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Analysis of the Novel Toe-To-Heel Air Injection (THAI) Process Using Simple Analytical Models

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Abstract

This paper investigates the discrepancy between numerical simulation results and field-derived correlations to determine the 'best' design method for the In-situ Combustion processes. This becomes especially necessary to facilitate their application to newer novel recovery techniques such as the Toe-To-Heel Air Injection (THAI) process where limited laboratory and simulation studies and no pilot / field data are available. Scale up of the laboratory models to field-wide applications using numerical simulation for In-situ Combustion (ISC) processes has not been well established in the literature. This paper attempts to correlate laboratory 1D combustion tube simulation experiment data to a pilot scale simulation of the THAI process using field tested semi-analytical correlations of Chu (1977), Nelson and McNeil (1961), Gates and Ramey (1980), Satman (1981) and Brigham (1980).

A 50 x 17 x 7 pilot scale model using Wolf Lake heavy oil reservoir data, stoichiometry and reactions was constructed to simulate the THAI process; following which a 1 x 1 x 25 1-D dry combustion tube experiment using similar fluid and injectant properties was constructed to facilitate the application of semi-analytical models to the process. This study has resulted in several observations that help in understanding the validity of production performance computations for the THAI process using a numerical simulator: CMG STARS® and laboratory 1D combustion tube simulation experiment data. The Gates and Ramey semi-analytical model was found inapplicable to the THAI process due the differences in reservoir properties of Wolf Lake compared to South Belridge for which the Gates and Ramey model was developed. The Satman modified model matched the initial production data well, however, significant differences in the predicted production values were observed. The Nelson-McNeil model was found to be the best initial prediction tool for field performance of THAI process; however, combustion tube experimental data requirement could be a limitation for quick application of this model.

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Introduction

This study is an attempt to correlate the simulation results with the simple analytical prediction tools to establish simple and reliable production estimates for the THAI In-situ combustion process. THAI and 1D combustion tube experiment simulations in CMG STARS® were conducted for this study. Subsequently analytical models were used for the performance prediction of the THAI process and were compared with the simulation results in order to test their applicability to the THAI process. Figure 1 shows the schematic of the intended work plan.

This paper includes a brief review of the In-Situ Combustion (ISC) process, its field applications and limitations as well as the Toe-To-Heel Air Injection (THAI) process. Further, the experimental and theoretical developments for the THAI process are summarized. Finally, the numerical simulation experiments for THAI and 1-D combustion tube experiment, and the applications of the analytical models for performance prediction of the simulation experiments are presented.

In-Situ Combustion (ISC) process

The In-Situ Combustion (ISC) process, which is one of the thermal EOR methods for recovery of heavy oil and bitumen, has been operational since early 20th Century and has been an integral part of the U.S. and world thermal EOR program producing nearly 1% of thermal oil in North America.

In Situ Combustion is achieved by burning a small fraction of reservoir oil so as to facilitate flow of the unburned oil fraction. ISC uses air injection for improving oil recovery and due to the strong exothermic reactions associated with the reaction between hydrocarbon (HC) and air; the reservoir matrix is strongly heated. ISC processes are particularly beneficial in heavy oil reservoirs since heating helps reduction in oil viscosity and helps it to flow (Butler, 1998). Also in-situ generation of heat in the reservoir results in high energy efficiencies in terms of heat utilization, high efficiency displacement drive mechanisms, and less total environmental impact (Moore et al., 1997).

Although ISC processes have the features like lower heat losses, heat conservation in the reservoir and in-situ production of steam to aid recovery (wet-combustion process) than its other counterpart – Steam Flood; it has been less successful. Lower successes of the ISC processes can be attributed to the difficulty in controlling the process. Fire-fronts tend to advance much more erratically than steam fronts and hence even reservoir sweep is much harder to achieve.

Renewed interests in the ISC process are seen mainly due to the development of newer and better profile control techniques like Combustion Override Split production Horizontal well (COSH) and Toe-To-Heel (TTH) Injection. These processes differ from the conventional ISC processes in that these newer processes are Short-Distance-

Displacement (SDD) techniques where oil is displaced only tens of feet compared to hundreds of feet for conventional ISC techniques.

Toe-To-Heel Injection

Gas injection into light oil reservoirs is a proven EOR technique, however application of these processes is limited by gas availability and cost. Due to its availability and economics, renewed interests in air injection technologies are seen (Greaves et al., 1999 (a)). In heavy oil reservoirs, where primary objective is the reduction in viscosity of reservoir oil to facilitate its mobility, air injection has been widely used for heat generation via In-Situ Combustion (ISC) process. Some of the recent 'successful' air injection projects include: West Hackberry field, LA, Medicine Pole Hills Unit, ND, Buffalo, SD, Horse Creek field, ND and H field, Indonesia (Greaves et al., 1999 (a)). Statistics of the North American ISC projects are presented in Table 1.

In spite of the inherent benefits of the ISC processes, limited controls on flood fronts and poor reservoir sweep efficiencies have resulted in limited success of the ISC process. In conventional horizontal floods, gravity segregation between the hot combustion gases and cold reservoir oil further reduces the reservoir sweep efficiencies to undesirably low levels. The typical ISC flood sweep efficiencies are ~ 30% (Greaves and Turta, 1997). Hence, *gravity-stabilization* of the ISC process is necessary.

The Toe-To-Heel Air Injection (THAI) is a new-patented process, which remedies the problems associated with conventional ISC processes by stabilizing the fire-flood-front. The main objective of Toe-To-Heel (TTH) type injection(s) are to prevent gravity segregation of the injected / displaced fluids in-situ and provide a more-or-less upright displacement front that eventually results in higher reservoir sweeps. This process was developed from the gravity stable ISC process as defined by Ostapovich and Pebdani (1993).

Ostapovich and Pebdani (1993) experimentally demonstrated that completing a vertical air injection well (transverse to the combustion front) relatively high in the reservoir and a horizontal production well relatively low in the reservoir results in downward progression of the combustion front due to the low-pressure sink provided by the production well. This arrangement results in gravity drainage of the heated reservoir oil, enhances the reservoir sweep, and enables heated oil to reach the production well.

However, in the Ostapovich and Pebdani (1993) process, premature breakthrough of the combustion front at a locus along the length of the transverse and horizontal leg results in an unswept reservoir zone between the toe and breakthrough locus (Greaves and Turta, 1997). The THAI process resulted from attempts to remove the limitation of the Ostapovich and Pebdani (1993) process. THAI process shows higher reservoir sweeps and better fire-flood-profile controls. The THAI is an integrated horizontal wells process, and operates via SDD as shown in Figure 2.

In the THAI process (Figure 3), a horizontal production well is located in the lower portion of a heavy viscous oil-bearing reservoir. A vertical injection well is located in the upper portion of the reservoir. Oxygen-enriched gas is injected down the injector well and ignited in the upper portion of the reservoir to create a combustion zone that reduces viscosity of oil in the reservoir as the combustion zone advances downwardly toward the horizontal production well, the reduced-viscosity oil draining into the horizontal production well under force of gravity.

Potential benefits of the THAI process include: Gas override elimination leading to lower producer gas coning problems, greater combustion front tracking and control capability, facilitation of gravity drainage of fluids to horizontal producer, reduced sensitivity to reservoir heterogeneity, and higher fluid injectivity (Greaves et al., 1999 (a) & (b), Greaves and Turta, 1997).

Recent Developments in THAI

Due to its SDD feature, THAI can be categorized in other newer heavy oil recovery methods like SAGD and VAPEX. In the THAI process, the mobilized heavy oil, in the Mobile Oil Zone (MOZ) ahead of the combustion front (Figure 3), drains into the open section of the horizontal producer a short-distance. The authors suggest that the 'striking' feature of the THAI process is the planar-vertical combustion zone (Figure 4), and the near complete elimination of the gravity over-ride results in an efficiency that is two-four times higher than steam in energy costs and lower emission loading (Greaves et al., 1999(a)).

Migration of injected air to the combustion zone occurs via the oxygen diffusion potential established under steady state conditions (Greaves et al., 1999(b)). The balance between stoichiometric oxygen flux required to burn the fuel (coke) ahead of the front and removal of combustion products and mobilized fluids is the key requirement for stability and growth of the THAI flood front (Greaves et al., 1999(a)), and is achieved due to the removal (production) of combustion products and mobilized fluids by the exposed section of the horizontal producer. Hence, Greaves et al., 1999(a) argue that THAI is a gravity stable process and is controlled by the pressure gradient established between draining reservoir section and inflow to the horizontal well.

