1974

The Epidemiology of Virus Diseases of Bell Peppers (Capsicum Annuum, L.) in Louisiana.

Harry Kenneth Whitam
Louisiana State University and Agricultural & Mechanical College

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STORAGE OF FRESH WATER IN SALINE AQUIFERS USING A WELL FIELD

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Department of Civil Engineering

by

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The computational procedure presented in this dissertation should enable the practicing engineer to design well fields for the storage of fresh water in horizontal saline aquifers in which there is no pre-existing ground-water movement. The recovery efficiency of the injection/storage/retrieval process can now be reliably computed, thus making possible an economic analysis of the process in any specified area. An economic comparison of the storage of approximately one billion gallons in a saline aquifer that underlies the New Orleans area was made with the present most feasible alternate—steel tanks. The results favored the saline aquifer storage project by a factor of more than 50 to 1.

The validity of the computational procedure was determined by comparing recovery efficiencies obtained from a laboratory-size miniature aquifer (miniaquifer) with recovery efficiencies predicted by the computational procedure. The computational procedure predicted the experimental data within 10 percent for multiple well systems. The predicted recovery efficiencies were invariably lower than the experimentally determined recovery efficiencies.

The aquifer parameters that must be determined before
the computational procedure can be used are thickness, permeability, porosity, storativity, longitudinal dispersivity coefficient, and viscosity and density of the native fluid. Of the parameters mentioned above the longitudinal dispersivity coefficient is the most difficult to obtain. The procedure used in this investigation to determine the longitudinal dispersivity coefficient for the miniaquifer can be readily adapted to field use.

In addition to the aquifer parameters, the well field configuration, the operation schedule of the field, the volume of fresh water to be injected, injection rates, probable duration of storage, production rates, and fracture pressure of the upper confining bed must be known in order to make an economic analysis.

When fresh water is injected into a horizontal, homogeneous, saline aquifer which has no pre-existing ground-water movement, the two most important factors which determine the amount of usable water that can be recovered are: (1) mixing of the two fluids due to molecular diffusion and convective dispersion, and (2) gravitational segregation of the two fluids due to density difference.
CHAPTER I

INTRODUCTION

One of the most important factors fostering the continued existence and growth of any community is an adequate and reliable supply of fresh water that is available on a daily basis, each and every day of the year. Many centers of population have to depend on surface run-off for their primary water supply, and since the available quantity of surface run-off is subject to wide variation, such population centers must build reservoirs to store surplus fresh water in times of plenty for use in times of low run-off or actual drought.

Rivers or streams that are subject to pollution by chemical spills, or natural pollution such as salt water intrusion from the ocean, are the sources of water for many important communities. Here, again, there is need to store an adequate supply of potable fresh water.

The storage of water in times of plenty for use in times of scarcity is not a novelty. In many areas of the world the topography is suitable for the construction of dams and the creation of reservoirs. However, in other areas of the world, such as the coastal zones, the land is too flat for the construction of dams and the creation of
impoundments, although fresh water may be available in surplus during certain times of the year. Also, in many industrialized areas, although the topography may be suitable, the land may have been preempted for use by industry, commerce, or residences and the problem of water storage sites arises in a slightly different guise. Nonetheless, water must be stored where water sources are intermittent, as a water supply that is not available on a daily basis, each and every day, will not support a population.

The usual answers to the problem of storing surplus water where potential reservoir sites are not readily available have been:

1. The construction of reservoirs at some distance from the point of use and conveying the water from the impoundments to the populated areas through large pipe lines.

2. In areas of flat topography, the construction of reservoirs within ring levees.

3. The construction of storage tanks.

Some of the disadvantages of the first two methods (in addition to initial construction costs) are: (1) susceptibility to pollution, (2) water loss through evaporation and/or seepage, and (3) the temporary or permanent submergence of large areas of land that might be used for other purposes. Surface storage in tanks eliminates the pollution and water-loss problems but when very large volumes are involved the cost of this method of storage is
usually prohibitive. Based on 1973 figures, it is estimated that the cost of tank storage in a typical urbanized area might be ten cents per gallon of storage capacity, in addition to the cost of land (Kimbler et al., 1973).

Many of the areas where surface storage is a problem are underlain by saline aquifers at depths as shallow as 500 feet (Kohout, 1970). As an alternate to surface storage of fresh water, many authors have suggested underground storage in these saline aquifers (Cederstrom, 1947; Moulder and Frazor, 1957; Esmail and Kimbler, 1967; Green and Cox, 1968; Kimbler, 1970; Moulder, 1970; Kumar and Kimbler, 1970; Kimbler et al., 1973). In brief, the storage of potable water in saline aquifers can be described as follows:

1. When a surplus of water exists it is injected into a suitable saline aquifer, miscibly displacing the native salt water away from the injection well.

2. After the desired quantity has been injected, the stored water is allowed to stand until needed.

3. The stored water is produced through the same well used for injection until either the salinity of the produced stream reaches an unsatisfactory level or until the demand is met.

These three steps constitute what is called one cycle. When there is again a surplus of potable water the process
is repeated. In step 3 it was noted that production was stopped when the salinity of the produced stream reached an unsatisfactory level. Technically, the term "breakthrough" is used to describe this condition. Throughout this investigation the term breakthrough is used to describe the condition when 3 percent of the produced stream consists of native fluid. The ratio of the volume of usable water recovered to the total volume injected is defined as "recovery efficiency." Several field tests of the process have been or are in the process of being conducted (Cederstrom, 1947; Moulder and Frazor, 1957; Green and Cox, 1968; Tibbals, 1970; Kimbler, 1971; Brown and Silvey, 1973). Although the published data from these tests are rather limited it appears that the process is feasible.

A few investigators (Kumar and Kimbler, 1970; Gelhar et al., 1972) have developed mathematical models for predicting the recovery efficiency of the underground storage technique. All of these models have been for a single-well, radial system.

In a field application of the process, however, it is unlikely that a single well will suffice when the question of deliverability is considered. Although the surplus water might be recharged at a slow rate over a long period of time (4 to 6 months), the water demand is likely to be high over a shorter interval of time (2 to 3 months). So it is likely that a number of wells would have to be installed to improve water deliverability. In fact, should a
number of such well fields be established as part of a municipal water supply system, they might be used to supply the short-term peak demands as well as long-term water supply when the surface source is temporarily shut down.

