ERA Public Facing Report
ESEIEH Progress Update

Reporting Period: February 2011 to August 2017

Project Title:	Effective Solvent Extraction Incorporating Electromagnetic Heating (ESEIEH™)
ERA Project ID:	F101150
Project Leader:	Mark Bohm
Lead Institution:	Suncor Energy Inc.
Project Partners:	Harris Corporation, Nexen Energy ULC, Devon Canada

A. Overall Project Objectives

Introduction

The Effective Solvent Extraction Incorporating Electromagnetic Heating™ (ESEIEH™) process is envisioned as a potential long-term replacement to the Steam Assisted Gravity Drainage (SAGD) process. It offers the potential for significant GHG reductions and cost efficiencies as shown in Figure 1 while offering to dramatically increase Alberta's economically recoverable bitumen reserves. The ESEIEH™ project is a collaboration of four industry petroleum and technology leaders: Devon Canada, Nexen Energy ULC, Suncor Energy Inc., Harris Corporation, with funding provided in part by Emissions Reduction Alberta (ERA).

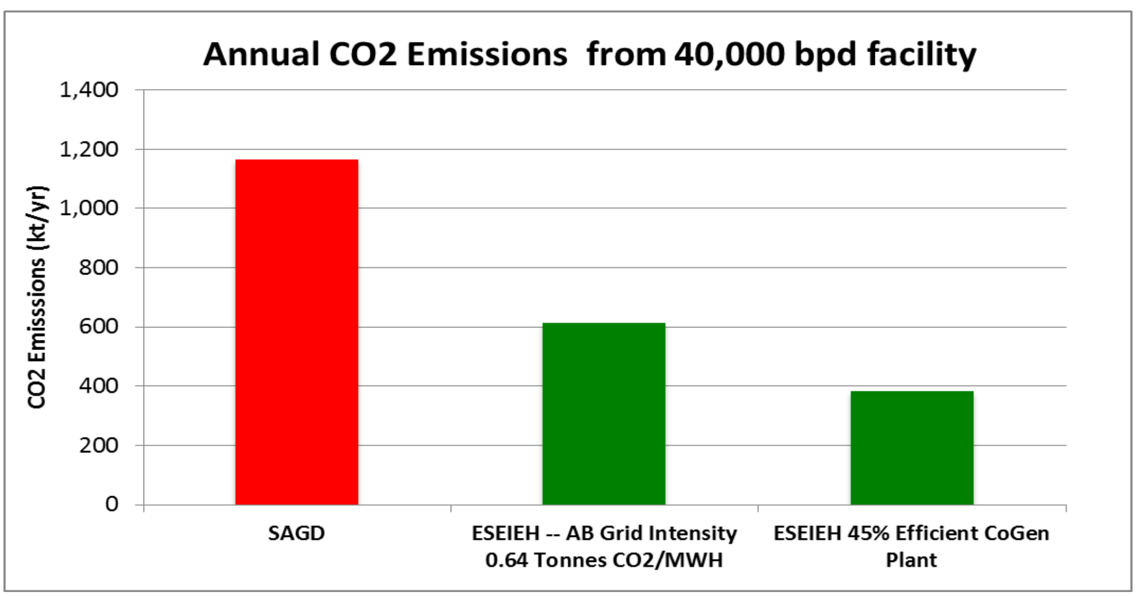


Figure 1 – Annual GHG Emissions SAGD vs. ESEIEH™

Effective Solvent Extraction Incorporating Electromagnetic Heating (ESEIEH™)

The scientific basis of the ESEIEH™ technology is the combination of electromagnetic (EM) energy to preheat a bitumen reservoir in conjunction with a light hydrocarbon solvent to mobilize and recover the bitumen. Application of this alternate energy source eliminates the need for water, water treatment and combustion of natural gas or other hydrocarbon sources for steam generation, bypassing process thermal losses and related GHG emissions.

The ESEIEH™ recovery process is controlled heating of a bitumen reservoir to a temperature range of 40-70°C combined with solvent extraction as shown in Figure 2. This provides an improvement over SAGD extraction rates with significantly lower overall energy requirements. The dramatic reduction of process emissions and lower energy requirements combine to create a less energy and GHG intensive bitumen recovery process with potentially much lower costs.

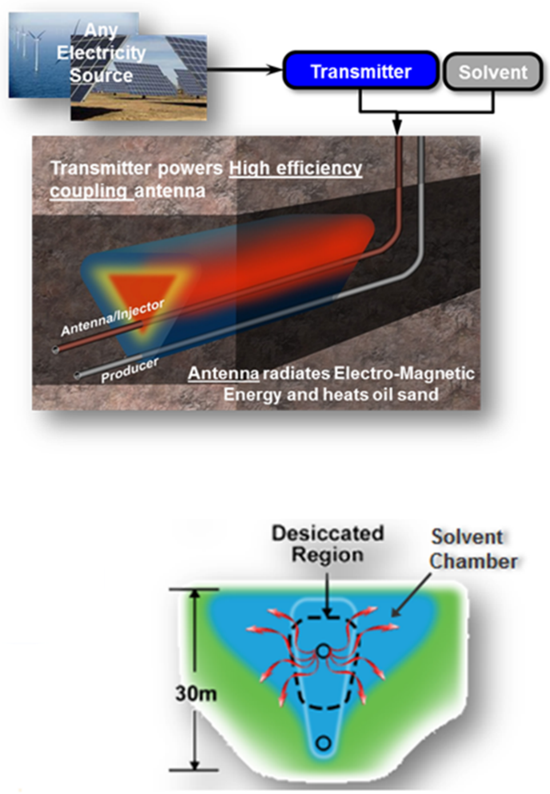


Figure 2 - ESEIEH™ Well Layout and Process

The ERA concerns addressed by this project include:

- Pronounced reduction in GHG emissions
- No potable water consumption
- Development of an environmentally benign process for bitumen extraction using alternative energy sources
- Potential reduced diluent requirements for transportation
- Elimination of boiler or coke waste
- Reduced facility/capital/footprints

The goal is to prove ESEIEH™ as an emissions-efficient bitumen extraction technology with economic advantages that assure adoption. Beyond this goal, ESEIEH™ has the potential to be extended to reservoirs that cannot be commercially developed with SAGD (thin pay, low pressure, middle zones, minimal cap rock, etc.). It may minimize capital and facility investment requirements by extending the life of existing facilities, and could potentially replace surface mining due to its low pressure and temperature characteristics.

Project Phases

The ESEIEH™ Project is intended to evaluate the combination of electromagnetic heating for rapid horizontal well pair startup, and sustained formation heating with concurrent injection of a solvent. The project includes numerical modeling studies, Radio Frequency hardware design and manufacture, facility design and construction, and two field trials.

The ESEIEH™ Project is comprised of three phases:

Phase 1 – RF Technology Proof of Concept: begins with the tasks necessary to define the RF system required for the field pilot test. The end of Phase 1 is the completion of the “Mine Face” test to verify RF energy penetration and absorption rates (2011-2013) at reduced scale and validate numerical model predictions. This is an RF heating demonstration in native oil sands and no solvents are used. The ESEIEH™ Project Team has completed Phase 1 through the successful execution of a mine face test at Suncor’s North Steepbank Mine.

Phase 2 – Small Scale Pilot at Suncor Dover lease: includes equipment and facility integration for a technical demonstration of the full ESEIEH™ process with a 100 m horizontal well pair and three vertical observation wells that contain the instrumentation necessary to characterize system behavior, oil recovery process and analyze the technology’s performance

Phase 3 – Continuance of the Small Scale Pilot at Suncor Dover lease: this phase is currently in progress; Phase 3 includes modified facilities and well configurations resulting from a December 2015 downhole arcing event that prompted a project redesign. The modification provides for the addition of a vertical injection well which permitted operation of the horizontal antenna independently of vaporized solvent injection.

B. Phase 1 Mine Face Test

Introduction

The mine face test represents the first demonstration of the ESEIEH™ process that combines the heat delivery of EM heating with the viscosity reduction of solvents to achieve an energy efficient oil recovery process. The project was executed by a consortium represented by Nexen Energy ULC, Suncor, Laricina Energy Ltd., and Harris Corporation with support from Emissions Reduction Alberta (ERA). The mine face test focused on a proof of concept that RF energy can be effectively used to heat oil sands and that coupled numerical models could adequately predict the results in-situ. The major test objectives were:

1. Demonstrate effective equipment installation and system performance.
2. Establish antenna performance metrics in oil sands
3. Obtain a comprehensive dataset to identify relevant physics of RF heating.
4. Provide technology validation for RF reservoir pre-conditioning to a coupled solvent process.

These objectives were demonstrated through the design, deployment, and operation of an RF heating system at a built-for-purpose pit at the Suncor North Steepbank Mine. The Coupled Electromagnetic Reservoir Simulator (CEMRS™) numerical method described below was validated and the test proved that the hardware could deliver the required lineal power density required for a commercial scale ESEIEH™ process.

Test Site and Equipment

Suncor's North Steepbank mine was selected as the test site for the first phase of the ESEIEH™ project. A built for purpose pit was constructed to provide access to the oil sand layer with a horizontal borehole rig. The specific location and depth of the antenna were determined through an examination of vertical appraisal well logs and core photos from a 2009 drilling program at North Steepbank, this location is denoted by the green star on Figure 3. The data showed that the composition of this region comprises rich oil sand interrupted by inclined hetero-lithic strata (IHS). The antenna was placed at a nominal elevation of 302 m above sea level covered by approximately 6 m of oil sand and IHS as well as 5 m of glacial till. There was 10 m of oil sand and IHS below the antenna. Figure 4 shows the antenna position superimposed on core photos of the test interval. Figure 4 highlights that the region immediately surrounding the antenna was composed of oil sand, mud and shale, which is representative of typical Athabasca oil sands heterogeneity.

Petrographic analysis was conducted on a core that was drilled 0.5 m offset from the center isolator of the antenna, which was located approximately 43.5 m from the well flange at the mine face. The formation permeability ranged from 60 millidarcy (mD) in a shale layer to as high as 8800 mD in a clean section of oil sand. The porosity ranged from 29% to 32% and the oil saturation was as high as 85% in clean oil sand sections and ranged from 26% to 50% in IHS layers. Water content measurements of the core samples showed a range of 1.3% to 14.7% and were deemed acceptable for RF heating.

The antenna and instrumentation layout for the experiment is shown in Figure 5. The horizontal bores were drilled to a penetration distance of approximately 59 m from the mine face at a depth of 11 m below the mine surface elevation. The A1 and A2 bores were completed as the primary and backup antenna bores, respectively. Five horizontal and vertical bores were drilled as observation wells. The antenna was installed in A1 inside a 27.3 cm (10.75 in) dielectric casing manufactured by Centron and the center of the antenna was placed 43.5 m from the mine face. The casing was plugged at the toe to prevent intrusion of reservoir materials. A fiberglass casing was chosen to enable the transmission of EM energy into the formation and to allow the antenna to be retrieved if necessary during the test. The cased approach was used in the mine face test primarily for accessibility. Note that the proposed commercial architecture does not require a dielectric casing.