Experimental investigations using various API gravity oils by Greaves et al., 1999(b), show that the creation of the 'narrow mobile oil zone' (Figure 3) is essential for sustained flood front, along with the cold heavy and viscous oil downstream of the front acting as a natural seal along the horizontal well and preventing bypass of gases. THAI process maintains steady state conditions both upstream and downstream of the mobile oil zone, resulting in significant reduction of the sensitivity of the process to reservoir heterogeneities (Greaves et al., 1999(a)).

Greaves et al., 1999(b) conducted 3-D semi-scaled combustion cell air injection experiments using light ("Forties Mix" (30.7 API)), medium (Clair (20.8 API) and heavy (Wolf Lake 10.95 API) crude oils. It was observed that a well-controlled, narrow mobile oil zone is created just ahead of combustion front, whose width depended on in-situ heavy oil characteristics and the extent of horizontal well sealing (due to cold reservoir oil) obtained. It was also suggested that the novel 'sleeve-back' technique, which allows perforated downstream sections of the horizontal well be shut in, could be used in light oil tests to mimic the THAI process. Experimental results showed very high oil recoveries (~ 85% OOIP) and upgrading of the heavy Wolf Lake crude to 20 API was observed along with significant viscosity reduction.

Xia and Greaves (2000) conducted 3-D physical model experiments on virgin Athabasca tar sand bitumen to investigate dry as well as wet combustion performance, and latter compared the results with a steam flood test, which was followed by air injection. Excellent ignition and stable combustion front characteristics were observed with > 80% OOIP oil recovery. THAI process yielded an oil upgrade of ~ 8 API degrees over the original along with over four orders of magnitude decrease in oil viscosity. Significant decrease in sulfur, N_2 and heavy metal contents were observed in the produced oil compared to original bitumen.

SARA analysis of the produced oil from the Athabasca bitumen showed lower fractions of asphaltenes, resins and aromatics with significant increase in the oil saturates fraction from 14.5% to 70%. This clearly demonstrates that asphaltenes are the main source of 'fuel' for the ISC-THAI process (Xia and Greaves (2001)).

Xia et al. (2002) conducted a series of 3-D combustion cell THAI/CAPRI experiments using Lloyd-Minster heavy crude (11.9 API). Excellent recoveries (> 79% OOIP) along with stable fire-front stabilities with sustained high temperature combustions (500 – 550 ^{o}C) were observed. Thermal upgrading of the crude, due to cracking was observed with an incremental conversion gain of up to 6.4 API points was achieved.

Simulation Approach to Forecast Combustion Performance

Original dataset of the THAI CMG STARS$^{®}$ simulation was obtained from CMG office in Houston, TX (Brugman, 2003). The CMG model was 50 x 17 x 7 Cartesian grid fitted on a 1000' x 340' x 70' reservoir pilot with 30% porosity, 66% initial oil saturation, 5000 mD I / J permeability with a K_V/K_H ratio of 0.1 and the fluid model being that of Wolf Lake reservoir. A 990-ft horizontal well was drilled at the base of the pilot and an injector was completed higher to facilitate toe-to-heel type injection. Figure 5 shows well placement for the numerical model.

Pilot Simulation

The CMG model obtained used enriched air (50% O_2 + 50% N_2) as the injection fluid. Simulation runs with the existing model as well as with varying air compositions (e.g. Normal Air: 79% N_2 + 21% O_2 and Flue Gas (OCRC, 2003): 6% H_2O + 13% CO_2 + 77.5% CO/N_2 + 3.5% O_2) were completed to study the effects of gas compositions and study the possibilities of CO_2 sequestration.

Enriched Air Injection

Figures 6, 7 and 8 summarize the results of the enriched air (50% O_2 + 50% N_2) injectant THAI simulation. The linear increase in cumulative air / water injection (Figure 7) and corresponding increase of the average reservoir temperature (Figure 7) and reservoir enthalpy (Figure 7) shows good air injectivity and sustained combustion front for THAI process. The water injection is mainly used as a heat scavenger to recover heat from the burned out regions of the reservoir and does not significantly affect the displacement process as seen from the decreasing oil steam ratio at increased air injection(s) (Figure 6).

Figure 8 summarizes the production profiles during the enriched air injection THAI. Nearly 58% (533.2 MBbl) of the original oil in place (OOIP) is recovered until gas breakthrough and the ultimate recovery is significantly high (74% OOIP (683.1 MBbl)). Excellent reservoir volumetric sweeps, and near vertical displacement front is observed during THAI displacement (Figure 9).

Normal Air and Flue Gas Injection

Excellent reservoir volumetric sweeps, and near vertical displacement front is also observed for the normal air and flue gas THAI injections, however lower available oxygen concentrations (21% and 3.5% respectively) result in comparatively lower fireflood front temperatures (Figure 10). The lower flood temperatures result in consistently lower incremental oil productions for normal air and flue gas THAI injections, respectively (Figure 11).

1D Combustion Tube Simulation

For the application of the simple analytical models to the THAI process require experimental combustion tube data to calculate the fuel lay-down and air requirements. A 1 x 1 x 25 1-D dry combustion tube simulation experiment, with only enriched air as injectant, was run to generate the required data to facilitate application of simple analytical models to predict the performance of the pilot THAI simulation. Wolf Lake reservoir fluid properties were used in the 1D simulation experiment to ensure consistency of comparison.

Figure 12 shows the oil, water-oil ratio (WOR) and production gas-oil ratio (GOR) for the 1D combustion tube experiment run. Figure 13 summarizes the individual gas component productions and Figure 14 shows the combustion frontal movement from the injector to producer. The temperature (consequently fireflood movement as shown in Figure 14) distributions for the combustion tube experiment for various times are shown in Figure 15.

Application of Simple Analytical Models to THAI Process

Field-tested semi-analytical correlations are another popular method for engineering of an In-situ Combustion (ISC) projects. Correlations like those of Chu (1977), Nelson and McNeil (1961), Gates and Ramey (1980), Satman (1981) and Brigham (1980) are in use since decades and form the basis of modern numerical simulators. This study uses these correlations to compare the CMG STARS® predicted THAI process performance.

It is important to note that all of the correlations used for the engineering designs of the In-situ Combustion processes are developed and based only on dry combustion. This assumption is justified since the water injected (in low quantities) has no effect on the displacement process and merely acts as a heat scavenger mechanism as shown earlier.

Satman and Brigham Correlation

Satman and Brigham (Satman et al., 1979) presented two correlations to predict the field wide oil recovery in ISC projects by correlating injection-production history from 12 dry combustion projects. The analytical model developed was verified using laboratory combustion tube data then applied to field data for the development of the correlation to predict field scale recovery.

The authors caution that the correlation may not be valid if any of the parameters of the reservoir in question are outside the range of data used to develop it. The suggested ranges of oil saturation, oil viscosity and reservoir thickness are: $0.36 < S_O < 0.79$; 10 cP $< \mu_O < 700$ cP and 4.4 ft $< h < 150$ ft respectively. The parameters used in the THAI simulation are: $S_O = 0.66$, $\mu_O = 1370$ cP, $h = 60$ ft, i.e. the oil viscosity is far outside the recommended range.

Satman et al. (1984) tried to expand the range of the equation by increasing the upper limit on oil viscosity; however, the upper limit is not clearly specified. The modified Satman correlation (Sarathi, 1999) was employed to predict oil recovery in the THAI process along with the ‘traditional’ Satman and Brigham approach to predict oil recovery for the THAI process.

Figure 16 shows the CMG STARS® simulation results for the THAI process. The Satman and Brigham approach was used to predict the oil recovery using the THAI parameters, and the results are shown in Figure 17. It is clearly seen that Satman and Brigham model predicts initial oil production quite well; however significant deviations from the actual production profile are seen in later stages of the project life. This deviation is mainly attributable to the inability of the Satman and Brigham model to handle high reservoir oil viscosities ($\mu_O > 700$ cP) as well as the inability to include the displacement mechanism (gravity drainage in the mobilized oil zone) in the model for the prediction of oil recovery.

Gates and Ramey Correlation

Gates and Ramey (1980) presented an engineering method for calculating air-oil ratios and oil recovery as a function of volume of reservoir burned, based on laboratory data as well as pilot and field data from Mobil's South Belridge, California, project. The authors caution that the reliability of the method is limited to reservoirs with characteristics similar to South Belridge, i.e. heavy oil (13 API), high permeability (3000 mD), high porosity (0.34%) and high oil content (1700 Bbl/Ac-ft). The parameters used in the THAI simulation are: significantly higher oil content (1970 Bbl/Ac-ft), lower porosity (0.30), significantly higher permeability (5000 mD) and lower gravity oil (10.95 API).

