

# Predictive Modeling Using the STARS Code

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# Predictive Modeling Using the STARS Code

Kenrick H. Lee

## 1. Purpose

The STARS (STeam and Additive Reservoir Simulator) code, a thermal enhanced oil recovery simulator, was used for predictive modeling of dynamic stripping at the gasoline pad. The focus of this work was to perform calculations to predict the impact of steam injection on the distribution of gasoline products in the soil, and to gain insight into the relative importance of the relevant flow and transport mechanisms. The results provided project management with useful design information on such items as well patterns, and the effectiveness of different injection and withdrawal schemes.

In the early phase of modeling, a number of preliminary runs were made. The purpose of these runs was to address questions on code performance, and also to examine the behavior of the flow system under simplified conditions. Information gained from these earlier runs was used to design larger input data sets for simulations that better model the behavior of the system under steam injection.

This chapter presents a description of the STARS code, followed by:

1. Simulations to evaluate the performance of coupled electrical heating and steam injection versus steam injection alone, applied to a hypothetical, heterogeneous, two-dimensional soil domain contaminated with benzene.
2. A fully three-dimensional, nonisothermal, simulation of dynamic stripping in the lower steam zone, including the full well pattern with six injectors and a single extractor. Electrical heating was not included in this analysis.
3. A fully three-dimensional simulation to examine the recovery of benzene from the lower steam zone, using simple isothermal extraction, without fluid injection.

## 2. The STARS Code

STARS, developed by the Computer Modeling Group (CMG) of Alberta, Canada, is a fully implicit, nonisothermal, four-phase (oil, water, gas, and solid fuel), multicomponent numerical model for simulating the coupled transport of heat, steam and other vapors, liquid water, oil and oil components including volatile organic compounds (VOCs). A detailed description of the model is presented by Rubin and Buchanan (1985). The basic flow

and transport mechanisms, the equations describing these mechanisms, and the solution techniques used, are described in the STARS Technical Manual (CMG, 1990a). Detailed user instructions, and a number of solved example problems are given in the STARS User's Manual (CMG, 1990b).

All three fluid phases may be mobile. Each phase may contain a variable number of components, with chemical reactions, component phase changes, and partitioning between the phases permitted. Adsorption of components onto the solid surfaces from the aqueous phase may follow a Langmuir isotherm, or adsorption data may be supplied in tabular form. Temperature effects on adsorption can be incorporated. Grid systems are block-centered, and may be cartesian, cylindrical, or curvilinear, with one, two, or three-dimensional configurations possible. Wells can operate under specified fluid flow rates or bottomhole pressures and are subject to a hierarchy of user-specified constraints. The code has a feature that allows conduction heat losses above and below a heated reservoir or aquifer. The model also features the option to use ninepoint finite difference discretisation in the x-y plane, instead of the usual fivepoint method. For problems with sharp steam fronts, use of the ninepoint option significantly reduces dependence of the numerical results on grid orientation.

A significant advantage of the STARS code is its versatility. The code is capable of modeling a wide range of fluid flow, heat and solute transport problems. These include flow and transport under water saturated and partially saturated conditions, reactive chemical transport with adsorption and phase changes, and strongly nonisothermal, multiphase, multicomponent flow and transport, such as steam injection and electrical heating of geologic media contaminated by VOCs. The code can be used to simulate air stripping for the reclamation of soils contaminated by VOCs and other volatile contaminants. In situ combustion can also be modeled.

There are also some disadvantages to consider when using STARS, particularly for chemical transport application in soil and groundwater contamination studies, where finer mesh sizes are required. Because of the wide range of calculations performed by the code in modeling a multicomponent, multiphase system, execution times are generally long for field-scale simulations. For example, simulation of the dynamic stripping demonstration might require over 3 weeks of CPU time on a Sun SPARC II workstation. With such long execution times, modeling costs tend to be high, and it is often not practical to perform an adequate number of sensitivity analyses. There are also a number of other problems which are related to the original design of STARS for oil reservoir simulation and not for groundwater

cleanup application. For example, the oil phase is not allowed to disappear completely from any node. Retaining a minimum oil saturation poses no problem in oil reservoir simulation where the goal is to optimize oil recovery. However, in soil and groundwater reclamation where maximum permitted concentration levels of some fuel hydrocarbons are in the parts per billion range, simulation of essentially complete cleanup is sometimes necessary. CMG has been very supportive in helping us work out or circumvent these problems. The code performed satisfactorily after some minor modifications were made by CMG.

### 3. Effect of Electrical Heating

A hypothetical two-dimensional simulation was done to examine the effects of coupled steam injection and electrical heating on benzene recovery from clays. This simple model was studied in an effort to assess the contribution of electrical heating to benzene recovery, while avoiding the complexities and long execution times associated with a full-scale, three-dimensional field simulation.

The domain, shown in Figure 1, consists of a vertical slab of sand containing a smaller slab of clay. The entire model is 10 m (32.8 ft) long, 4 m (13.1 ft) high, and 0.5 m (1.6 ft) thick. The inner clay slab is 3.5 m (11.4 ft) long and 1.5 m (4.9 ft) high. The problem was discretised into a 20 by 8 rectangular grid with a uniform grid dimension of 0.5 m. The outer edges of the flow domain are no-flow boundaries. The injector is screened only in the lowest block, while the extractor is screened throughout the height of the domain. One clay block and two sand blocks contain free product gasoline at 60% saturation.

The chemical components considered are benzene, water, and a heavy oil (a pseudocomponent). The phases are aqueous, oil, and gas. Benzene is volatile, slightly soluble in the aqueous phase, and may adsorb onto the soil solids. The heavy oil is insoluble and nonvolatile, and therefore resides exclusively in the oil phase. Benzene partitioning between the aqueous and gas phases is based on an equilibrium partitioning coefficient equal to the ratio of the pure benzene vapor pressure and the total gas pressure. Benzene partitioning between the oil and aqueous phases is based on the aqueous solubility of benzene, which increases with temperature. Adsorption data are supplied in tabular form. Water partitioning between the aqueous and gas phases is based on steam table data.

The initial benzene concentration distribution in the aqueous phase is shown in Figure 2. The peak concentration, about 34 ppm, occurs in the blocks containing free product. All remaining blocks have a benzene concentration of 10 ppm in the aqueous phase. The initial mass of benzene in the system total 0.42 kg. Steam at 95% quality was injected at 0.1 gpm of equivalent condensed cold water. The production well, which was operated simultaneously with the injector, produced at a fixed bottomhole pressure of 350 kPa (51 psig).

Three separate runs were made. In the first run, all clay blocks were heated electrically at a power density of 100 W/m<sup>3</sup> during steam injection. In the second run, steam injection was implemented without electrical heating. Isothermal injection and extraction were examined in the third run. The simulation time was 200 days.

For the two nonisothermal runs, the temperature distribution at various times is shown by the isotherms in Figure 3. Temperatures with electrical heating are compared to those without electrical heating. At day 2 it is apparent that the clay is heated at a slower rate than the sand because steam is preferentially flowing through the higher-permeability sand. At day 5, temperatures inside the clay remain much lower than temperatures in the sand, setting up sharp temperature gradients directed from the outer edges of the clay towards the center. These temperature gradients decrease as the clay is heated. For the electrically-heated clay, temperature gradients decrease more rapidly, and are eventually reversed, as seen at day 20. After 100 days of combined steam injection and electrical heating, temperatures in the interior of the clay slab are substantially higher than those in the sand. Without electrical heating, the 100-day temperature field is more uniform, with no significant temperature differences between the two soil types.

The benzene mass recovery history for the three cases considered are compared in Figure 4. Figure 4a shows details of recovery during the first 20 days, and Figure 4b presents the recovery history for the entire 200-day simulation period. The thermal methods recover benzene at a much higher rate than the isothermal method, because the thermal loading produce rapid volatilization and mobilization of the contaminant. For each of the two thermal runs, about 0.25 kg of benzene is extracted from the system during the first 5 days of operation. This initial benzene mass was removed mainly from the sands, and the effect of electrical heating is not apparent during this early period. However, at later times when most of the remaining contaminant mass is located in the clay, steaming alone is clearly ineffective while the coupled steam injection and electrical heating system continues

to remove benzene. The recovery rate is progressively slower with time. A mass of 0.39 kg, or 92% of the initial benzene in place, was recovered in the first 100 days of operation. After 200 days, a total of 1.2 g of benzene remained, predominantly in the clay, and the peak concentration was 1.8 ppm.