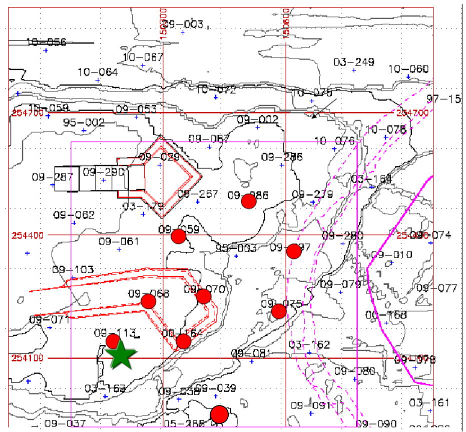


Figure 3 - Mine Face Test Site Location

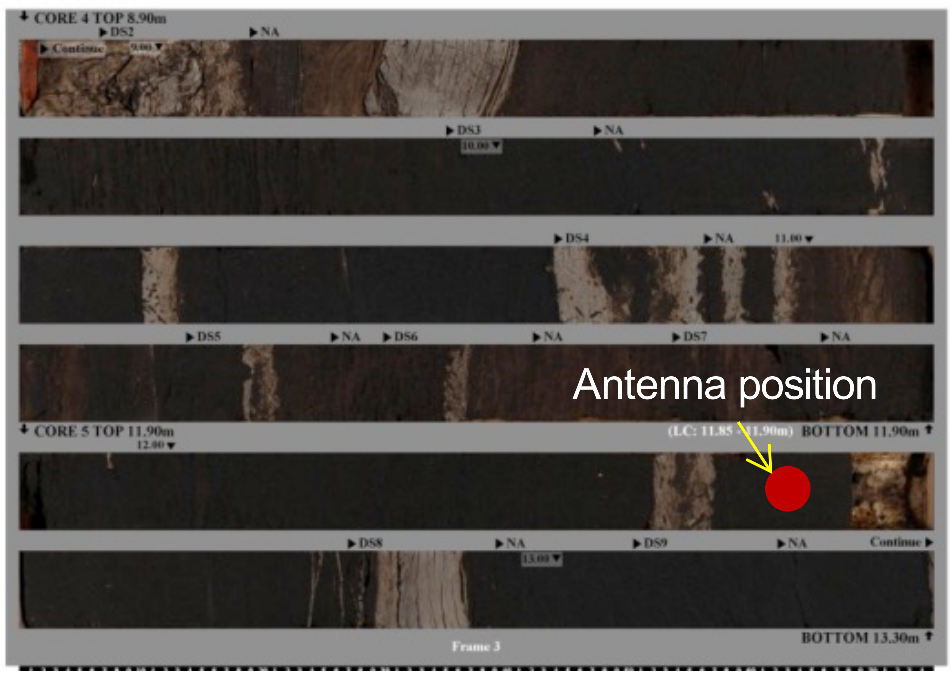


Figure 4 – Test Site Core Photos

The horizontal and vertical observation wells were built from 11.4 cm (4.5 in) Centron fiberglass tubing to minimize interference with the EM fields that were broadcast from the antenna. All of the wells were instrumented with fiber distributed temperature sensors. The OB1, OB2 and OB3 vertical wells were each fitted with 15 discrete optical temperature sensors (Neoptix OmniFlex™) and these served as the primary sensors for the experiment. The OB1, OB2, and OB3 wells were drilled at an offset of 0.5 m from the edge of the A1 casing. The bores extended below the antenna centerline elevation in order to capture the temperature distribution both above and below the antenna. As such, these vertical observation wells captured the radial temperature distribution around the antenna.

Figure 5 - Aerial View of the Antenna Layout & Mine Face Experiment Instrumentation Bores

A ¼ wavelength dipole antenna was constructed from 15.2 cm diameter aluminum tubular sections separated by dielectric isolators located at the center feed and tip of the heel section of the dipole. A photo of the antenna prior to installation in the well bore is shown in

Figure 6. The linear shape and tubular construction was selected to enable the form factor to be scaled to longer antenna field tests in the future. The modular antenna design could be configured at various lengths between 10 m and 15 m.

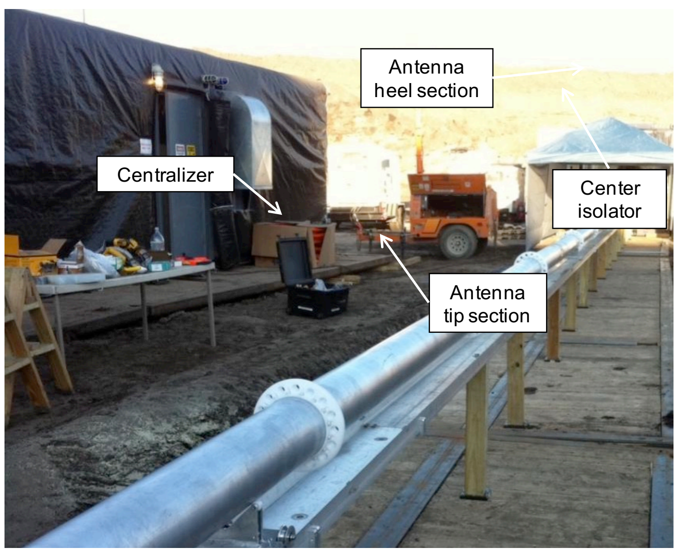


Figure 6 – Dipole Antenna Installation

Electrical measurements prior to the test indicated that a 12.2 m antenna length would provide the best impedance match to the formation over the duration of the test at the intended operating frequency of 6.8 MHz. This frequency was selected because it lies within the industrial band reserved by Industry Canada for use by industrial equipment. However, there is no restriction on frequency if there is sufficient shielding to surface.

Power was provided from the transmitter to the center feed of the antenna through a copper coaxial transmission line. Protective equipment was installed adjacent to the heel isolator to prevent stray EM radiation from propagating along the metal tubular back to the mine face.

The layout of the surface facilities is shown in Figure 7. A 100 kW transmitter provided RF power to the antenna. The transmitter could operate over a frequency range of 4 to 12 MHz. The transmitter shelter provided both heating and cooling so that the transmitter could operate over an external temperature range from -40°C to 40°C. Both temperature extremes were nearly experienced during the initial testing of the system components in Florida during summer and Suncor's North Steepbank Mine site near Fort McMurray winter conditions.

Operations were conducted from an office trailer that monitored the major subsystems of the test. A nitrogen generation system was housed in a connex (a standard-sized shipping container) and provided the nitrogen supply for the test equipment. A storage connex was used to ship and store the antenna and transmission line components. It also functioned as a work shelter during the construction and installation of the antenna and instrumentation. A 230 kW diesel powered electrical generator and 30 kW backup generator provided power to the site. Communication of the test data and subsystem status was provided by a Harris CAPROCK® self-acquiring trailer mounted VSAT satellite communications link and permitted real time continuous data monitoring and control of the test to the engineering teams at the Florida and Calgary offices.

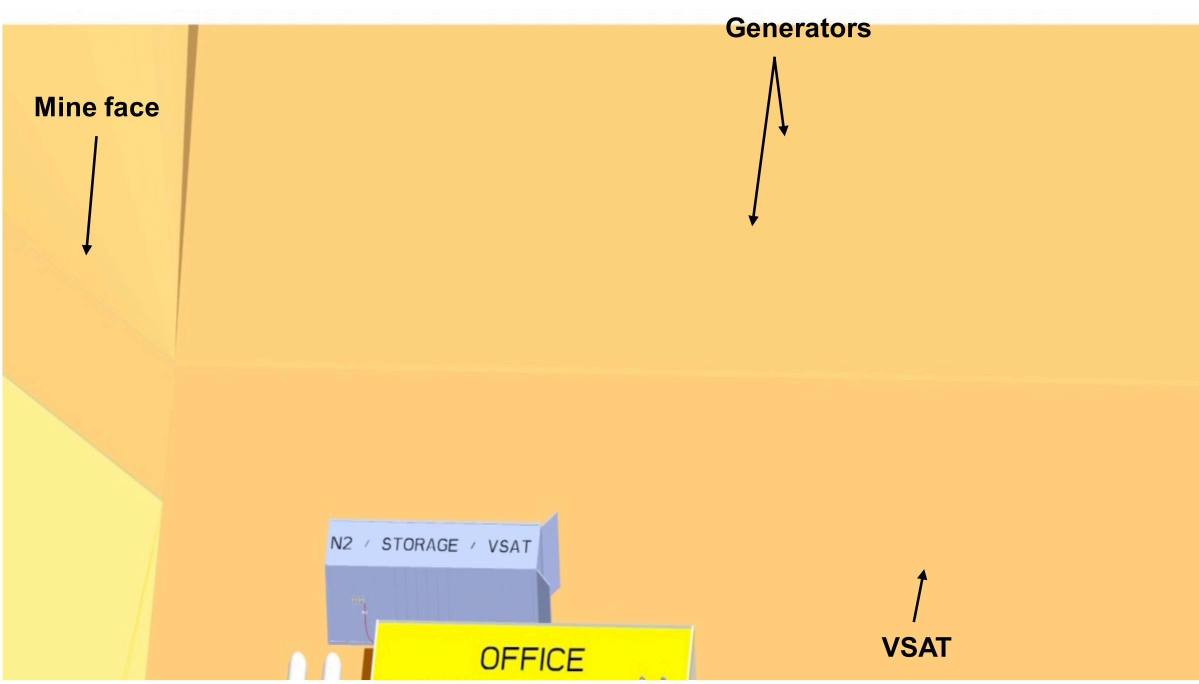


Figure 7 – Surface Facility Layout

Numerical Model of the Mine Face Test

Harris developed a "Coupled Electromagnetic Reservoir Simulator" (CEMRS™) in order to address the interdependent relationship between the reservoir composition and the RF heating pattern. It is important to capture this interaction because a change in reservoir composition, for example through desiccation, changes the performance of the RF transducer and the heating from the transducer changes the composition of the reservoir. The reservoir composition also affects the electrical impedance of the antenna. The use of coupled EM and reservoir simulators enables the design of a transducer that operates efficiently over the entire production life of the reservoir. A single operating frequency was used at the mine face test. Up-front CEMRS™ modeling was used to pre-determine the optimum antenna length.

The coupling process implemented in CEMRS™ is graphically represented in Figure 8. CEMRS™ uses Computer Modeling Group's STARS® thermal reservoir simulator, ANSYS HFSS® Electromagnetic (EM) simulator and Harris-provided coupling software with built-in electrical material models for oil sands. For this test, an oil sands electrical model was used as a baseline, but was modified to match the resistivity of a well log at the test site.

