Heat and Mass Transfer in Porous Media

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ABSTRACT

Field test data on the OOSI MR3 experiments are used as a basis for exhibiting the computational capabilities of the WAFE computer code, which is a generalized tool for the analysis of heat and mass transfer in multi-dimensional domains of porous geothermal materials.

INTRODUCTION

Many geophysical processes associated with alternative energy sources involve the multiphase, multi-dimensional flow of heat and mass in porous media. Geothermal steam generation, coal gasification, and oil shale retorting are but a few examples. Furthermore, the identification and subsequent avoidance of potential environmental difficulties, which may arise as a result of the various energy extraction methods, also rely on an in-depth understanding of these processes.

In developing mathematical representations that enable us to predict and evaluate various geophysical flows, we rely heavily on the close interplay between theory, laboratory experiments, and field testing. Theory is the process of correlating the relationship between fundamental principles and observables. Comparing theoretical results with laboratory data, we adjust our models where necessary and build a predictive capability for the large-scale field events.

The fluid flows of interest involve complicated, multiphase interactions that occur on a microscopic level. Each species in the fluid can exchange mass, momentum, and energy with each other species and with its surroundings. Mass exchange results from melting, boiling, condensation, and chemical reactions. The species exchange momentum as a result of these phase transitions and by frictional interactions with each other. Energy is also exchanged during chemical reactions and during the phase transitions. The theoretical models are described by a set of mathematical equations based on macroscopic representations or averages of these microscopic processes.

A somewhat different complexity results because of the three-dimensional nature of most geophysical media. That is, non-homogeneous variations in the material and structural properties of the media often occur on a geometrical scale comparable to the length scales of the variations of the field variables. To realistically examine fluid flow in such environments, our theory must account for this multi-dimensionality.

The equations describing such fluid flows are amenable to analytic solution techniques only in very restricted circumstances. Powerful numerical solution techniques, which must be implemented on large, fast computers, usually are required to address multiphase, multi-dimensional heat and mass transfer in porous media. For the work reported below we use a computer code called WAFE[1] to numerically simulate these flows. WAFE models time-dependent, two-dimensional, three-phase heat and mass transfer in a porous medium with cylindrical or rectangular geometry.

The porous matrix is assumed to be at rest. It can be modeled as a single interconnected structure, or as a conglomeration of spherical fragments having radii characteristic of a rubblized bed. Matrix properties can vary spatially, and the permeability of any given region can be anisotropic.

APPLICATION: Modeling a Modified In-situ Retort

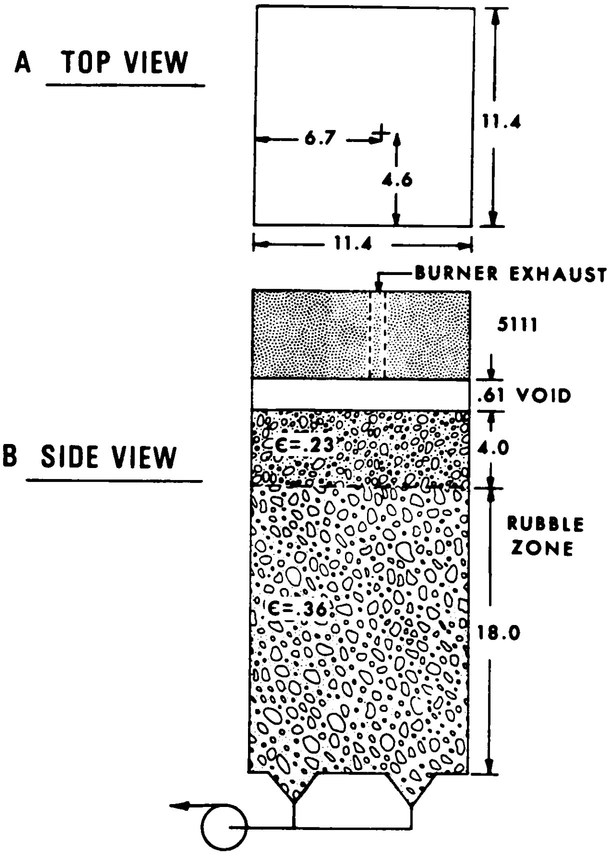
Traditional methods for obtaining oil from oil shale require the shale to be mined and transported to surface retorting facilities. The process can be very expensive because many tons of rock must be handled daily. In-situ retorting of unaltered beds appears impossible because of the low natural permeability of the shale. In-situ retorting of rubblized beds offers an economically favorable compromise. In such a modified in-situ retort the shale bed is rubblized, combining mining and blasting techniques. The fragmented rock is more permeable than the undisturbed shale and allows the convective heat and mass transport that makes subsurface retorting possible.