For the thermal runs, Figure 5 shows the effect of electrical heating on the aqueous phase concentration history at a node located close to the center of the clay slab. This is the clay node that initially contained free product. For both runs, concentrations initially increase because the aqueous phase solubility of benzene increases with temperature. However, high temperatures generated by electrical heating in the clay cause the development of strong fluid pressure gradients in the low-permeability soil. These pressure gradients drive benzene in the liquid and gas phases away from the center of the clay and into the flowing steam in the sand. The result is a decrease in benzene concentration within the clay.

The unique pressure distribution generated as a result of electrically heating the clays seems to be an important phenomenon affecting benzene recovery. Aqueous phase pressure distributions after 20 days of thermal recovery are shown in Figure 6. Figure 6a shows the pressures with electrical heating while Figure 6b shows the pressures without electrical heating. With electrical heating, sharp pressure gradients are developed within the clay, with lower pressures at the clay-sand interface and higher pressures close to the center of the clay slab. Similar pressure gradients are not developed when the soil is heated by steam injection alone, even after steaming for sufficiently long periods to attain clay temperatures in excess of 130 C. This difference in pressure distributions explains the inability of steam injection alone to effectively remove benzene from the clay. *Even at higher clay temperatures from steam injection alone, pressure gradients sufficiently large to drive fluids containing benzene out of the clay are not created. When the clay is electrically heated from within, strong pressure gradients, with higher pressures close to the center of the clay, are generated to create fluid fluxes out of the clay soil and into the sand.*

In summary, these simulation results show that steam injection and vacuum extraction alone will be ineffective in the remediation of heterogeneous soils containing significant concentrations of gasoline hydrocarbons in the lower-permeability fraction. However, the remediation would be significantly more effective if electrical heating of the low-permeability soils is applied to complement steam injection and vacuum extraction. In addition, the results show that thermal methods are much more effective than

isothermal methods.

## **4. Full Pattern Simulation of Lower Steam Zone Stripping**

### **4.1. Flow Domain and Discretization**

A three-dimensional simulation using the entire pattern, including all seven wells, was made to predict the effect of steam injection and vacuum extraction in the lower steam zone. The entire pattern was modeled because no approximate symmetry element could be found. The injection perimeter was not circular, and benzene concentrations varied widely. Moreover, soil heterogeneity and spatial variations in aquifer thickness made the choice of a symmetry element even more inappropriate. For these runs, we included soil heterogeneity and anisotropy, as well as variations in aquifer thickness.

The region modeled is the lower steam zone and sections of the overlying aquitard in the gasoline pad area. The six injectors were located roughly on the perimeter of an ellipse, with a single producer inside the ellipse. Figure 7 shows well locations and x-y grid dimensions in the immediate gasoline pad area. Finer grid sizes are used close to the wells and larger sizes at greater distances away from the wells. The flow domain is discretized into 40x40x4 blocks, giving a total of 640 blocks. The four levels have block thicknesses of 1.83 m (6 ft) for Level 1 (the lowest level) and 1.22 m (4 ft) for each for the three remaining levels, giving a total domain thickness of 5.49 m (18 ft). Based on pump test and laboratory data, the permeability was set at 3 md for the clays, 100 md for silts, and 50 to 100 d for the aquifer soils which are sands and gravels. Porosities were averaged at 0.39 for silts and clays, and 0.31 for sands and gravels. Also from laboratory measurements, a horizontal to vertical anisotropy ratio of 2.4 was used for all soils. Site-specific relative permeability and capillary pressure data were not available and therefore typical data for the site soils were estimated from the literature. The chemical components and phases modeled are identical to those considered in the two-dimensional simulation described earlier. Adsorption data for benzene at ambient temperature were available from laboratory tests, but no data on temperature effects were available and therefore had to be estimated. Laboratory data were supplied by Dorothy Bishop's Laboratory. Thermal properties of the soil were also estimated from values in the literature.

The aquifer thickness at any x-y location is determined by the combined thickness of the sand and gravel blocks at that location. As shown in Figure

8, aquifer thickness in the gas pad area varies between about 2.43 m (8 ft) and 5.49 m (18 ft). The aquifer pinches out east and west of the gas pad area. No hydrologic boundaries are evident to the north and south.

#### 4.2. Initial and Boundary Conditions

Since no hydrologic boundaries were observed to the north and south, constant head boundaries were used at sufficiently large distances from the wells. No-flow boundaries were used to the east and west to simulate aquifer pinchout. Initial pressure head at the base of the aquifer was 8.84 m (29 ft) of water. Initial benzene concentrations, obtained from borehole sampling, were supplied by Weiss Associates. Benzene concentrations were reported as mass fraction of the total sample mass, while the code accepts concentrations in the three fluid phases and adsorbed concentration on the solid. The following relationship was derived to convert from total mass fraction to mass fraction in the water phase:

$$C_w = \frac{C_T (\rho_w S_w \phi + \rho_b)}{S_w \phi + \rho_b K_d} \quad (4.1)$$

where

- $C_w$  concentration of benzene in the aqueous phase (g/g)
- $C_T$  total mass fraction of benzene in the sample (g/g)
- $\phi$  soil porosity
- $\rho_b$  dry bulk density of the soil (g/cc)
- $\rho_w$  density of the aqueous phase (g/cc)
- $S_w$  aqueous phase saturation (equal to 1.0 here)
- $K_d$  distribution coefficient for benzene in the soil (cc/g)

Initial benzene content of the oil phase was approximately 1.5% by weight.

#### 4.3. Steam Stripping

Steam was injected into the lower steam zone through all 6 injectors. Each injector operated at a specified constant rate of 5 gpm of equivalent condensed cold water. The quality of injected steam was 95%. The producer, which operated on a minimum bottomhole pressure of 76 kPa (11 psig),

was activated simultaneously with the 6 injectors. Each well was screened through all four layers. The system was simulated for a period of 16 days.

The execution time for this run was very large. The run used over three weeks of CPU time on an IBM-550 Workstation.

#### 4.3.1. Results

Figure 9 shows Level 1 temperatures at days 2, 5, 8, 10, 13, and 16. From as early as day 2, it is observed that the steam zones from injectors GIW-814 and GIW-820 are growing slower than steam zones from the other four injectors. The slower growth of the two zones is due to their locations in thicker sections of the aquifer. At day 5, some of the steam zones have coalesced, and by day 10 the only isolated steam zone is that from GIW-814. At this point the combined steam zones have a rough horseshoe shape and contaminants within the injection ellipse are not completely enclosed by steam. A cold zone exists between the wells GIW-814 and GIW-813. This kind of steam zone development will result in slower mobilization of contaminants within the injection ellipse. The problem can be overcome by injecting at a higher rate in GIW-814, forcing earlier coalescence of the steam zones from GIW-814 and GIW-813. At day 13 all the steam zones are fully coalesced.

It is apparent from Figure 9 that steam breakthrough at the producing well did not occur until sometime between days 10 and 13, even though steam had encroached to within about 3 m of the well as early as day 5. This delay in steam breakthrough was probably due to the influx of colder water drawn from the cold zone between GIW-814 and GIW-813. Therefore, pumping from the producer, with this well pattern, might actually be cooling the producer and thereby delaying steam breakthrough.

The effect of clays on the temperature distribution is shown in Figure 10. This figure shows the ten-day temperature profile along an east-west section through the producer. After 10 days of steaming, temperatures in the clays in this region are still substantially lower than values in the sand. Such slow heating of the finer-grained soils is due to their lower permeability which limits fluid fluxes, and consequently, convective heat transfer. The lower temperatures in silts and clays cause reduced volatilization of the volatile and semivolatile hydrocarbons in these soils. Even after some volatilization, contaminant removal from clays and silts is expected to proceed at a much slower rate because of the lower fluid flux due to the low permeability.

