NUMERICAL MODELING OF JP-8 REMEDIATION BY STEAM INJECTION INTO ARTIFICIAL FRACTURES IN A CLAY MATRIX.

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Abstract

The in situ extraction of semivolatile hydrocarbons from low permeability soils requires extraordinary techniques such as extremely high vacuums, solvent flooding, or the injection of warm air. Fluid migration and associated mass transfer rates are very low in these cases and result in unacceptably close well spacings or long durations to achieve desired remediation goals. An alternative technique is the injection of steam to both increase the volatilization rate and flush the hydrocarbon from the pore spaces of the soil matrix.

We report here the results of from an Advanced Applied Technology Demonstration Facility (AATDF) project which investigated the effect of hydraulic fracturing and steam injection in order to develop a design and implementation guide to the remediation of semi-volatile contaminants in fine grained soils. This paper addresses numerical simulation experiments conducted to assist in selecting appropriate spacings for the fractures and the vapor extraction wells relative to the steam injection wells. In addition, the simulations will be used to gain a better understanding of the processes involved so that these pilot scale studies can be expanded to remediate larger areas.

Numerical experiments were carried in two dimensions represented by depth and distance (z,x). This domain, representing a depth of 6.2 meters and a distance of 7.5 meters was descritzed into a 27 by 21 matrix. Spacing between elements varied, with smaller horizontal spacings (0.25) adjacent to the sand layers and smaller vertical spacing (0.25) adjacent to the wells. The fractures themselves were 0.025 m. The matrix was assumed to be a homogeneous clay with extremely low permeability (K_h.=0.1 darcy, K_v =0.05 darcy) and an effective porosity of 10%. Steam injection was simulated by adding water with an enthalpy of 2.66×10^{6} J/Kg directly to the appropriate elements. Under most conditions, this resulted in a temperature of approximately 107^{E}C at the injection point. Vacuum extraction wells were simulated using the On Deliverability well type, with a production index of 2×10^{-12}.

The numerical simulation of the injection of steam into a narrow sand fracture surrounded by a clay matrix, was found to be extremely sensitive to the initial water saturation conditions. In addition, the rapid changes in water saturation and temperature that ensue as the steam front propagates through the media resulted in many non-convergent simulations. Results from the numerical simulation experiments for varying fracture spacing and differing scenarios for the vacuum and injection rates will be presented. The simulations will be compared with actual field data to demonstrate that the steam can be focussed to increase the area (volume) raised to above 75 ^{E}C. For sites where the production of steam is expensive, configurations which minimizes amount of steam while maximizing the heating are proposed.

The experimental results clearly demonstrate that steam injection through artificially created fractures is an effective process for the remediation of volatile and semi-volatile hydrocarbons in low permeable environments. Vapor extraction without the accompaniment of steam was not possible due to the low permeability of the soil. Thus, using the combined process of hydro-fracturing and steam heating, the TPH as JP8 concentrations, within the treated areas to a depth of 20 feet, were reduced from between 2,000 and 7,000 mg/kg to less than 300 mg/kg in about 3 months.

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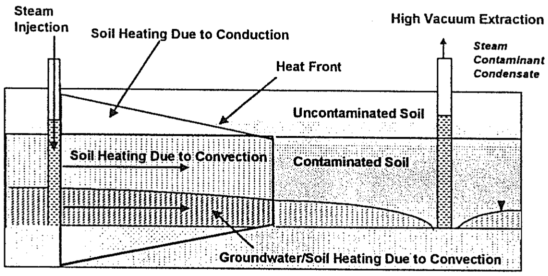
AATDF FRACTURE/STEAM DEMONSTRATION PROJECT
Fort Hood, TX

FLUOR DANIEL GTI

Model for Subsurface Heating by Steam Injection



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Steam Injection Technology Description

- Steam is injected into vadose and saturated zone to heat the soils by forced convection
  - ✓ Increases semi-volatile vapor pressure
  - ✓ Decreases viscosity
  - ✓ Decreases interfacial tension and residual saturation
- Steam generated by on site source
- Target Temperature = 212° F

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Technology Description
Essential Elements

- ■ **Heat Transfer to Soil**
  - Forced Convection
  - Conduction (Heat Loss)
- ■ **Vapor Pressure Increase**
  - Faster VOC Removal
  - Semivolatile Removal
- ■ **Viscosity Reduction**
  - Increase Heavy Oil Mobility
  - Easier Free Product Pumping
- ■ **Thermal Desorption**
  - Steam Distillation
  - Reduced Interfacial Tension
  - Reduced Residual Saturation
- ■ **Thermal Enhancement Methods**
  - Hot Air Injection
  - Steam Injection
  - RF Heating