Complicated questions concerning the optimization of oil yield remain unanswered. Some of these questions relate to the chemistry of the oil shale extraction processes. Another crucial issue is the multi-dimensional structure of the rubblized bed. For example, given a rubble bed with nonuniform material properties and multiple injection ports for the retort fuel, we ask if the planarity of the retort front can be controlled. If it can not, large regions of shale may be excluded and the oil yield correspondingly decreased. Numerical simulation of a modified in-situ retort provides a relatively inexpensive means by which these questions can be addressed. The theoretical investigations will allow us to better design and control field retorts.

In an oil shale retort, physical and chemical processes are closely coupled. The fluid flow affects the chemistry, and the chemistry affects the fluid flow. To develop an integrated model we separate the processes, examining first the fluid dynamics and second the chemistry. In this report we discuss calculations and comparisons with field-test data that address the physical transport processes in the absence of chemistry. For this purpose we have utilized data from the OOSI MR3 field experiment.

The essential features of the field experiment are as follows. A bed of shale roughly cubicle in shape was fractured to a roughly uniform degree of rubblization, and was mined in such a way as to allow for a region of hot gas insertion through the top and gas withdrawal from the bottom. A burner operated as an inert gas generator, injecting hot combustion products and steam into the open region beneath a sill. Blowers in the bottom of the bed establish a vertical downward flow through the rubble zone. The rubble bed was extensively instrumented with cased thermocouples which estimate the rubble particle surface temperature. The test data[2] to be used for model comparisons is restricted to the burner ignition attempts during November 1980. For this test, only a negligible amount of kerogen decomposition occurred; and therefore chemical reactions need not be considered.

The MR3 experimental configuration is summarized in Figure 1. Figure 1a is a horizontal view of the rubble bed. The burner is located slightly off-center, as indicated in the figure. Figure 1b shows a vertical slice through the burner and the bed. The locations of the sill, open space, burner, and rubble bed are indicated.



MR3 RETORT CONFIGURATION
(measurements in meters)

Figure 1

Figures 2 and 3 summarize the thermocouple data at a time of 28,685 s. Figure 2 shows the x=o plane; Figure 3, the y=o plane. The temperature front in each plane has a definitely non-planar structure. Furthermore, the three-dimensionality of the bed is emphasized when the two planes are compared. In the x=o plane the flow is undercutting a thin region of lower permeability near the surface. In the y=o plane a region of reduced permeability extends to greater depth as indicated by the absence of undercutting. We discuss these aspects of the multi-dimensionality in the calculational summary below.