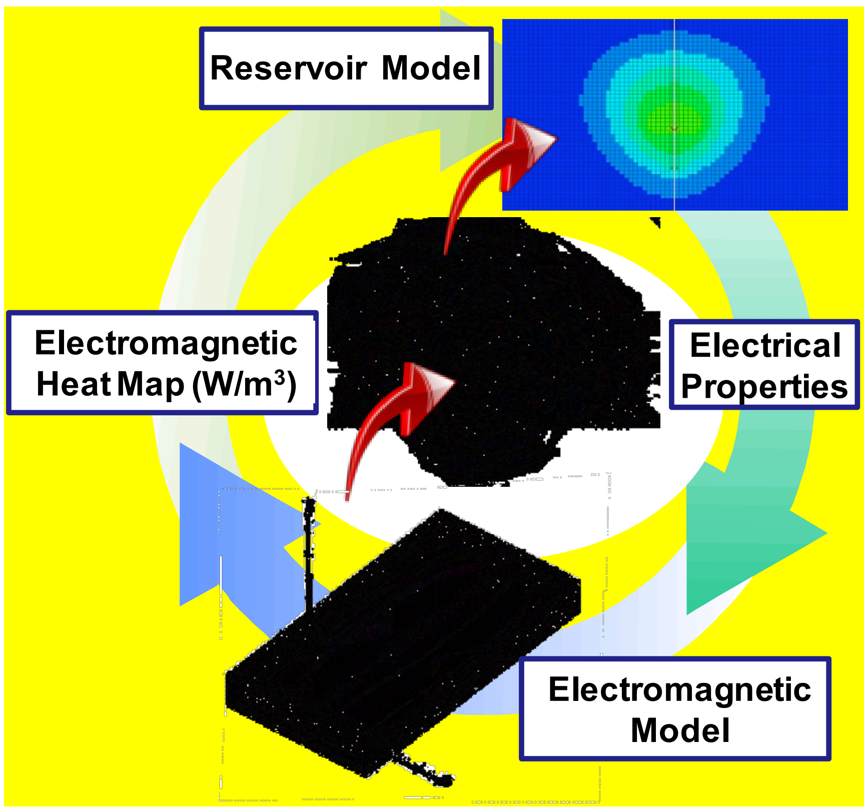


Figure 8 - Graphical Representation of the EM & Reservoir Solver Coupling

The EM model is provided with a specific antenna design, target operating frequency and appropriate boundary conditions. The EM model is solved and the heat map is interpolated from the finite element mesh onto the reservoir mesh. The reservoir simulator is executed for another time step, updating values for temperature and composition, and then the coupling loop is repeated, explicitly coupling the solvers.

CEMRS™ was initially validated against a well-defined EM heating problem that could be solved with standard numerical tools. PTC's MATHCAD® was used to solve the differential equations that describe the heat dissipation and thermal response in a 1-D electrically resistive slab as a result of an incident EM plane wave on one surface.

The transient temperature profile was calculated by CEMRS™ and compared to the MATHCAD® solution for a plane wall geometry of finite thickness with ε_r of 8 and a σ of 0.01 S/m. In this example, the power density varied spatially but was constant in time. Temperature profiles generated by CEMRS™ were compared to the MATHCAD® results at several times for thermally insulated boundary conditions.

Figure 9 shows that over a 10 day period the CEMRS™ predictions were essentially identical to the MATHCAD® results.

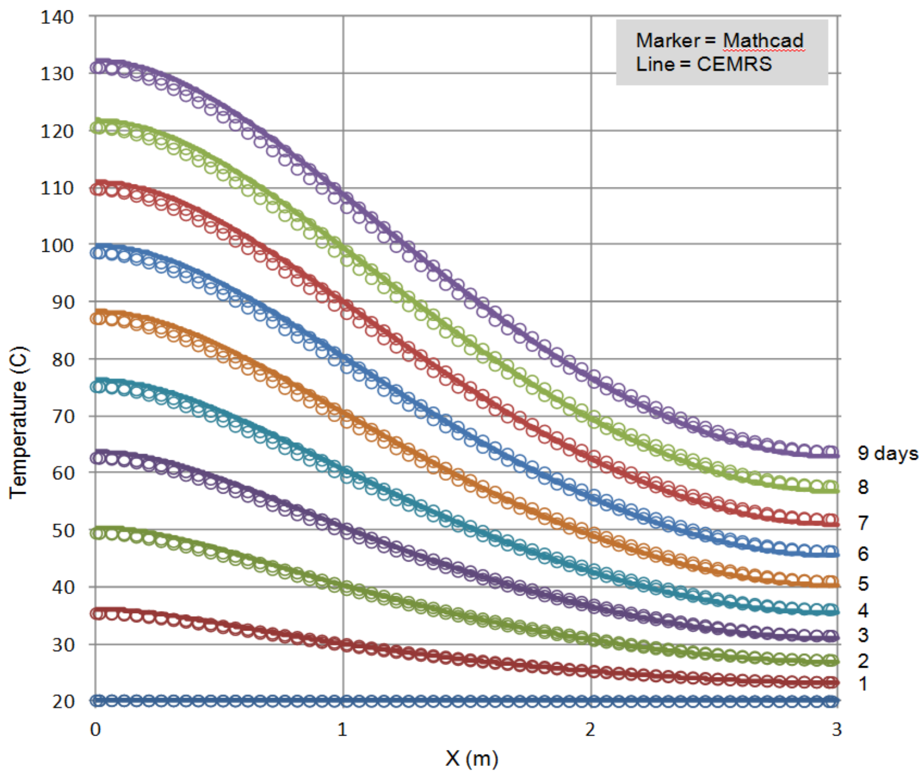


Figure 9 - CEMRS™ vs. MATHCAD® Temperature Profiles over 10 days

The CEMRS™ model of the test configuration comprises three components: the reservoir model, the EM model, and the control software that couples the solvers and defines the electrical material model. Two orthogonal views of the mine face reservoir model are shown in Figure 10. The model domain was 10 m x 15.8 m x 15.8 m (21 x 63 x 63 cells) in the axial, transverse and vertical directions, respectively. For computational efficiency, only half of the antenna and formation was modeled.

The symmetry plane was a vertical cut orthogonal to the antenna axis at the center of the antenna dipole. Figure 10(b) shows the plane of symmetry from the top view at a horizontal plane that coincides with the antenna depth. All non-symmetry boundaries were modeled as no flow with heat transfer to a semi-infinite body. The location of the antenna is denoted by a white outline. The wellbore was modeled with zero initial oil and water saturation to account for the presence of the nitrogen filled casing surrounding the antenna. Stratification of shale layers around the antenna were included in the model at elevations derived from the core photos and simulated as horizontal layers of low permeability (K_h from 10 to 100 mD). The shale layers are shown in Figure 10(a) as well as the reduced horizontal permeability of the sealed vertical observation well (e.g. OB2).

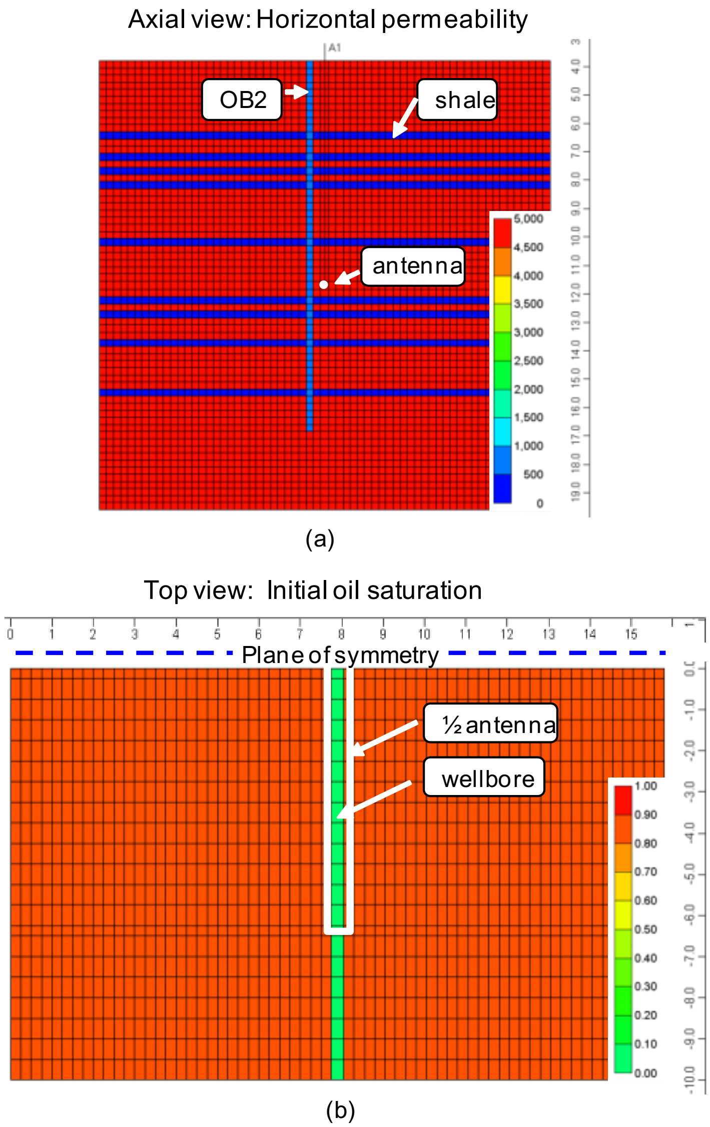


Figure 10 - Reservoir Model Domain
(a) axial view of horizontal permeability
(b) top view of initial oil saturation at the antenna elevation (distance units = m)

The EM model is shown in Figure 11. The center vertical plane of the antenna was modeled as a symmetric electric field boundary and all other boundaries were modeled as free radiation surfaces. A typical model contained about 140,000 tetrahedral elements. The antenna was modeled with a line source at the center feed and was enveloped by a 10.4 inch (26.4 cm) air cavity created by the casing. Each element in the model received updated electrical properties from the material model at every coupling interval. Updates between the reservoir and EM model were controlled by the coupling software and occurred every 0.5 days. Table 1 shows some of the key properties used in the CEMRS™ model.

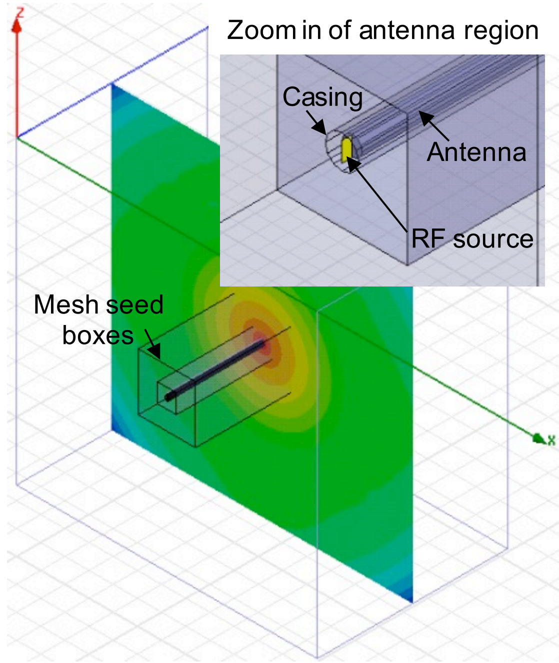


Figure 11 - EM Model of the Antenna & Oil Sand

Parameter	Value
Porosity	0.31
Average oil saturation	0.81
Average water saturation	0.19
Kh (mD)	5000 in pay 10 to 100 in shale
Kv (mD)	0.6*Kh
Rock heat capacitance (J/m^3)	2.44E+06
Rock thermal conductivity (J/m-C-d)	751680
Oil thermal conductivity (J/m-C-d)	11500
Water thermal conductivity (J/m-C-d)	53500
Gas thermal conductivity (J/m-C-d)	1400
Thermal conductivity model	Anand
Antenna length (m)	12.25
Antenna OD (m)	0.152
Casing ID (m)	0.247
Initial conductivity (S/m)	Matched to well log

Table 1 - CEMRS™ Mine Face Test Final Model Parameters

To capture the vertical stratification of electrical properties at the test site, the resistivity log from the nearest vertical well was converted to conductivity and the model conductivity was scaled in every cell to match the initial conductivity of the well log along the depth of the model. Figure 12 shows the well log data interpolated onto the CEMRS™ model. In this graph, the antenna was the datum point at a relative depth = 0 m (~ 11 m below surface). Because permittivity logs were not available, permittivity was estimated based on the water weight of the oil sand.