Figure 11 shows initial benzene concentrations in the lower steam zone.

This figure does not clearly show the concentrations and is meant to indicate the general contaminant distribution. The maximum concentration is about 32 ppm. The plume observed north of the injection ellipse is not expected to be recovered in the injection scheme simulated here.

Essentially full recovery within the steam zone is shown in Figure 12. Higher concentrations are observed ahead of the steam front due to recondensation of vaporized benzene. Figure 13 shows the cumulative mass of benzene extracted as a function of time. The benzene recovery rate is initially 1.2 kg/day, gradually dropping off with time. After about 14 days of steaming, the recovery rate is essentially zero. Total benzene recovered is 8.6 kg from an initial mass of 151 kg. The high-permeability aquifer soils within the injection ellipse are essentially cleaned at this point. However, high benzene concentrations still occur in the clays within the injection ellipse, and in both sands and clays outside of the ellipse. At this stage, steaming should be stopped. The major effect of additional steam injection would be to drive contaminants, carried ahead of the condensation front, further away from the gasoline pad as the steam front advances.

Concentrations in clays, both inside and outside of the injection ellipse, were essentially unaffected by the 16-day steam injection and vacuum extraction. Because of the low permeability, convective heat transfer into the silts and clays was severely limited, making heat transfer dependent on the relatively low thermal conductivity of the soil. Even after the temperatures in the clays were substantially elevated, fluid fluxes and therefore contaminant recovery remained extremely low. These results suggest that steam injection and vacuum extraction without electrical heating, will not be effective in recovering significant masses of gasoline hydrocarbons from the low-permeability fraction of heterogeneous soils at the gasoline pad. However, this technique could be used for relatively rapid recovery of these hydrocarbons from the more permeable soils.

#### 4.4. Isothermal Extraction

A base case simulation using isothermal extraction was done to assess the need for thermal recovery methods. The problem geometry, initial and boundary conditions, were identical to those for the full-pattern run described earlier. However, no fluids were injected into the aquifer; benzene recovery was effected strictly by pumping from the producing well, EW-816. The producer was pumped at 30 gpm for 100 yr. Two separate runs were made. Benzene diffusion in the aqueous phase was included in the first run,

using a diffusion coefficient of  $1.0 \times 10^{-9}$ . Diffusion was excluded in the second run, so that the effect of diffusion on the results can be examined.

Cumulative benzene recovery for the first 100 days is shown in Figure 14. The benzene is recovered at a relatively rapid but decreasing rate during the first 20 days or so. This high initial recovery represents removal from mobile NAPL saturations and high aqueous phase concentrations in the more permeable aquifer soils. At 100 days, the recovery rate is much lower, because benzene concentrations in the aqueous phase are substantially reduced, and the NAPL is immobile because saturations are reduced below the residual value. At this point, benzene concentrations in the silt and clay soils remain at essentially the initial values, and recovery is controlled by advective and diffusive fluxes through these low-permeability soils. Solute movement by liquid advection and liquid diffusion through silts and clays are extremely slow processes with significant concentration changes taking decades.

Figure 15 shows cumulative benzene recovery for the full extraction period of 100 yr. At the end of the 100-yr period, only about 40 kg of the initial 151 kg of benzene is recovered. Inclusion of diffusive transport adds only 17% to the total mass recovered, which shows that liquid advection does play a strong role in transporting the contaminant out of the clays.

Contaminant recoveries shown in Figures 13 and 14 seem to suggest that isothermal extraction compares well with steam injection and vacuum extraction. Sixteen days of steaming yielded 8.3 kg of benzene, as compared with 7.0 kg for the same period using isothermal extraction. However, steaming cleaned the higher permeability soils within the injection ellipse much more rapidly, and almost completely. Isothermal extraction is limited to recovery of dissolved contaminants and NAPL at saturations above the residual value, but the cleanup radius extends well beyond the injection ellipse. Since NAPL concentrations below the residual value can not be recovered by advection, recovery is strongly dependent on the low aqueous phase solubility of benzene. One disadvantage with steaming is that contaminants initially outside of the injection ellipse will usually not flow to the extractor, but are instead driven further away from the test area. Well location is therefore extremely important. Recovery may be increased by using cyclic injection, where periods of steam injection are followed by periods where the injectors are shutin, allowing the steam zone to collapse bringing some contaminants back into the ellipse. The long execution times made simulation of these cycles impractical.

#### **4.4.1. Summary**

These results show that steam injection and vacuum extraction without electrical heating will rapidly and efficiently cleanup benzene from the more permeable soils within the injection ellipse. Benzene masses within the silts and clays in the injection ellipse will not be significantly recovered, and essentially no benzene masses outside the ellipse will be recovered. Cyclic steam injection may improve this recovery. Isothermal pump-and-treat is not an attractive remedial option for cleanup of benzene from the gasoline pad.

### **5. Future Runs**

After completion of the Dynamic Stripping Project, history matching should be done to improve code calibration. The STARS code will then become an even more effective tool for use in designing the mop-up operation following dynamic stripping.

### **6. References**

Rubin, Barry and W. Lloyd Buchanan, "A General Purpose Thermal Model," *Soc. Pet. Eng. J.* Vol. 25, No. 2, pp. 202-214, April 1985.

CMG, *STARS Technical Manual*, Version 4.0, Computer Modeling Group, Alberta, Canada, October 1990a.

CMG, *STARS User's Manual*, Version 4.0, Computer Modeling Group, Alberta, Canada, October 1990b.

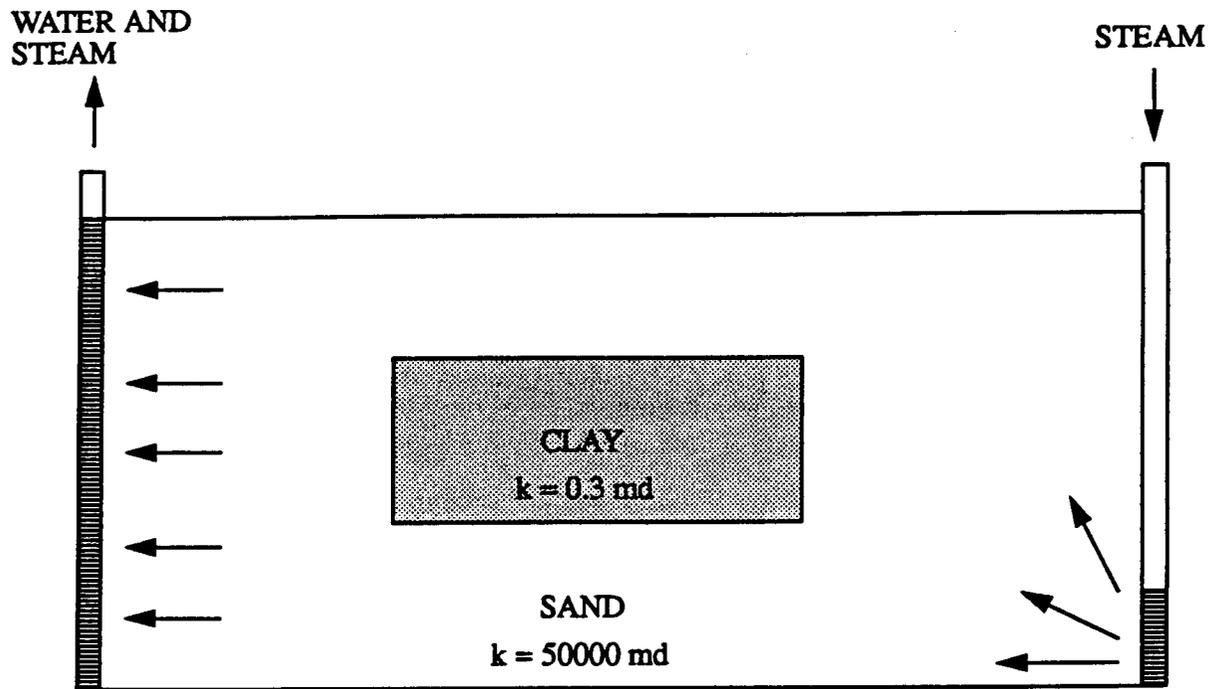


Fig. 1. Schematic of heterogeneous soil domain cleaned by combined steam injection and electrical heating.