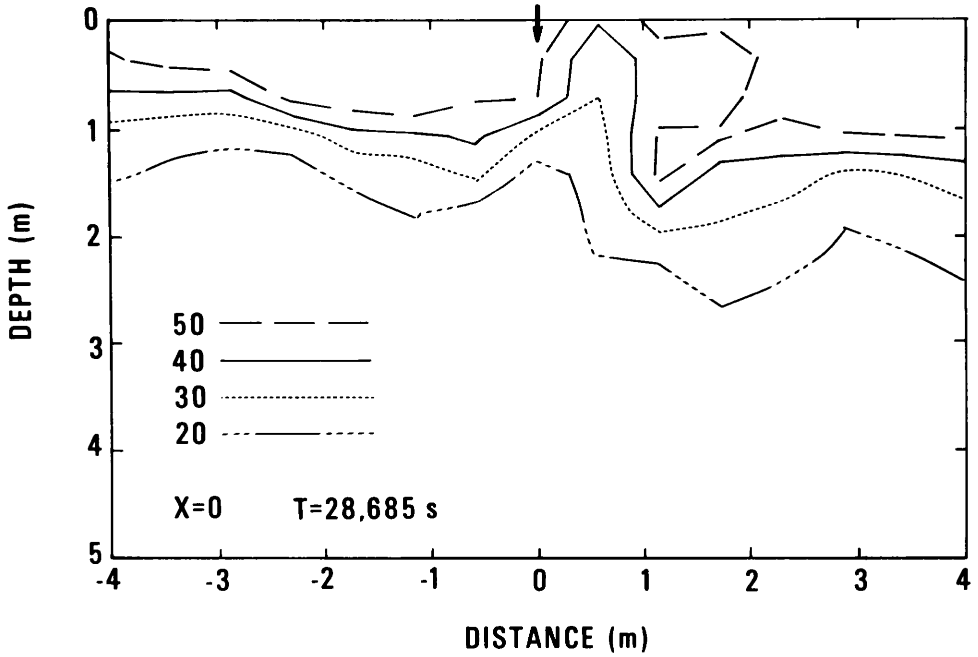


Figure 2

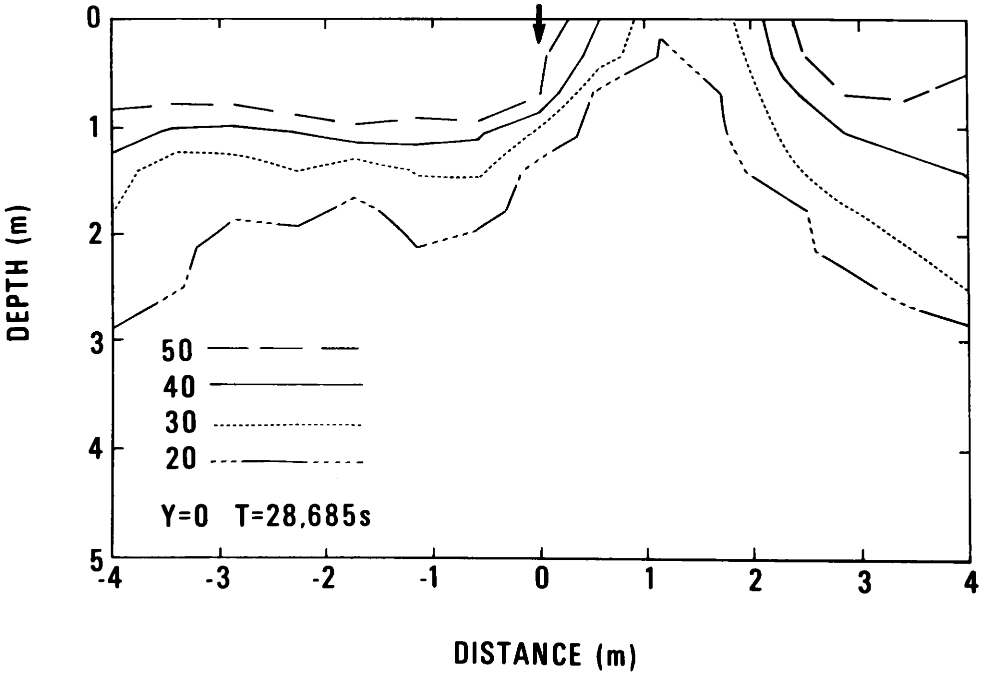


Figure 3

Three calculational configurations are investigated. Each assumes cylindrical symmetry. For the purpose of this study we need only consider the shale in the upper regions of the bed. Steam and burner gases are injected on the axis in the center of the open region. Figure 4 summarizes the three calculational configurations. In Figure 4a we show a thin annular cap of low permeability near the rubble surface. In the discussion below we refer to this as our first configuration. The second configuration is similar and is shown in Figure 4b, which shows a thin disc of low permeability in the center. The radius of the disc used in the second configuration is the same as that of the inner edge of the annulus described in the first configuration. The third configuration shown in Figure 4c, has a cylindrical core of low permeability. The core has the same radius as the disc but extends to the lower boundary of the bed. Unlike the low permeability material in the annulus and disc, the permeability in the core is lower by only a factor of 10 than that of the surrounding rubble. We assume for the low permeability disc and annulus a permeability of .01 darcy, for the rubble bed a permeability of 63 darcy, and for the core a permeability of 6.3 darcy. The various mass and energy source rates are constant over the time interval investigated. Steam and noncondensable gases are injected at the rate of 86.0 g/s and 101.2 g/s, respectively. The total energy insertion rate is 2.63×10^{12} ergs/s.