In this investigation a mathematical model to predict the recovery efficiency of a multiple well system has been developed. The validity of the mathematical model was verified under a wide variety of parameters using experimental results obtained from a laboratory size miniature aquifer (miniaquifer). The computational procedure used in the mathematical model is an extension of that used by Kumar (1968).

Since this investigation is concerned with a miscible displacement process in a porous medium, the results are directly applicable to other miscible displacement processes in porous media such as the underground disposal of water soluble wastes, the leaching of ores, the storage of natural gas in aquifers when an inert cushion gas is used, secondary and tertiary recovery of petroleum, and the cycling of retrograde gas-condensate reservoirs.
CHAPTER II

DISCUSSION OF THEORY

2.1 General

In the storage of fresh water in saline aquifers the factors which can influence the recovery efficiency are: (1) mixing of the two fluids due to molecular diffusion and convective dispersion, (2) gravitational segregation of the two fluids due to density difference, (3) viscous fingering due to a difference in viscosities between the injected and native fluids, (4) aquifer heterogeneities, (5) aquifer dip, and (6) pre-existing ground-water movement in the storage aquifer. Throughout this investigation the following assumptions are made:

1. A horizontal, homogeneous, isotropic storage aquifer of infinite areal extent.
2. The viscosities of the injected fluid and the native fluid are equal.
3. No pre-existing ground-water movement in the storage aquifer.

Hence, the factors influencing recovery efficiency which are studied in this investigation are: (1) mixing of the two fluids due to molecular diffusion and convective dispersion and (2) gravitational segregation of the two fluids due to density difference.
2.2 Mixing Due to Molecular Diffusion and Convective Dispersion

If two miscible fluids of different composition are in contact, a transfer of molecules will result. As time passes, the random movement of molecules creates a mixed zone between the two fluids; that is, the two fluids diffuse into one another. This process is called molecular diffusion.

When one fluid miscibly displaces another fluid in a porous medium the mixing between the two fluids will be greater than that due to molecular diffusion alone. The additional mixing is primarily dependent on pore geometry and is a result of the varying velocity field and constant intermingling of flow paths as the displacement process progresses. This additional mixing is called convective dispersion. Convective dispersion is classified as longitudinal or transverse. Longitudinal dispersion is in the direction of gross fluid movement, while transverse dispersion is in a direction perpendicular to gross fluid movement. Previous investigations have shown that longitudinal dispersion is 6 to 20 times greater than transverse dispersion (de Josselin de Jong, 1958; Pozzi and Blackwell, 1963). In this investigation transverse dispersion is neglected.

Taking into consideration mixing due to molecular diffusion and longitudinal dispersion, Raimondi et al. (1959) and Hoopes and Harleman (1967) state that if a fluid moves radially outward from a line source through a
homogeneous, isotropic, porous medium, displacing a fluid of the same viscosity and density, the mixing of the two fluids is described by the following equation:

\[
\frac{\partial^2 c_i}{\partial t^2} + \frac{Q}{r} \frac{\partial c_i}{\partial r} = \left( \frac{\alpha r}{Q} + \frac{D r^2}{Q^2} \right) \frac{\partial^2 c_i}{\partial t^2} \quad \ldots \ldots \ldots \quad (2.1)
\]

Where:  
- \( c_i \) = concentration of injected fluid at radius, \( r \), and time, \( t \).
- \( r \) = radius. (cm)
- \( t \) = time. (seconds)
- \( Q = q/(2\pi h \phi) \) (cm\(^2\)/sec)
- \( q \) = volumetric flow rate. (cc/sec)
- \( h \) = aquifer thickness. (cm)
- \( \phi \) = aquifer porosity. (fraction)
- \( D \) = coefficient of molecular diffusion of fluids in porous medium. (cm\(^2\)/sec)
- \( \alpha \) = longitudinal dispersivity coefficient of porous medium. (cm)

In the derivation of Equation 2.1 it is assumed that the coefficient of molecular diffusion, \( D \), is a constant. This is not completely accurate because the value of \( D \) is dependent on concentration (Jost, 1960). However, this dependence is small and for practical purposes the value of \( D \) may be considered constant (Perkins and Jonston, 1963). Stoessell (1974) has shown experimentally that the value of \( D \) in a porous medium similar to that used in the experimental work of this investigation is about
Also assumed in the derivation of Equation 2.1 is that longitudinal dispersion is proportional to the first power of the average velocity of fluid movement through the porous medium, the proportionality constant being the longitudinal dispersivity coefficient, $\alpha$. Aris and Amundson (1957) have shown that this assumption is valid if the velocity is slow enough to allow diffusion to equalize the concentration within each pore space. If the velocity is high enough so that concentration equalization does not occur dispersion becomes proportional to a higher power of velocity. Most experimental data indicates that this higher power has an upper limit of about 1.2 (Brigham et al., 1961; Perkins and Johnston, 1963). It is felt that this deviation from the assumption on which Equation 2.1 is based is not large enough to invalidate the equation when viewed from an engineering standpoint.

The value of the longitudinal dispersivity coefficient, $\alpha$, for a porous medium is a characteristics of the porous medium and increases with increasing uniformity coefficient (as the material contains a greater range of particle size) and/or increasing intrinsic permeability (Raimondi et al., 1959). Experiments by Brigham et al. (1961) and Bentsen and Nielsen (1965) have shown that the value of $\alpha$ is also a function of the ratio of the viscosity of the displaced fluid to the viscosity of the displacing fluid. The larger the value of the ratio the
larger the value of $\alpha$. Throughout this investigation a viscosity ratio of unity was maintained. The value of $\alpha$ for the miniaquifer used in the experimental work in this investigation was found to be 0.02 cm. The computational procedure used to obtain this value of $\alpha$ is discussed later.