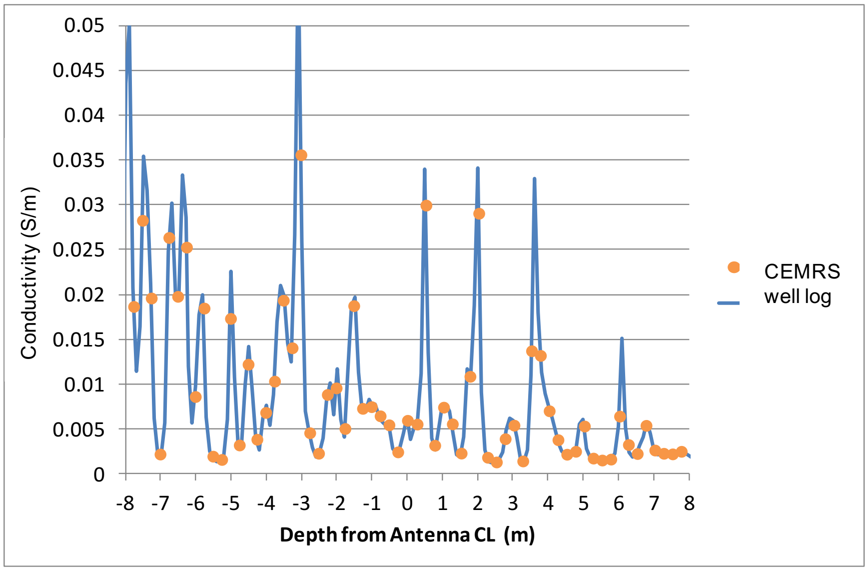


Figure 12 – Formation Conductivity vs. Relative Depth from Antenna Centerline

Test Results and Discussion

The mine face test was conducted in three stages. The first stage was a gradual ramp to a low power state of 28 kW that held the formation temperature just under the saturation temperature of water (100°C at 1 atm.) in order to collect a data set that preceded the desiccation of the formation. Once desiccation began the electrical properties of the formation would change drastically since water was the primary receptor of the EM energy. The second stage was designed to ramp to the full design power of 49 kW to observe the effects of desiccation on the radial and axial propagation of the EM fields. The final stage was to turn off the antenna and collect data during the cool down period to better validate the thermal properties of the model.

The entire mine face test duration was 11 weeks and included RF equipment setup, the RF heating period, cool down and demobilization. The RF power was initiated on November 20th, 2011 and the power schedule shown in Figure 13 was executed. The first stage ramped the power to 28 kW in 6 days and then held to soak the formation at a temperature just below 100°C. After 10 days of low power operation, sufficient data was collected to compare with simulations for the pre-desiccated condition. This was an important test stage because there was little fluid movement and the dominant heat transfer modes were RF radiation and heat conduction. For stage 2 between day 10 and day 14, the power was ramped linearly to the maximum power level of 49 kW, or 4 kW/m for the 12.25 m long antenna. Note that although 4 kW/m was selected as the maximum power density for the mine face test, the antenna was operated extensively at power densities as high as 8 kW/m in extended dry run tests in moist sand at the Florida test site.

The system was run at 49 kW until day 17. At this time, oil was observed within the annulus formed by the bore hole and casing along the length of the bore up to the mine face. The mobile oil was virtually free of water. In order to avoid any oil drainage at the mine face, the RF power was lowered to 12 kW to maintain formation temperature and a concrete plug with a sampling port was constructed in the annulus at the sand face. This operation took 10 days. Once the concrete was cured, the power was reset to 49 kW and powered almost continuously for 7 days until the middle of day 34.

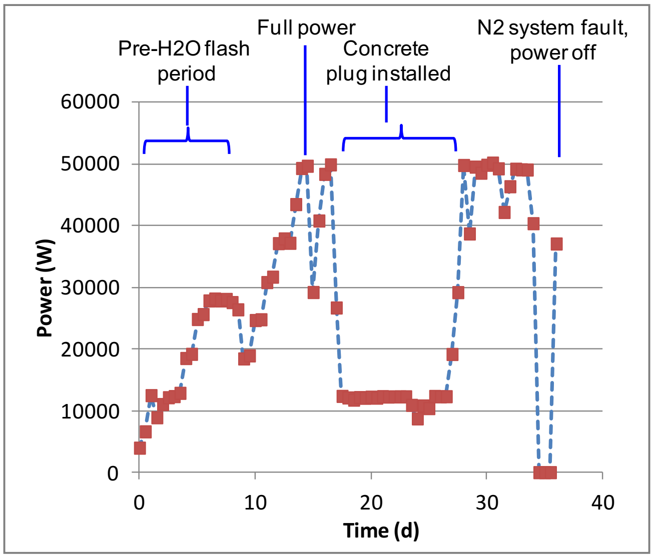


Figure 13 – Antenna Power Schedule

Figure 14 shows a 3-D composite of the vertical temperature distribution from the discrete fibers on the OB2 (a) and OB3 (b) wells. The radial distance axis is a measure of the vertical distance from the antenna centerline elevation to the sensor position. The plots show how the radial temperature profile in the formation evolved during the test. Figure 14(a) shows that the temperature along OB2 increased monotonically with time until the power was throttled back to 12 kW on day 17. At this time, the temperature adjacent to the antenna cooled while the temperature at a radial distance of greater than 2 m increased due to continued exposure to RF heating and heat conduction from the relatively warmer center. After the cementing operation concluded on day 27, the power was increased to 49 kW and the temperature at all distances increased until the power was shut off on day 34. During the ensuing cool down period, the central region cooled while the formation at a radial distance greater than 3 m increased by heat conduction from the warmer central region. The empty sectors that appear in Figure 14(a) after day 20 were attributed to a dropout of two fiber optic sensors. The temperature profiles near the toe of the antenna (OB3) evolved in a similar fashion to those at OB2, but at a lower magnitude with a peak temperature of 100°C observed at that axial location.

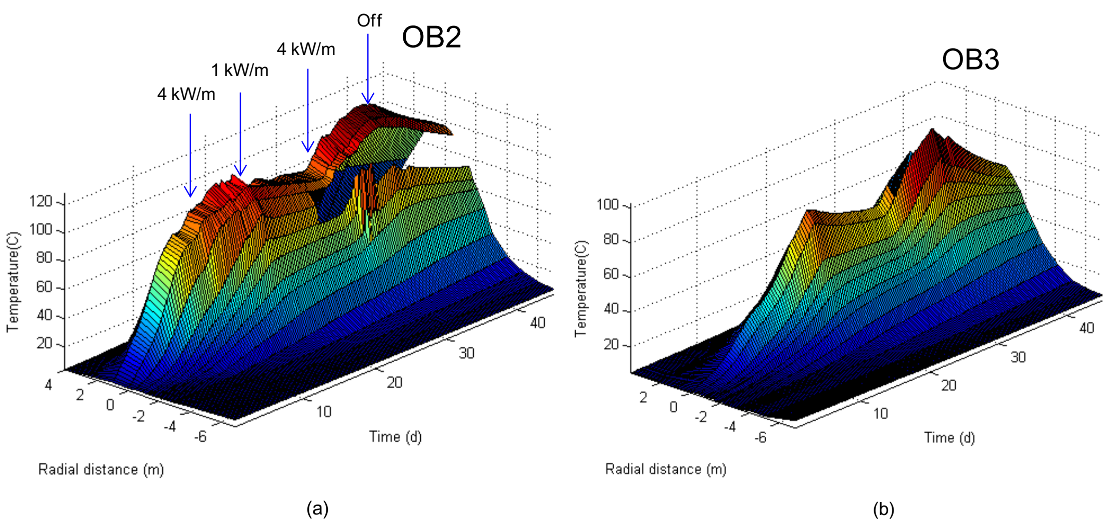
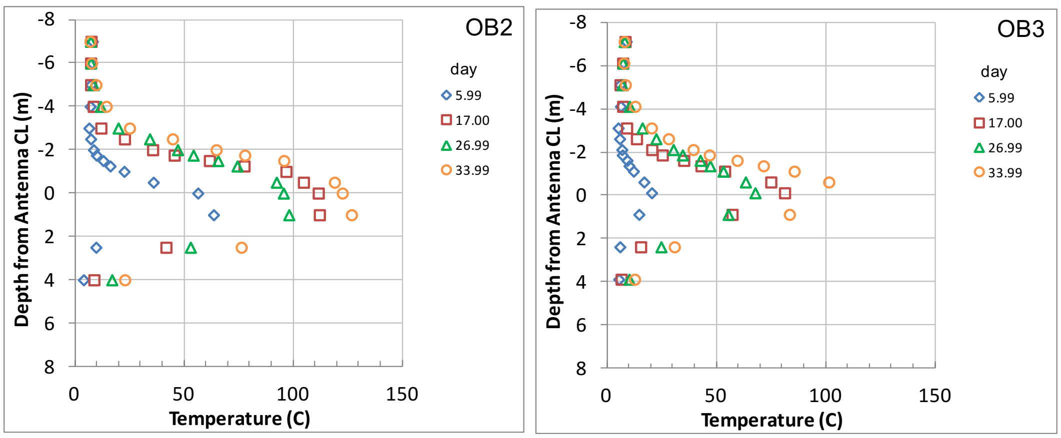


Figure 14 - Surface Plots of the Temperature Field Evolution (OB2, OB3)

Figure 15 displays the temperature data from OB2 and OB3 on line graphs at several instances during the test. The antenna elevation is represented by the zero coordinate with depth on the ordinate and temperature plotted along the abscissa. The temperature increased throughout the test with the exception of a decrease in temperature at the antenna elevation during the low power operation between day 17 and 27. The maximum formation temperature of 127^{o}C occurred approximately 0.5 m to 1 m below the antenna, not at the antenna centerline.

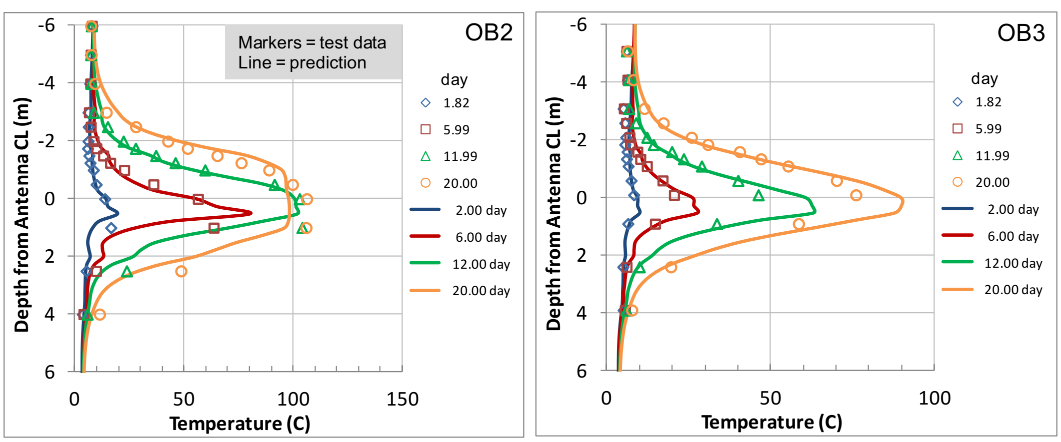


(a) (b)

Figure 15 – Vertical Observation Well Temperature Profiles (OB2, OB3)

Numerical Model Results

The as-tested power profile was input into the baseline CEMRS™ model that was developed prior to the test. The predictions were compared to the measured data in Figure 16. This represented a blind correlation since the model was not adjusted from the initial settings. The data included the time period from 2 to 20 days, which was generally prior to the flashing of water in the formation. The correlation was quite good at all times and elevations although the model under predicted the temperature near the antenna elevation (depth 0 m) at the center of the antenna (OB2) by 10^{o}C and over-predicted the temperature at the tip (OB3) by 10^{o}C at day 20.