Dynamic Stripping Project, Gas Pad  
INITIAL BENZENE CONCENTRATIONS IN AQUEOUS PHASE (ppm)  
Time = 0.0 day

5-181

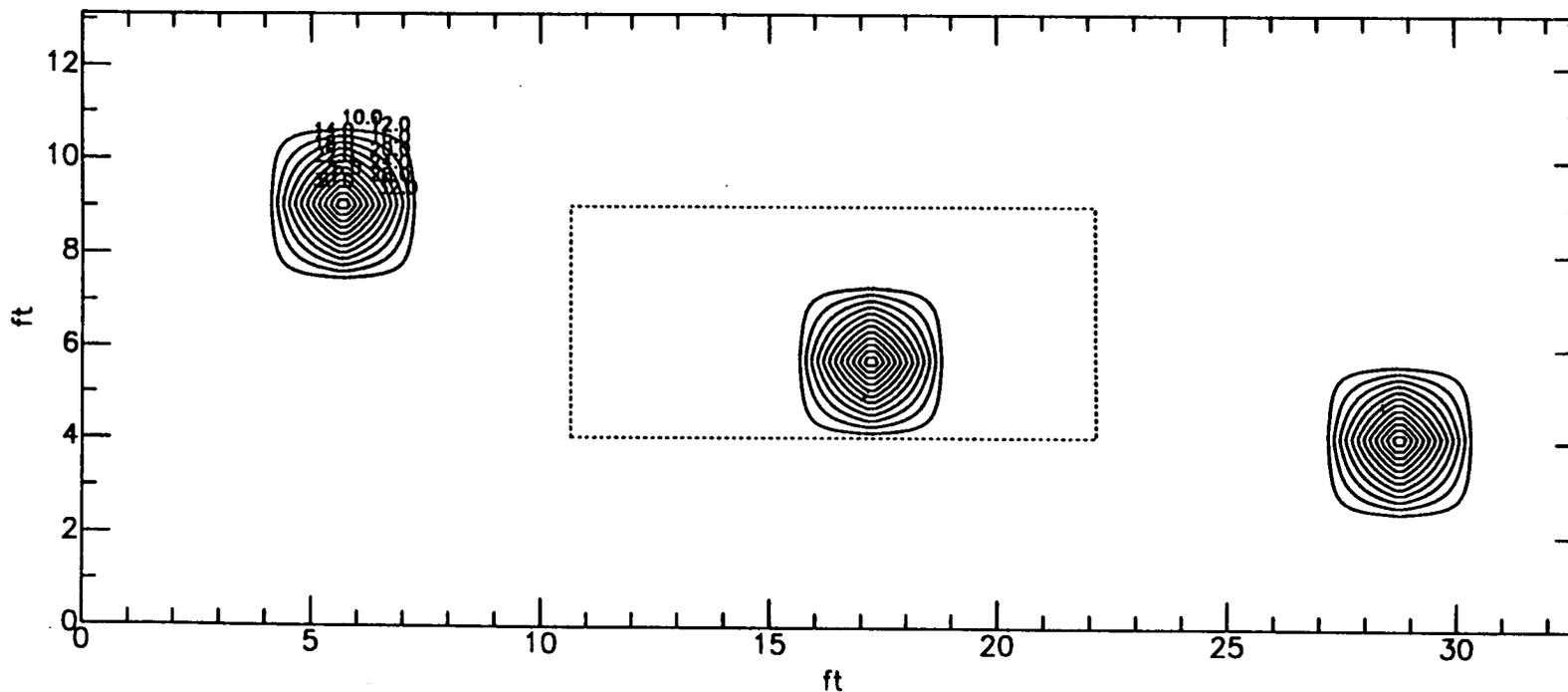


Fig. 2. Initial benzene concentrations in aqueous phase. Hatched lines indicate boundaries of clay. Maximum concentration is 32 ppm.

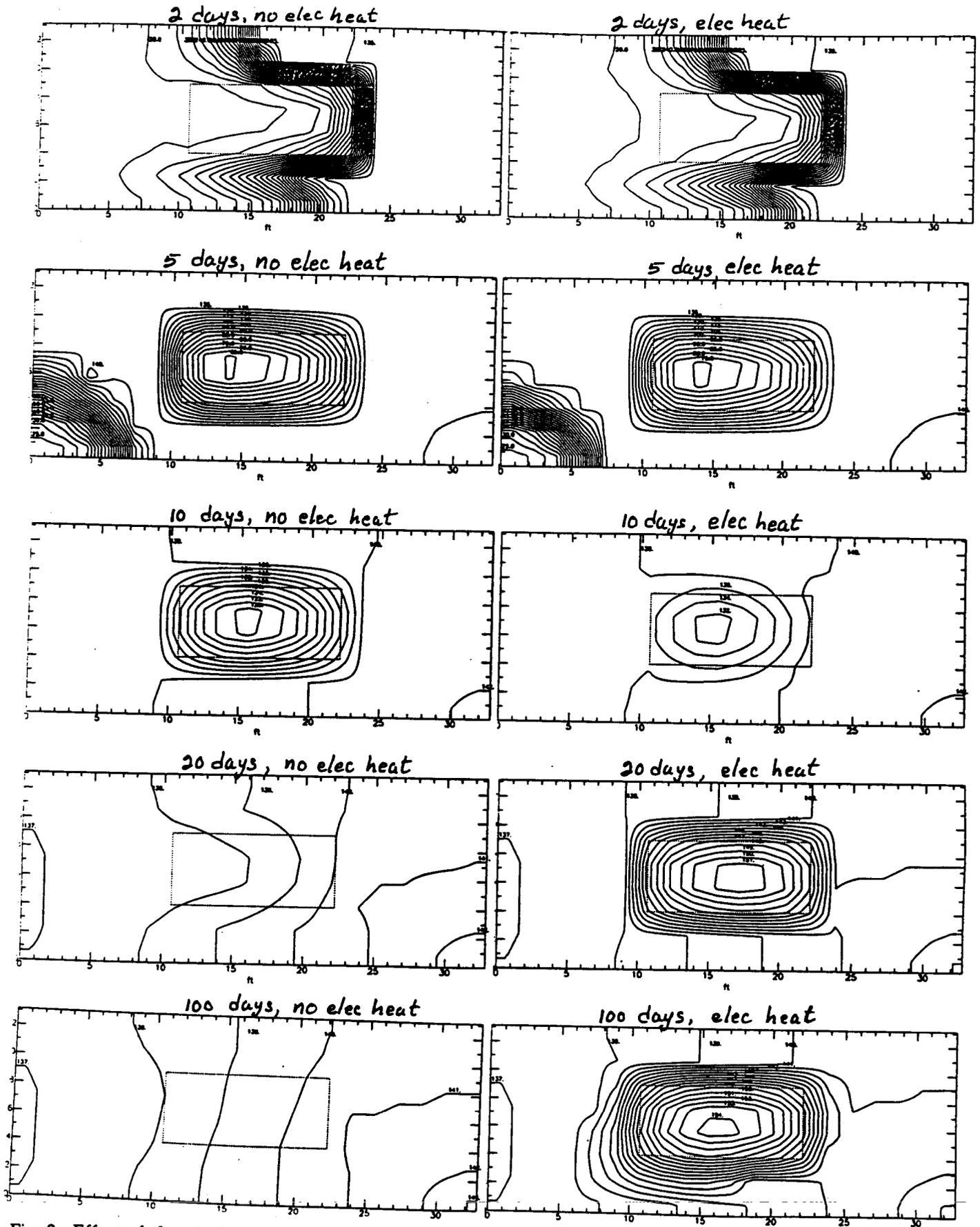
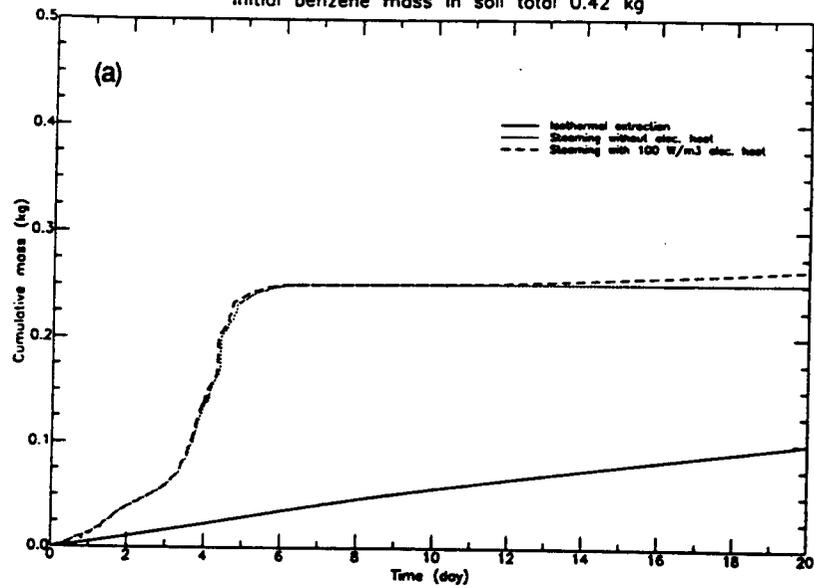