For the continuous injection of a fluid at a steady rate with a concentration $c_0$ at $r = 0$, Raimondi et al. (1959) and Hoopes and Harleman (1967) proposed the following solution to Equation 2.1:

$$\frac{c_i}{c_0} = \frac{1}{2} \text{erfc} \left[ \frac{r^2/2 - Qt}{(4/3 \alpha R^3 + D/Q R^4)^{1/2}} \right] \ldots \ldots (2.2)$$

Where: $R =$ radius of injected fluid at time $t$, assuming no mixing or gravitational segregation. (cm)

$\text{erfc} (\xi) =$ complementary error function of $\xi$.

$$\text{erfc} (\xi) = \frac{2}{\sqrt{\pi}} \int_{\xi}^{\infty} e^{-w^2} dw$$

Equation 2.2 satisfies the boundary conditions $c_i(r = 0, t > 0) = c_0$ and $c_i(r = \infty, t = 0) = 0$; however, it does not satisfy the initial condition, $c_i(r, t = 0) = 0$. This is due to the fact that in obtaining Equation 2.2, it was assumed that $\partial c/\partial t = 0$ at $t = 0$. Hoopes and Harleman (1967) state that this assumption is approximately true away from the immediate vicinity of the source; however, it is not true within 10-20 particle diameters of the source. The validity of the solution given by Equation 2.2 has been
demonstrated experimentally by Bentsen and Nielsen (1965), Hoopes and Harleman (1967) and Esmail and Kimbler (1967).

It can be shown (see Appendix A) that Equation 2.2 can be written as:

\[
\frac{c_i}{c_0} = \frac{1}{2} \text{erfc} \left[ \frac{r^2 - R^2}{2 \sqrt{f(t)}} \right] \quad \ldots \ldots \ldots \quad (2.3)
\]

Where: \( f(t) = 4/3 \alpha (2 \cdot Q \cdot t)^{3/2} + D \frac{(2 \cdot Q \cdot t)^2}{Q} \)

In terms of concentration of native fluid, \( c_n \), it can be shown (see Appendix A) that Equation 2.3 can be written as:

\[
\frac{c_n}{c_0} = \frac{1}{2} \text{erfc} \left[ \frac{R^2 - r^2}{2 \sqrt{f(t)}} \right] \quad \ldots \ldots \ldots \quad (2.4)
\]

Gardner et al. (1962) have extended the solution given by Equation 2.4 to apply to successive injection and production half-cycles. The following equations are essentially those given by Gardner et al. (1962) except that they have been rearranged, simplified and subscripted. The concentration at any radius, \( r \), and for any injection or production half-cycle can be computed by using the appropriate form of the solution:

\[
\frac{c_n}{c_0} = \frac{1}{2} \text{erfc} \left[ \frac{R^2 - r^2}{\text{DNUM}(1 \text{ or } p) \cdot j} \right] \quad \ldots \ldots \quad (2.5)
\]
Where:

First Injection Half-Cycle

\[ \text{DNOM}_{I,1} = 2[f_{I,1}(t_1)]^{1/2} \]

First Production Half-Cycle

\[ \text{DNOM}_{P,2} = 2[f_{P,2}(t_2) - f_{P,2}(t_1) + f_{I,1}(t_1)]^{1/2} \]

Second Injection Half-Cycle

\[ \text{DNOM}_{I,3} = 2[f_{I,3}(t_3) - f_{I,3}(t_2) + f_{P,2}(t_2) - f_{P,2}(t_1) + f_{I,1}(t_1)]^{1/2} \]

Second Production Half-Cycle

\[ \text{DNOM}_{P,4} = 2[f_{P,4}(t_4) - f_{P,4}(t_3) + f_{I,3}(t_3) - f_{I,3}(t_2) + f_{P,2}(t_2) - f_{P,2}(t_1) + f_{I,1}(t_1)]^{1/2} \]

etc.

Where:

\[ f_{I,j}(t_k) = \frac{4}{3} \alpha(2Q_{I,j} t_k)^{3/2} + \frac{(2Q_{I,j} t_k)^2}{Q_{I,j}} \]

\[ f_{P,j}(t_k) = \frac{4}{3} \alpha(2Q_{P,j} t_k)^{3/2} + \frac{(2Q_{P,j} t_k)^2}{Q_{P,j}} \]

\[ Q(I \text{ or } P,j) = \frac{r_{\text{final}}^2 - r_{\text{initial}}^2}{2\Delta t} \] (cm²/sec)

\[ \Delta t = \text{time for fluid to travel from } r_{\text{initial}} \text{ to } r_{\text{final}}. \] (sec)
\[ t_1, t_2, t_3, \ldots = \text{time measured from start of first injection half-cycle. (sec)} \]

\[ I,P = \text{subscripts for injection and production respectively.} \]

\[ j,k = \text{integers} \]

Equation 2.5 has been verified by Esmail and Kimbler (1967) for two complete cycles.

2.2 Gravitational Segregation

Due to Density Difference

When fluids of unequal densities are in contact in a porous medium gravitational forces cause the less dense fluid to rise relative to the more dense. The interface will assume a progressively greater angle with respect to the vertical. Gardner et al. (1962) have shown mathematically and Esmail (1966) has shown experimentally that for a viscosity ratio of unity the interface may be treated as a plane surface in linear systems. Kumar (1968) has shown experimentally that this also appears to hold for radial systems.

Gravitational segregation in porous media may be separated into two cases. One case is the so-called "static" case where there is no bulk flow of fluids except that arising from convective currents attributable to gravity. The second case is called dynamic gravitational segregation, since it occurs in the presence of bulk flow (Esmail and Kimbler, 1967). An example of the latter would
be the gravitational segregation that occurs during the displacement of a fluid by an injected fluid of different density. Esmail (1966) assumed and Kumar (1968) later verified that for a viscosity ratio of one, dynamic and static gravitational segregation are, for practical purposes, equal and that results obtained from linear systems may be directly related to radial systems by correcting the linear results to radial geometry.