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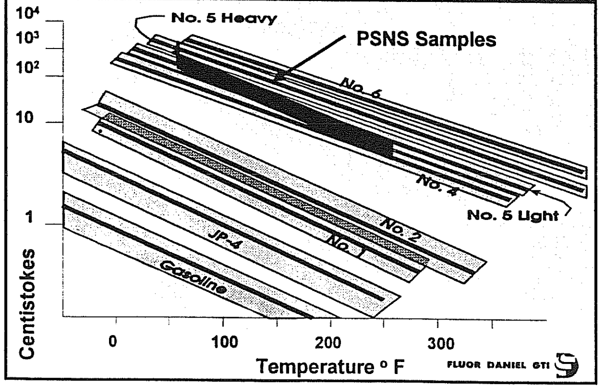
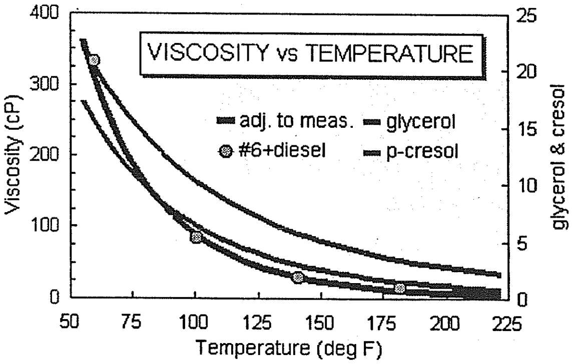
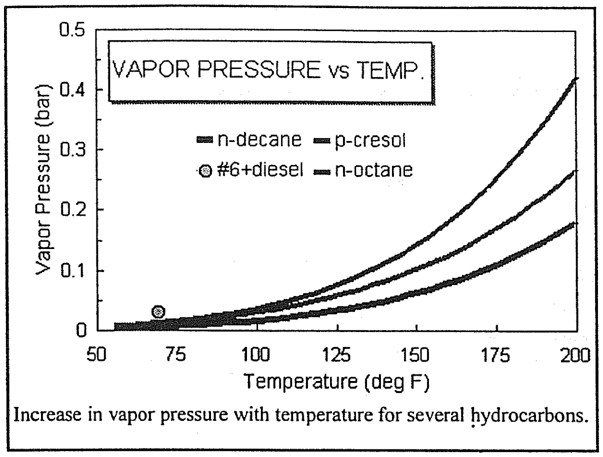
Kinematic Viscosity Vs Temperature
ASTM D-445 Results



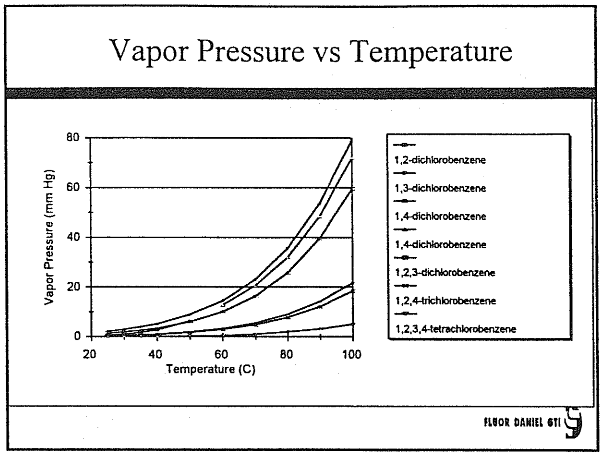
FLUOR DANIEL GTI



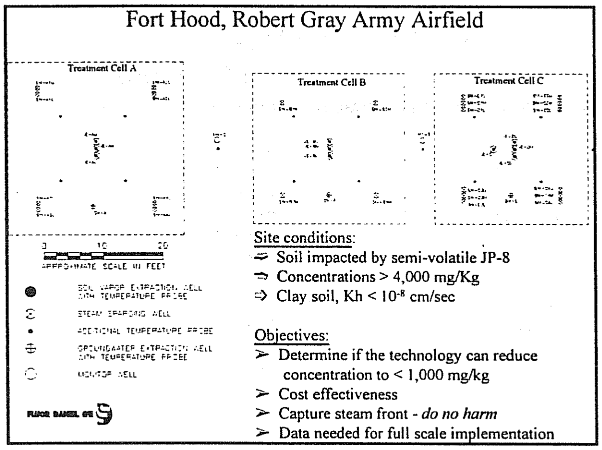
The effect of temperature on the viscosity of several hydrocarbons. Note that water has a value of 1.0 and that glycerol and cresol are plotted on the right axis, while that for the #6 fuel refers to the left axis.



Increase in vapor pressure with temperature for several hydrocarbons.