Calculations with the first configuration were designed to exhibit convection of gas, condensed water, and heat through a porous hole in an otherwise impermeable cap over the bed. This example was chosen as a cylindrically symmetric representation of the likely bed configurations leading to the results in Figures 2 and 3. Those regions are clearly evident where the heat has been appreciably convected down into the shale, for example the right side of either figure. In particular, the undercut 50 °C contour on the right side of Figure 2 suggests convection under the ledge of a low permeability cap.

The results of the calculations are shown in Figures 5 and 6 for the same elapsed time as in Figures 2 and 3. Figure 5 exhibits the pressure contours, with large gradients across the annulus, and slanting gradients below its inner edge, which tend to drive the convecting gases into an undercutting flow. The temperature contours in Figure 6, however, indicate a larger degree of undercut than shown in Figures 2 and 3. Notice that some heat has also penetrated the lateral regions of unrubblized rock, as a result of conduction.

The vertical temperature profile along the centerline in Figure 6 can be compared qualitatively with any of several vertical profiles in Figures 2 and 3. The closest resemblance appears to be along a vertical traverse near the left of center in Figure 3 or the far right of Figure 2.

To focus more particularly on the regions occluding convection, just to the right of the center in Figures 2 and 3, we performed a calculation with a central impermeable disc, the second configuration. Figure 7 shows the results, again at the same elapsed time. In this case the temperature contours resemble even more closely the experimental results, although the calculated contours still undercut the impermeable cap more strongly than indicated by the field data.

The third configuration, with intermediate permeability in a cylindrical core, was investigated to see if this configuration would even more accurately characterize the bed. The fluid temperature profiles are exhibited in Figure 8, and indeed the impediment to convection is evident, but the undercutting contours no longer occur, especially in agreement with Figure 3.

CONCLUSION:

Although some geophysical flows may be one one-dimensional, we have observed in both field tests and numerical calculations that bed inhomogeneities can significantly alter the flow configurations to three-dimensionality. Numerical analysis not only serves as a means for characterizing the properties of such a bed, but more important, allows for a systematic analysis of the consequences of such inhomogeneities. For practical oil shale retorting developments, we believe these considerations may be crucial to the optimization of yield.