Gardner et al. (1962a) studied static gravitational segregation of miscible fluids in linear, horizontal systems. They report that, for practical purposes, the projection of the interface on the horizontal can be approximated by the equation:

\[
\left(\frac{2XL}{h}\right)^2 = \frac{16}{3} F^2 \frac{k_H}{k_V} \left(\frac{t}{t_o}\right)^2 \frac{(t/t_o)^2}{(1 + t/t_o)} \quad \ldots \ldots \ldots \ldots (2.6)
\]

Where:

\(2XL\) = projection of the interface on the horizontal. (cm)

\(h\) = aquifer thickness. (cm)

\(k_H\) = horizontal intrinsic permeability. (cm\(^2\))

\(k_V\) = vertical intrinsic permeability. (cm\(^2\))

\(F\) = a dimensionless factor dependent on viscosity ratio. (\(F = 1.0\) for a ratio of one)

\(t\) = time. (sec)

\(t_o = \frac{4}{3} \frac{\phi \cdot h \cdot \bar{u} \cdot F}{k_V \cdot g \cdot \Delta \rho}\) (sec)

\(\phi\) = porosity. (fraction)
\[ \overline{\mu} = \text{average viscosity of the two fluids, (poise)} \]
\[ g = \text{acceleration due to gravity, (cm/sec}^2) \]
\[ \Delta \rho = \text{density difference between the fluids. (gm/cc)} \]

Equation 2.6 is based on the assumption of a sharp interface between the two fluids. Esmail (1966) contended that in practice, a sharp interface would not result and a mixed zone would be present due to diffusion and dispersion. He further reasoned that this mixed zone would retard the effect of gravitational segregation and yield a smaller rate of interface laydown than the sharp interface theory would predict.

Esmail (1966) introduced a term for the density gradient, \( S \), which he defined as the quotient of the density difference and the mixed zone length. Assuming a horizontal, homogeneous, isotropic porous medium, he used dimensional analysis and experimental data from several linear systems to obtain the following equation that describes gravitational segregation in linear systems:

\[ \frac{2XL}{h} = f(\psi) \quad \ldots \ldots \ldots \ldots \ldots \ldots \quad (2.7) \]

Where:

\[ \psi = \left[ \frac{k \cdot g \cdot \Delta \rho \cdot t}{\overline{\mu} \cdot \phi \cdot h} \right] \left[ \frac{(\overline{\mu})^{2/3} \cdot S}{(\Delta \rho)^{5/3} \cdot (g)^{1/3}} \right]^{1/2} \]

\[ f(\psi) = \text{some function of } \psi \]

In each of Esmail's experimental runs he started with a known mixed zone length which remained constant.
throughout the experiment. He also started each experiment with the interface vertical at time = 0 and then recorded values of $2XL/h$ as time progressed.

To find the functional relationship between $2XL/h$ and $\psi$ the experimental data obtained by Esmail (1966) were plotted (see Fig. 2.1). The data were divided into two sections and a curve fitted to each part. The equation of the curve for the first part was:

$$\frac{2XL}{h} = 20.0 \psi ; \quad (0 \leq \psi \leq 0.1) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2.8)$$

and for the second part

$$\frac{2XL}{h} = 0.8 + 12.5 \psi - 4.8 \psi^2 ; \quad (0.1 < \psi < 1.0) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2.9)$$

Since there was no data beyond $\psi = 1.0$ the functional relationship was rather arbitrarily taken to be:

$$\frac{2XL}{h} = 6.5 + 2.0 \psi; \quad (\psi \geq 1.0) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2.10)$$

It will be shown later that this relationship yields results of recovery efficiency on the safe side (lower than those actually observed).

In computing the values of $\psi$ plotted in Figure 2.1, Esmail (1966) calculated the density gradient on the basis that the mixed zone length was the distance between the radii where the concentrations of native fluid were 3 percent and 97 percent. This same basis was used throughout this investigation when mixed zone lengths were computed.
Figure 2.1 Dimensionless Correlation Used to Compute Gravitational Segregation
CHAPTER III
DEVELOPMENT OF COMPUTATIONAL PROCEDURE
FOR CALCULATING RECOVERY EFFICIENCIES

3.1 General

The following treatment assumes a horizontal, homogeneous, isotropic, storage aquifer of infinite area extent, which has no pre-existing ground-water movement. Additional assumptions are that the ratio of the viscosities of the injected and native fluids is unity and that the flow geometry is radial. The factors which influence recovery efficiency that are considered are: (1) mixing due to molecular diffusion and longitudinal convective dispersion, and (2) gravitational segregation due to density difference.

3.2 Calculation of Mixing Due to Molecular Diffusion and Longitudinal Convective Dispersion

Consider Figure 3.1 which idealizes the flow system during an injection half-cycle and in which gravitational segregation is ignored. The injected fresh water displaces the native salt water away from the source. As the interface between the fresh water and salt water moves in the aquifer, the mixing between the two fluids will...
Figure 3.1 Schematic Representation of the Displacement Process During an Injection Half-Cycle. Gravitational segregation is ignored.
generate a transition or mixed zone in which the composition of either fluid will vary from 100 percent to 0 percent. The length of this mixed zone as it moves in the aquifer is dependent on the total distance traveled by the interface, the velocity at which the interface moves, the total time of contact between the liquids, the properties of the liquids, and the properties of the porous medium.

In Figure 3.1, R is the radius of the injected fluid at any time t, assuming no mixing. Therefore, the average value of $c_i/c_o$ or $c_n/c_o$ at radius R is 0.5. In this computational procedure the mixed zone length at any time t, and about any radius R, is computed using the appropriate form of Equation 2.5.

3.3 Calculation of Gravitational Segregation Due to Density Difference

The density difference between the injected fresh water and the native salt water will cause the mixed zone between the two liquids to incline with respect to the vertical (see Fig. 3.2). The less dense fresh water will rise over the more dense salt water. The gravitational segregation between the two fluids at any time can be represented by the tangent of the angle, $\theta$, that the 50 percent concentration line makes with respect to the vertical and is given by the dimensionless group $2XR/h$.

Equations 2.8, 2.9, and 2.10 cannot be used directly to calculate gravitational segregation in a radial system.
Figure 3.2 Schematic Representation of the Displacement Process During an Injection Half-Cycle. Both mixing and gravitational segregation are included.
for two reasons. These are: (1) they describe gravitational segregation in linear systems only, and (2) the density gradient, $S$, is not a constant value but varies continuously as the injection, storage, and retrieval process progresses. In order to use Equations 2.8, 2.9, and 2.10 to compute gravitational segregation in a radial system, it is necessary to first use a stepwise procedure to allow for the continuously changing value of $S$, and second, to apply a correction to approximate the computed values of gravitational segregation to radial geometry. The method by which the equations are applied is outlined below.