Vapor Pressure vs Temperature



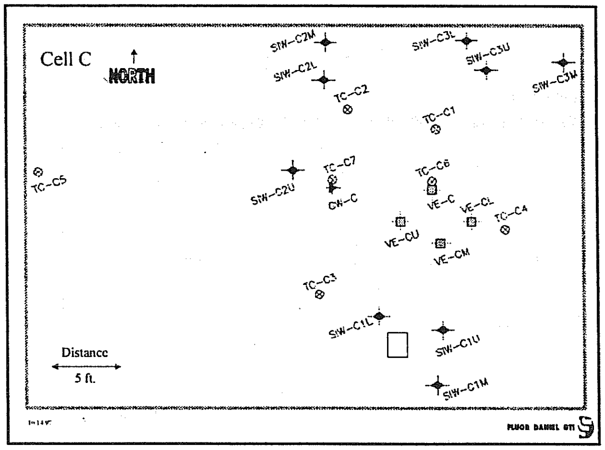
Fort Hood, Robert Gray Army Airfield

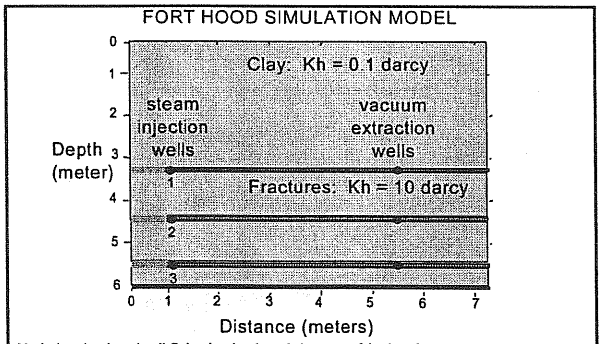
Site conditions:

- ⇒ Soil impacted by semi-volatile JP-8
- ⇒ Concentrations > 4,000 mg/Kg
- ⇒ Clay soil, Kh < 10^{-8} cm/sec

Objectives:

- ➢ Determine if the technology can reduce concentration to < 1,000 mg/kg
- ➢ Cost effectiveness
- ➢ Capture steam front - *do no harm*
- ➢ Data needed for full scale implementation





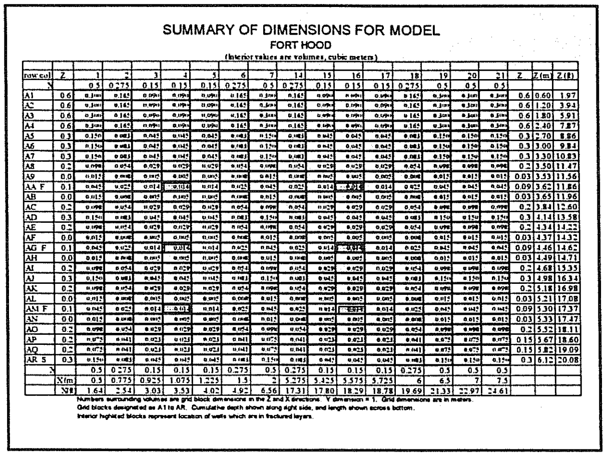
FORT HOOD SIMULATION MODEL

Vertical section through cell C showing the planned placement of the three fractures at depths of 3.5, 3.5 and 5.5 meters. Only half of a diagonal is shown since the layout is symetric about the injection well.

The bulk lithology is taken to be a dense clay with a horizontal permeability of 0.1 and a vertical permeability of 0.05 darcy.

The fractures are assumed to be filled with a well graded sand with a uniform permeability of 10 darcy.

The water table will be maintained at 6.5 meters by pumping from a fourth fracture installed at that depth.



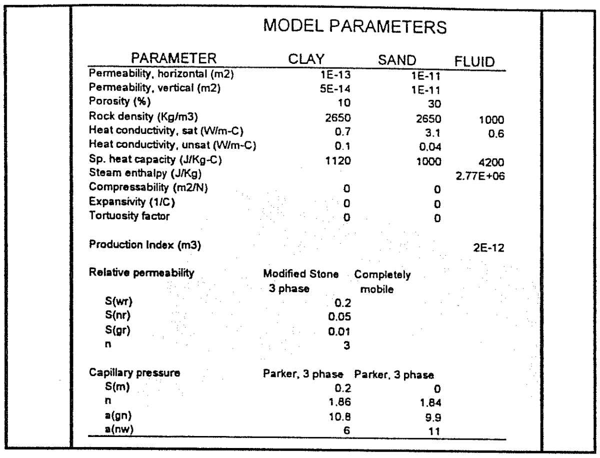
SUMMARY OF DIMENSIONS FOR MODEL

FORT HOOD

(Interior values are volumes, cubic meters)

