# HEAT AND FLUID FLOW EXPERIMENTS TO MEASURE GEOTHERMAL RESERVOIR PHYSICAL PARAMETERS

William E. Brigham
Stanford University
Stanford, CA 94305

## BENCH-SCALE MODELS

The test objectives and apparatus involved in the bench-scale models were presented in Progress Report No. 1 (Ref. 1). In brief, these experiments were designed to test fundamental concepts for nonisothermal boiling two-phase flow through porous media. This work is aimed at the entire reservoir, while the chimney model deals most directly with the wellbore and near-well reservoir conditions. The combination should be broadly useful in the new field of geothermal reservoir engineering.

The term "geothermal reservoir engineering" is an adaptation of "petroleum reservoir engineering," the branch of engineering which deals with assessment, and planning, of optimum development of petroleum reservoirs. Fortunately, there is much that is useful for geothermal engineering in the literature of oil recovery. Oil recovery by steam injection (Ref. 2) and underground combustion (Ref. 3) present some of the important features of nonisothermal two phase flow which appear pertinent to geothermal reservoirs. In addition, there is a considerable body of useful data on the properties of rocks and fluids as a function of temperature and pressure. Many of these data are summarized in Reference 4. Prior to this work there was only one specific study of the flow of single-component (water) two-phase (thus nonisothermal) flow in porous media (Ref. 5). In particular, there was no information on the important phenomena involved when normally immobile liquid saturations (practical irreducible water saturation) vaporize with pressure reduction.

The first bench-scale models use steady-state flow experiments involving linear flow (in the axial direction) through cylindrical cores.

### The Linear Flow Model

The linear flow model is described in Progress Report No. 1 (Ref. 1) and in Reference 6. Equipment was constructed to perform linear flow experiments through cylindrical consolidated cores. Both natural (Berea) and synthetic cement consolidated sand cores were used. A schematic diagram of the completed apparatus is shown in Fig. 1. Fondu calcium aluminate cement, silica sand of about 100 Tyler mesh size, and water were used as the materials to make the synthetic cores. The mixture was poured into a mold formed with a plastic tubing in which a glass tubing for a liquid content probe and a thermocouple tubing were held in place. The liquid saturation probe was originally developed by Baker (Ref. 7) in connection with a study of oil recovery by injection of steam. The instrument uses the difference in dielectric constant between the liquid water and steam present in the pore space.

It was decided to run a series of basic single-phase experiments prior to performing the boiling two-phase, nonisothermal flow experiments. These included: (1) measurement of absolute permeability to gas arid liquid water at a range of temperatures, (2) injection of hot water into a system containing water at a lower temperature, (3) cold water injection into a system containing hot water initially, and (4) injection of steam into a system containing liquid water at a lower temperature. Detailed results are presented in Ref. 6.

As an example, Figure 2 presents temperature versus distance along the core for injection of hot water into a core initially at room temperature. Much useful information can be extracted from data such as are shown in Fig. *2.* Basic information on single-phase nonisothermal flow, effective thermal conductivities in the direction of flow, and heat loss radially from the core may be found. In regard to radial heat loss, two determinations can be of interest: (1) the thermal efficiency of the injection, and (2) the overall heat transfer coefficient for the core within the sleeve *to* the surroundings. Both types of evaluation have already been made successfully. An example of the heating transients that occur when hot fluid is injected into a cold porous medium can be seen in Figure 3. The computed results compare rather well with the experimental results; however, improved mathematical modeling can improve the computed match of these data.

An additional preliminary series of experiments was run to determine the in-place boiling characteristics of a flowing system. Figure 4 shows a particularly interesting experiment wherein the original fluid in place was hot water at high pressure. Notice that cooler water was injected at one end, causing a temperature transient with time, while at the other end, a two-phase boiling zone was set up which remained at a fixed temperature with time. Further analysis of these data and other similar data will be forthcoming during this next year.

## Permeability Measurements

Recent work on the effect of temperature on relative permeability suggested that absolute permeability was also a temperature dependent property of rocks. Equipment was designed to measure absolute permeability under conditions of elevated temperature and overburden pressure (Ref. 8). Several fluids were used to make these measurements, namely, distilled water, white mineral oil, nitrogen, and helium.

Several conclusions can be drawn from the results. First, the temperature effect on permeability depends on the nature of the saturating fluid. In the case of water-saturated cores, permeability decreased with increasing temperature for all the samples studied. Over a temperature span of 70-325°F, permeability reductions of up to 65% were observed.

For oil-saturated samples, a slight increase in permeability was observed with increasing temperature in the low temperature range, followed by a decrease. However, this thermal sensitivity barely exceeded the range of experimental error.