Consider Figure 3.3 which illustrates the stepwise procedure for calculating the value of gravitational segregation before approximation to radial geometry. Note that only the 50 percent concentration lines are considered. Let the fresh water be injected to a radius of $R_{\text{max}}$. Divide the distance $R_{\text{max}}$ into equal intervals such as $0 R_1, R_1 R_2$, etc. The length of the mixed zone is calculated at the center, $C_1$, of the first interval using the appropriate form of Equation 2.5. This value of mixed zone length at $C_1$ is used to compute the value of density gradient, $S_1$, at $C_1$. It is assumed that the density gradient has had a constant value of $S_1$ over the interval $0 R_1$. Using the value of $S_1$ and the real time of travel, $t_1$, from 0 to $R_1$ the horizontal projection $(2XL)_1$ at the end of the first interval can be calculated using
Figure 3.3 Schematic Representation to Illustrate the Calculation of Gravitational Segregation before Approximation to Radial Geometry.
Equation 2.8, 2.9, or 2.10. For the second interval, $R_1 R_2$, the mixed zone length is computed at the center, $C_2$, of the interval. The mixed zone length at $C_2$ will be greater than at $C_1$, therefore $S_2$ will be less than $S_1$. It is now assumed that the density gradient has had a constant value of $S_2$ over the interval $0 R_2$. Using $S_2$, a pseudo-time, $t_1^*$, is calculated which will give a horizontal projection at the end of the first interval that is equal to $(2XL)_1$. The pseudo-time, $t_1^*$, will be greater than $t_1$ since $S_2$ is less than $S_1$. The real time of travel from $R_1$ to $R_2$ is added to this pseudo-time to give total time, $t_2$, which is then employed to calculate the horizontal projection, $(2XL)_2$, at the end of the second interval. The assumption that the density gradient remains constant from 0 to the end of the interval in question and the introduction of pseudo-time is necessary due to the manner in which the correlation given in Figure 2.1 and Equations 2.8, 2.9, and 2.10 were derived. This has been previously discussed in Chapter II. The calculations for subsequent intervals are carried out in a similar fashion. For the last interval of the injection half-cycle, the time of static storage before production begins is included in the total time before making calculations of gravitational segregation.

In the preceding treatment, the projection of the interface was calculated on the basis of a linear geometry. In radial geometry, the projection of the interface is
less than that for linear geometry for injection half-cycles and greater for production half-cycles. The calculated projections shown in Figure 3.3 must be converted to radial geometry. Consider Figure 3.4 which illustrates the approximation of gravitational segregation calculations to radial geometry. Lines $p_1p'_1$ and $p_2p'_2$ represent the 50 percent concentration lines at the ends of the first and second intervals respectively, before the approximation to radial geometry. Note that $p_1p'_1$ and $p_2p'_2$ in Figure 3.4 are the same as $p_1p'_1$ and $p_2p'_2$ in Figure 3.3. For the first interval it is assumed that no correction is necessary, that is, $(2XL)_1 = (2XR)_1$. The corrected projection, $(2XR)_2$, at the end of the second interval is obtained in the following manner: Compute the radius to point (a) such that the annular area, $\pi[R^2_2 - a^2]$, is equal to the annual area, $\pi[R^2_2 - p^2_1]$. Compute the radius to point (a') such that the annual area, $\pi[(a')^2 - R^2_2]$, is equal to the annual area, $\pi[(p^2_1)^2 - R^2_2]$. This gives the line aa' which is the line $p_1p'_1$ converted to radial geometry at the end of the second interval. The additional tilting of the interface in traveling from $R_1$ to $R_2$ is given by the difference, $[(2XL)_2 - (2XL)_1]$. This difference is equally distributed on each side of the line aa'. Hence:

$$ba = a'b' = \left[\frac{(2XL)_2 - (2XL)_1}{2}\right]$$

The horizontal projection, $(2XR)_2$, of the line bb' is the
Figure 3.4 Schematic Representation to Illustrate the Approximation of Gravitational Segregation Calculations to Radial Geometry.
projection of the 50 percent concentration line in radial geometry at the end of the second interval. The calculations for subsequent intervals are carried out in a similar manner.

3.4 Calculation of Recovery Efficiency

Stored fresh water is produced until the leading edge of the mixed zone reaches the breakthrough radius, RBT (see Fig. 3.5). The breakthrough radius would be the wellbore radius for a single well system. For a multiple well system, the breakthrough radius would be the radius from the center of the well pattern to the outer ring of wells. The volume of water contained in the frustrum of the cone having a height, h, and upper and lower radii of RU50 and RL50 respectively, is the volume of unrecovered fresh water (see Fig. 3.5).

The cumulative recovery efficiency is calculated by a computational program from the equation:

\[
\text{Cum. Recovery Efficiency} = \frac{\text{Cum. volume of fresh water} \text{ water injected} - \text{Volume of unrecovered fresh water}}{\text{Cum. volume of fresh water injected}}
\]

The recovery efficiency for a particular cycle is computed from the equation:

\[
\text{Recovery Efficiency} = \frac{\text{Cum. vol. of fresh water} \text{ water injected} - \text{Vol. of unrecovered fresh water} - \text{Vol. of fresh water recovered in previous cycles}}{\text{Volume of fresh water injected during cycle}}
\]
Figure 3.5 Schematic Diagram to Illustrate the Calculation of Recovery Efficiency.
3.5 Multiple Well Systems

The preceding has dealt primarily with single well systems. In a field application of the storage process it is most likely that a well field will be used instead of a single well. In this investigation it was assumed that these well fields would be symmetrical and would have a well at the center of the pattern (see Fig. 3.6). It was also assumed that the fields would be operated so that the injected bubble of fresh water would remain essentially circular.