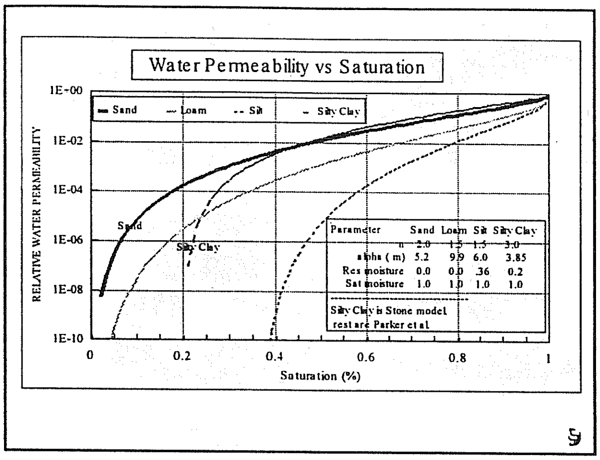
row col	Z	1	2	3	4	5	6	7	14	15	16	17	18	19	20	21	Z	Z(m)	Z(ft)
X		0.5	0.275	0.15	0.15	0.15	0.275	0.5	0.275	0.15	0.15	0.15	0.275	0.5	0.5	0.5			
A1	0.6	0.300	0.165	0.090	0.090	0.090	0.165	0.300	0.165	0.090	0.090	0.090	0.165	0.300	0.300	0.300	0.6	0.60	1.97
A2	0.6	0.300	0.165	0.090	0.090	0.090	0.165	0.300	0.165	0.090	0.090	0.090	0.165	0.300	0.300	0.300	0.6	1.20	3.94
A3	0.6	0.300	0.165	0.090	0.090	0.090	0.165	0.300	0.165	0.090	0.090	0.090	0.165	0.300	0.300	0.300	0.6	1.80	5.91
A4	0.6	0.300	0.165	0.090	0.090	0.090	0.165	0.300	0.165	0.090	0.090	0.090	0.165	0.300	0.300	0.300	0.6	2.40	7.87
A5	0.3	0.150	0.083	0.045	0.045	0.045	0.083	0.150	0.083	0.045	0.045	0.045	0.083	0.150	0.150	0.150	0.3	2.70	8.86
A6	0.3	0.150	0.083	0.045	0.045	0.045	0.083	0.150	0.083	0.045	0.045	0.045	0.083	0.150	0.150	0.150	0.3	3.00	9.84
A7	0.3	0.150	0.083	0.045	0.045	0.045	0.083	0.150	0.083	0.045	0.045	0.045	0.083	0.150	0.150	0.150	0.3	3.30	10.83
A8	0.2	0.098	0.054	0.029	0.029	0.029	0.054	0.098	0.054	0.029	0.029	0.029	0.054	0.098	0.098	0.098	0.2	3.50	11.47
A9	0.0	0.015	0.008	0.005	0.005	0.005	0.008	0.015	0.008	0.005	0.005	0.005	0.008	0.015	0.015	0.015	0.03	3.53	11.56
AA F	0.1	0.045	0.025	0.014	0.014	0.014	0.025	0.045	0.025	0.014	0.014	0.014	0.025	0.045	0.045	0.045	0.09	3.62	11.86
AB	0.0	0.015	0.008	0.005	0.005	0.005	0.008	0.015	0.008	0.005	0.005	0.005	0.008	0.015	0.015	0.015	0.03	3.65	11.96
AC	0.2	0.098	0.054	0.029	0.029	0.029	0.054	0.098	0.054	0.029	0.029	0.029	0.054	0.098	0.098	0.098	0.2	3.84	12.60
AD	0.3	0.150	0.083	0.045	0.045	0.045	0.083	0.150	0.083	0.045	0.045	0.045	0.083	0.150	0.150	0.150	0.3	4.14	13.58
AE	0.2	0.098	0.054	0.029	0.029	0.029	0.054	0.098	0.054	0.029	0.029	0.029	0.054	0.098	0.098	0.098	0.2	4.34	14.22
AF	0.0	0.015	0.008	0.005	0.005	0.005	0.008	0.015	0.008	0.005	0.005	0.005	0.008	0.015	0.015	0.015	0.03	4.37	14.32
AG F	0.1	0.045	0.025	0.014	0.014	0.014	0.025	0.045	0.025	0.014	0.014	0.014	0.025	0.045	0.045	0.045	0.09	4.46	14.62
AH	0.0	0.015	0.008	0.005	0.005	0.005	0.008	0.015	0.008	0.005	0.005	0.005	0.008	0.015	0.015	0.015	0.03	4.49	14.71
AI	0.2	0.098	0.054	0.029	0.029	0.029	0.054	0.098	0.054	0.029	0.029	0.029	0.054	0.098	0.098	0.098	0.2	4.68	15.35
AJ	0.3	0.150	0.083	0.045	0.045	0.045	0.083	0.150	0.083	0.045	0.045	0.045	0.083	0.150	0.150	0.150	0.3	4.98	16.34
AK	0.2	0.098	0.054	0.029	0.029	0.029	0.054	0.098	0.054	0.029	0.029	0.029	0.054	0.098	0.098	0.098	0.2	5.18	16.98
AL	0.0	0.015	0.008	0.005	0.005	0.005	0.008	0.015	0.008	0.005	0.005	0.005	0.008	0.015	0.015	0.015	0.03	5.21	17.08
AM F	0.1	0.045	0.025	0.014	0.014	0.014	0.025	0.045	0.025	0.014	0.014	0.014	0.025	0.045	0.045	0.045	0.09	5.30	17.37
AN	0.0	0.015	0.008	0.005	0.005	0.005	0.008	0.015	0.008	0.005	0.005	0.005	0.008	0.015	0.015	0.015	0.03	5.33	17.47
AO	0.2	0.098	0.054	0.029	0.029	0.029	0.054	0.098	0.054	0.029	0.029	0.029	0.054	0.098	0.098	0.098	0.2	5.52	18.11
AP	0.2	0.075	0.041	0.023	0.023	0.023	0.041	0.075	0.041	0.023	0.023	0.023	0.041	0.075	0.075	0.075	0.15	5.67	18.60
AQ	0.2	0.075	0.041	0.023	0.023	0.023	0.041	0.075	0.041	0.023	0.023	0.023	0.041	0.075	0.075	0.075	0.15	5.82	19.09
AR S	0.3	0.150	0.083	0.045	0.045	0.045	0.083	0.150	0.083	0.045	0.045	0.045	0.083	0.150	0.150	0.150	0.3	6.12	20.08
X		0.5	0.275	0.15	0.15	0.15	0.275	0.5	0.275	0.15	0.15	0.15	0.275	0.5	0.5	0.5			
	X(m)	0.5	0.775	0.925	1.075	1.225	1.5	2	5.275	5.425	5.575	5.725	6	6.5	7	7.5			
	X(ft)	1.64	2.54	3.03	3.53	4.02	4.92	6.56	17.31	17.80	18.29	18.78	19.69	21.33	22.97	24.61			