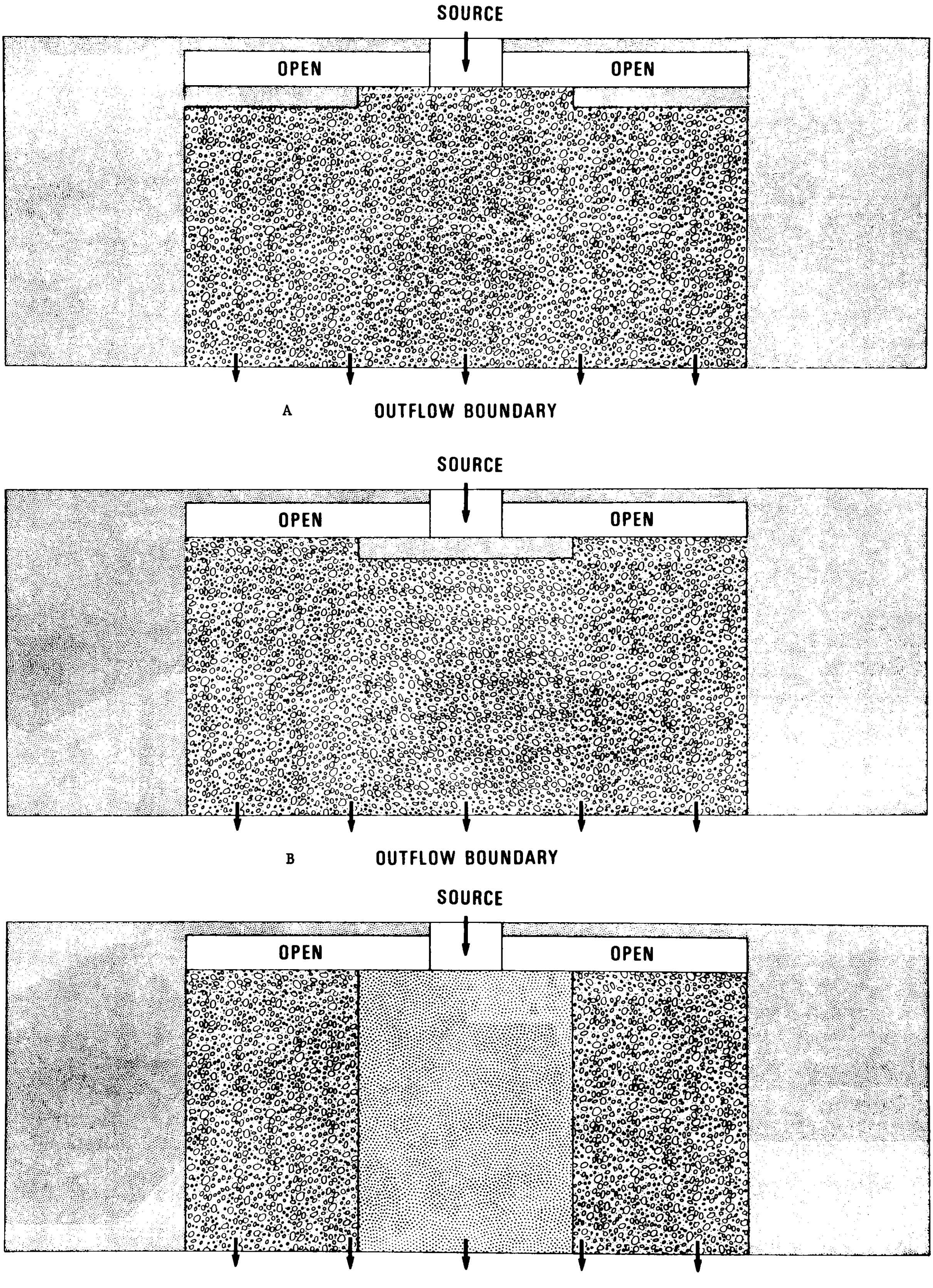

SOURCE
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Figure 4