The operating procedure for a well field configuration such as that shown in Figure 3.6c would be as follows: (1) Inject into the center well until the lagging edge of the mixed zone passes the inner ring of wells. (2) Start injection in these wells (with injection continuing in the center well) until the lagging edge of the mixed zone passes the outer ring of wells. (3) Inject into all nine wells until the desired quantity is injected. (4) Allow the injected water to stand until needed. (5) Produce all nine wells until breakthrough occurs at the outer ring of wells, at which time production from the well field is stopped. Subsequent cycles are made with injection beginning in all nine wells simultaneously. The water required to initially "sweep out" the pattern is termed "cushion water" and is water that will, for practical purposes, never be recovered.

The mathematical procedures for computing recovery
Figure 3.6 Some Possible Well Field Patterns

a.) FOUR WELL PATTERN

b.) FIVE WELL PATTERN

c.) NINE WELL PATTERN
efficiencies that have been proposed thus far have been for single well systems. To use these procedures for multiple well systems, it must be assumed that all injection and production takes place through the center well of the multiple well pattern. The experimental results that will be presented in the next chapter indicate that this is a valid assumption as long as the well field is symmetrical and is operated so that the injected bubble of fresh water remains essentially circular.

3.6 Computer Programs for Computing Recovery Efficiencies

Detailed computer programs have been developed for computing recovery efficiencies for one, two, and three cycle operation of the storage process. A description and listing of these program are presented in Appendix B. The programs presented are for single well systems only, but complete instructions are given on how to modify the programs for multiple well use. The programs are in FORTRAN IV language and are written for use on an IBM 360/65 system.
CHAPTER IV

EXPERIMENTAL PROCEDURE AND RESULTS

4.1 General

The experimental work was conducted in three stages. The first stage consisted of the construction of a synthetic sandstone miniaquifer. The second stage involved the determination of the physical properties of the miniaquifer such as homogeneity, porosity, permeability, and longitudinal dispersivity coefficient. With this data the performance of wells and well fields in the miniaquifer could be used as a standard against which the calculation procedure could be tested. In the third stage several injection-production runs were made with a wide variation of the parameters that affect recovery efficiency. The recovery efficiencies obtained from these experimental runs were compared with those predicted by the computational procedure in order to ascertain the validity of the procedure.

It should be noted that a miniaquifer is not a model of some prototype but is an actual independent, physical system. Consequently, if a mathematical model (a computational procedure) will predict such things as mixed zone lengths, gravitational segregation, movement of injected
fluid, etc., in the miniaquifer there is every reason to believe that it will do the same for a field situation: both the miniaquifer and a water-bearing sand or sandstone involve laminar flow through porous media and the equations take cognizance of the size or thickness of an aquifer only through the magnitudes of the hydrologic constants. That is, whether a sandstone is half an inch thick or 500 ft thick, the same Darcy equation expresses the relationship between discharge and change in potential, only the numerical coefficients being different.

4.2 Description of the Miniaquifer

The technique used for the construction of the miniaquifer is described in detail in Appendix C and was similar to that employed by Caudle (1963), Esmail (1966), Kumar (1968), and Painter (1971). The miniaquifer is half of a rectangular system whose dimensions are 305 cm by 292 cm by 3.81 cm thick, bordered completely by an isopotential and containing a nine-well array at the center (see Fig. 4.1). Note that if the well field is operated such that the rate of well 3 is the same as the rate of well 9, well 4 the same as well 8 and well 5 the same as well 7, a line of symmetry (also a no-flow boundary) exists as shown in Figure 4.1. Hence, the interface positions on one side of the line are mirror images of the interface positions on the other side of the line. Taking advantage of this symmetry, it was necessary to construct
Figure 4.1 System Represented by Miniaquifer Used in This Study.
only half the system (305 cm by 146 cm by 3.81 cm thick).

In the experimental procedure wells 1, 2, and 6 were treated as half wells. Figure 4.2 is a photograph of the miniaquifer together with the monitoring equipment used during the experiments. Fluid was injected into, or withdrawn from, each well by means of constant-speed positive-displacement pumps (see Fig. 4.3), each of which had been precisely machined and calibrated. Each pump consists of a cylinder and a piston powered by a synchronous motor. By means of properly selected gear ratios, the rate of injection or production can be set at a predetermined value. The available injection and production rates range from 8.046 cc/min to $0.334 \times 10^{-2}$ cc/min.

4.3 The Effect of Boundaries

One of the assumptions made in this investigation (Chapter II) was that the flow systems were of infinite areal extent. The miniaquifer previously described violates this assumption. It was therefore necessary to determine the maximum radius to which a bubble of fluid could be injected in the miniaquifer before boundary effects became appreciable. To determine this maximum radius, it was assumed that injection would take place at a constant rate in well 1 of the system shown in Figure 4.1. Using the image well technique to take into account the isopotential boundaries, the frontal positions of the injected bubble were computed for various injection times.
Figure 4.2--View of miniaquifer, pumps, and instrumentation. Note camera on support for photographing frontal position of injected fluid. In left foreground are three large-barrel pumps and one small-barrel pump. Chemical oscillometer and recorder on stand just above well field. To left of oscillometer are individual controls for each well.
Figure 4.3--View of three large-barrel and three small-barrel pumps used in experiments.
It was then assumed that the system was infinite (no boundaries) and frontal positions for the injected bubble were computed at the same injection times as for the finite system. Figure 4.4 is a comparison of these frontal positions. It can be seen that there is no noticeable difference until a radius of 60 cm is reached and even at a radius of 100 cm, the difference is small. In the experimental runs made in this investigation the radii of the injected bubbles seldom exceeded 60 cm, hence, the assumption of a system with infinite areal extent is reasonable.

4.4 **Fluids Used in Experiments**

Instead of salt water and fresh water, analog fluids were used in all of the experiments. The analog fluids were made of various mixtures of naphtha, Soltrol 170, carbon tetrachloride, and iodobenzene. These fluids are miscible in all proportions. The properties of the pure fluids are given in Table 4.1. The densities were measured using a Chainomatic Gravitometer. The viscosities were measured using an Ostwald Viscometer. The same equipment was used to determine the properties of the fluid mixtures.