(a) (b)

Figure 16 - Baseline CEMRS™ Model vs. OB2, OB3 Test Data Comparison (Day 2 - 20)

Figure 17 shows a comparison of the baseline CEMRS™ predictions with the test data from day 20 to day 43. Again, there was general good correlation along the profile tails. However, during the heating period through day 33 the model predicted lower temperature than the test data at the antenna depth. The simulation showed that water evolved from the high permeability oil sand at 100°C, and at 110°C in the low permeability shale below the antenna.

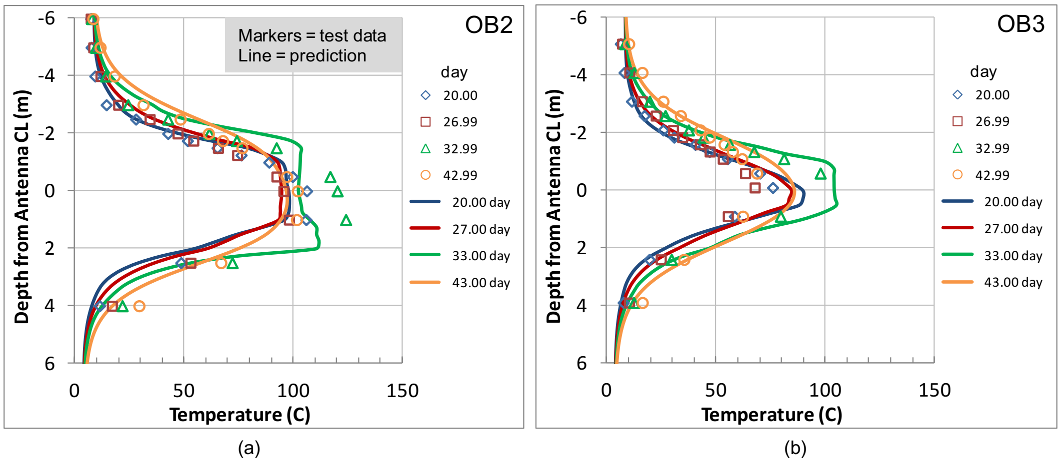
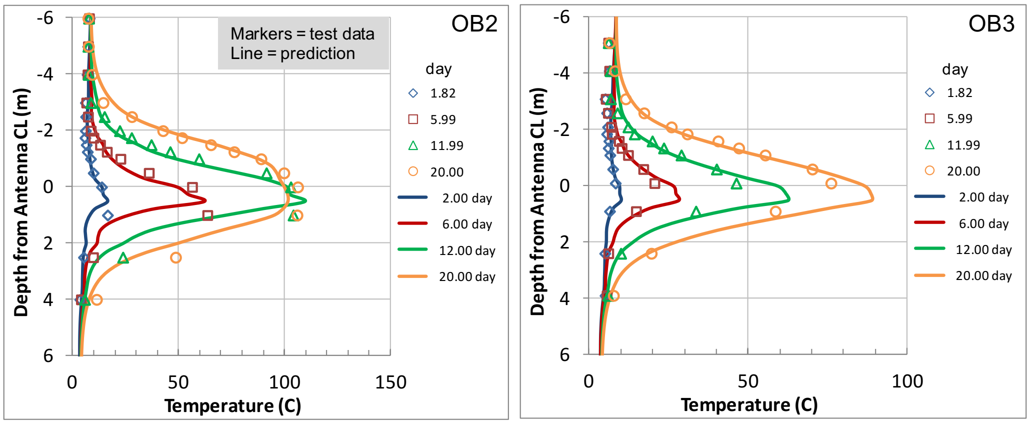


Figure 17 - Baseline CEMRS™ Model vs. OB2, OB3 Test Data Comparison (Day 20 - 43)

The shale layers reached temperatures above 100°C, potentially a result of the pore pressure exceeding 1 atm. due to fluid thermal expansion in these structures. The model correctly predicted that during the cool down phase (day 33 to 43) the temperature decreased around the antenna, but increased beyond a radius of 2 m from the antenna. This was due to the redistribution of energy by heat conduction since the RF power was off. The model results at OB3 showed a slower decrease in temperature compared to the test data at this time.

Two changes were made to the baseline model to better history match the data. Firstly, based on observations that the model under predicted the peak temperature in the OB2 profile, the shale layer permeability was adjusted from 60 mD to 10 mD. This change increased the peak pressure and saturation temperature of the water within the shale. Secondly, the baseline model used a simple volumetric mixing rule to determine the bulk thermal conductivity of the formation based on the makeup of the constituent parts (sand, oil, water, gas). This resulted in a small range of thermal conductivity between wet and dry oil sands ($k_{eff} = 1.24$ W/m-C at $S_w = 0.2$, and $k_{eff} = 1.18$ W/m-C at $S_w = 0.0$). The cool down data of OB3 suggested that higher thermal conductivity was present at the wet tip because the temperature data decreased faster than the model predictions. However, the data at the desiccated center suggested that less conductivity was required for the model to match the cool down period. A more accurate model of the thermal conductivity of oil sands as a function of water saturation was developed by Somerton and use of this correlation resulted in higher and lower thermal conductivity under wet and dry conditions, respectively ($k_{eff} = 1.87$ W/m-C at $S_w = 0.2$ and $k_{eff} = 0.57$ W/m at $S_w = 0$).

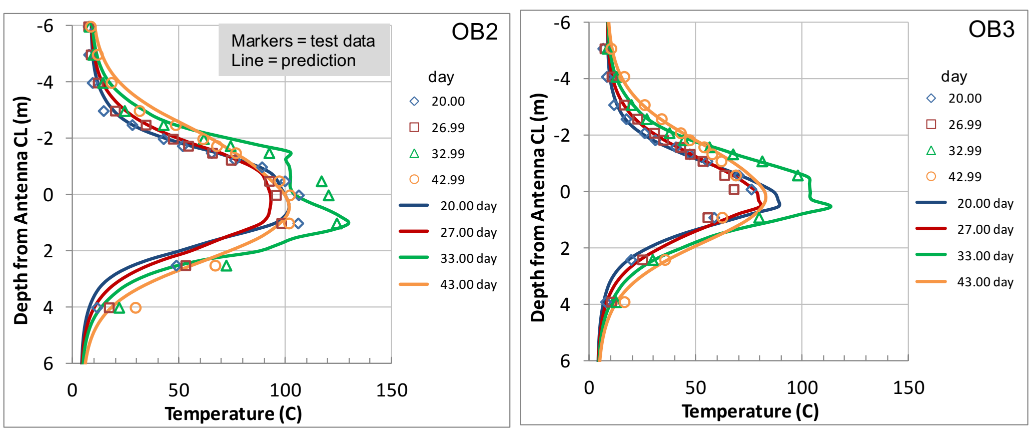
The STARS® model thermal conductivity coefficients were tuned to match the Somerton correlation at $S_w = 0.2$ and $S_w = 0$. A comparison of the modified model to the data from day 2 to day 20 is shown in Figure 18. The adjustments did not dramatically change the model results during the pre-desiccation period. The comparison improved near the antenna and at the temperature peak in shale layer just below the antenna.



(a) (b)

Figure 18 - Adjusted CEMRS™ Model vs. OB2, OB3 Test Data Comparison (Day 2 - 20)

The result of the modifications was most evident by day 33 day when the formation had actively flashed water for approximately 7 days as shown by Figure 19. The adjusted model correctly captured the peak temperature observed at OB2, 1 m relative depth, although the model still under predicted the temperature at relative depth 0 to -1 m. Similar results were observed for OB3 at day 33. The predicted temperature decay near the antenna during cool down from day 34 to 43 also improved in the adjusted model. In general, the agreement between the adjusted model and test was quite good, especially given the large variation in applied power during the experiment.



(a) (b)

Figure 19 - Adjusted CEMRS™ Model vs. OB2, OB3 Test Data Comparison (Day 20 - 43)

The water saturation was not directly measured during the mine face test. However, the CEMRS™ model was used to predict the water saturation distribution during the test. The water saturation in an axial plane at the center of the antenna is shown in Figure 20 at day 33. Note that the red dot on Figure 20 marks the antenna position; the distance units are in meters. Green contours indicated little to no water saturation within a 1.2 m radius of the antenna at that time. It was noted during the test that water vapor was venting at the mine face and it confirmed that water was removed from the heated zone.

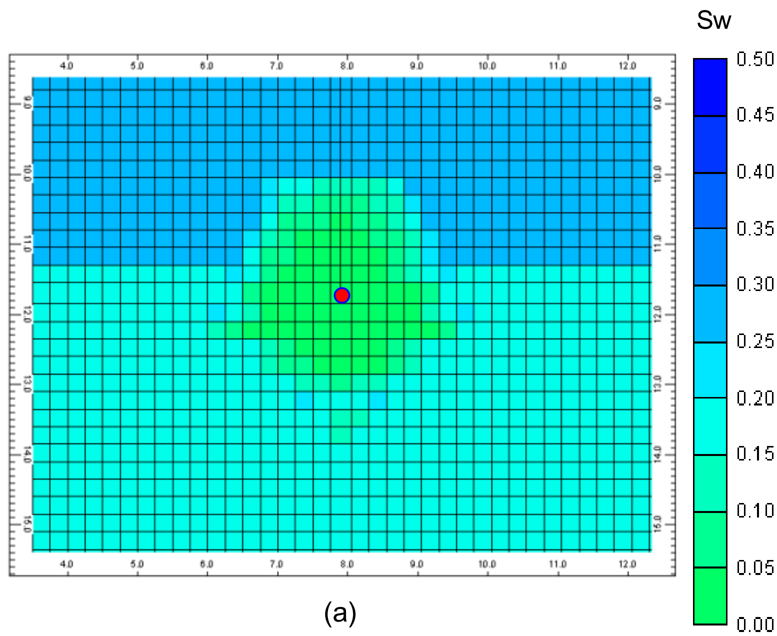


Figure 20 - Predicted Water Saturation at Day 33 (m)

The model was also used to predict the temperature distribution as if the test was run at 49 kW (4 kW/m) continuously for 60 days. The maximum temperature achieved was 130°C and occurred under the shale layers directly below the antenna as shown by Figure 21 which illustrates the axial view of the projected temperature field after 60 days of 4 kW/m heating at 6.78 MHz from the antenna center. The temperature rose to 130°C and 35°C at radii of 2.5 m and 5 m, respectively. Heating above the initial formation temperature extended to a radial distance of 7 m in this time period. The predicted temperature distributions are encouraging for horizontal SAGD well startup given the typical separation between an injector and producer is 5 m. Configuring both the injector and producer as antennae would significantly accelerate the hydraulic communication between the wells.