Preliminary calculations according to the Gates and Ramey model show that the reservoir fuel content is 379.08 Bbl/Ac-ft and the atomic Hydrogen to Carbon (H/C) ratio is 3.18. Both of these values are significantly higher than those for the South Belridge, California reservoir of 280 Bbl/Ac-ft and 1.6 respectively. The Gates and Ramey model predicted producing water-cut for the THAI process to be 48.55%, which is significantly higher than the actual producing THAI water-cut of 31.50%. The Gates and Ramey model predicts higher water-cut values mainly due to the low H/C ratio and higher connate water saturations in the South Belridge field for which this model was developed.

Non-agreement of the preliminary calculations led to the investigation of the applicability of the model to the Wolf Lake reservoir THAI model. It was found that the wide differences in the reservoir characteristics between those of South Belridge and Wolf Lake (used for THAI simulation) as illustrated below make the application of the Gates and Ramey model unsuitable for the present modeling. The major differences between the South Belridge (SB) and Wolf Lake (WL) reservoir are:

1. Significantly lower H/C ratios in SB compared to WL.
2. Lower connate water saturations (0.34 WL) compared to SB (0.37).
3. WL reservoir has higher initial oil saturations (0.66) compared to SB (0.60).
4. Vastly differing fuel densities (343 lbm/Bbl for SB compared to 609.93 lbm/Bbl for WL reservoir).
5. Orders of magnitude difference in the air requirements for WL – THAI process compared to SB fireflood.

Furthermore, the inability of the Gates and Ramey model to directly address the influence of many reservoir specific parameters (Ambastha and Kumar, 1999) such as: reservoir permeability, heterogeneity, dip, oil viscosity, relative permeability effects, oil distillation effects (as modeled by equilibrium K values), and multiple chemical reaction modeling result in limited applicability of this model to novel processes such as THAI.

Nelson McNeil Method

Nelson and McNeil (1961) presented an engineering procedure to evaluate the performance of dry In-situ Combustion (ISC) project. Sarathi (1999) suggests that although the Nelson-McNeil method has a large number of assumptions, the method was based on considerable field experience and hence may give reasonable estimates.

Fuel Deposit Estimate

The fuel deposit is the most important parameter for the ISC processes, since extent of fuel deposit dictates the sustainability of the fireflood front. The regression correlations of Chu (1977), along with Alexander and Showalter fuel deposit estimate plots (Sarathi, 1999) were used to estimate and compare the fuel deposit estimated by the combustion tube simulation experiment. Table 2 summarizes the results.

The absolute minimum fuel content required to sustain any given combustion front is estimated to be 1.05 lbm/ft^3 (Sarathi, 1999). Table 2 shows excellent agreement of values between the combustion tube simulation experiment, Alexander and Showalter.

Nelson-McNeil Procedure

Application of the Nelson McNeil procedure requires the combustion tube experiment data. The data generated from the combustion tube simulation experiment was employed to predict the performance of the THAI pilot simulation. The standard Nelson McNeil procedure is available elsewhere (Sarathi, 1999). The results are included as Table 3 with corresponding parameters shown in similar colors and italics.

Excellent agreements between the Nelson McNeil procedure for total air injection requirement, air injection rate required, fuel consumed and predicted total oil recovery are observed. Slight deviations in the total water productions are observed. This is acceptable since the Nelson McNeil procedure is adapted for dry combustion, and in the THAI simulation low quantities of water (50 Bbl/D) were injected as heat scavengers resulting in this difference. Hence the Nelson McNeil model is more robust and versatile in comparison with the other analytical correlations examined. The gas injection schedule for the THAI process as predicted by the Nelson McNeil procedure is shown as Figure 18.

Although the Nelson McNeil procedure was adapted to the conventional 5-spot pattern, good agreements in the oil recoveries were observed. Sensitivity analysis of the injection air rates showed that the frontal advancement rates in the THAI process are significantly low (6.86E-6 ft/D). The lower lateral frontal advancement helps address the observed very high reservoir sweeps and near perfect vertical sweeps. Furthermore, gravity drainage to the horizontal well from the mobilized oil zone (MOZ) being the dominant recovery mechanism in THAI, the lower frontal advancement rates help facilitate better gravity drainage.

Conclusions

1. The novel THAI process has been successfully modeled using CMG STARS® simulator.
2. Use of enriched air helps sustain higher frontal temperatures, consequently higher oil recoveries.
3. Excellent agreements between the simulated combustion tube experiments and pilot THAI simulations are observed.
4. Reliable fuel deposit estimates for ISC processes can be obtained using Alexander and Showalter plots in absence of experimental combustion tube data.
5. Satman and Brigham method is only applicable for the evaluation of process performance early on in the process.
6. Gates and Ramey semi-analytical procedure is applicable to only those reservoirs, which are similar to Mobil's South Belridge project. The important reservoir parameters that need to have synonymous values are reservoir fuel content, fuel densities and the atomic Hydrogen-to-Carbon (H/C) ratios.
7. The Nelson McNeil procedure was highly successful in the performance prediction of the novel THAI process, although it is the oldest of all the correlations considered.
8. Nelson McNeil procedure may be used to quickly compute expected production performance for an ISC project with characteristics similar to those of Wolf Lake.
9. Applications of these correlations have provided valuable insights into the actual recovery mechanism of improved recovery in THAI due to enhanced gravity drainage from the mobilized oil zone, and improved volumetric sweeps by intelligent well placement.

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Tables and Figures

Table 1: ISC Projects in North America (Moritis, 1992 – 2002, Sarathi, 1999)

Project	**Operator**	**Initiation Date**	**Type**	**Oil °API**	**Injectors**	**Producers**	**Production BBL/D**
UNITED STATES							
Bellevue, LA	Bayou St.	1970	Wet	19	15	85	400
Midway Sunset, CA	Texaco	1982	Dry	11.5	10	47	1,000
Medicine Pole Hill, ND	Continental	1985	Dry	39	7	17	725
Buffalo, SD	Continental	1979	Dry	30	12	21	550
W. Buffalo, SD	Continental	1987	Dry	30	6	15	365
S. Buffalo, SD	Continental	1983	Dry	30	19	40	1,420
W. Hackberry, LA	Amoco	1995	Dry	33	N/A	N/A	280
Mt. Poso, CA	AERA	1997	Dry	N/A	N/A	N/A	N/A
Horse Creek Field, ND	Total	1996	Dry	32.2	3	11	400
CANADA							
Battrum, Saskatchewan	Mobil	1966	Wet	18	15	94	3,700
Battrum, Saskatchewan	Mobil	1967	Wet	18	7	35	1,200
Battrum, Saskatchewan	Mobil	1965	Wet	18	3	22	1,350
Wabaska, W. Alberta	Amoco	1994	Dry	14	1	2	260

Table 2: Fuel Deposit Estimates

Correlation	**Fuel Deposit (lbm/ft^3)**
Absolute minimum fuel content	1.05 lbm/ft^3
Chu	1.30 lbm/ft^3
Alexander	**2.60 lbm/ft^3**
Showalter	**2.17 lbm/ft^3**
Combustion Tube Experiment	**2.43 lbm/ft^3**

Table 3: Nelson-McNeil Procedure Results

Parameter	**Value**
Combustion Tube Simulation Experiment	
CO gas produced	0.1478 ft^3
CO_2 gas produced	2.40785 ft^3
Total gas production	10.9137 ft^3
Total air injection requirement	*11.0358* ft^3
Nelson-McNeil Method	
Carbon in fuel burned (W_C)	0.080918 lbm
Water due to combustion (W_W)	0.0856591 lbm
Hydrogen in fuel burnt (W_H)	0.0320437 lbm
Total fuel consumed (W_F)	0.112962 lbm
Volume of sand burned (V_B)	0.0679913 ft^3
Fuel consumed (W)	1.6614 lbm/ft^3
Total air injection requirement	*11.035779* ft^3
Air injection per fuel consumed	97.6937 ft^3/lbm
Air injected per sand burned	162.3099 SCF/ft^3
Average effective air permeability	11.94 mD
THAI air requirement (calculated)	4.4E+12 MMCF/Ac-ft
Total air requirement (calculated)	7088000 MMCF
Air injection rate (calculated)	529764.1683 SCF/D
Total oil recovery (calculated)	602616.994 Bbl
Total water recovery (calculated)	220434.7 Bbl
% Error in oil recovery calculation	**5.76%**
% Error in water calculation	**41.76%**
Toe-To-Heel Air Injection (THAI) Process Simulation	
Air injection requirements	5.2E+12 MMCF/Ac-ft
Total air requirement (simulation)	8370016 MMCF
Air injection rate (simulation)	529764 SCF/D
Total oil recovery (simulation)	683144 Bbl
Total water recovery (simulation)	527768 Bbl