Fig. 3. Effect of electrical heating on soil temperature.

Dynamic Stripping Project, Gas Pad  
 EFFECT OF STEAM INJECTION AND ELECTRICAL HEATING ON BENZENE RECOVERY  
 Initial benzene mass in soil total 0.42 kg



Dynamic Stripping Project, Gas Pad  
 EFFECT OF STEAM INJECTION AND ELECTRICAL HEATING ON BENZENE RECOVERY  
 Initial benzene mass in soil total 0.42 kg

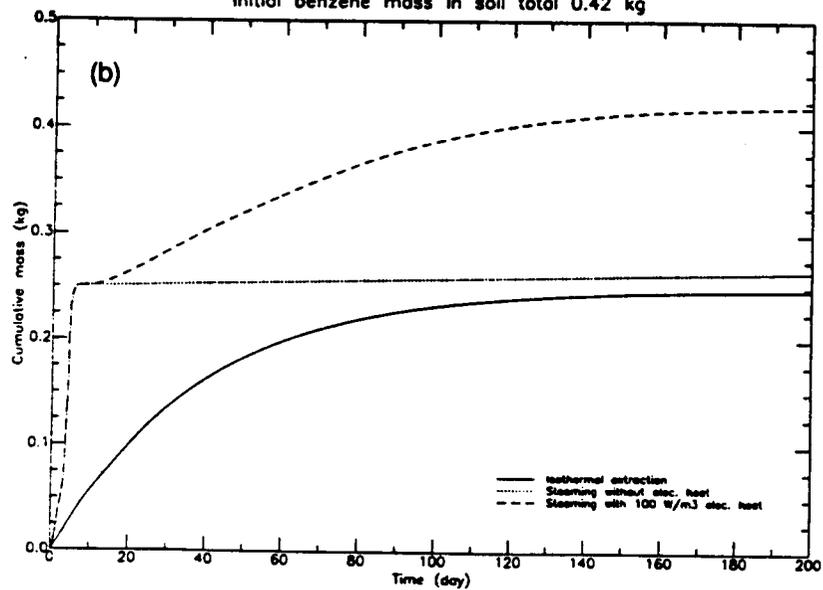


Fig. 4. Comparison of benzene recovery histories from thermal and isothermal runs.

Dynamic Stripping Project, Gas Pad  
BENZENE AQUEOUS PHASE CONCENTRATION HISTORY IN CLAY BLOCK (11,1,4)  
EFFECT OF ELECTRICAL HEATING

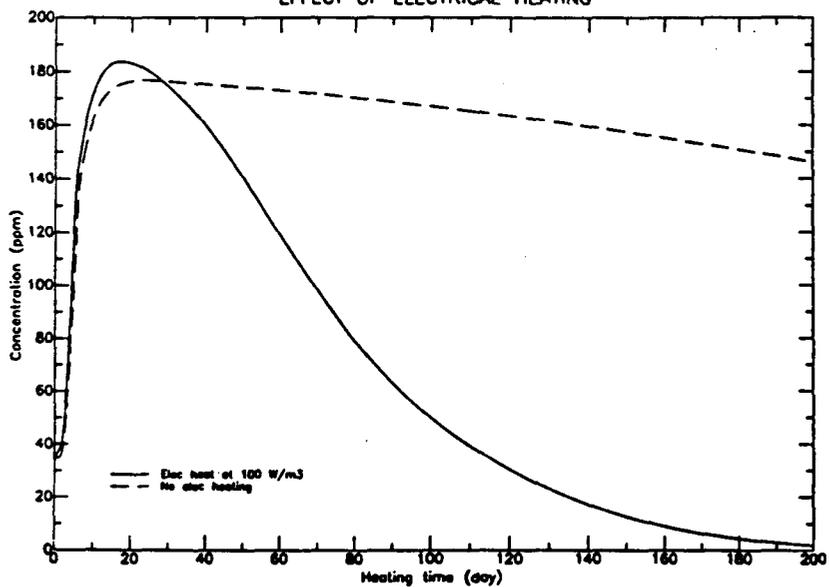
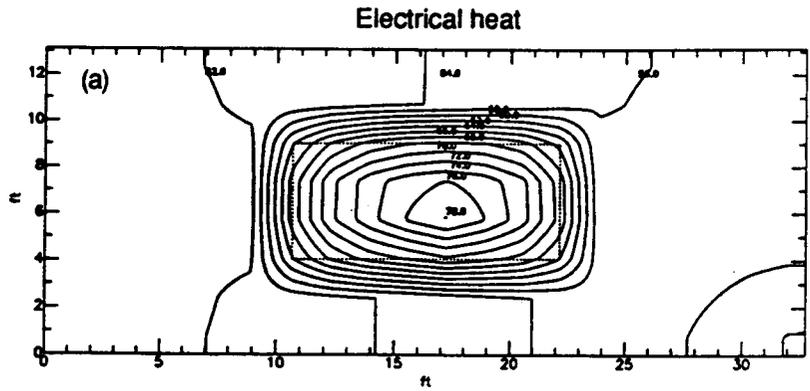


Fig. 5. Effect of electrical heating on benzene recovery from node at center of clay.

Dynamic Stripping Project, Gas Pad  
WATER PRESSURES AT 20 DAYS (psig)  
Electric heating at 100 W/m<sup>3</sup>



Dynamic Stripping Project, Gas Pad  
WATER PRESSURES AT 20 DAYS (psig)  
No electric heating

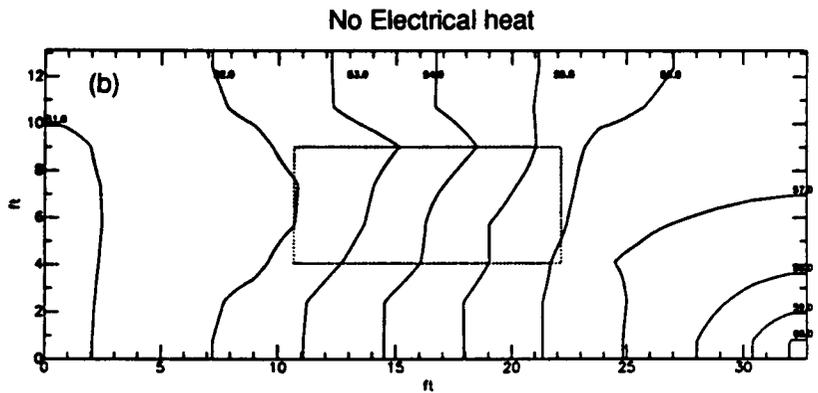


Fig. 6. Effect of electrical heat on pressure distribution.