Numbers surrounding volumes are grid block dimensions in the Z and X directions. Y dimension = 1. Grid dimensions are in meters.
Grid blocks designated as A1 to AR. Cumulative depth shown along right side, and length shown across bottom.
Interior highlited blocks represent location of wells which are in fractured layers.



MODEL PARAMETERS

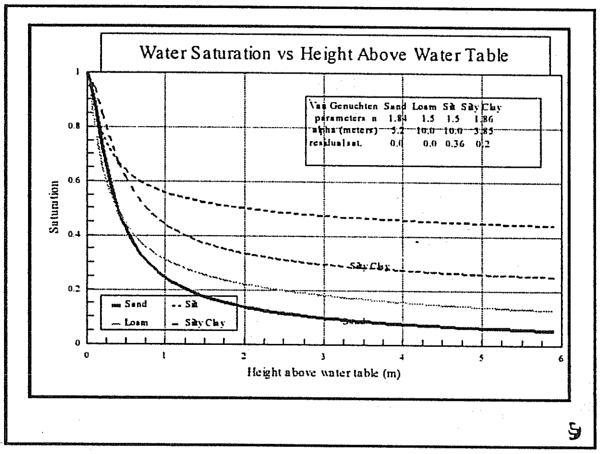
PARAMETER	CLAY	SAND	FLUID
Permeability, horizontal (m2)	1E-13	1E-11	
Permeability, vertical (m2)	5E-14	1E-11	
Porosity (%)	10	30	
Rock density (Kg/m3)	2650	2650	1000
Heat conductivity, sat (W/m-C)	0.7	3.1	0.6
Heat conductivity, unsat (W/m-C)	0.1	0.04	
Sp. heat capacity (J/Kg-C)	1120	1000	4200
Steam enthalpy (J/Kg)			2.77E+06
Compressability (m2/N)	0	0	
Expansivity (1/C)	0	0	
Tortuosity factor	0	0	
Production Index (m3)			2E-12
Relative permeability	Modified Stone 3 phase	Completely mobile	
S(wr)	0.2		
S(nr)	0.05		
S(gr)	0.01		
n	3		
Capillary pressure	Parker, 3 phase	Parker, 3 phase	
S(m)	0.2	0	
n	1.86	1.84	
a(gn)	10.8	9.9	
a(nw)	6	11	



Water Permeability vs Saturation

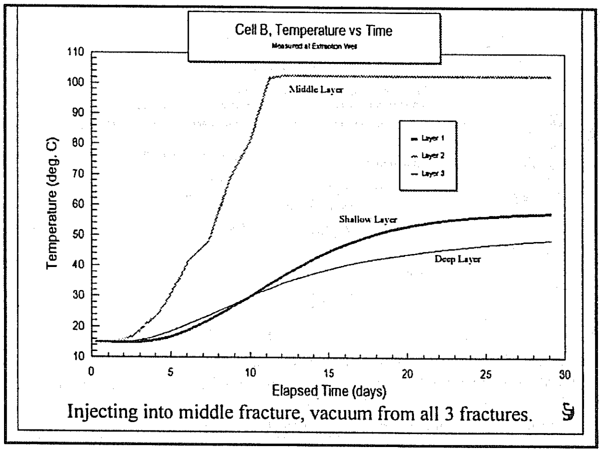
Parameter	Sand	Loam	Silt	Silty Clay
n	2.0	1.5	1.5	3.0
alpha (m)	5.2	9.9	6.0	3.85
Res moisture	0.0	0.0	.36	0.2
Sat moisture	1.0	1.0	1.0	1.0