On the other hand, absolute permeability to gas was found to be independent of temperature. Slip phenomena are affected by temperature, and a linear relationship between the Klinkenberg slip factor and temperature was found and explained by analysis of theory. Also, inertial ("turbulence") factors were determined and found to be independent of temperature.

One of the objectives of this work had been to simultaneously measure the effect of thermal stresses and mechanical stresses on permeability. It was found that regardless of the nature of the saturating fluid, the level of confining pressure affected permeability in the same manner, that is, permeability decreased with increasing confining pressure. For the thermally sensitive, water-saturated cores, increasing the confining pressure had the additional effect of intensifying the temperature dependence. This pressure-temperature interaction is shown to a marked degree in Figure 5.

In the light of the results obtained, it appears that the temperature effect was not caused by changes in the physical properties of the fluids, such as viscosity or density, because fluids with such a large viscosity and density contrast as oil and gas essentially yielded the same results; nor was the temperature effect caused by thermally induced mechanical stresses acting alone, as no significant permeability changes were found for oil or gas flow. Instead, the unique results obtained for water flow suggest that a combination of rock-fluid interaction, thermal stresses and mechanical stresses was responsible for the permeability reductions observed, the dominant factor being the surface effect.

## Geothermal Reservoir Physical Model

Whiting and Ramey (Ref. 9) presented the application of energy and material balances to geothermal reservoirs. Although applied to a field case with success, later applications indicated a need for modification (see Refs. 10, 11, and 12). The need for actual data to test conceptual models has been apparent for some time (Ref. 13). Previous works concerned unconsolidated sand models, although a study by Strobel did include a consolidated sand. Strobel's study concerned cyclic production and reheating of a single consolidated sandstone geothermal reservoir model. This work has been repeated with both natural and synthetic sandstone cores with more complete instrumentation. These data are not only important for the determination of proper material and energy balance procedures for gravity-dominated geothermal systems, but they are also of great help in determining the vapor pressure changes that occur as the in-place liquid evaporates and the liquid interfaces become highly curved. An example of vapor pressure lowering can be seen in Figure 6 (Ref. 14).

## MATHEMATICAL MODEL

Advances have been made in the modeling of geothermal fluids production in four main directions. The first direction is a general view of the many complex thermal, fluid dynamic, and other physical processes. The second is the formulation of a mathematical description of a simplified system to obtain a solution describing the behavior of this system. The third is matching the bench-scale experimental results to simulate the boiling flow of steam and water at elevated temperatures. Figure 7 presents the results of one simulation of a bench-scale geothermal reservoir model experiment. Figure 7a presents the computed pressure history, while Fig. 7b presents the computed liquid content of the system. Although not shown, the temperature history of the system was also computed. Development of a more sophisticated model continues.

The fourth major direction of mathematical development is aimed toward a graphical-analytical approach to solution of the heat-mass flow problem. The method of characteristics is a well-known solution techn que which appears to be applicable to this problem. An analogy may be drawn between this and the classic problem of water or gas displacing oil n petroleum reservoir engineering (i.e., the Buckley Leverett equations and the Welge equations). Solutions to these displacements are simple graphical constructions. It appears likely that similar techniques may be used in the fluid-heat flow system, and work will be continuing on this concept during the coming year.

## CONCLUDING REMARKS

During 1975 the main components of the projects in the Stanford Geothermal Program were completed and initial runs performed successfully. Augmentation of system instrumentation, completion of improvements in design, and collection of experimental data are well under way. It is encouraging that many of the experimental results have been found amenable to theoretical analysis, thus the systems behave reproducibly and logically.

As in any research program, ideas for new experimental techniques and new methods of data evaluation have developed as the program proceeds. These new ideas also are being actively pursued.