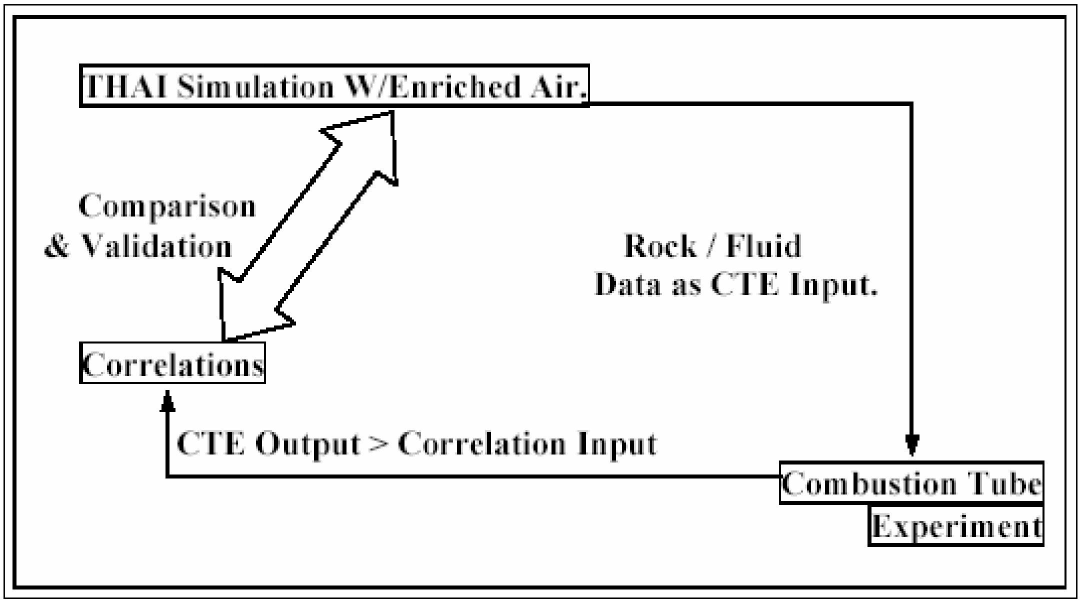


Figure 1: Schematic of the work-plan for this work.

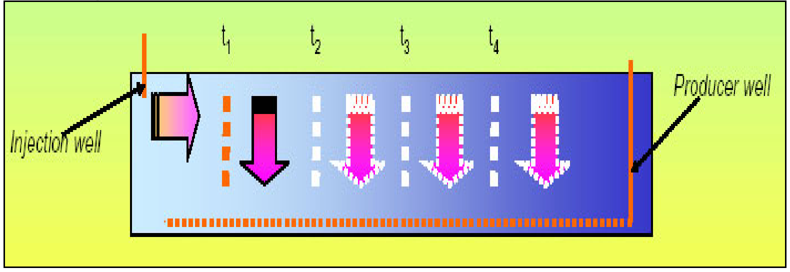
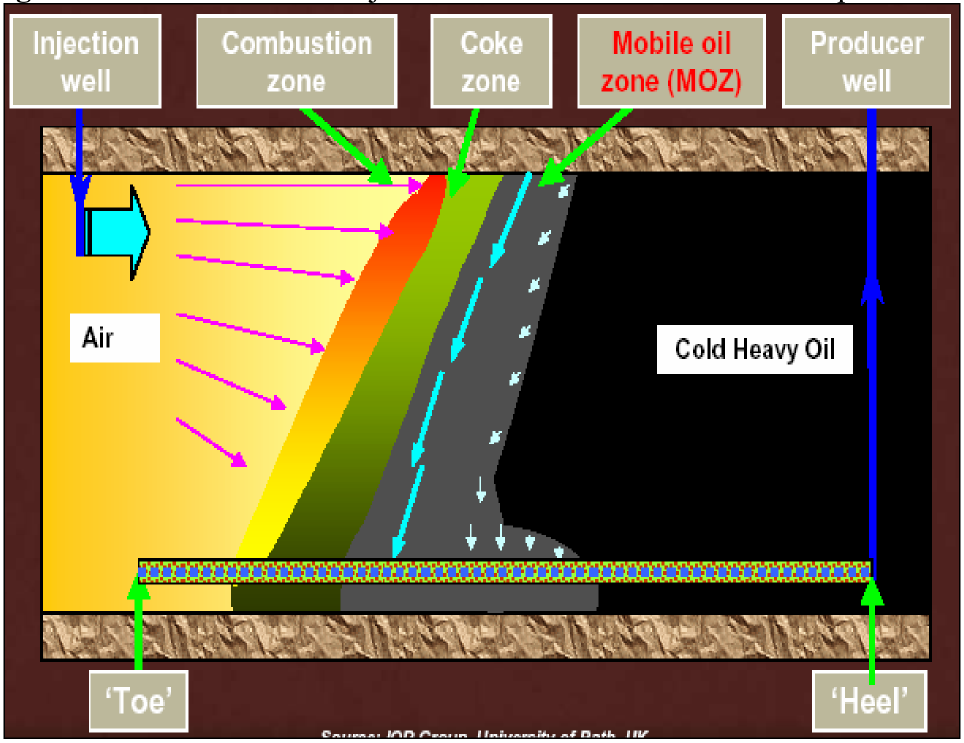


Figure 2: Toe-To-Heel Air Injection Process – Short Distance Displacement.



Source: IOR Group, University of Bath, UK

Figure 3: Toe-To-Heel Air Injection Process Schematic.

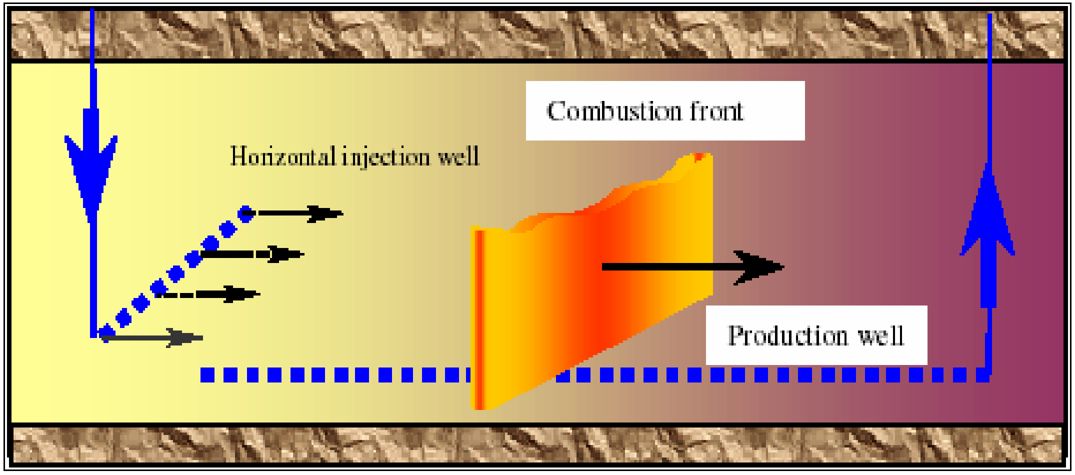


Figure 4: Planar-Vertical Combustion Front in THAI Process (Schematic).

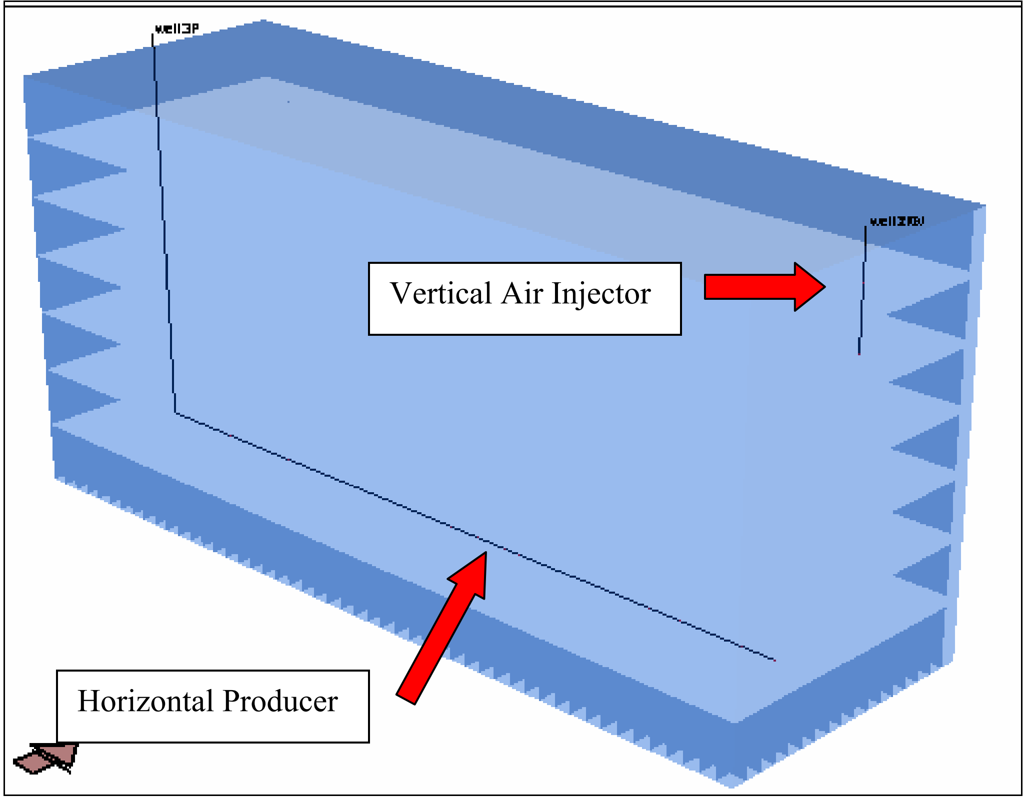


Figure 5: Well placement for THAI simulation model.