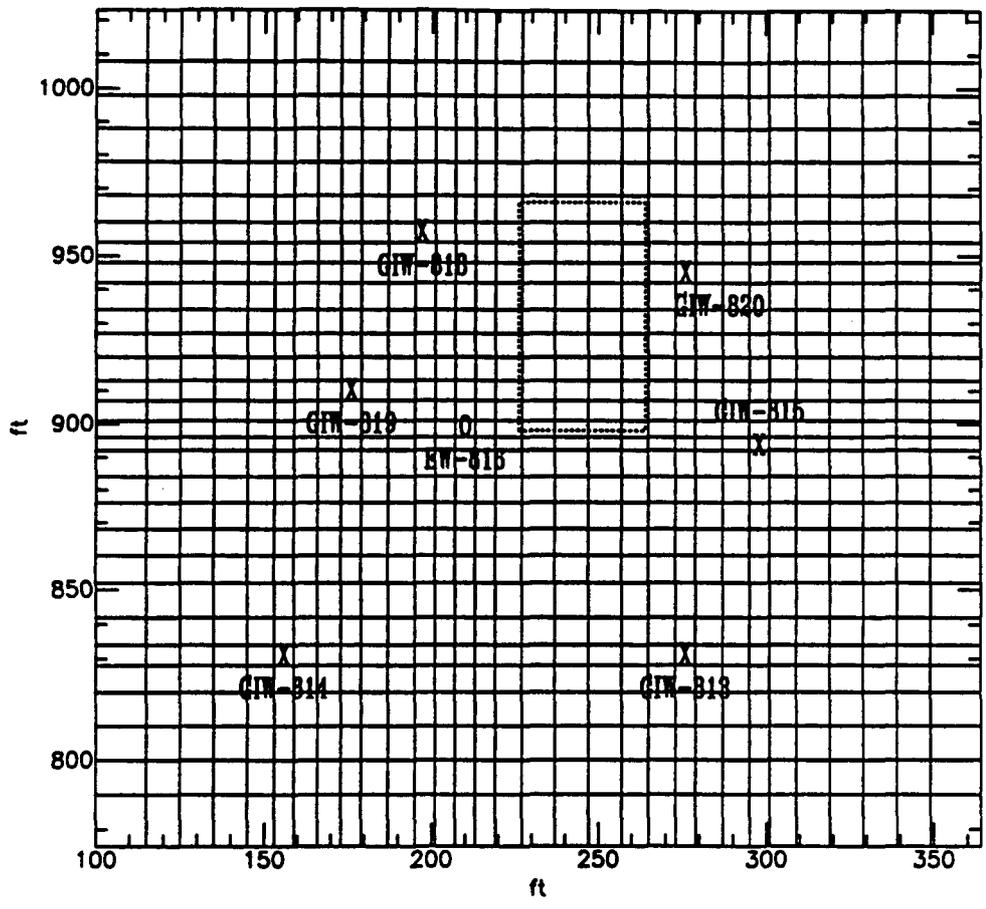


Fig. 7. Well locations and discretization in x-y-plane in the gasoline pad area. 'X' indicates location of an injector and 'O' indicates location of the extractor.

Lower Steam Zone isopach Map

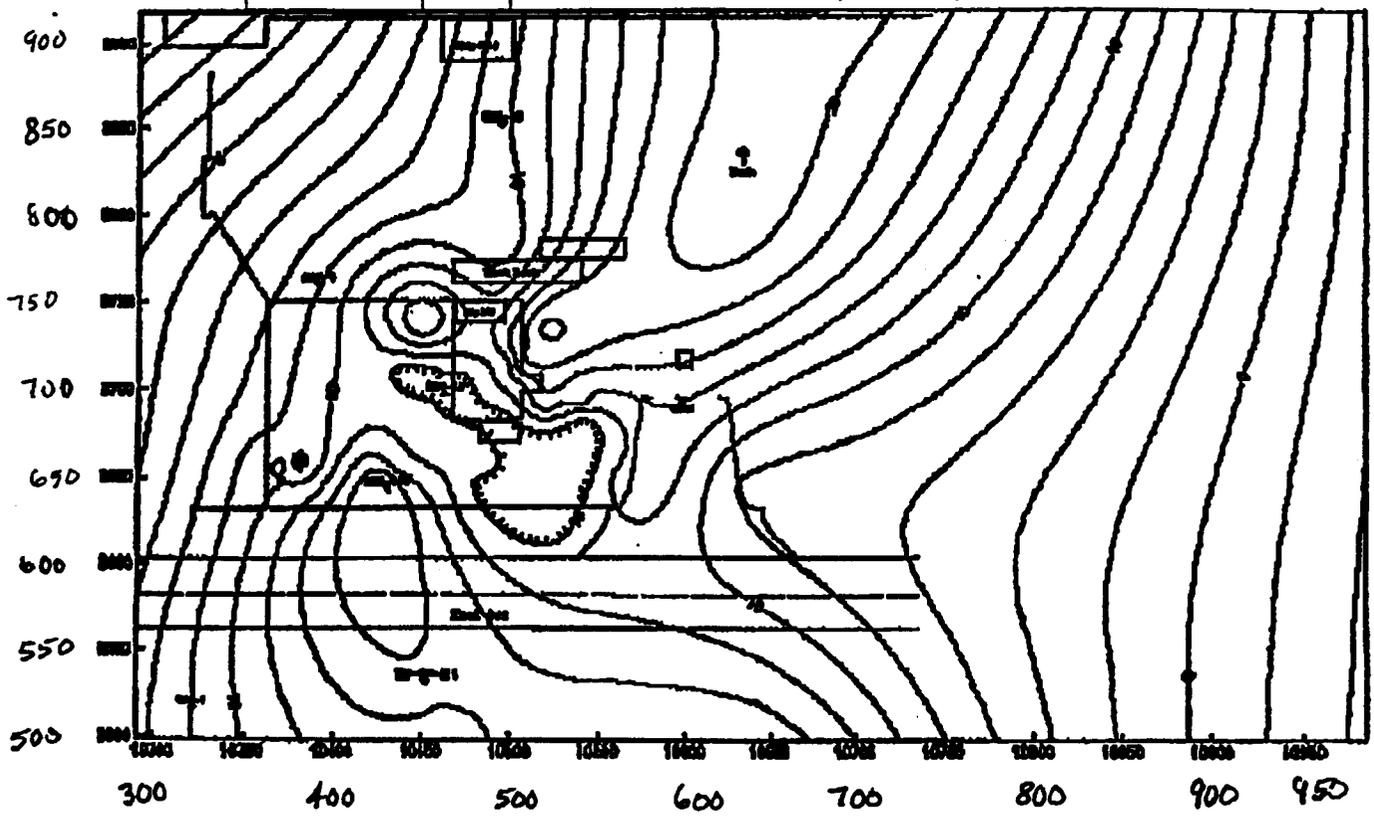


Fig. 8. Lower steam zone isopach map.