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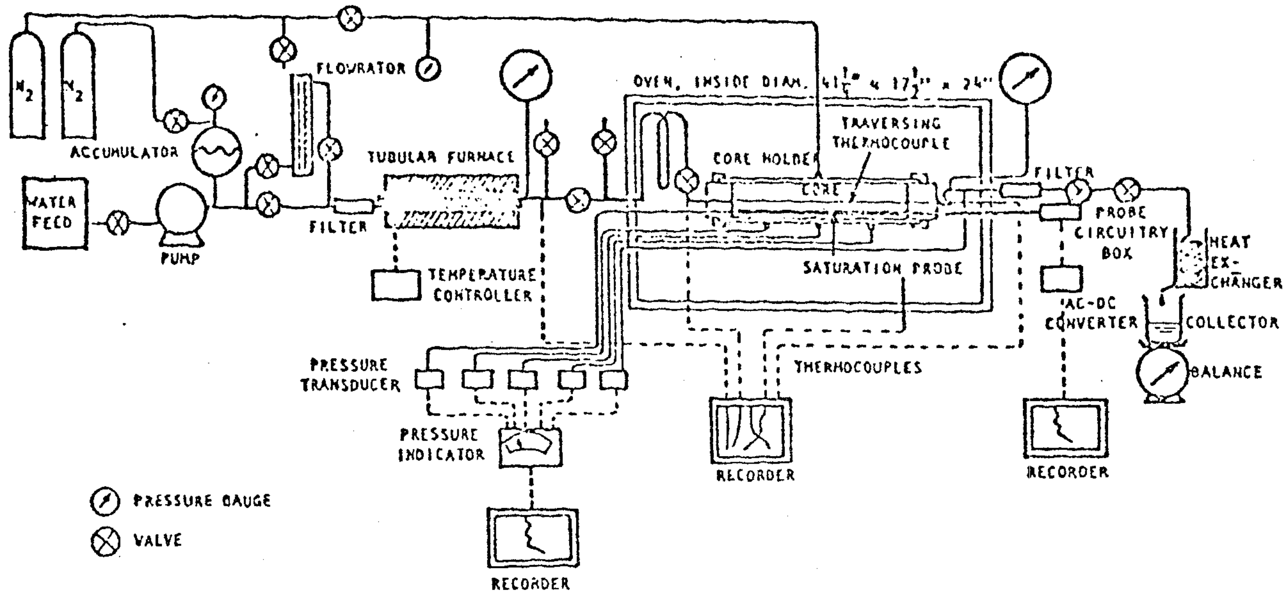