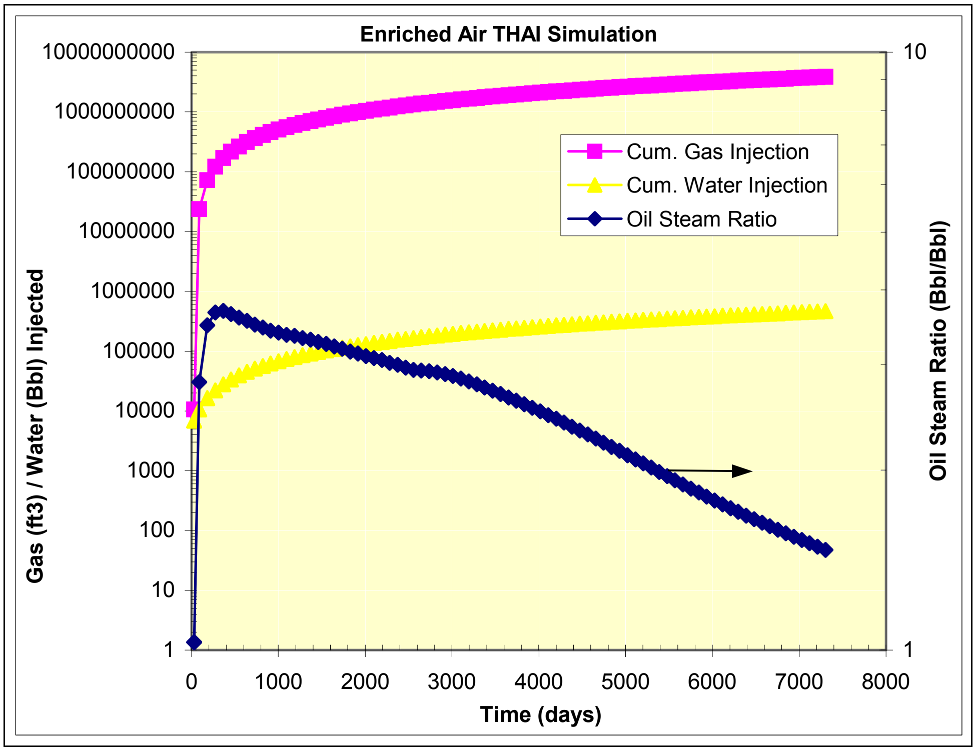


Figure 6: Cumulative oil-steam-ratio, cumulative gas injected, and cumulative Water injected for enriched gas THAI.

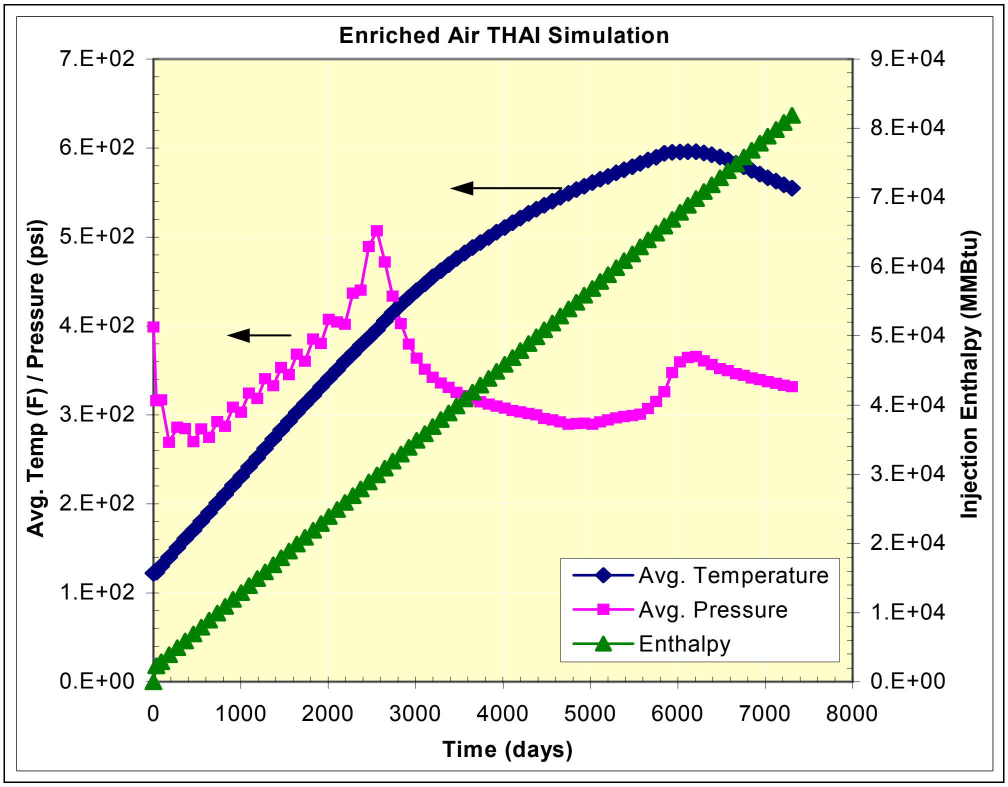


Figure 7: Average temperature, average pressure and injected enthalpy for Enriched gas THAI.

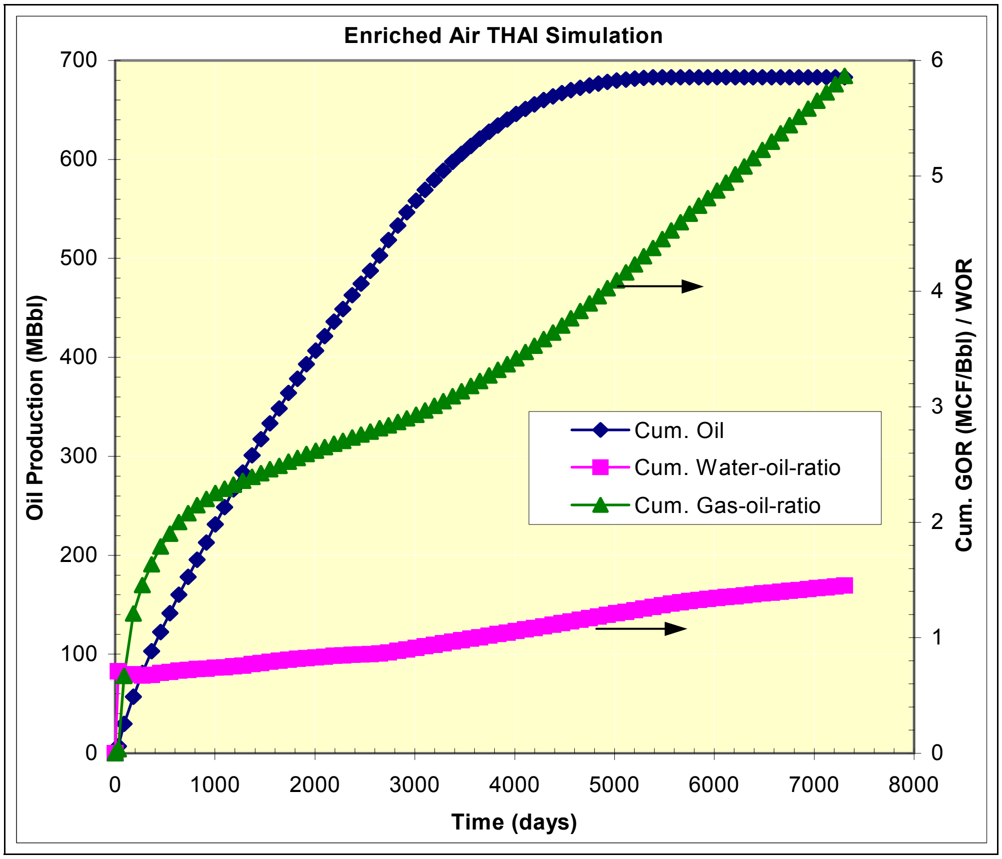


Figure 8: Cumulative oil production, cumulative water-oil-ratio, and cumulative gas-oil-ratio for enriched gas THAI.