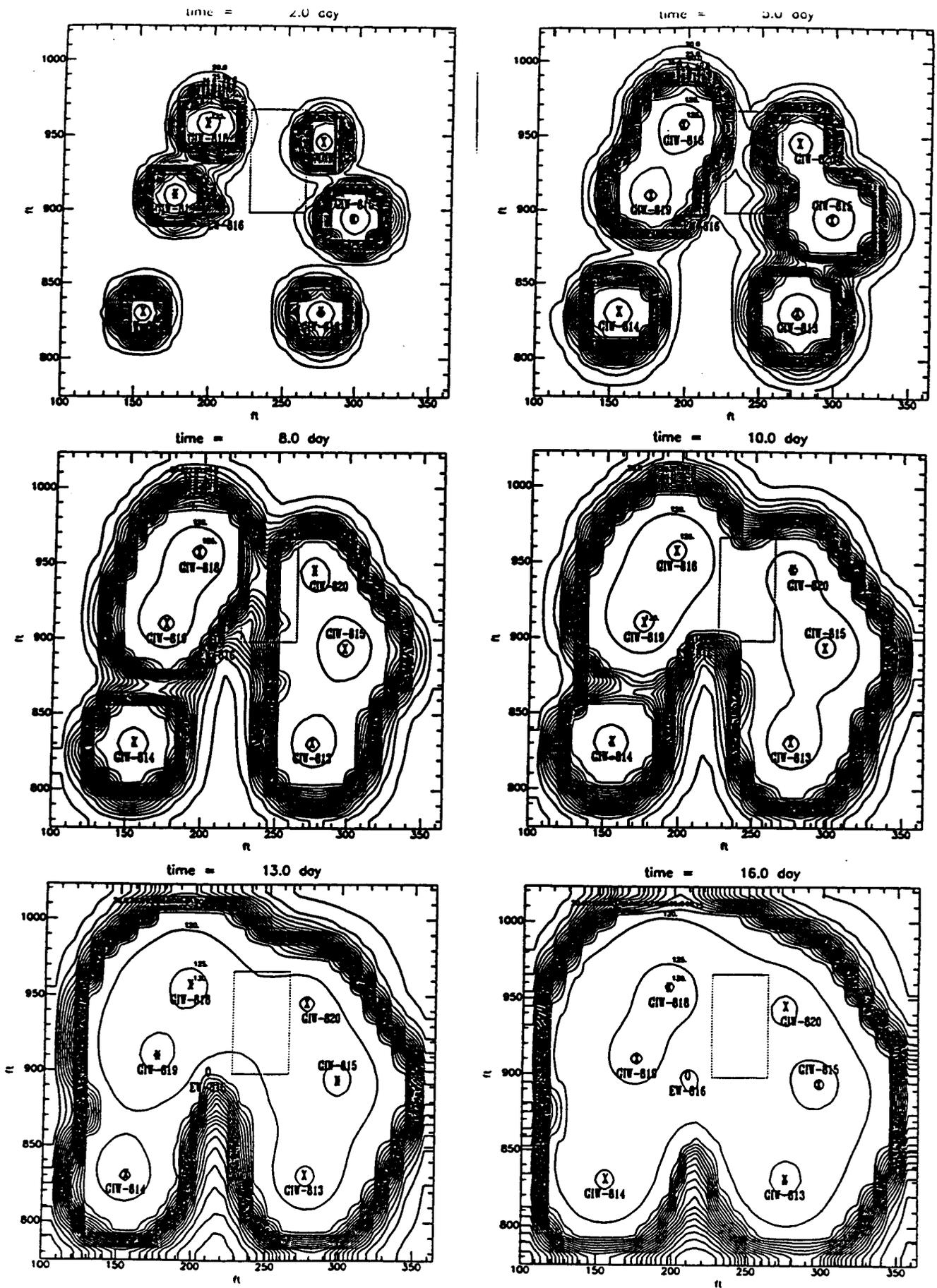


Fig. 9. Temperatures in the lower steam zone at days 2, 5, 8, 10, 13, and 16. Temperatures are shown in °C.

TEMPERATURES (C) ALONG EAST-WEST VERTICAL SECTION THROUGH PRODUCER  
 time = 10.0 day

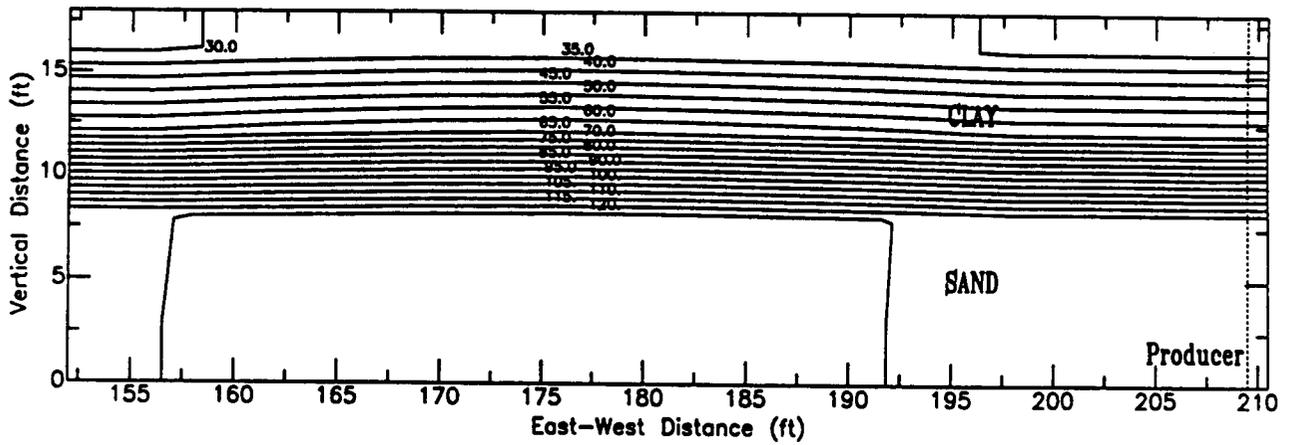
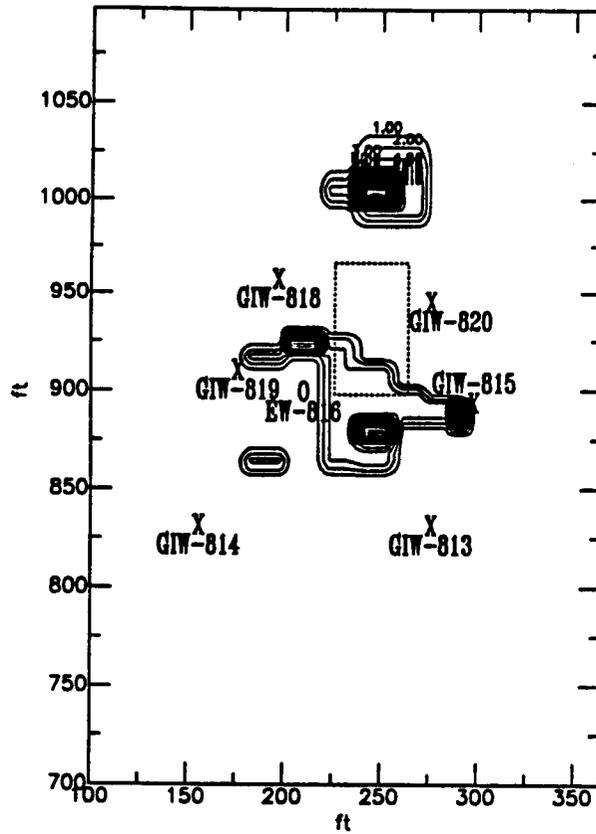


Fig. 10. East-west section through the producer showing temperatures in steam zone and in the overlying aquitard. The simulation time is 10 days.

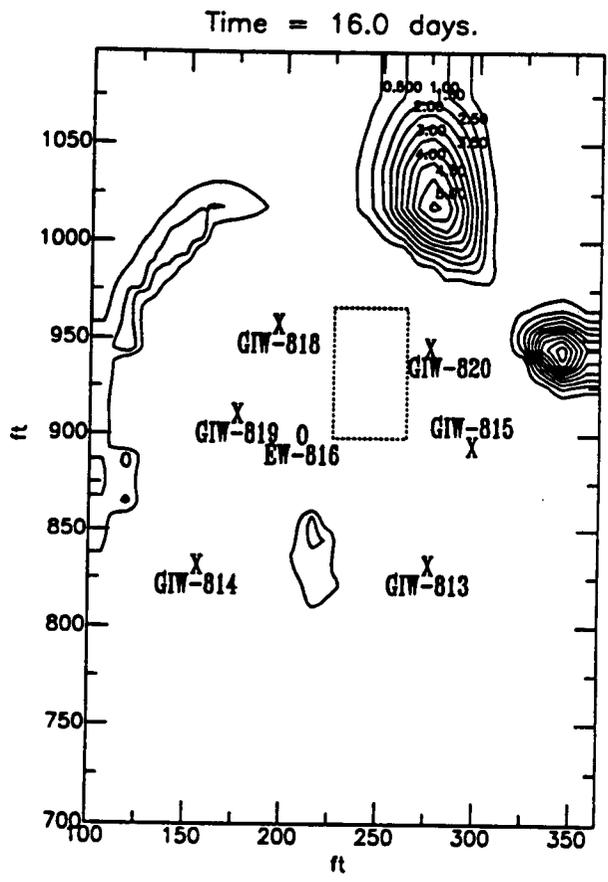
Dynamic Stripping Project, Gas Pad, Padf Runs  
INITIAL BENZENE CONCENTRATIONS IN AQUEOUS PHASE, LEVEL 1 (ppm)  
time = 0.0 Maximum Concentration = 32 ppm.