Fig. 1. Schematic diagram of the linear flow model apparatus

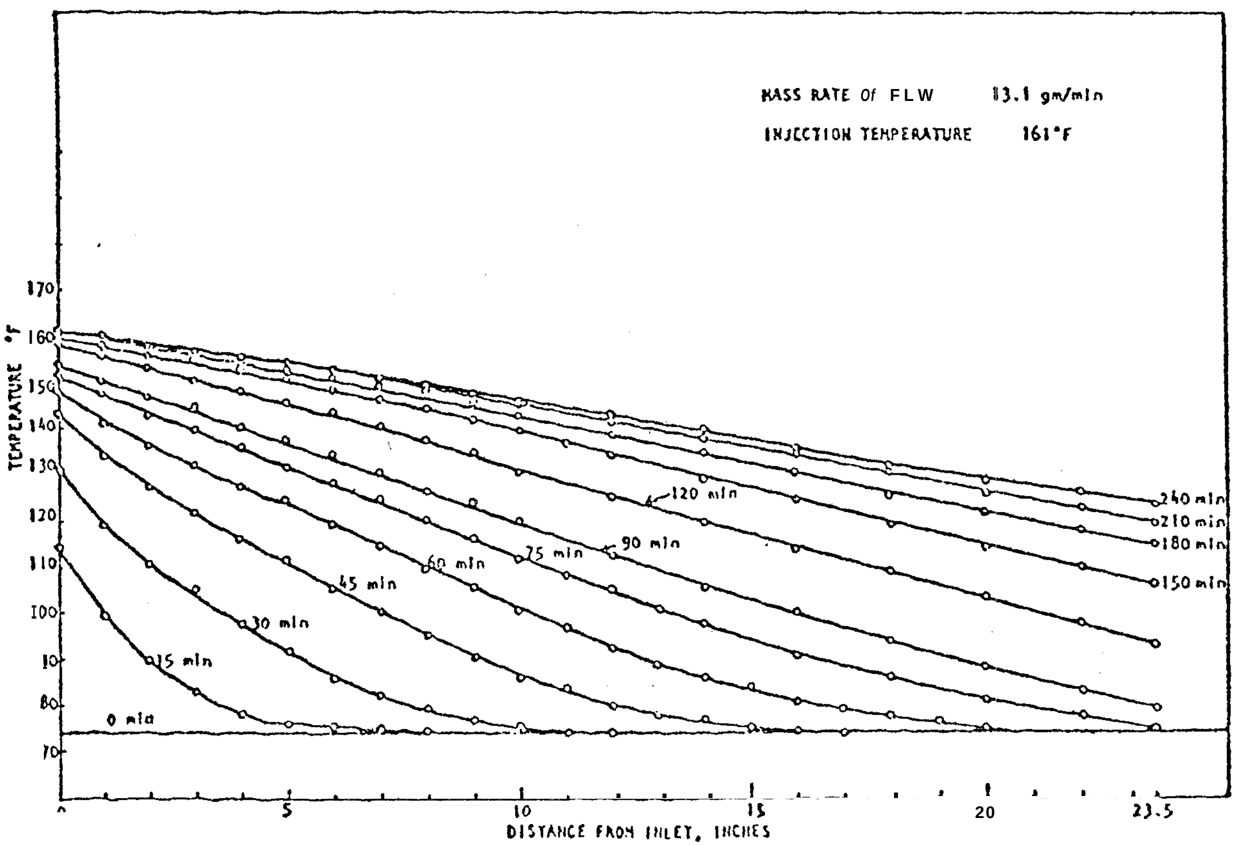



Fig. 2. Temperature vs distance for hot water injection

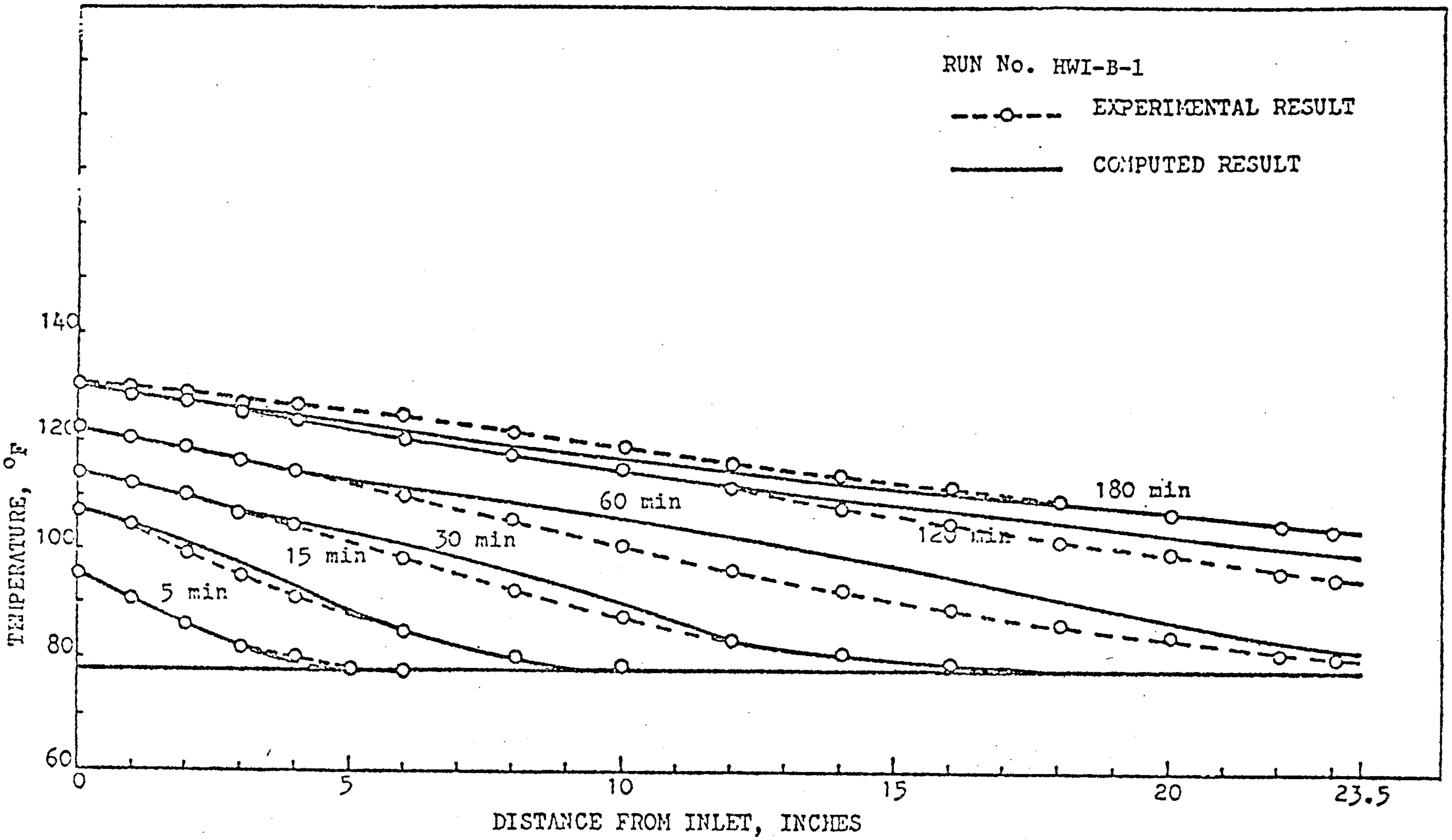