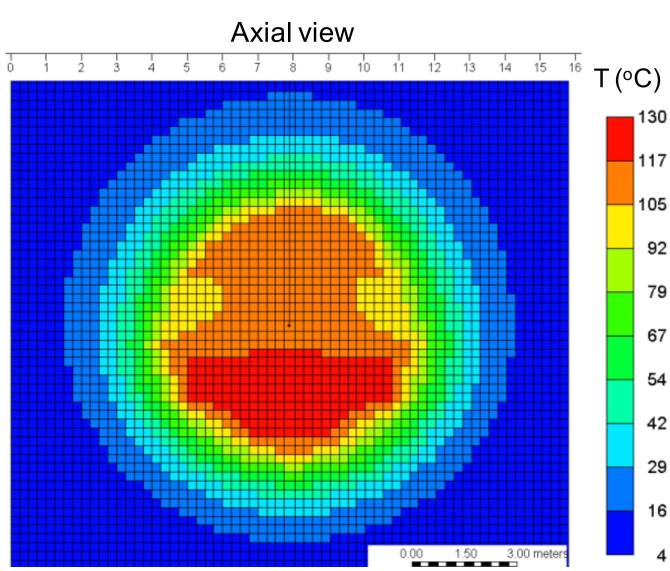


Figure 21 - Projected Temperature Field after 60 days of 4 kW/m heating at 6.78 MHz

Mine Face Test Conclusions

The mine face test represented the first phase demonstration of the ESEIEH™ process. The Phase 1 project primary goals were to demonstrate RF heating of native oil sands at an intermediate scale compared to field implementation and collect a rich data set to validate multi-physics simulations of RF enhanced oil recovery processes. During the program, a modular RF heating antenna was developed that could be configured in lengths from 10 m to 15 m and was tested at 12.25 m. The antenna was inserted into a dielectric horizontal well bore and radiated up to 4 kW/m lineal power density at 6.78 MHz into native oil sands at the Suncor North Steepbank Mine.

A maximum sustained RF power of 49 kW was delivered to the formation and the average power over the 34 day active heating period was 26 kW. The maximum formation temperature observed was 127^{o}C and was recorded on the OB2 instrument string 1 m below the antenna. The peak temperature was located within a shale layer and confirmed the importance of these materials in modeling in-situ RF heating processes in oil sands.

The temperature data collected from the vertical observation wells were compared with predictions from the CEMRS™ model. Correlation between the test and baseline model was good. The match was improved by decreasing the permeability of the shale layers and by calculating oil sand thermal conductivity based on the correlation developed by Somerton. The history matched model predicted a temperature rise of 130^{o}C and 35^{o}C at radii of 2.5 m and 5 m, respectively, if the system were run at 4 kW/m for 60 days. At these observed heating rates, the RF system configuration appears to align well with the fundamental goals of proving the merits of ESEIEH™ as an emissions-efficient bitumen extraction technology. It is also worth noting that the RF penetration radius will be significantly larger at commercial antenna lengths of nominally 800 m because of the lower operating frequency.

Despite a shortened operating period, all of the objectives of the mine face test were met. A modular antenna and supporting RF system were designed, manufactured, and installed in a native oil sands test site prepared at the North Steepbank Mine. Robust heating of the oil sands was demonstrated at power levels that were consistent with field level recovery processes in a heterogeneous formation. Furthermore, a comprehensive dataset was collected that validated the CEMRS™ tool.

C. Phase 2 Small Scale (In-Situ) Pilot

Introduction

After a successful Phase 1 and review of same, the Technical Committee recommended sanctioning Phase 2 of the Small Scale Pilot. This review was held following the completion of the detailed design work to support an in situ pilot. Approval was requested to advance detailed engineering, procurement, construction, and test execution with the specific activities being:

- 100 m antenna / injector well
- Production well
- Sufficient instrumentation arrays to collect data and control test
- 2 observation wells + 3 contingent observation wells
- Surface facilities, control system and infrastructure
- Operations for 7 month test period
- Geological and geophysical interpretations and geo-modeling
- Reservoir recovery modeling and correlation with field data
- Electromagnetic heating system technology development; transmitter, transmission line (surface and sub-surface), antenna, concept of operations, and test procedures
- Data management
- Decommissioning & reclamation

Phase 2 objectives were defined as follows:

1. Demonstrate and measure bitumen drainage due to RF heating and propane vapor – empirical test.
2. Measure other key economic indicators including solvent retention, power consumption and delivery efficiency of EM energy to the reservoir.
3. Test the sensitivity of drainage to operating conditions such as power, solvent injection rate or pressure, production rate controls etc.
4. Provide field data to guide predictive numerical modeling and optimization.
5. Determine the behavior and disposition of solution methane under ESEIEH™ conditions.
6. Pilot ESEIEH™ RF hardware and well design with respect to functionality, reliability and efficiency.

Immediately following the review, Laricina Energy withdrew from the project for internal reasons. As a result, partner sanctioning of the project was deferred pending successful negotiations with Devon Energy to enter the consortium. Suncor, Nexen and Harris continued to advance the project work with full Integrated Project Team (IPT) engagement on the expectation that partner sanction would be ratified by the end of the year.

Partner technical assurance reviews proceeded and amended partner agreements were executed in January 2014. Full partner sanction was received April 2014. Following partner sanction, the project scope was expanded to include:

- An additional observation well

- An additional 17 months to the test period (total of 24 months)

Test Site

Suncor's Dover site (Township 93 Range 4 W4) was picked to host the Phase 2 pilot for a variety of reasons: good to excellent reservoir quality, well understood geology, and close proximity to Suncor's MacKay River operation. Dover is famous as being the birthplace of SAGD with the Underground Test Facility (UTF) being directly beside the selected ESEIEH™ site which was once used for the Vapor Extraction (VAPEX) pilot as shown on Figure 22.

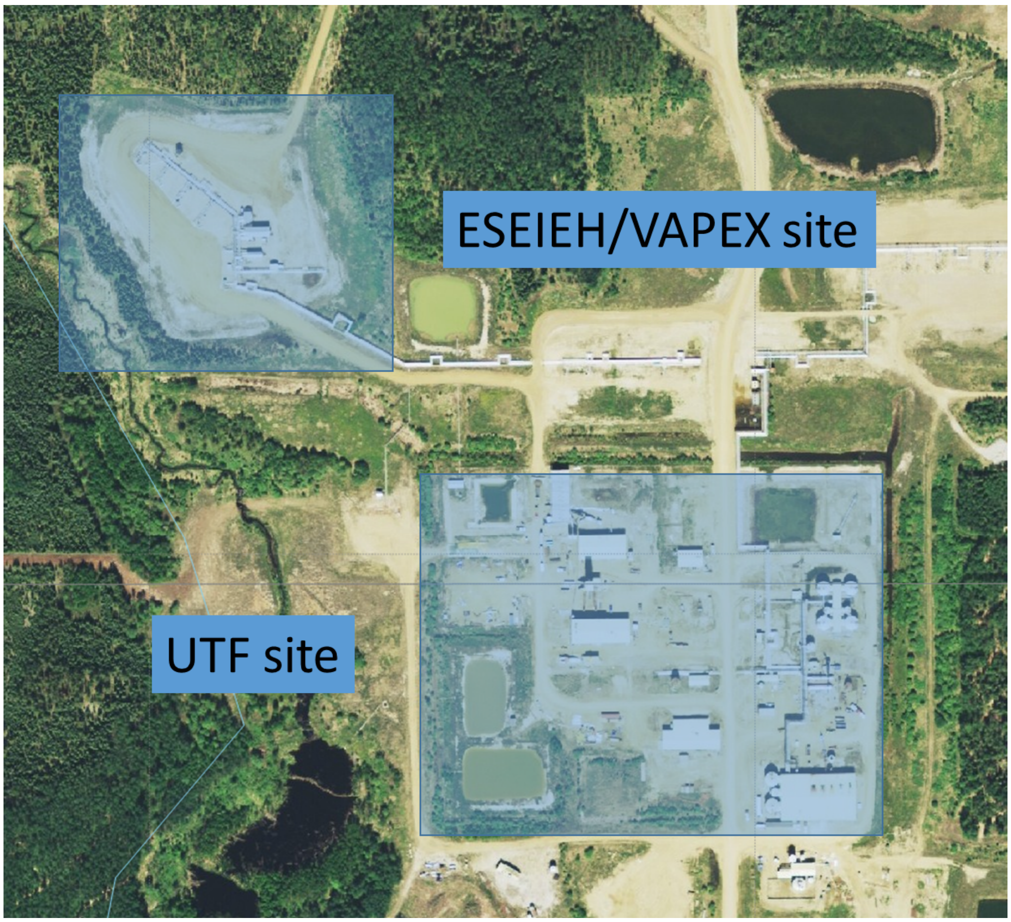


Figure 22 - ESEIEH™ Test Site

Well Design

The antenna/injector well design (EZI-1) was a synthesis of the Phase 1 antenna, and a standard SAGD injector with multiple design enhancements as illustrated by Figure 23.

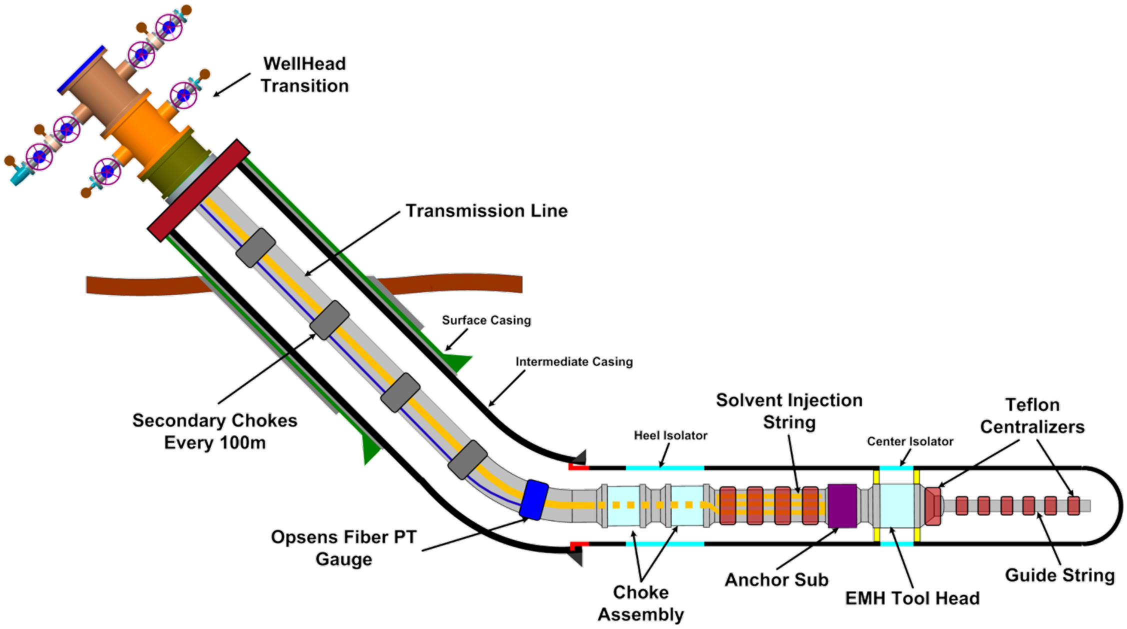


Figure 23 - ESEIEH™ Phase 2 Antenna/Injector (EZI-1)

The producer well (EZP-1) was run with a standard slotted liner and a progressive cavity pump (PCP) for artificial lift (The project selected a PCP but the process will work with virtually any pump, e.g. ESPs). Three observation wells were drilled with RF transparent casing, and equipped with pressure and distributed temperature sensors.