Analog fluids were used for two reasons: (1) such fluids are more desirable for experimental use than fresh water and salt water in that much better control of properties is possible, for example, a wide range of density
Figure 4.4 Comparison of Frontal Positions for a Finite System and an Infinite System.
differences between native fluid and injected fluids can be obtained without changing the viscosity ratio, (2) introduction of water into a synthetic sandstone matrix similar to that used in the construction of the miniaquifer, sometimes causes the matrix to inexplicably deteriorate.

TABLE 4.1--Properties of Pure Fluids Used in Experimental Runs

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Density at 22°C (gm/cc)</th>
<th>Viscosity at 22°C (cp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Naphtha</td>
<td>0.747</td>
<td>0.570</td>
</tr>
<tr>
<td>2 Soltrol 170</td>
<td>0.771</td>
<td>2.504</td>
</tr>
<tr>
<td>3 Carbon Tetrachloride</td>
<td>1.590</td>
<td>0.992</td>
</tr>
<tr>
<td>4 Iodobenzene</td>
<td>1.832</td>
<td>1.573</td>
</tr>
</tbody>
</table>

1 Naphtha; V.M. & P.; Humble Oil and Refining Co.; Baton Rouge, La.
2 Soltrol 170; Aliphatic Hydrocarbon; Phillips Petroleum Co.; Bartlesville, Okla.
3 Carbon Tetrachloride; Technical Grade; F. H. Ross & Co.; Baton Rouge, La.
4 Iodobenzene; Matheson, Coleman & Bell Mfg. Chemists; Norwood, Ohio.

Painter (1971) found that a mixture of 45 percent Soltrol and 55 percent naphtha by volume has a viscosity equal to that of carbon tetrachloride. Thus by adding carbon tetrachloride to the mixture of Soltrol and naphtha, a more dense fluid can be obtained without any change in viscosity.

The miniaquifer was initially saturated with a fluid
mixture that contained 43.5 percent Soltrol, 53.2 percent naphtha, and 3.3 percent carbon tetrachloride (percents are by volume). The injected fluids were prepared starting with the basic 45-55 percent Soltrol-naphtha mixture. To this was added 2.5 percent iodobenzene, enough carbon tetrachloride to obtain the required density difference, and an oil-soluble red dye. The purpose of the dye was to make the progress of the injected fluid visible. The purpose of the iodobenzene was to make the dielectric constant of the injected fluid different from that of the native fluid. During a production half-cycle, when native fluid appeared in the produced stream, the change in dielectric constant of the produced fluid was sensed by a capacitance cell (see Fig. 4.5) which was connected to a chemical oscillometer. When the oscillometer detected a change in capacitance, it generated a millivolt signal which caused the pen on a millivolt recorder to move. The response of the recorder and the concentration of native fluid in the produced stream were linearly related (see Fig. 4.6). When the concentration of native fluid in the produced stream reached 3 percent, breakthrough (as defined in this study) had occurred. A schematic of the experimental apparatus is shown in Figure 4.7. For clarity, a flow line and coaxial cable are shown connected to one well only. In reality there is a flow line to each well and a coaxial cable running from each well to the rotary coaxial switch.
Figure 4.5 View of Capacitance Cell Used to Detect Concentration Changes.
Figure 4.6 Plot of Recorder Reflection Versus Concentration of Native Fluid in Produced Stream.
Figure 4.7 Schematic of Experimental Apparatus.
It should be noted that in all the experimental runs, the more dense fluid was injected. This does not affect the experimental results in any way since the recovery efficiencies obtained would be the same for a given set of conditions regardless of whether the injected fluid was more dense or less dense than the native fluid. The more dense fluid was injected because it was more convenient to do so in the experimental work.

4.5 Determination of Miniaquifer Permeability

To determine the permeability of the miniaquifer, a pressure gauge was attached to the isopotential. A pressure transducer with a readout was attached to the well field controls so that the pressure at any well could be monitored. Well 1 was opened to flow under the hydrostatic head produced by the fluid in the fluid reservoir (see Fig. 4.7). The flow rate was determined by observing the time it took for a measured volume of fluid to flow from well 1. During this flow period, the pressures at the isopotential and at wells 2, 3, 4, 5, and 6 were recorded. The pressures for wells 2, 4, and 6 were 1.32 psig and their distances from well 1 are the same—31.12 cm. The pressures for wells 3 and 5 were 1.27 psig and their distances from well 1, 22.00 cm. The pressure at the isopotential was 1.62 psig and the minimum distance from well 1 to the isopotential is 142.00 cm. The flow rate was 0.943 cc/sec and the fluid viscosity was 0.946 cp.
Darcy's Law for steady state radial flow of an incompressible fluid is:

\[ q = \frac{2\pi h k}{\mu} \left( \frac{p_2 - p_1}{\ln \left( \frac{r_2}{r_1} \right)} \right) \]  

(4.1)

Where:
- \( q \) = volumetric flow rate (cc/sec)
- \( h \) = aquifer thickness (cm)
- \( k \) = intrinsic permeability of aquifer (darcies)
- \( \mu \) = absolute viscosity of fluid (cp)
- \( p_2 \) = pressure at radius \( r_2 \) (atm)
- \( p_1 \) = pressure at radius \( r_1 \) (atm)
- \( r_2 \) = radius (cm)
- \( r_1 \) = radius (cm)

From Equation 4.1, a semi-log plot of pressure versus radius should be a straight line. The pressures for the flow test were plotted as shown in Figure 4.8. A straight line was drawn through the point plotted for wells 2, 4, and 6 and the point plotted for the isopotential since these pressures would most closely approximate those for a truly radial system. Using Equation 4.1 and a flow rate of 0.943 x 2 or 1.886 cc/sec to allow for the fact that well 1 is a half well, the permeability of the miniaquifer was calculated to be 5.57 darcies.
Figure 4.8 Plot of Pressure Versus Radius Used to Determine Miniaquifer Permeability.
4.6 **Determination of Mini-aquifer Homogeneity and Porosity**

The mini-aquifer homogeneity and porosity were determined during Run No. 1. The complete operating procedure and parameters for Run No. 1 are given in Appendix E. The density difference between the native fluid and injected fluid was made very low (0.002 gm/cc) for this run so that gravitational segregation would not be a significant factor.