FIGURE 3. COMPARISON OF THEORETICAL AND EXPERIMENTAL TEMPERATURE DISTRIBUTIONS FOR HOT WATER INJECTION, BEREA SANDSTONE

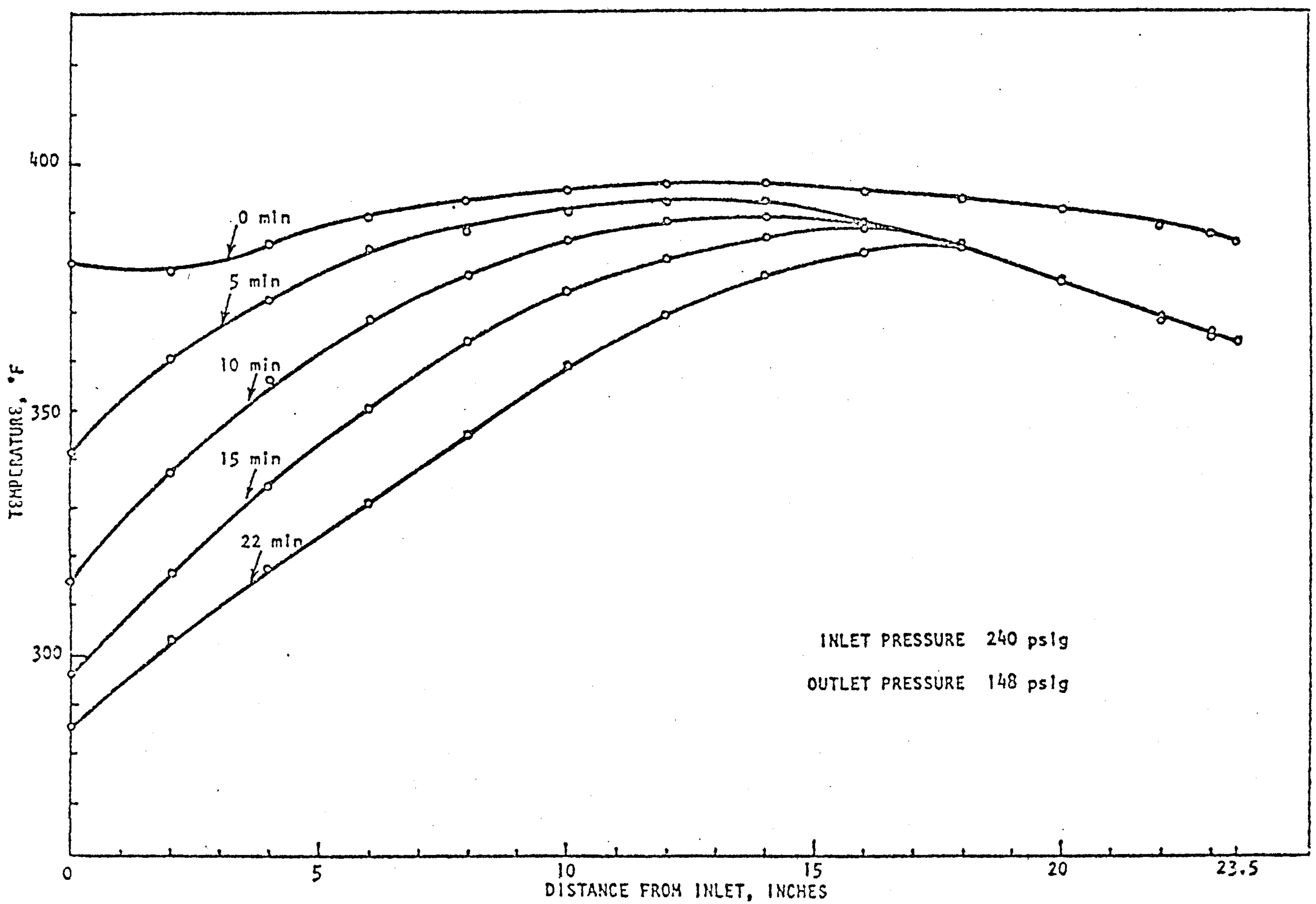



FIGURE 4. TEMPERATURE VS. DISTANCE FOR TWO-PHASE FLOW, SYNTHETIC SANDSTONE.