Following the design and fabrication of a prototype antenna, a handling test depicted by Figure 24 was successfully completed. The purpose of the test was to provide training to Suncor's designated completion rig contractor and crew, and to test equipment interfaces and tool handling capabilities.

Figure 24 - Handling Test

Well Placement

The 100 m lateral length horizontal wells were drilled in 2014 between the 2 VAPEX well pairs at a 50 m standoff. Calculations showed that the reservoir at this location would be unaffected by the VAPEX vapor chamber. Two observation wells (EZOB-1, EZOB-2) were drilled at the center of the antenna/injector and one (EZOB-6) at the heel for data collection as shown by Figure 25. The producer was drilled in clean bitumen at 279 mTVDSS with the injector drilled at 284 mTVDSS as shown by Figure 26.

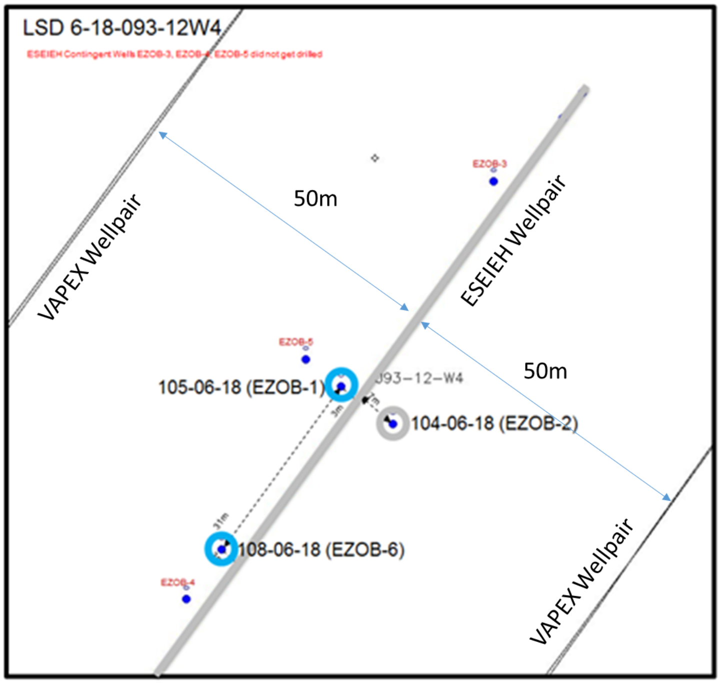


Figure 25 - Well Placements

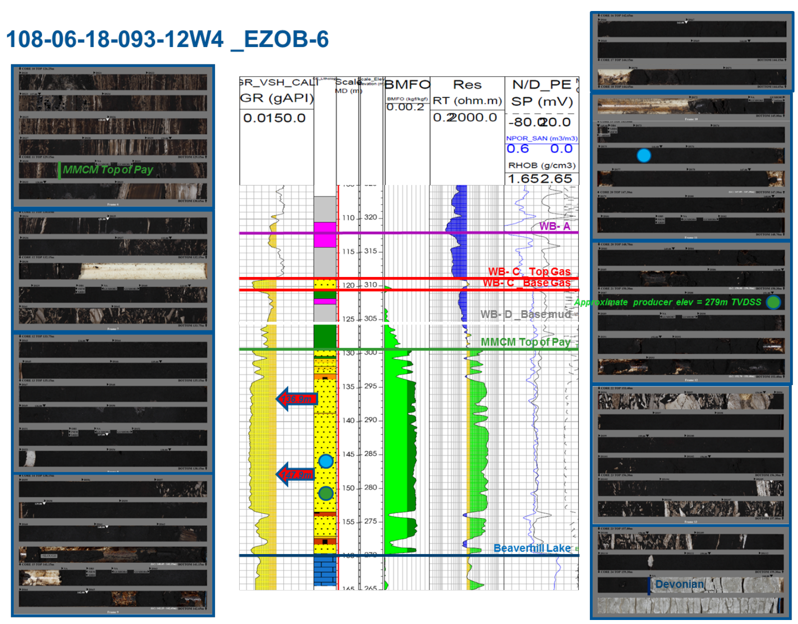


Figure 26 - EZOB-6 Core and Well Pair Placements

Coupled Electromagnetic Reservoir Simulator (CEMRS™)

During the early period of Phase 1 of the ERA project Harris worked closely with Laricina to conduct initial simulations of the ESEIEH™ recovery process. The models have since expanded significantly through joint engagement with all current project partners. The model of the Dover site was updated in three stages; the first model was a 2-D domain based on course reservoir descriptions and well logs. This model was updated with more detailed reservoir descriptions from Suncor geologists and the electrical properties were matched to surrounding well logs, and a 3D model of the test site was constructed by extruding the updated 2-D model along the axis of the antenna.

The initial 2-D model was used to conduct a survey of candidate RF power profiles that could be applied during the test. In the model, the antenna was operated at the highest power (4 kW/m) for the first 60 to 90 days in order to promote timely hydraulic connection between the injector and the producer. After communication was established the RF power was reduced and it was found that the oil rate reduced less than linearly with the sustaining power. Based on numerical modeling, a nominal sustaining power of 1 kW/m was proposed for the test in order to promote an energy efficient recovery process. A detailed study was conducted to evaluate the effects of linear, exponential and cyclic sustaining powers. It was found that a linearly decreasing power profile maximizes the oil rate. The study also concluded that methane accumulation within the formation may occur as a result of liberation of the dissolved methane in the native bitumen. The sustaining solvent injection rate was predicted to be ~ 1000 kg/day with a maximum usage of 2500 kg/day recommended for facility design. It was determined that the solvent usage was reduced by limiting the bottom-hole gas volume produced from the producer.

Facilities

The final design of the ESEIEH™ surface facilities consist of six major components illustrated by Figure 27 through Figure 29:

1. Transmitter House or T-house – Houses the 500kW transmitter and instrumentation that supplies the RF power downhole
2. Dielectric Fluid Conditioning System (DFCS) House or D-House – Houses the DFCS which provides capability to condition dielectric fluid used in the system.
3. Separator Building/Flare - The separator building contains the production handling capabilities for the pilot. This was an original VAPEX facility which was ‘repurposed’ for the pilot.
4. Product Storage Tank - The Product Storage Tanks is a skid-mount 10’x30’ 400 bbl vessel complete with off-loading pumps and metering facilities.
5. Solvent Storage Tank - The Solvent Storage Tanks is a skid-mounted vessel complete with product loading/metering facilities responsible for containing propane solvent for process injection
6. MCC Building - The MCC Building houses all the control units to support the pilot operations (common power bus, programmable controllers, metering, communications, etc.) This was an original VAPEX facility which was ‘repurposed’ for the pilot.

Field Construction started in September 2014 and was finished in May 2015. Commissioning took place immediately after with the systems being ready for start-up on July 9 2015.

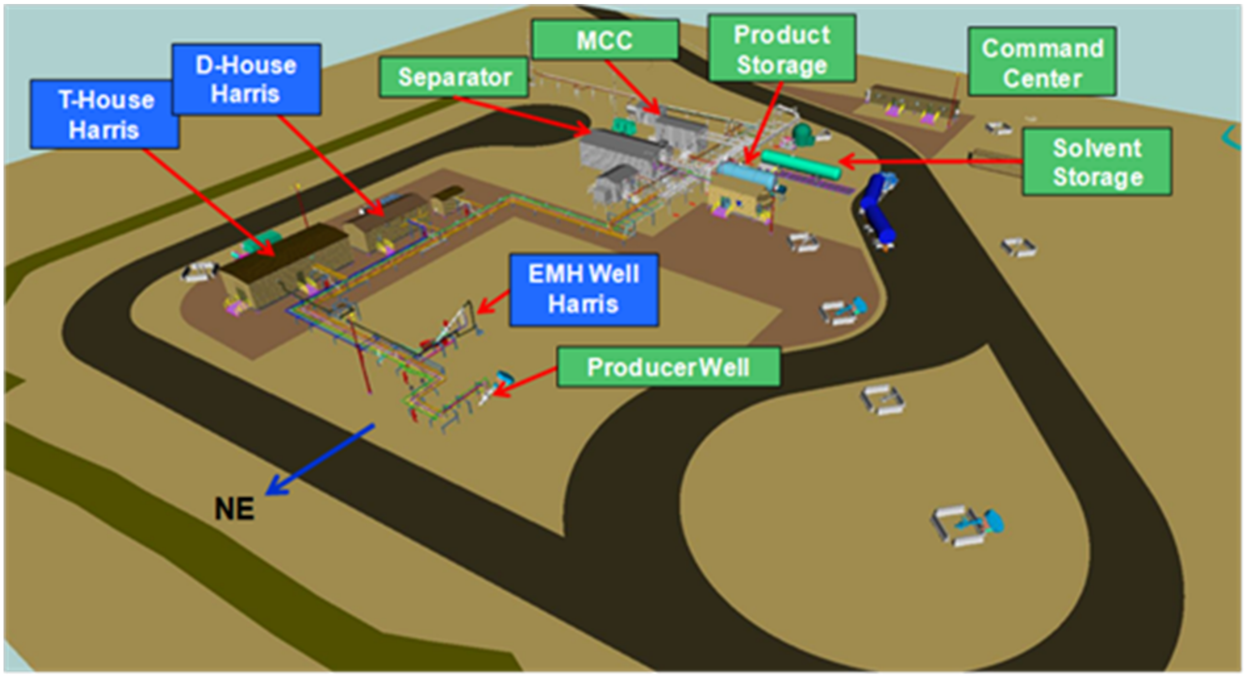


Figure 27 - ESEIEH™ Small Scale Pilot Facilities

1) T-House
2) D-House
3) Instrument Air
4) Tx Cooler
5) Surface Transmission Line
6) Inlet/Outlet Barrier
7) Injector Well
8) Producer Well
9) Propane / Diesel / Bitumen Lines

Figure 28 - ESEIEH™ Phase 2 Built Facilities (Well Pad)

1) Flare Stack
2) Flare House
3) MCC
4) Propane Storage
5) Product Storage
6) Diesel Storage
7) Emergency Shower
8) Product Separation Building
9) Command Center

Figure 29 - ESEIEH™ Phase 2 Built Facilities (Production Train)

Pilot Operations

The pilot test plan was officially executed on the morning of July 9, 2015. Throughout the next days the power was increased per the operating plan. Excluding the minimal downtime on July 11th and 12th, Figure 30 indicates that the reservoir was initially heating up as expected.

