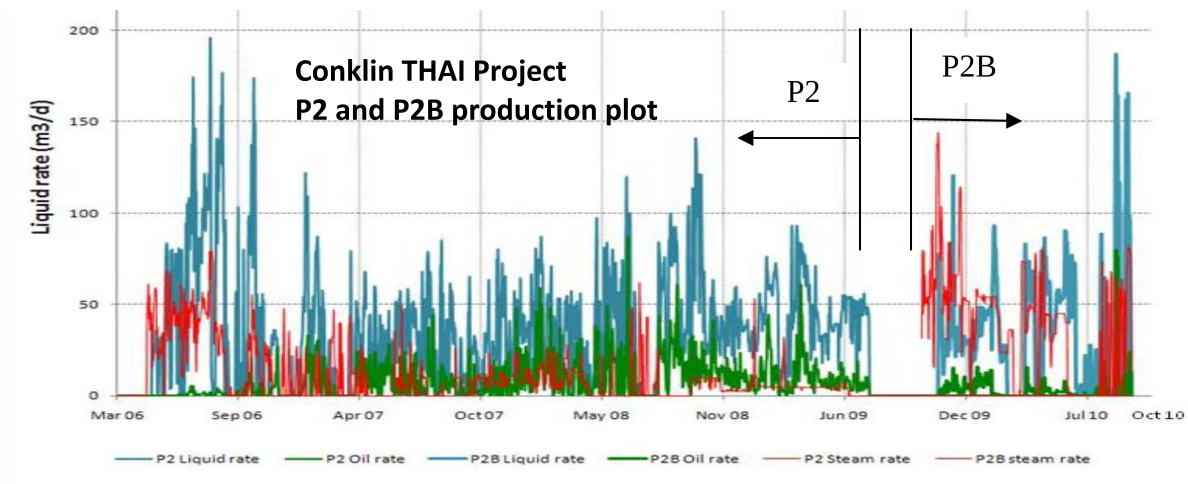


Figure 5: Performance of the Whitesands THAI Pilot, pair A2-P2 (produced gas composition and oil production). Innovative Energy Technology Programs (IETP) Study, 2008. P2B is the replacement well for P2.

Kerrobert Project (initiated in 2009): Heavy oil reservoir with **b**ottom **w**ater (BW). The thickness of the BW zone was almost equal to that of the oil zone (25 m). Generally, there were fewer operating problems than in Whitesands Pilot. BW had a negative effect (high water cuts). The semi-commercial project has operated for 6 years and it was still ongoing, as of June 2017. The operational performance (Fig. 6) 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 upgrading during its entire operation; Fig. 7, shows a 3 to 7 API point increase for the Pilot. In Kerrobert 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 upgraded oil has 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).

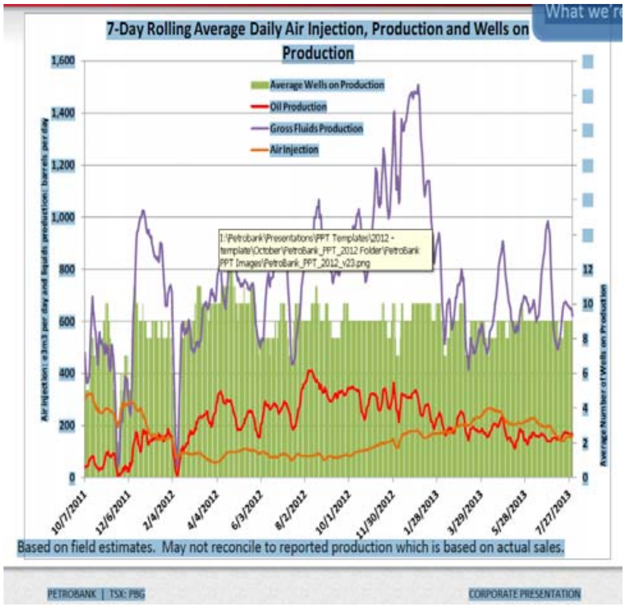


Figure 6. Performance of the Kerrobert THAI™ Project (2011-2013). Source: Petrobank presentation, August 2013 (www.petrobank.com)

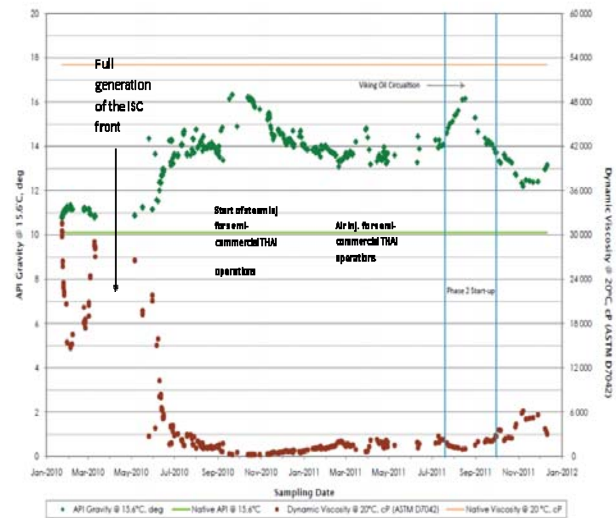


Fig. 7: Produced oil quality during Kerrobert THAI pilot (in-situ upgrading) in the period January 2010-July 2011(Petrobank website).

Outside Canada THAI pilots and future of the process: Besides the important learnings from these two projects, in addition, other learning came from two Chinese THAI pilots [(Shuguang (Liaohe) and Fengcheng (Xinjiang Oilfield)] and two THAI pilots carried out in India (Balol Field and Lanwa Field). Based on the learnings from these six pilots, mentioned in this brochure, it can be concluded that presently the technical validity of THAI applied in a DLD configuration (DLD-THAI process) is validated. However, its economic performance needs to be significantly improved if it is to take its place as a major oil recovery/upgrading technology. So far, the SLD-THAI process has not been field tested, systematically, but could provide a much 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 4 THAI field tests.

The candidate reservoir should meet the following conditions:

- No extensive bottom water (BW); thickness of BW zone less than 30% 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/m3
- Horizontal permeability (K_H) > 200 mD
- K_V/ K_H > 0.25
- Water cut< 70%

The last three conditions (permeability and water cut) 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 is applicable to reservoirs with small gas cap reservoirs; this condition is practically equivalent to a high permeability streak at the top of formation and the performance will be lower.

January 2018
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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