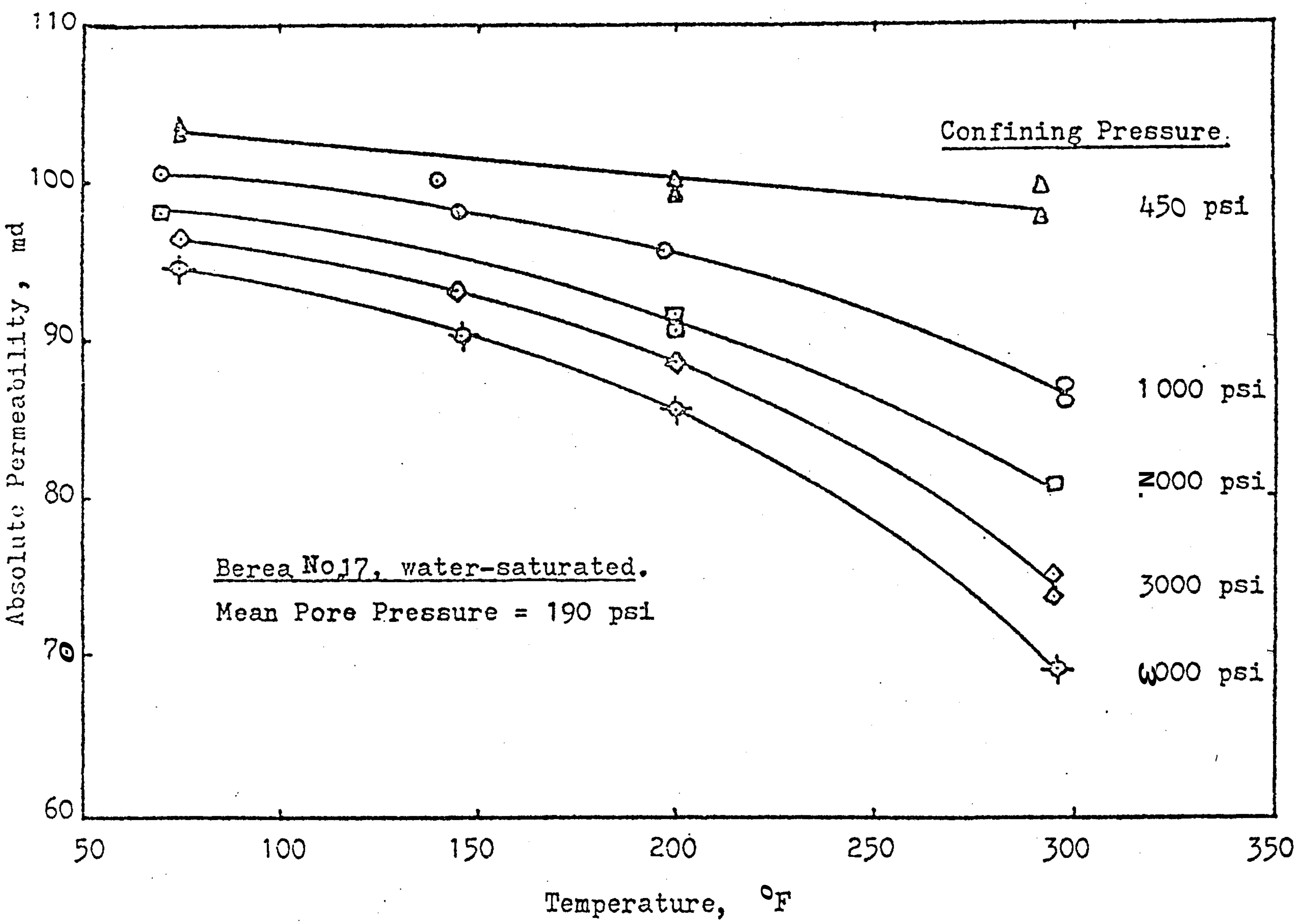



Figure [illegible] Permeability Change with Temperature and Confining Pressure.