Started version: 1.7  
loc /us/loc/star 1001.egf

Thu May 6 20:00:48 1993

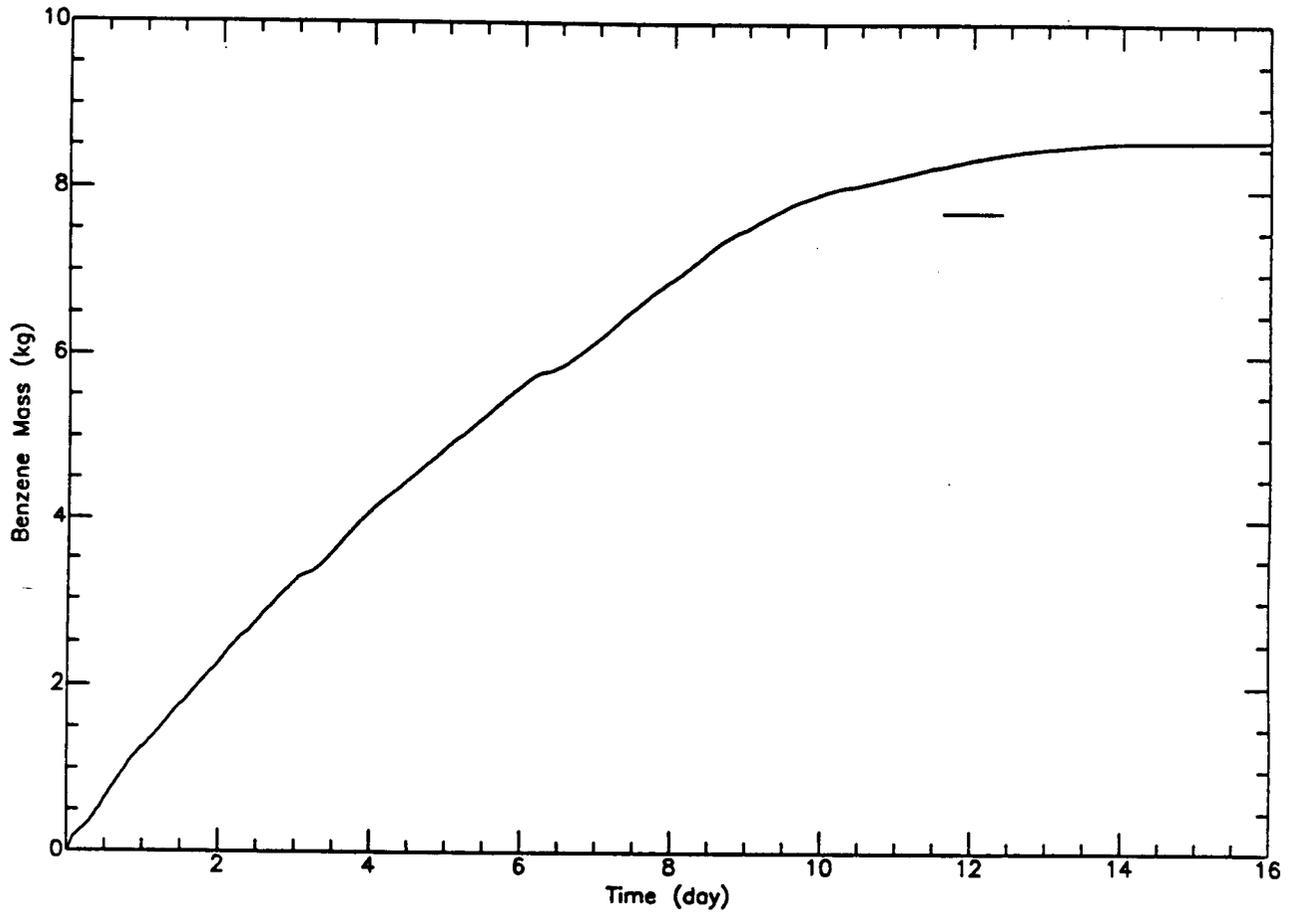
Fig. 11. Initial benzene concentrations in the aqueous phase of the lower steam zone. Maximum concentration is 32 ppm.



Startcol version: 1.7  
 loc /u/lee/star 1001.sgf

Thu May 6 09:55:17 1993

Fig. 12. Benzene concentrations in aqueous phase, level 1 (ppm).



Starbnd version: 1.7  
lee /u/lee/star 1001.sgf

Thu May 6 09:31:30 1993

Fig. 13. Cumulative benzene extraction from lower steam zone.

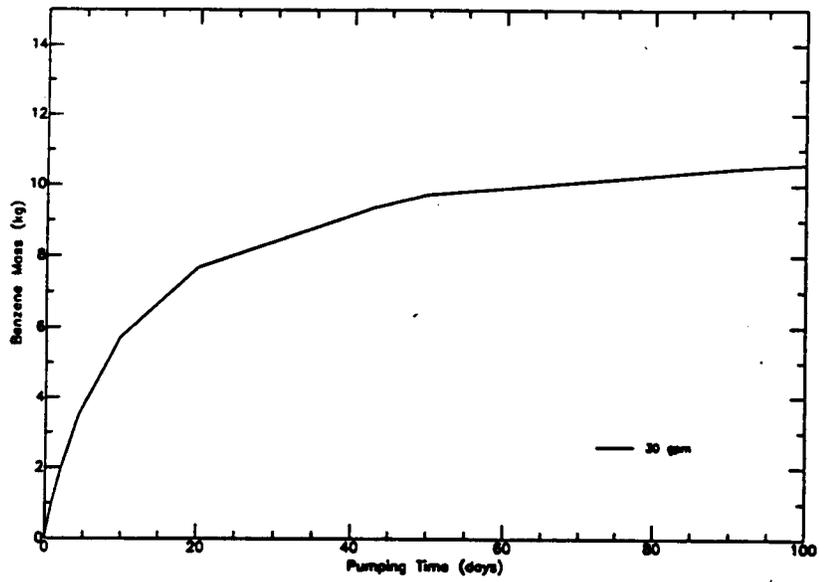


Fig. 14. Cumulative benzene recovery for 30-gpm extraction rate, pumped to 100 days.

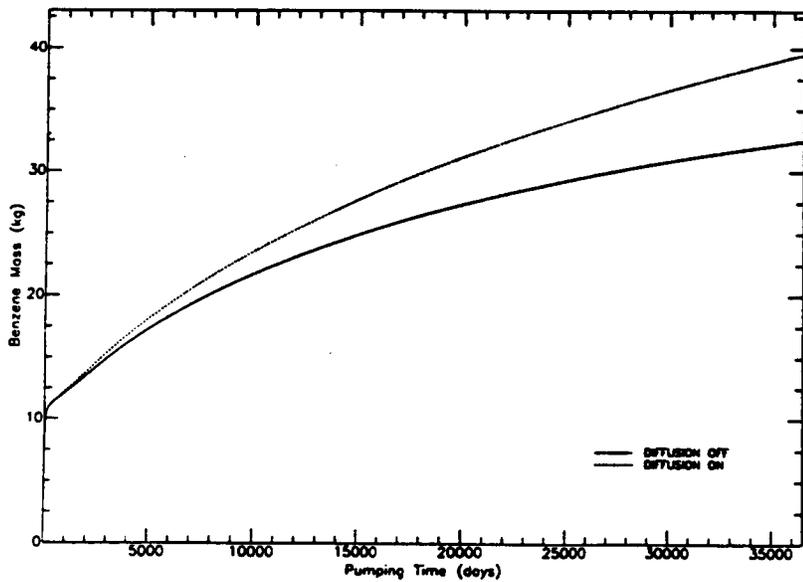


Fig. 15. Cumulative benzene recovery for 30-gpm extraction rate effect of diffusion on 100-year extraction.