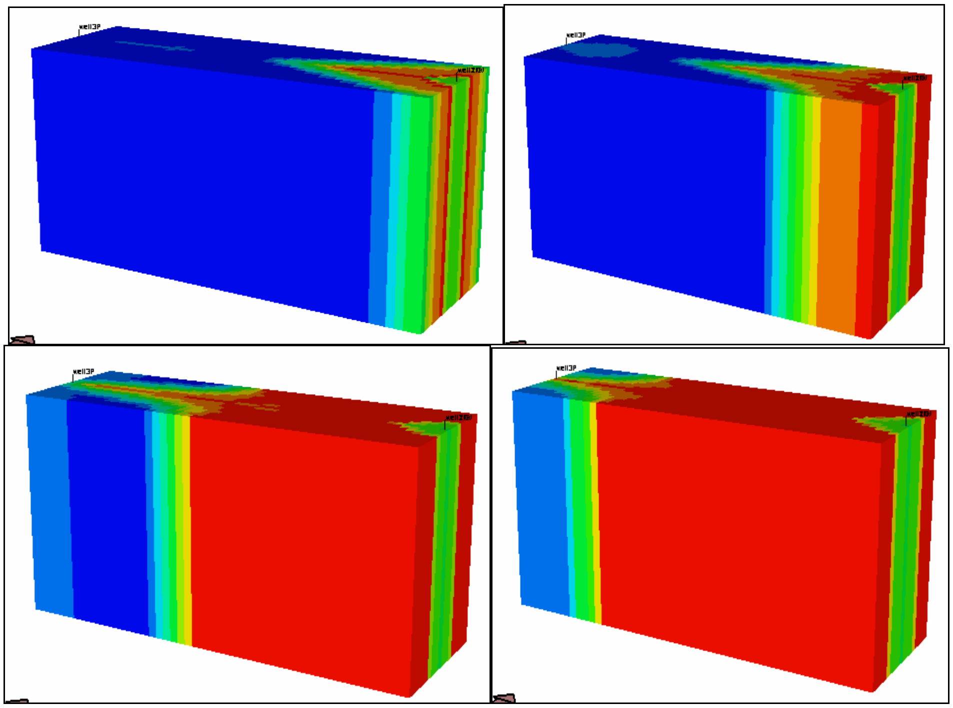


Figure 9: Near-vertical displacement fireflood front and temperature distribution for enriched gas THAI.

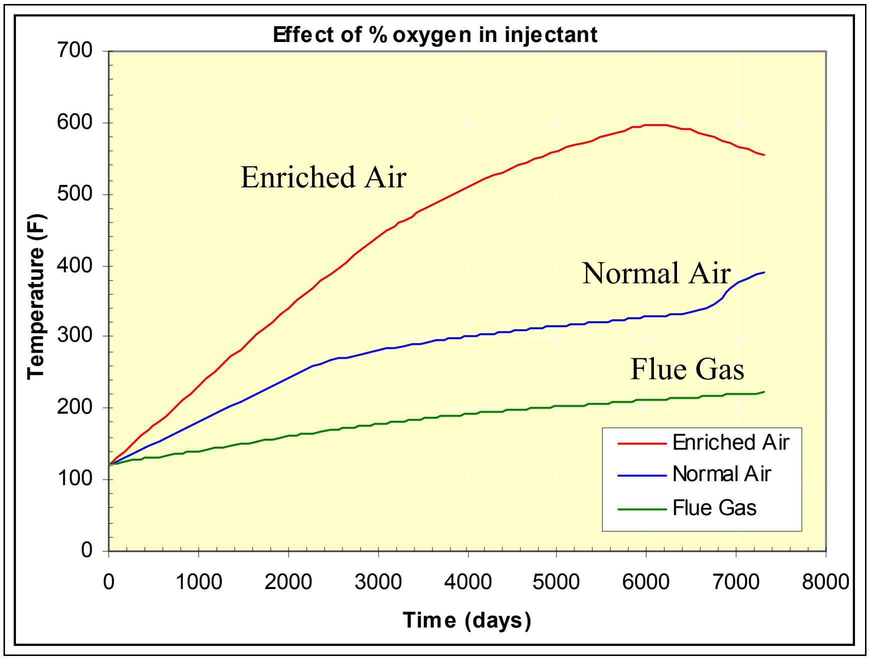


Figure 10: Effect of oxygen concentration on temperature.

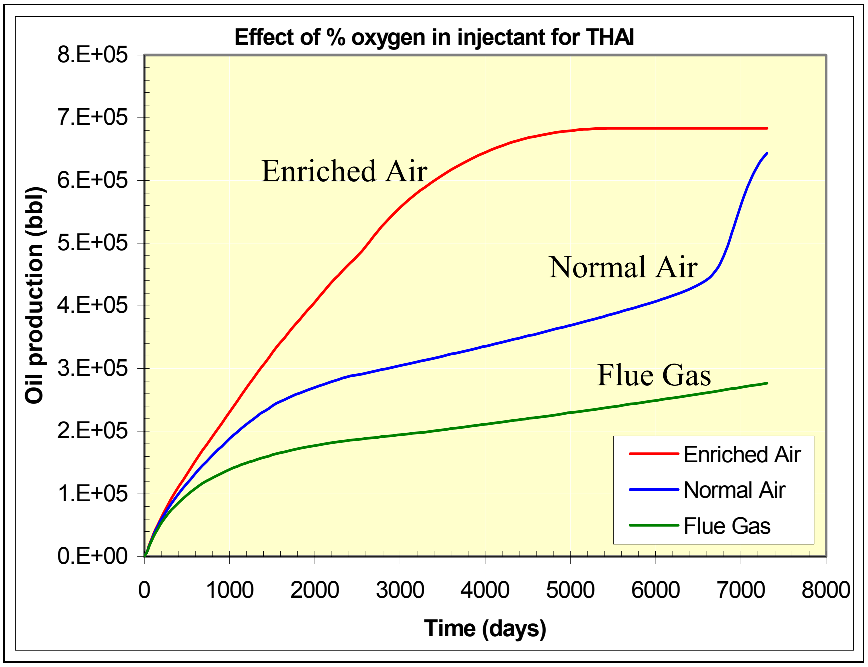


Figure 11: Effect of oxygen concentration on oil production.

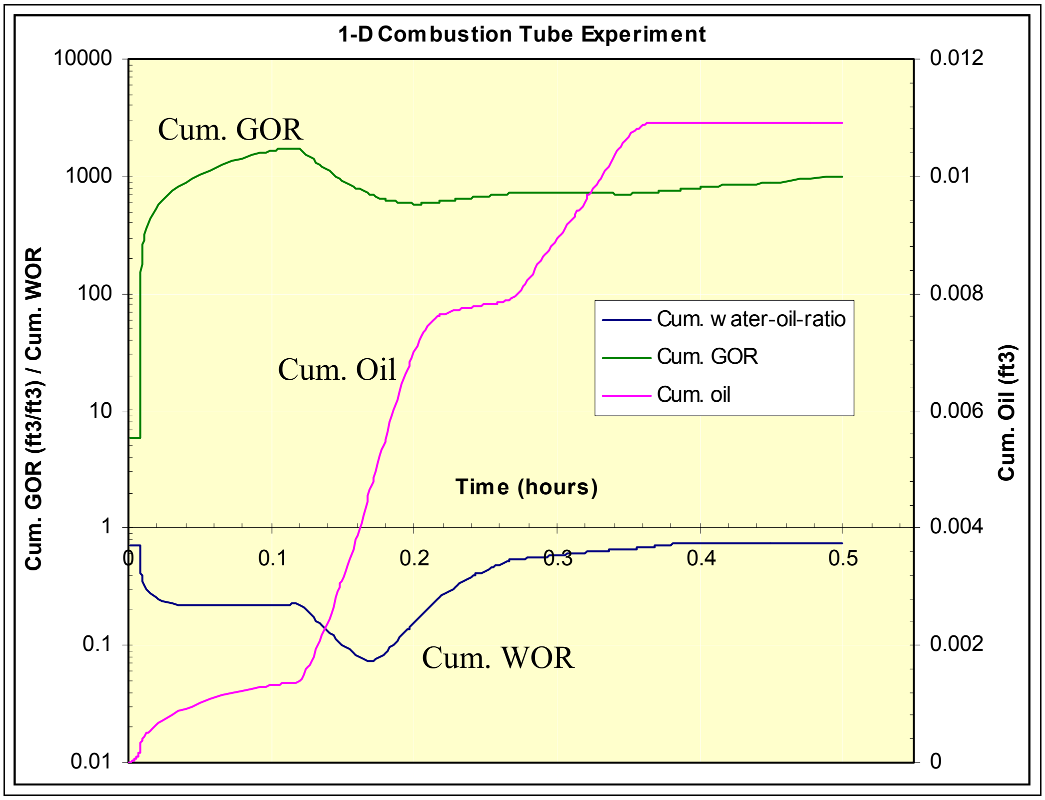


Figure 12: Cum. water-oil-ratio, gas-oil-ratio and oil production for 1-D Combustion Tube Experiment.