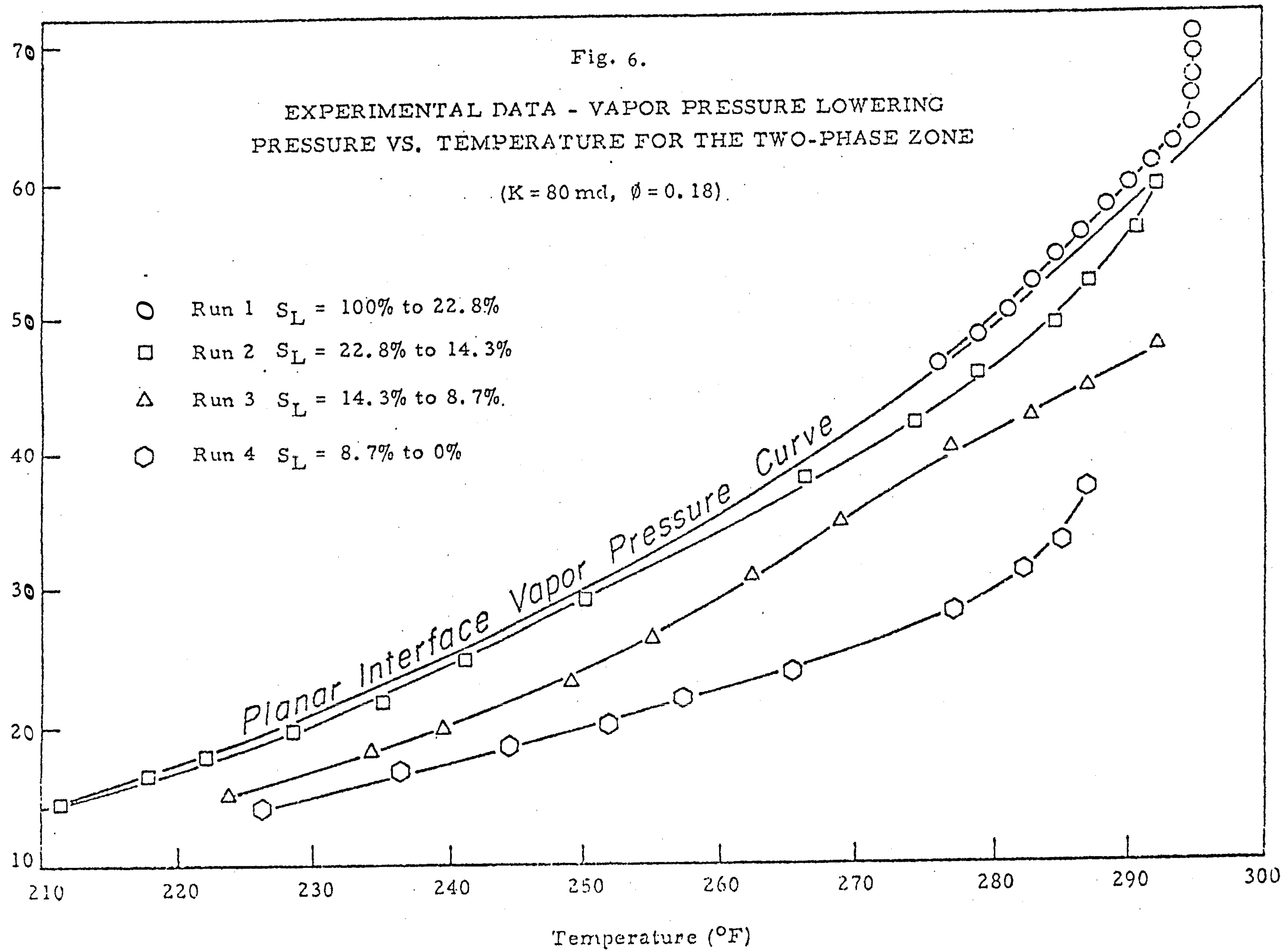
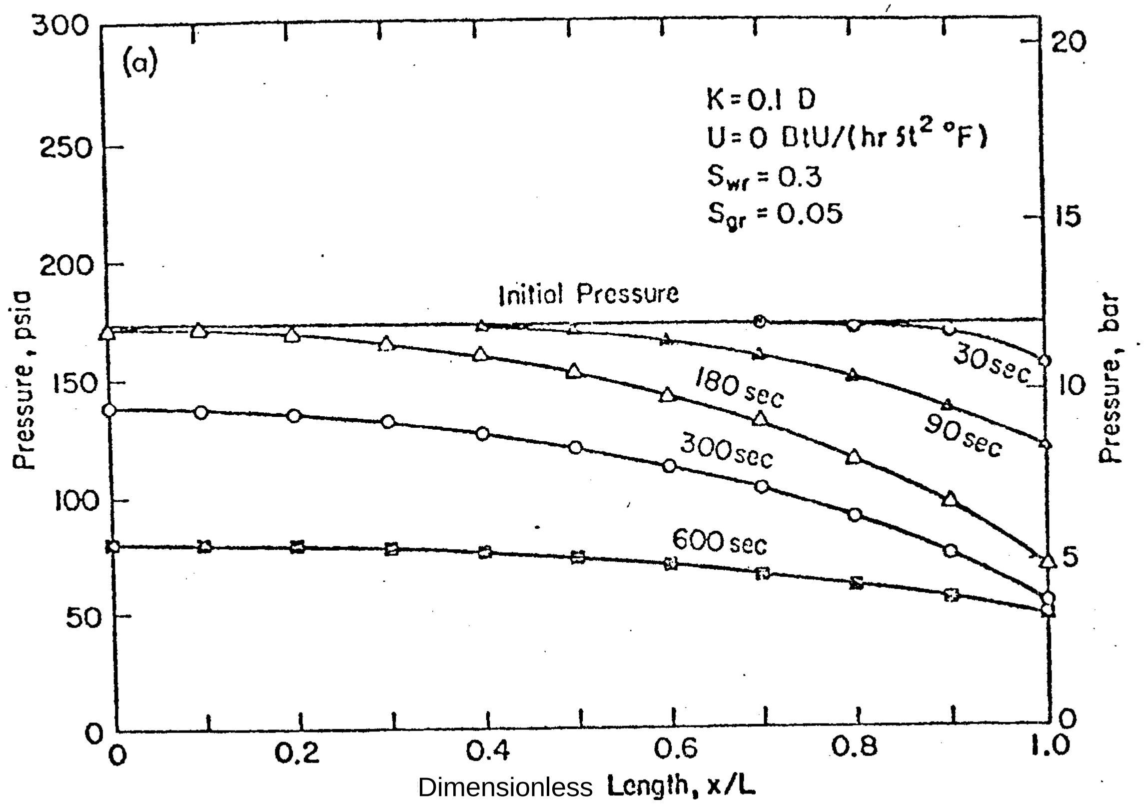