Silty Clay is Stone model
rest are Parker et al



Water Saturation vs Height Above Water Table

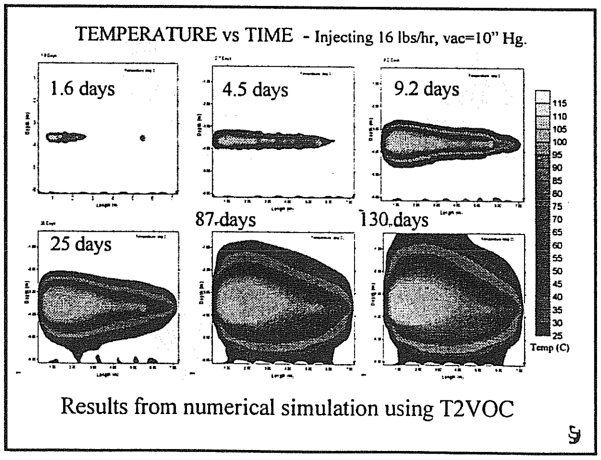
Van Genuchten parameters	Sand	Loam	Silt	Silty Clay
n	1.84	1.5	1.5	1.86
alpha (meters)	5.2	10.0	10.0	3.85
residual sat.	0.0	0.0	0.36	0.2



Cell B, Temperature vs Time

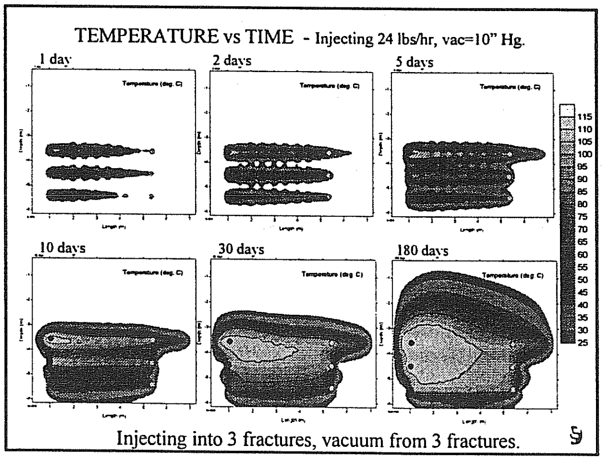
Measured at Extraction Well

Injecting into middle fracture, vacuum from all 3 fractures.



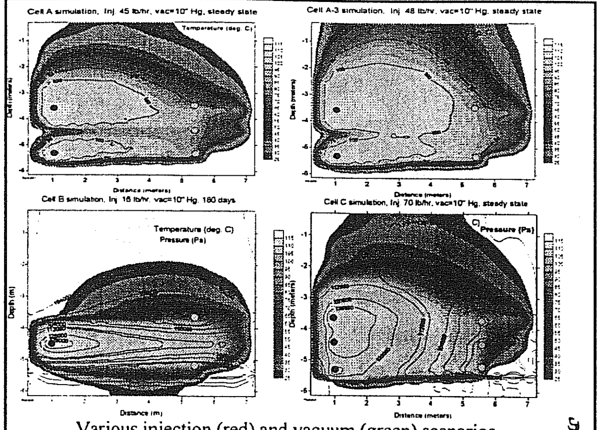
TEMPERATURE vs TIME - Injecting 16 lbs/hr, vac=10" Hg.

Results from numerical simulation using T2VOC



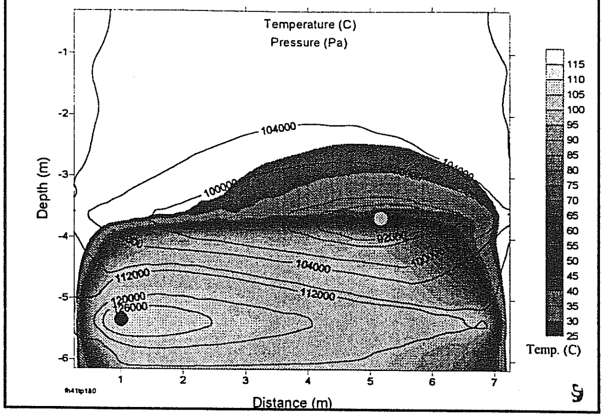
TEMPERATURE vs TIME - Injecting 24 lbs/hr, vac=10" Hg.