As injection progressed, the front of injected fluid was observed to advance in essentially radial arcs (see Fig. 4.9). The advancement of the front in radial arcs was considered sufficient evidence that the mini-aquifer was homogeneous and isotropic.

As the position of each front was marked (see Fig. 4.9), the time of injection corresponding to that front was recorded and the volume of fluid injected up to that time computed. The area within each frontal position was computed and a plot of area swept versus volume injected was made (see Fig. 4.10). For any injection time:

$$\text{Volume Injected} = (\text{Area Swept}) \cdot h \cdot \phi$$

or:

$$h \cdot \phi = \frac{\text{Volume Injected}}{\text{Area Swept}} = \text{Slope of Plot (Fig. 4.10)}$$

Using the above equation and Figure 4.10, the porosity of the mini-aquifer was computed to be 0.25.
Figure 4.9--Photograph showing the circular advance of the injected fluid front (injection is taking place in well 1).
Figure 4.10 Plot of Volume Injected Versus Area Swept for Run No. 1.
4.7 Determination of the Longitudinal Dispersivity Coefficient For the Miniaquifer

To determine the longitudinal dispersivity coefficient for the miniaquifer, two experimental runs (Run No. D-1 and Run No. D-2) were made. In both runs, the densities and viscosities of the injected and native fluids were exactly matched so that there would be no gravitational segregation. Fluid was injected in well 1 at a constant rate (24.138 cc/min for both runs) for a predetermined length of time (7090 seconds for Run No. D-1, 7441 seconds for Run No. D-2). The injected fluid was then produced through well 1 at a constant rate (24.138 cc/min for both runs) and a complete concentration profile of native fluid in produced stream versus total time since start of injection was obtained for both runs. Points from these concentration profiles are plotted on Figure 4.11.

Using the computer program described in Appendix D, theoretical concentration profiles were computed for the above conditions and for a range of longitudinal dispersivity coefficients. In both cases (Run No. D-1 and Run No. D-2) the concentration profiles computed using a dispersivity coefficient of 0.02 cm most closely matched the experimentally determined concentration profiles. On this basis, the longitudinal dispersivity coefficient of the miniaquifer was taken as 0.02 cm.
Figure 4.11 Comparisons of Computed and Observed Concentration Profiles Used in Computing the Longitudinal Dispersivity Coefficient. (a) Comparisons for Run D-1; (b) Comparisons for Run D-2.
4.8 Comparison of Experimental and Predicted Results

Seventeen experimental runs were made in the mini-aquifer using a wide range of the parameters that affect recovery efficiency. Complete descriptions and results of 16 of these runs are presented in Appendix E. Run No. 7 was of no quantitative value, hence, no results for this run are presented.

Table 4.2 compares the observed and predicted recovery efficiencies for single well operation. For single well operation all the predicted values of recovery efficiency were less than the observed values. On the average the difference between the predicted and observed values for the first cycle was 13 percent with a range of 8 to 19 percent. For the second cycle, the average difference was 7 percent with a range of 4 to 10 percent. The third cycle had an average difference of 7 percent with a range of 5 to 8 percent. In all runs that were carried out for more than one cycle, the recovery efficiency improved with each cycle and the results of computation more nearly approached the observed recovery efficiency.

Table 4.3 compares the observed and predicted recovery efficiencies for multiple well operation. For multiple well operation all the predicted values of recovery efficiency were equal to or less than the observed values except for the first cycle of Run No. 15. On the average, the predicted values of recovery efficiency for the first
<table>
<thead>
<tr>
<th>Run No.</th>
<th>First Cycle</th>
<th>Second Cycle</th>
<th>Third Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Predicted</td>
<td>Observed</td>
</tr>
<tr>
<td>1</td>
<td>93%</td>
<td>85%</td>
<td>--</td>
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<td>2</td>
<td>94</td>
<td>86</td>
<td>95%</td>
</tr>
<tr>
<td>3</td>
<td>91</td>
<td>77</td>
<td>94</td>
</tr>
<tr>
<td>6</td>
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<td>--</td>
</tr>
<tr>
<td>Run No.</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>--------</td>
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<td>------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Observed</td>
<td>Predicted</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>86%</td>
<td>82%</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>90%</td>
<td>76%</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>90%</td>
<td>76%</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>91%</td>
<td>78%</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>80%</td>
<td>78%</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>71%</td>
<td>72%</td>
</tr>
</tbody>
</table>
cycle were 8 percent lower than the observed values. The range of differences ranged from -1 to 14 percent. For the second cycle the average difference was 6 percent with a range of 0 to 11 percent. The third cycle had an average difference of 9 percent with a range of 5 to 11 percent. In all runs that were carried out for more than one cycle, the recovery efficiency improved with each cycle.
5.1 General

To illustrate the relative economy of storing fresh water in saline aquifers, it will be assumed that the municipal water department of an urbanized, coastal area (such as New Orleans) has excess filter capacity and requires additional storage capacity. The additional storage facilities should have the capability of supplying potable water at the rate of 10,800,000 gpd from November 1 through January 31 (92 days). This period is the normal duration of low flow for the river which is the primary water source of the area and the period of the poorest quality water. The required storage capacity needed is approximately one billion gallons. For purposes of calculation the "exact" number, 92 x 10,800,000 or 993,600,000 gallons, will be used. Less mineralized water, suitable for storage, is normally available from February 1 through July 15.

In such a densely populated urban area the most feasible way (from a purely physical standpoint) of obtaining surface storage is through the use of closed steel tanks, when topography, possible contamination during
hurricanes, and evaporation during droughts are taken into consideration. An alternate method of storage would be the injection of the excess fresh water into a saline aquifer if a suitable aquifer is available. Assuming that a suitable storage aquifer exists, an economic comparison between the two methods of storage follows.

5.2 Storage in Steel Tanks

According to Kimbler et al. (1973) a good estimating figure for tank cost is ten cents per gallon of storage capacity. Hence, the cost of tanks to store 993,600,000 gallons will be 99,360,000 dollars. The cost of tank farm piping is estimated to be 200,000 dollars. