lems of sexual physiology and the means of adding a highly homozygous strain of fish to the very few now available (*9*). To the latter end, it is planned to assess, by means of fin transplantation (*10*), the degree of genetic relationship among monoparental siblings and other progeny and parents of this species (*11*).

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28 July 1961

Influence of Dead-End Pores on Relative Permeability of Porous Media

Abstract. The network model is used to show that wetting phase relative permeability of porous media is only slightly influenced by the fraction of that phase trapped in dead-end pores. On the other hand, the trapping of nonwetting phase in dead-end pores is a major influence on the shape of the nonwetting phase relative permeability curve. Laboratory experiments on porous media are suggested to test these network model predictions.

Simultaneous flow of two or more fluid phases occurs in soil, oil-bearing geological formations, and biological systems. In soils and biological systems the phases are water and air; in oil-bearing rock they are oil, water, and gas. Petroleum production technologists have made extensive studies of multiphase fluid flow in porous media and they have developed the definitions and working concepts.

For fluid systems of practical interest —water and air, or water, oil, and gas —there is usually only one fluid that wets the pore surfaces while the other (or others) do not. The wetting phase for water-air and for water-oil-gas is usually water. The wetting phase is believed to be spread over the pore surface; nonwetting phase occupies the center of the pore spaces and is surrounded by wetting phase.

When two or more fluid phases simultaneously occupy the pore space in a porous material the permeability to any phase is less than the single phase permeability. Permeability is defined as the volumetric rate of flow of a fluid of unit viscosity through a cube of unit cross section under a unit pressure gradient. The permeability of the porous material to any phase in the presence of other phases, divided by the single phase permeability, is known as the relative permeability. Relative permeability to a given phase is a function of the amount of that phase present in the pore spaces and is usually plotted as a function of "saturation," that is, the volume of a phase present divided by the total pore volume. Curves *A* and *E* of Fig. 1 are typical.

The factors that govern the shape of relative permeability curves are not yet well known. Studies of network models which point to the interconnection of pores into a network structure as the most important factor have been presented previously (*1, 2*). That there are other factors operating is indicated by the difference in shape of the wetting and nonwetting phase relative permeability curves.

In this paper, the previously reported network model data are reexamined to determine the amount of a given phase present in a network that is trapped in dead-end pores and therefore cannot flow. For single-phase flow, the network model has no dead-end pores and may be a good representation of real porous media, such as sandstone or sintered glass (*3*). When two immiscible phases are present in a porous medium, then the network model predicts that a situation may arise in which tubes (pores) filled with one phase cause some tubes containing the other phase to become dead-ends. There are no data on real porous media with which to check this prediction. Experiments on miscible displacement suggested at the conclusion of this report may give such data.

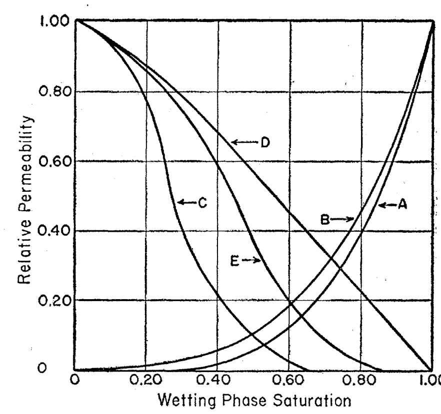

Fig. 1. Relative permeability curves for the network model (curves *A, B, C,* and *D*) and for sandstone (curve *E*). *A* and *C*, Wetting and nonwetting phase relative permeability, respectively, based on total volume; *B* and *D*, wetting and nonwetting phase relative permeability based on flowing volume; *E*, nonwetting phase relative permeability for sandstone.

The network data presented in this report, although of no quantitative significance when applied to real porous media, do indicate trends and the general appearance of relative permeability curves. These data can guide experiments designed to study the influence of pore structure on flow and diffusion in porous material.

The results of the reexamination of the data from an earlier paper (*1*, Figs. 5 and 6, pp. 147, 148; and Table 1, pp. 167, 168) are presented here as typical of networks which most closely represent real porous media (*4*).

At each saturation given in Table 1 of reference (*1*) the volume of each phase in dead-end tubes was recorded. This volume was subtracted from the total volume of the phase in the net-

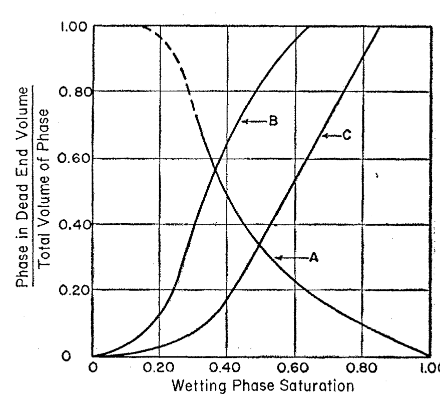

Fig. 2. Fraction of phase trapped in dead-end tubes. *A*, Wetting phase (from curves *A* and *B* of Fig. 1); *B*, nonwetting phase in network model (from curves *C* and *D* of Fig. 1); *C*, nonwetting phase for sandstone (from curves *E* and *D* of Fig. 1).

work to yield a saturation based on flowing volume only. Figure 1 of the present report shows the relative permeability curves obtained for increasing nonwetting phase saturation. Curves *A* and *C* are the wetting and nonwetting phase relative permeability, respectively, plotted on the basis of total volume; curves *B* and *D* are the wetting and nonwetting phase relative permeabilities plotted on the basis of flowing volume. In this graph, as in all relative permeability graphs obtained from the network model, the nonwetting phase curve based on total volume seems too far to the left when compared with curves for sandstone. This difference is believed to be a result of the small number of tubes in the model (about 400) compared to the number of pores in a sandstone sample used for relative permeability measurements. Curve *E* in Fig. 1 is typical of sandstones and is shown here for comparison.

It is apparent from Fig. 1 that the wetting phase relative permeability curve is about the same when based on total volume of wetting phase present or on flowing wetting phase. Dead-end volume is not an important influence on this curve. The factors governing the shape of the wetting phase relative permeability curve can be summarized in descending order of importance as follows. Wetting phase permeability decreases with increasing nonwetting phase saturation because: (i) large pores are removed from the network that carries wetting phase; (ii) the path of the wetting phase becomes more tortuous; and (iii) some wetting phase is trapped in dead-end pores which are not available as flow paths.

Figure 1 shows that nonwetting phase permeability is greatly influenced by dead-end volume. When plotted on the basis of saturation of flowing volume, the nonwetting phase relative permeability curve is almost a 45° line, which indicates that nonwetting permeability is almost proportional to flowing phase saturation. The data of Fig. 1 are replotted in Fig. 2 to show the fraction of a given phase that is in dead-end tubes at any total saturation of that phase.

The factors that govern the nonwetting phase relative permeability can be summarized in descending order of importance as follows. Relative nonwetting phase permeability increases as the saturation of that phase increases because: (i) more pores become available to carry nonwetting phase; the additional pores are progressively smaller as the nonwetting phase saturation increases; (ii) less nonwetting phase is in dead-end pores as its saturation increases; and (iii) the flow paths become less tortuous.

This study of the influence of dead-end pore volume suggests several experiments on real porous media to check the predictions of the network model. Handy's (*5*) two-tracer miscible displacement study seems to offer the best experimental procedure. In Handy's experiment, both a fast diffusing and slow diffusing tracer are in the displacing fluid. The dispersion of the slow diffusing tracer is taken to be a measure of dispersion due to mixing only; dispersion of the fast diffusing tracers is a measure of both mixing and diffusion. Dead-end pore volume will increase loss only of the fast diffusing tracer from the displacement front. The two-tracer displacement tests should be carried out with two immiscible phases present and two tracers in each phase. Dead-end volume will cause a separation of the tracer concentrations. By repeating the experiment at different saturations, it should be possible to obtain a measure of dead-end volume as a function of saturation (*6*).

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6. Acknowledgement is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for support of this research.

14 August 1961

Ancient Agriculture in the Negev

I wish to address myself in the main to the problem of the *teleilât el 'anab*, the gravel-stone heaps and mounds, which were referred to in an article in *Science* by Evenari *et al.* (*1*).

In two articles (*2, 3*) I have detailed my position on the possible function of the *teleilât*. Briefly, I maintain that the gravel-stone mounds and heaps (called "conical heaps and ridge mounds" in my articles) were the result of excavations of pits and ditches in which mainly vines were planted, and that the "flower-pot" heaps (not illustrated or described in the article by Evenari *et al.*; see *2*, pp. 24–26) were built to put a sterile area to the same use. Over the years, the action of the elements has filled up the excavations, leaving only the stone heaps in evidence.

My main point in connection with the pits and ditches is that they formed collection basins *primarily* for rain water. The undisturbed surface surrounding the pit or ditch served as a small runoff area which supplied the necessary supplementary supply of water for the vine planted in the pit or ditch. If hand watering were necessary, as might be the case in the event of a severe drought, any water applied would be concentrated near the roots of the plant. This would be the case regardless of where the vines were planted.

In reference 28 of their article (*1*), Evenari *et al.* make rather short shrift of my evidence (*2*) and make it appear that I considered that the only water the vines received came from hand irrigation from water stored in cisterns. I have written (*2*, p. 27): "We must *not*, above all, think that vines were planted *within* the mounds, but rather in pits or trenches. In other words, the conical heaps and ridge mounds came about as a result of digging holes into the ground in which vines, and in some cases, trees were planted. . . . Aside from enabling the farmer to cultivate his vine properly, each basin or trench, which could easily have been partitioned into a series of basins, would hold winter rains and irrigation water near the roots. . . . In addition to hand irrigating the vines from water stored in cisterns, it was also possible to run small channels on an oblique line from pit to pit or trench to trench, which would catch a portion of the slope runoff during the rainy season and direct it into the basins. It is for this reason, I believe, that one never finds ridge mounds following the contour of a slope but running down it; if they had been raised along the contour, runoff would have been denied to the areas below. Furthermore, because of the heavy downpours which often occur in this region, excess runoff could have been trapped at the base of a slope and channeled into a cistern where it