Injecting into 3 fractures, vacuum from 3 fractures.

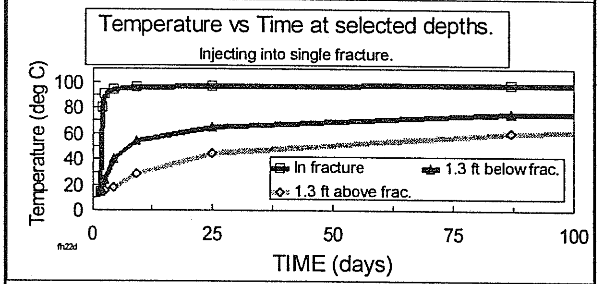


Various injection (red) and vacuum (green) scenarios.

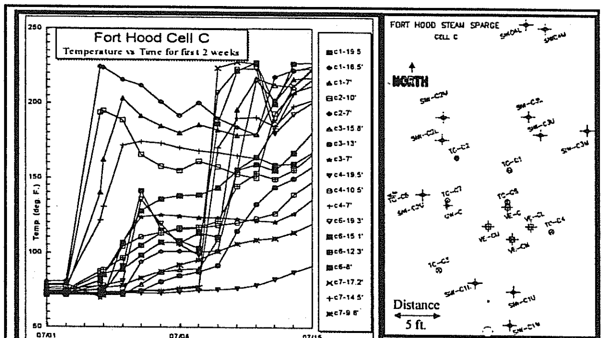
Top and bottom fractures, Inj 16 lb/hr, vac = 10" Hg,



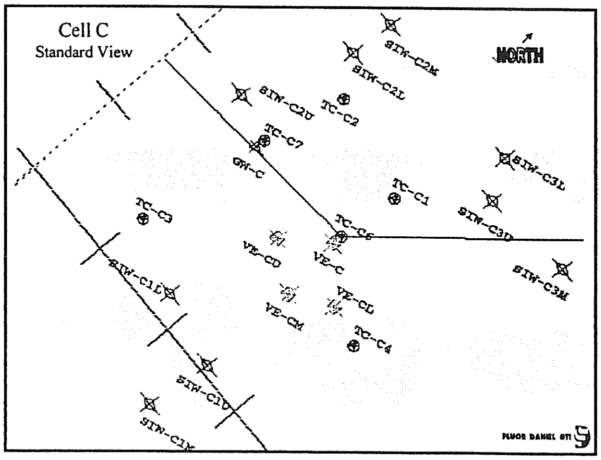
TIME SERIES - Injecting 16 lbs/hr, vac=10" Hg.

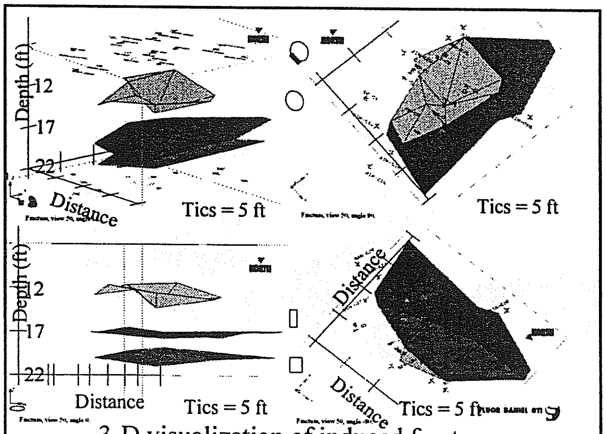


Numerical simulation showing the effectiveness of the sand filled fracture to provide a pathway for the steam is demonstrated by the rapid change in temperature at the extraction point, with steam breakthrough occurring in less than 10 days. In the clay, at 1.3 ft (0.45 m) above and below the fracture significantly longer times are required for heating to occur.

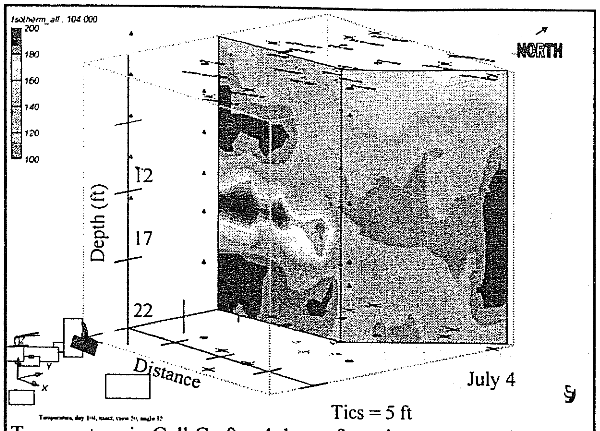


Observed heating in response to steam injection.