Fig. 6.
EXPERIMENTAL DATA - VAPOR PRESSURE LOWERING
PRESSURE VS. TEMPERATURE FOR THE TWO-PHASE ZONE
(K = 80 md, ∅ = 0.18)
Run 1 $S_L$ = 100% to 22.8%
Run 2 $S_L$ = 22.8% to 14.3%
Run 3 $S_L$ = 14.3% to 8.7%
Run 4 $S_L$ = 8.7% to 0%
Planar Interface Vapor Pressure Curve
70
60
50
40
30
20
10
210
220
230
240
250
260
270
280
290
300
Temperature (°F)



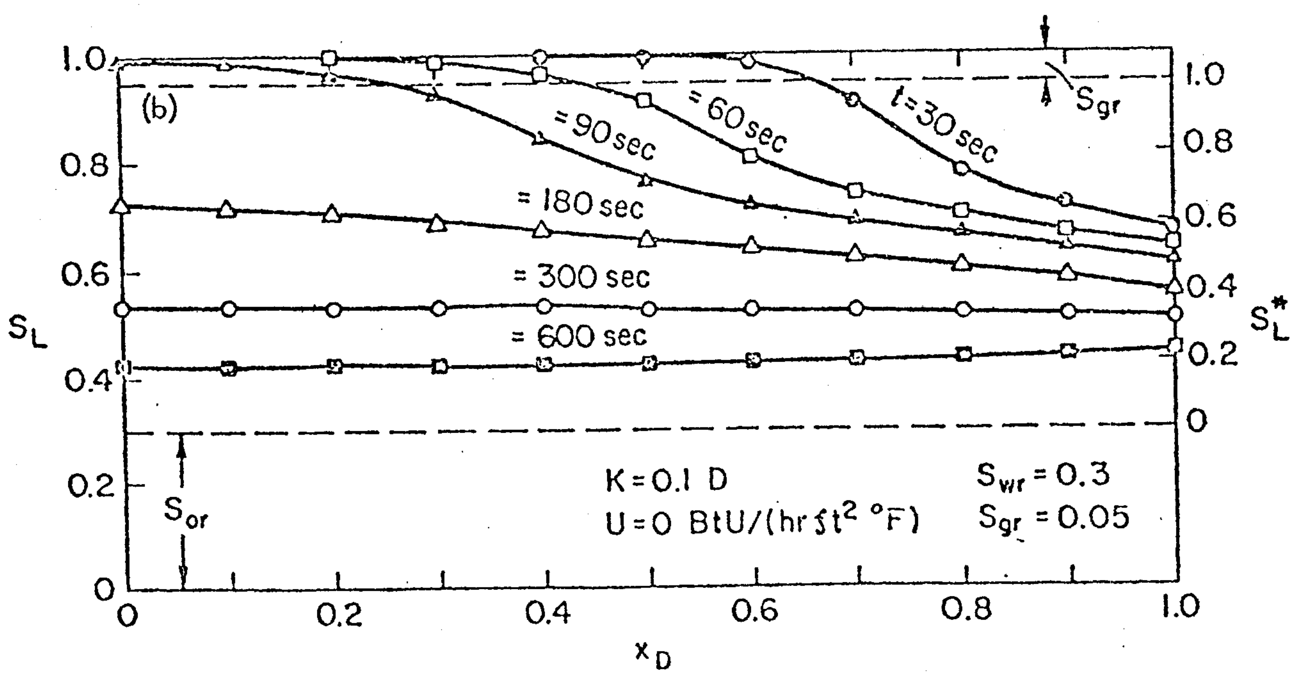




Fig. 7, (a) Simulation No. 1 of pressure history, (b) simulation No. 1 of saturation history