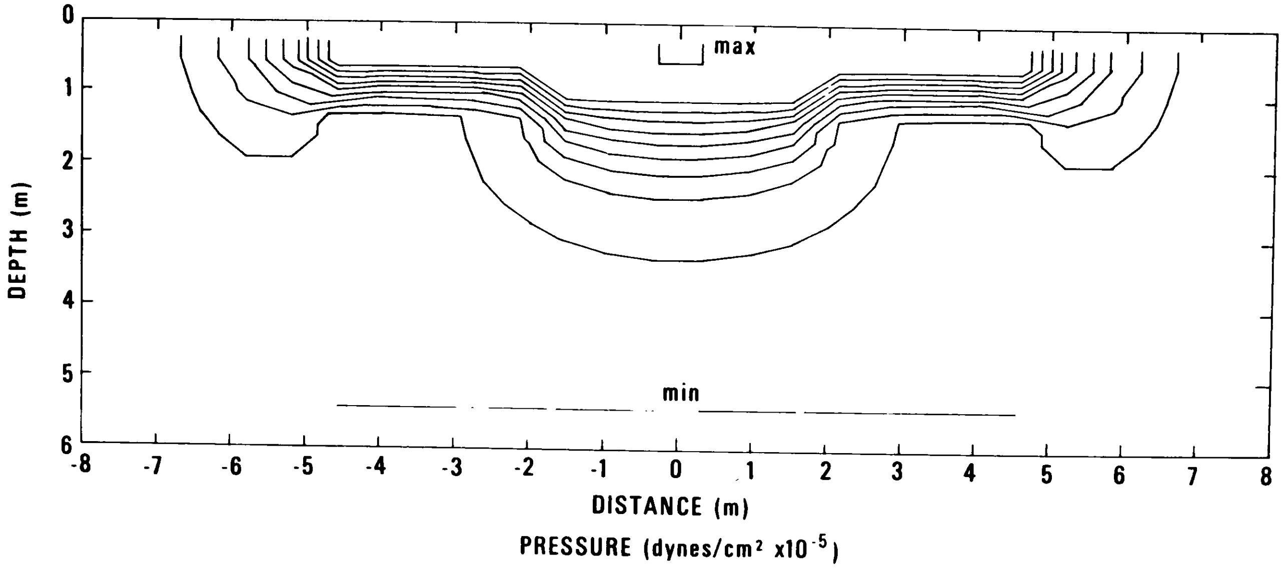


Figure 5

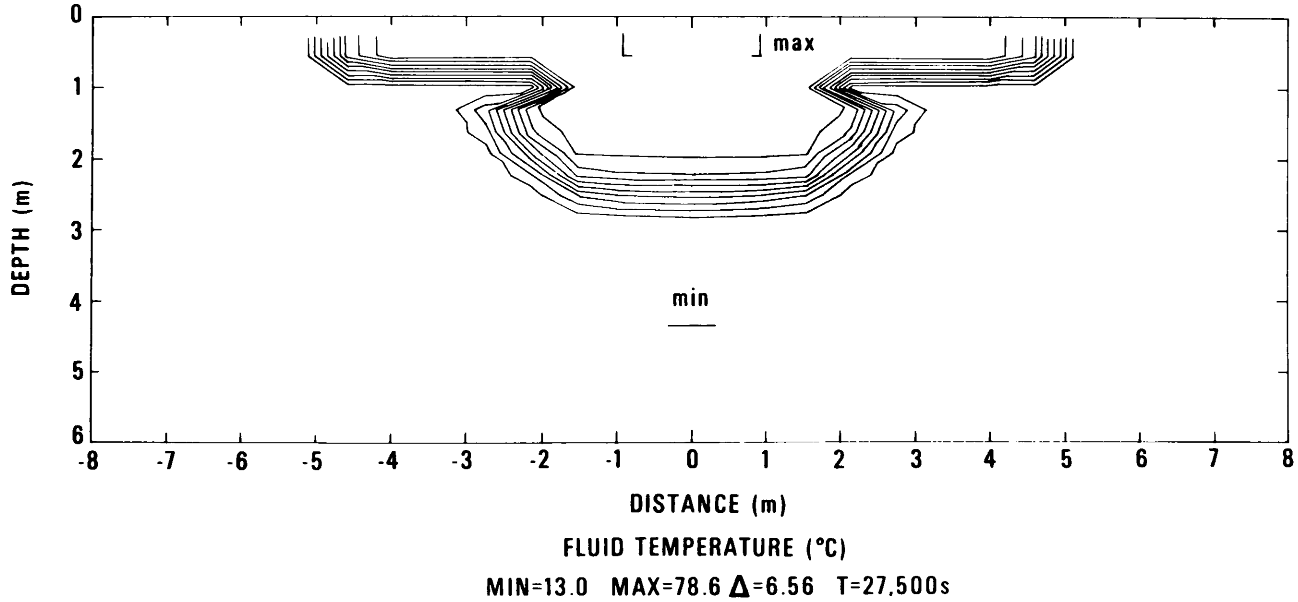
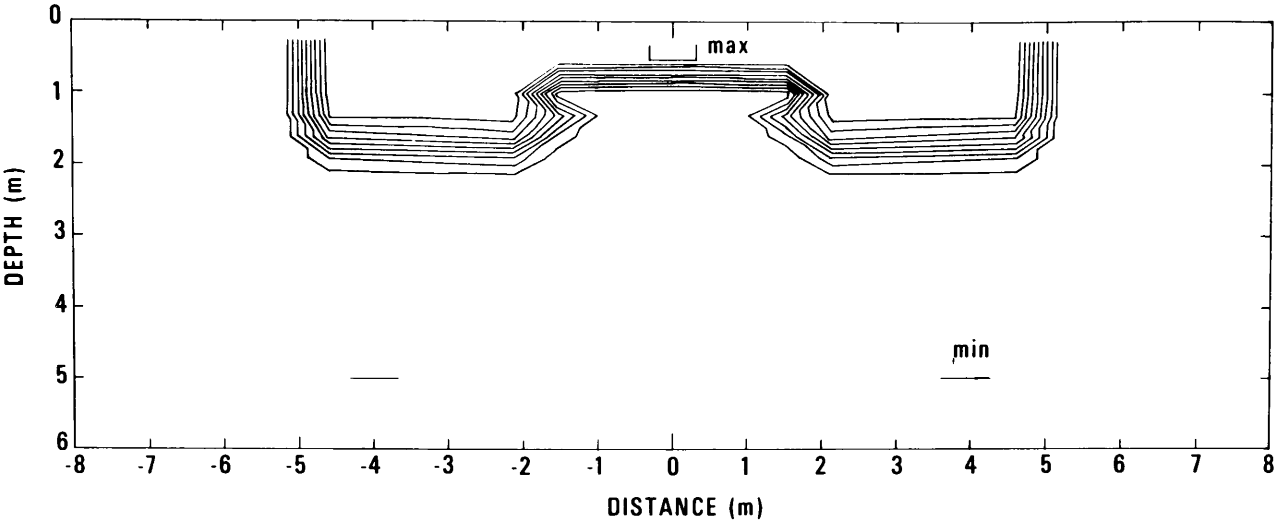