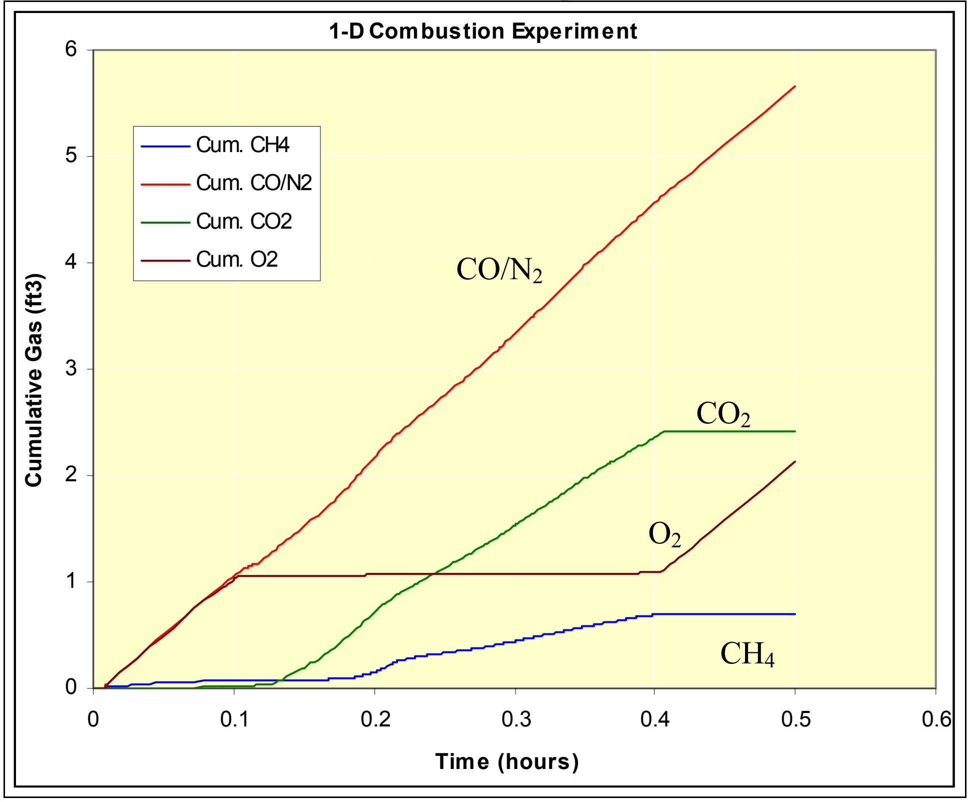


Figure 13: Individual gas component production for 1-D combustion tube experiment.

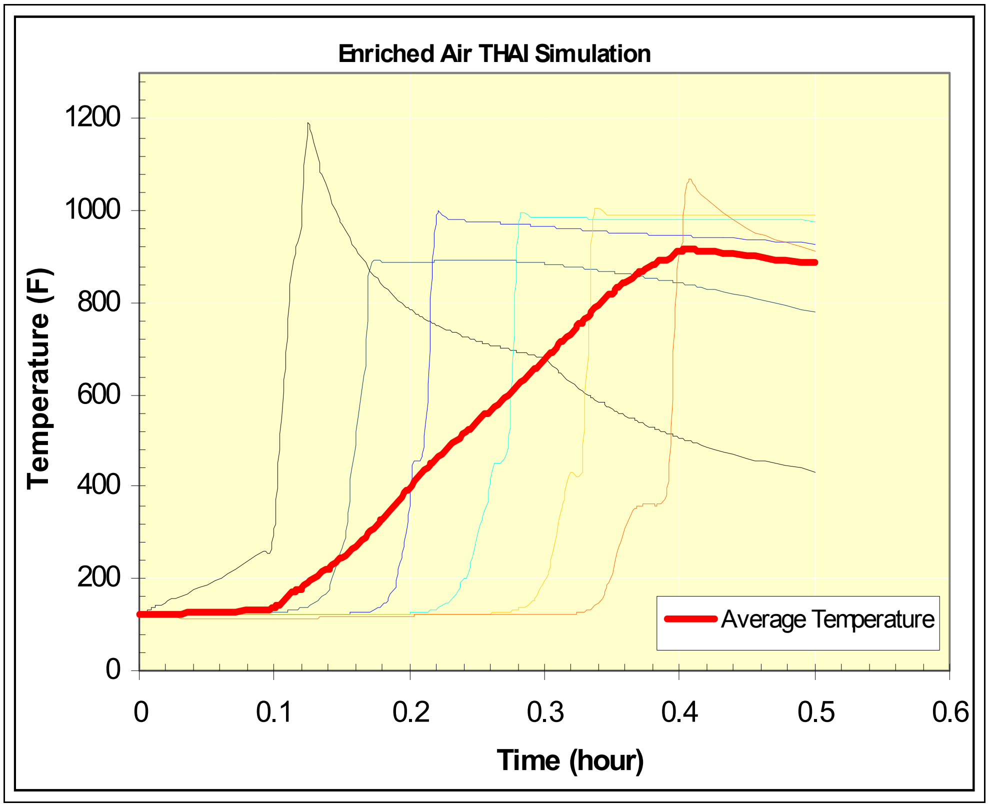


Figure 14: Movement of fireflood front (for varying times – depicted by thin lines) and average temperature distribution (thick line) for the combustion tube experiment (CTE).

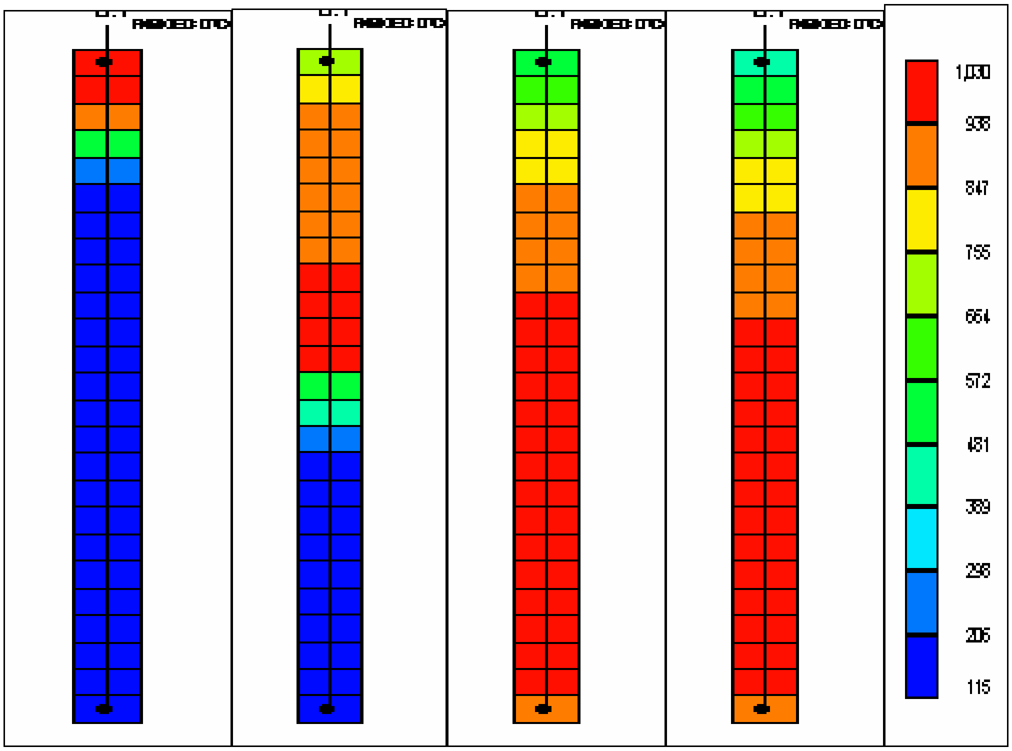


Figure 15: Temperature distributions for 1-D combustion tube experiment (Last column depicts the legend for color versus temperature)