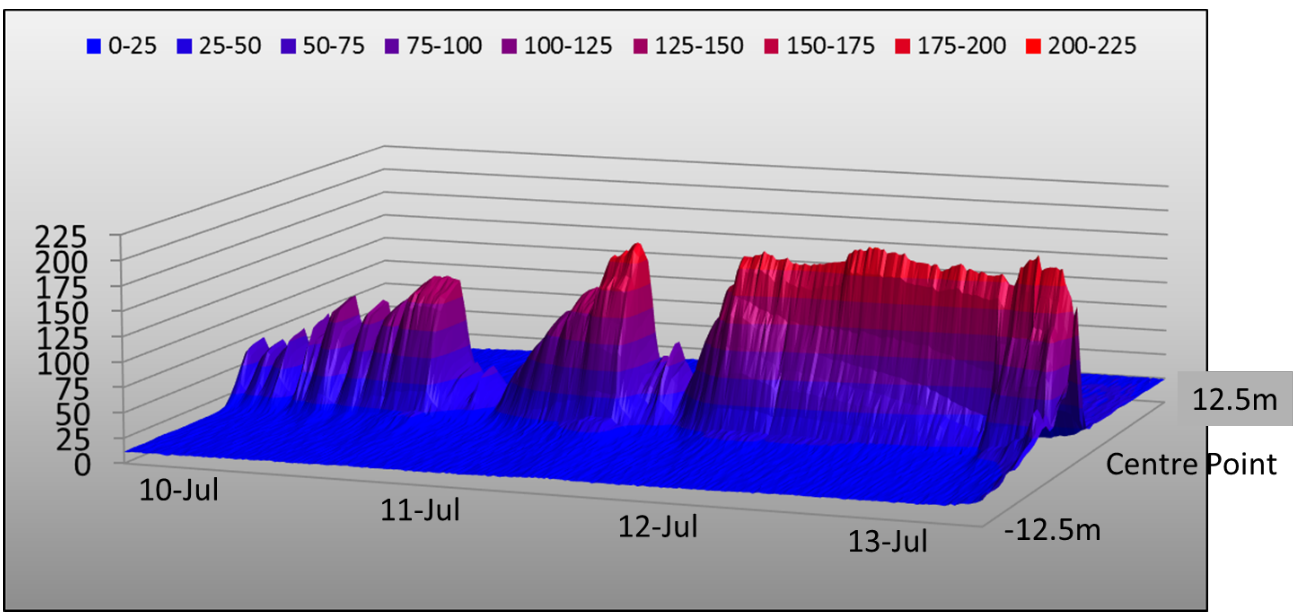


Figure 30 - Start-up Temperature Profiles (Center Point)

A significant electrical event occurred on 1645 hours on July 13, 2015 which triggered a power shut-down and an observed rapid temperature drop from 180^{o}C to 60^{o}C. Harris concluded that the resulting condition was either due to contamination or an influx of high conductivity water to the antenna feed area following power shut down. Operations were immediately suspended to conduct an investigation.

A series of nitrogen/diesel/dilbit displacement operations were conducted on EZI-1 over the next few months to determine the effect of fluid displacement in the reservoir and attempt to diagnose the problem without pulling the antenna completion.

Operations continued to operate through mid-November 2015 at reduced power at steady state temperature, however high power operation was not possible due to the elevated voltage standing wave ratio (VSWR) level.

The EZI-1 wellhead inspection was completed in mid-November 2015 and confirmed that the N_2 barrier was damaged. The damage appeared to be caused by an arcing event due to the presence of metal debris. The contamination was very high and likely the source of the voltage breakdown experienced downhole. The inlet-outlet barrier (IOB) was removed and shipped to Harris in Florida. An inspection of the surface facilities identified significant metal debris in the surface lines and thermal accumulator vessel. After further testing of the downhole assembly, it was concluded that the antenna was non-operational and likely damaged as a result of presence of metal debris in the wellbore that was deposited during the drilling and completions operations.

Operations were suspended on December 9, 2015. The antenna was extracted from the well in March 2016 in support of the failure investigation.

D. Phase 3 Restart

Phase 2 Investigation

Following the suspension of the Phase 3 Operations, the ESEIEH™ Technical and Management Committees concluded that the following critical elements would be conducted prior to the project moving forward with the Phase 3 Restart. An investigation team was established to collect key evidence in support of a formal RCA.

i. formal technical investigation,

ii. Root Cause Analysis (RCA)

iii. and a formal gate review

A Root Cause Analysis session was convened with a scope that included;

i. developing a 'sequence of event' chart leading to the failure(s)

ii. defining causal factors

iii. facilitating a root cause analysis on each causal factor

iv. facilitating the development of a corrective action plan

The primary causal factors for this incident were determined to be the presence of external rust and foreign objects/debris ("FOD") from the intermediate casing that was pushed into the tool head isolator. These causal factors were likely a result of remediation procedures used during the initial completion, which introduced metal FOD and rust downhole.

The root cause of the failure was identified as a combination of technical and quality controls issues that occurred during well construction. The root cause analysis identified several corrective actions to improve all facets of material selection, construction processes, and improve robustness of the downhole equipment to prevent a recurrence in the next phase of operations.

In response to the root cause analysis outcomes, work was immediately undertaken to investigate alternative configurations for risk reduction. Initial study work was led by Suncor with close collaboration with Harris. This work was supported by detailed design work which included both detailed electrical analysis and numerical modeling.

Phase 3 Redesign Activities

In August 2016, a selection was made supporting a redesigned mono-bore horizontal antenna well configured with a dedicated vertical solvent well as depicted by Figure 31. The 'mono-bore' design provides the best opportunity to ensure an optimal operating environment for the antenna. Note that this mono-bore design is for the test only; an integrated antenna/injector is planned for commercial applications.

Unfortunately, the existing intermediate casing did not allow for the integration of solvent injection with the redesigned antenna well, therefore a separate vertical solvent well was required to meet the overall testing objectives. This recommendation was supported by significant modeling work to assess impacts on the coupled recovery process.

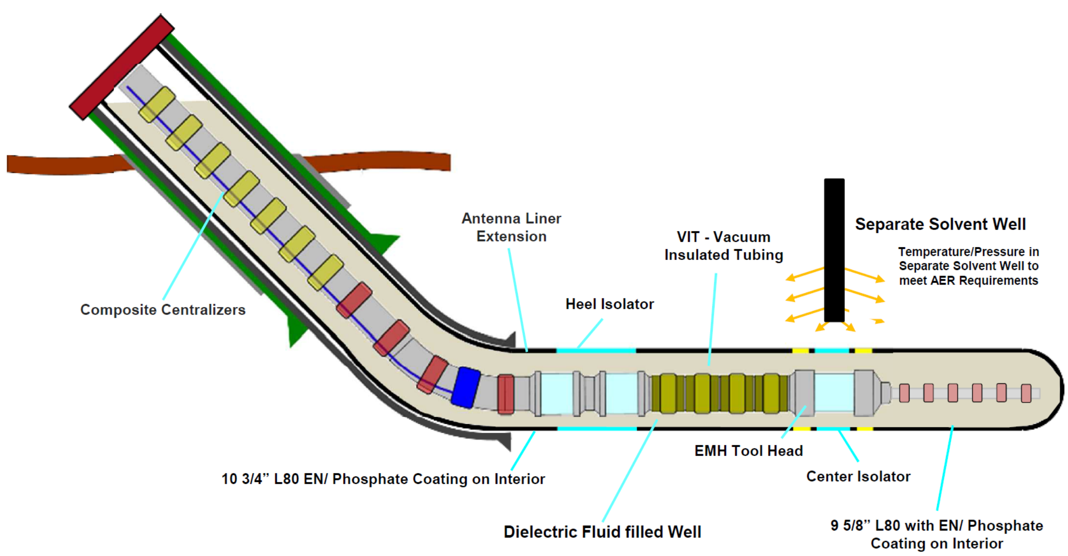


Figure 31 - Revised Design - ESEIEH™ Phase 3 Antenna/Injector (EZI-1)

Current Status

Detailed design work was completed including the required surface facility modifications to adapt to the vertical solvent configuration as shown by Figure 32. Project sanction for Phase 3 Restart was awarded by the ESEIEH™ partnership in July 2017.

As of Q3 2017, the majority of the equipment has been procured, fabricated and repaired. Drilling operations are expected to commence by the end of November 2017 with project restart planned for early in the first quarter of 2018.

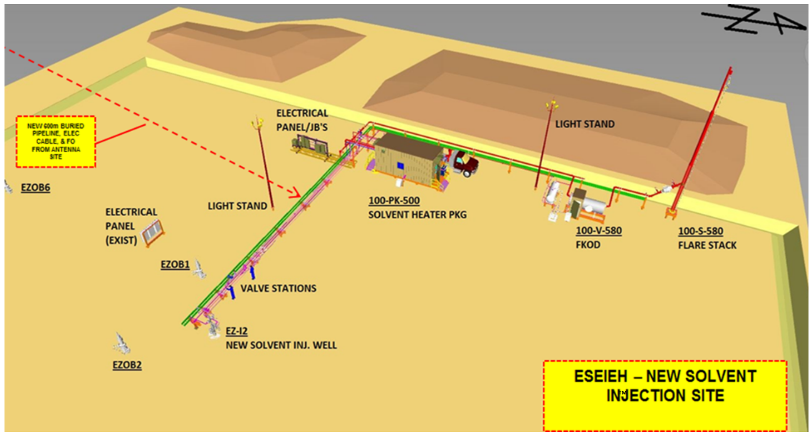


Figure 32 - Revised Design - ESEIEH™ Phase 3 Solvent Injection Site (EZI-2)

E. Synopsis

The ESEIEH™ project has yielded a number of successful outcomes to help demonstrate Radio Frequency (RF) heating of native oil sands at an intermediate field scale. In addition a rich data set ranging from validation of the multi-physics simulations to understanding the design and operational aspects of the system has been compiled. Specific outcomes are summarized as follows:

- The project validated RF heating physics in native oil sands and the modeling software during the Phase 1 Mine Face Test
- Further enhancements have been made to the modeling software
- The Phase 2 In-Situ Test was commissioned and started at the Dover Test site.
- Phase 2 suffered a shutdown due to metallic debris impacting surface and subsurface RF Heating equipment
- The ESEIEH™ consortium completed a Root Cause Analysis and implemented corrective action in material selection, drilling & construction process, and improving the robustness of the RF equipment.
- The test site is currently being updated and a re-start to the test is expected in the first quarter of 2018.

A key deliverable of the project remains to evaluate the mechanical operation of the RF system, as well as reservoir interactions and solvent performance. A full energy and mass balance evaluation of ESEIEH™ will provide the ability to refine the system design and operations to commercial scale, and enable comparison with other recovery processes. A history-matched numerical reservoir simulation model will help assess opportunities to commercially deploy the technology.

It is a critical time in our industry where innovation is urgently needed, and the project partners recognized that urgency with the establishment of the ESEIEH™ consortium back in 2010. The incurred project costs to date are approximately $75MM CAD which includes an ERA contribution of $16MM CAD. Funding provided through Emissions Reduction Alberta, offers a critical contribution to support the actions required to ensure a transition to a lower-carbon future in Alberta while offering a recovery technology that enables Alberta's oil sands to compete globally on both cost and environmental performance.

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