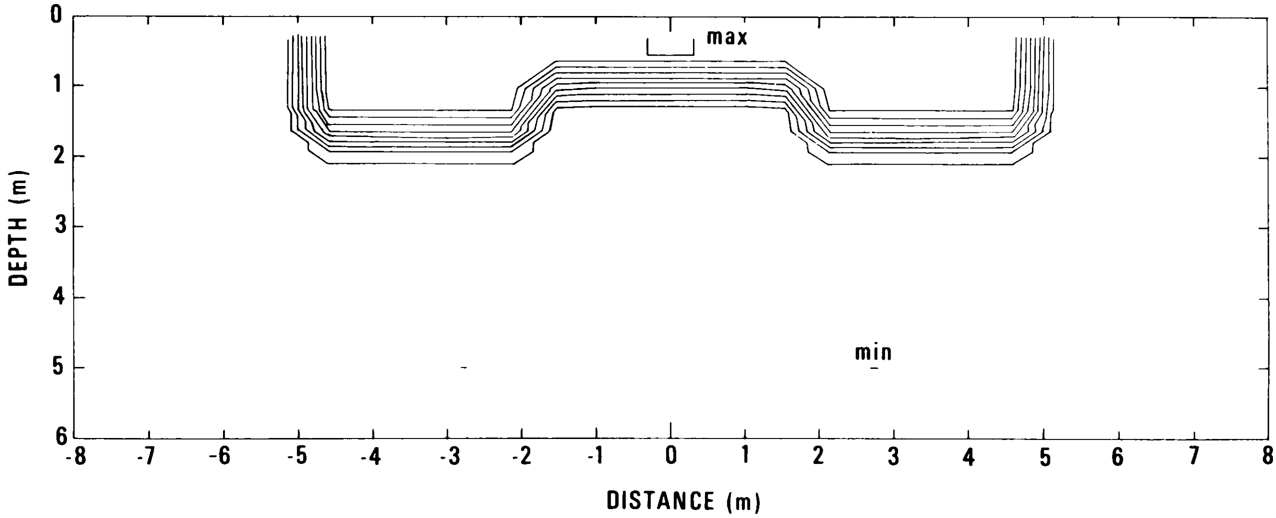
Figure 6



FLUID TEMPERATURE (°C)

MIN=13.0 MAX=76.7 Δ=6.37 T=27,500s

Figure 7



FLUID TEMPERATURE (°C)

MIN=13.0 MAX=76.8 Δ=6.38 T=27,500s

Figure 8

REFERENCES

1. B. J. Travis, "WAFE, A Model of Three-phase, Three-Component Mass and Heat Transport in Porous Media" to be published.
2. T. J. Bartel and C. E. Tyner, Oil Shale Program 20th Quarterly Report, Oct.-Dec. 1980, SAND 81-1038, to to published.