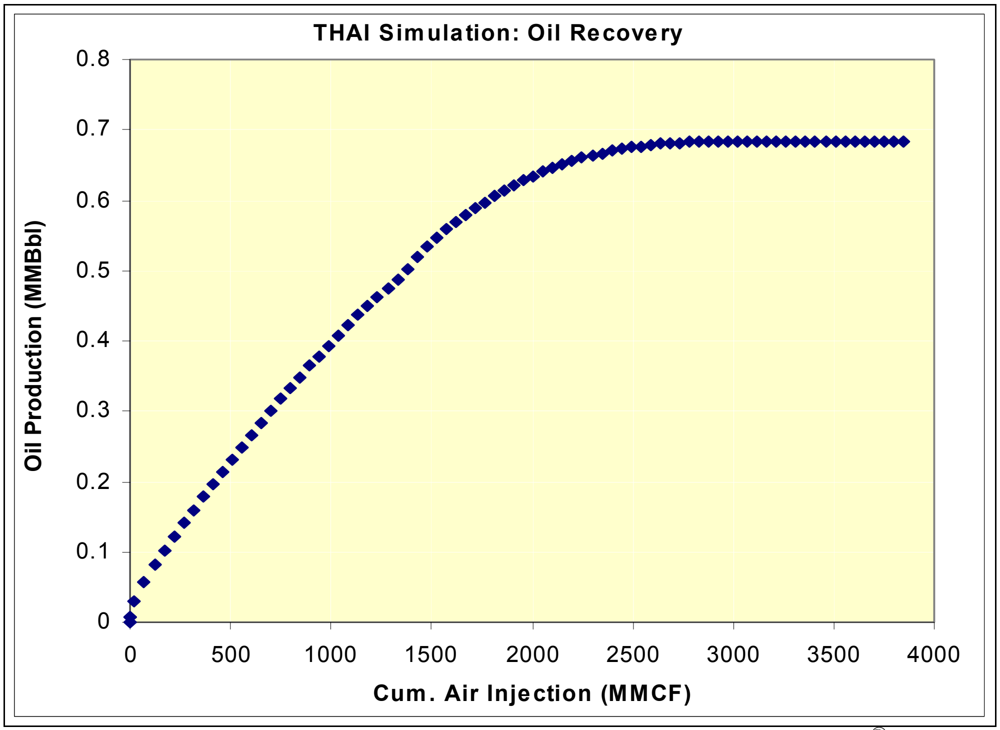


Figure 16: Oil recovery vs. cumulative air injection for THAI (STARS® simulation)

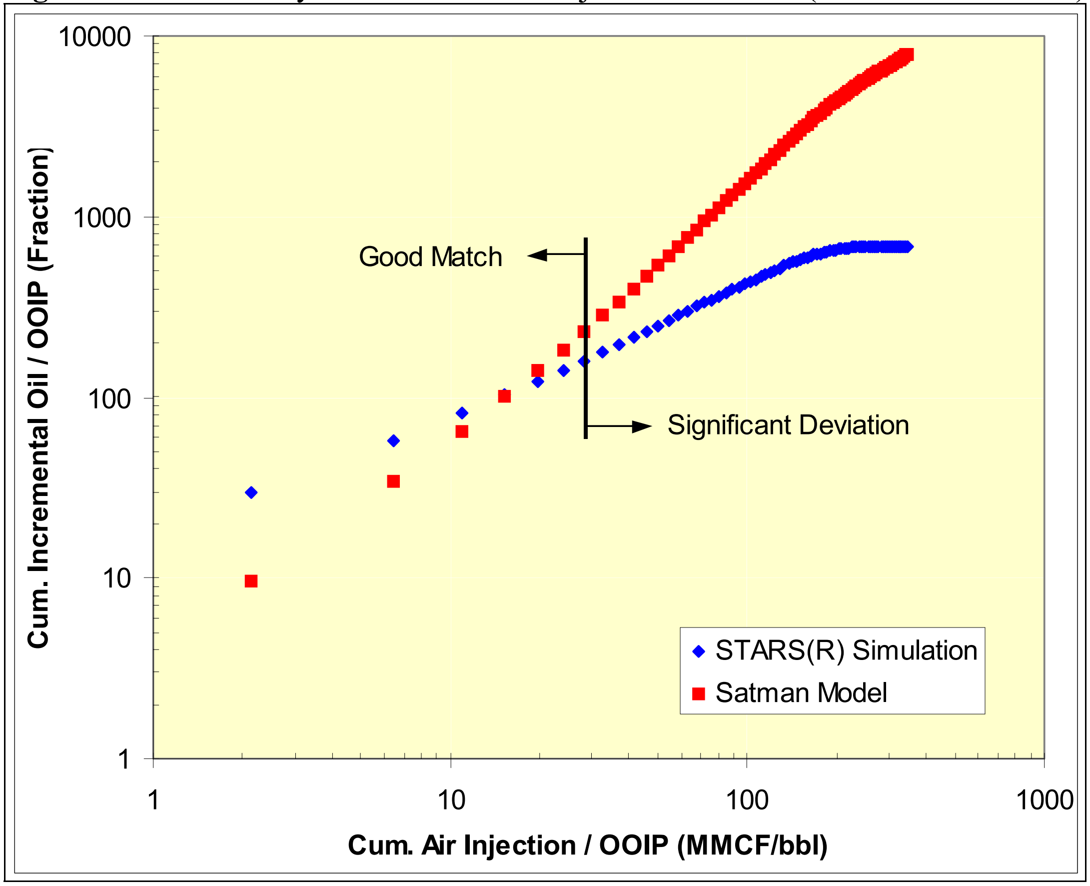


Figure 17: Predicted vs. actual (simulation) recovery for Satman Model.

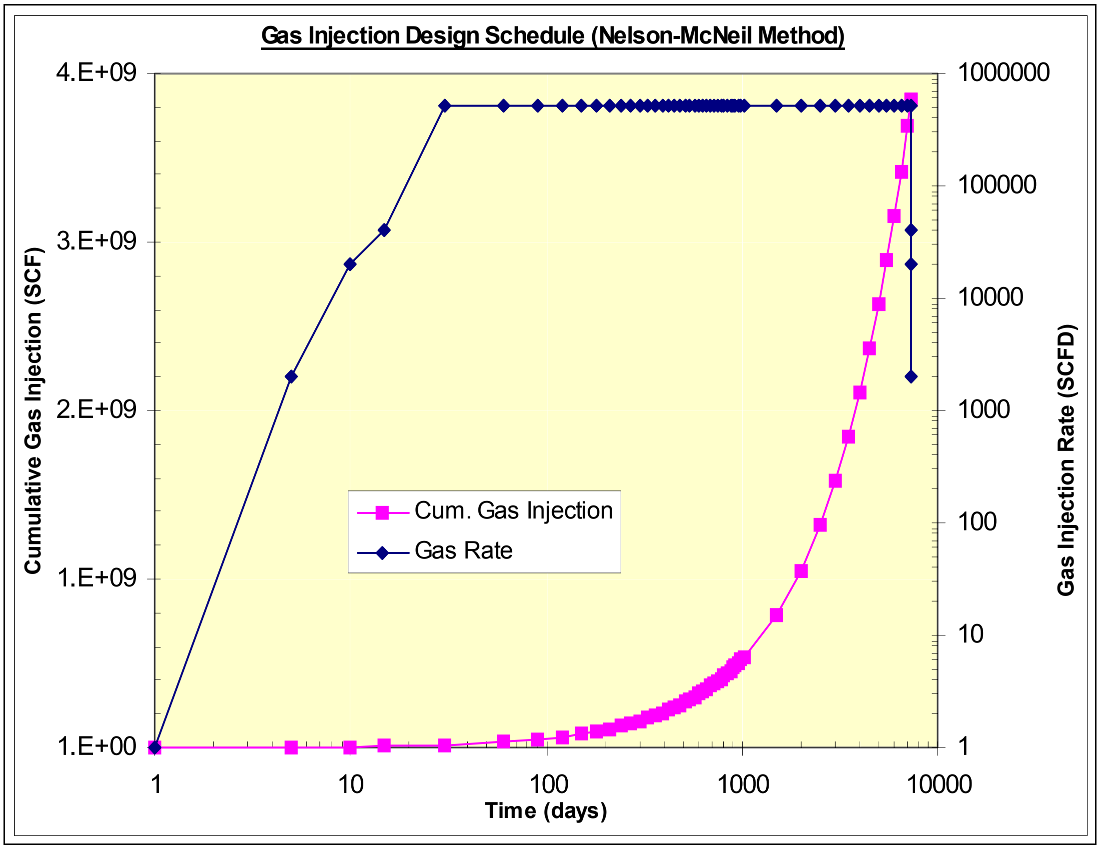


Figure 18: THAI Gas Injection Schedule For Nelson-McNeil.