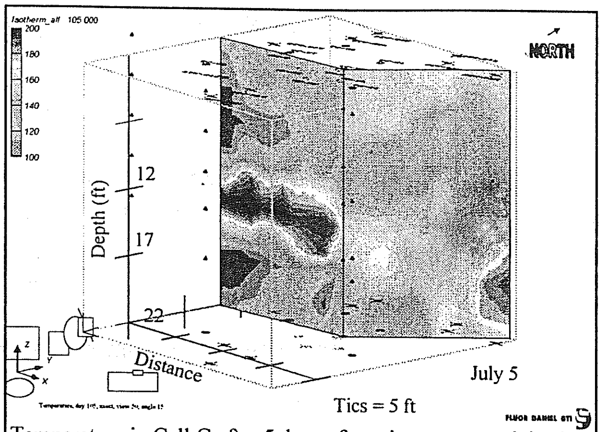




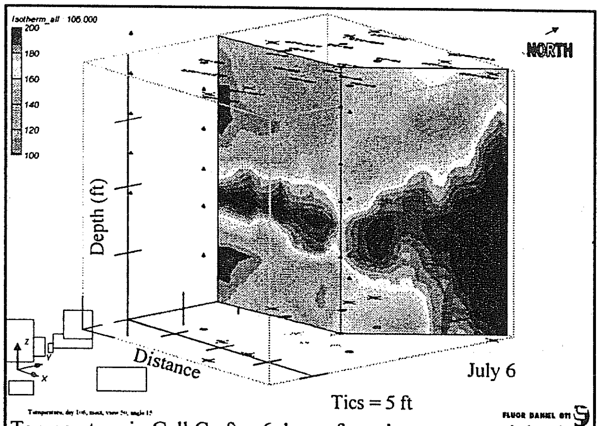
3-D visualization of induced fractures.



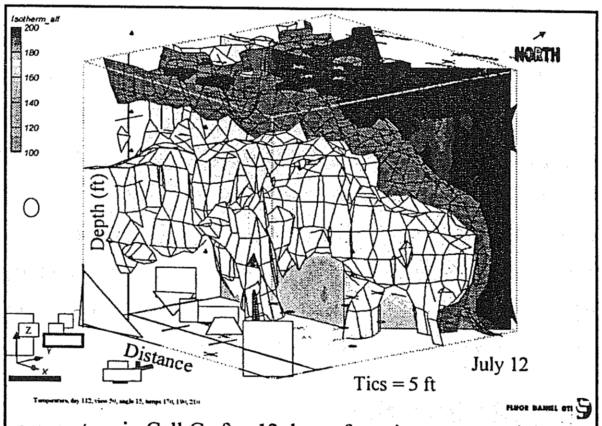
Temperature in Cell C after 4 days of continuous steam injection



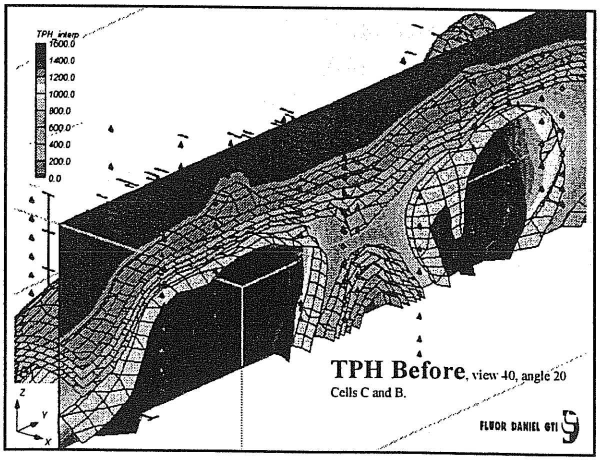
Temperature in Cell C after 5 days of continuous steam injection



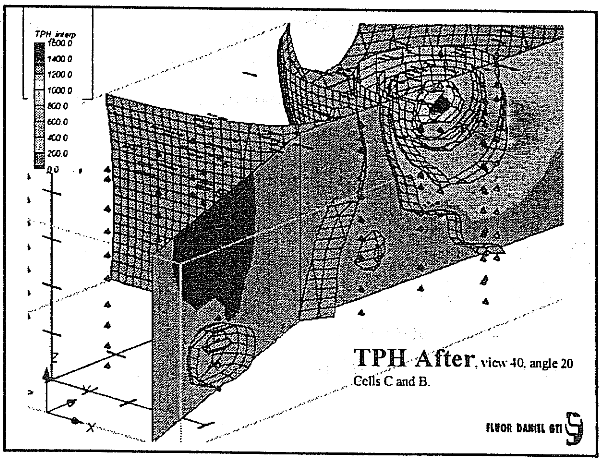
Temperature in Cell C after 6 days of continuous steam injection



emperature in Cell C after 12 days of continuous steam injection



TPH Before, view 40, angle 20
Cells C and B.



TPH After, view 40, angle 20
Cells C and B.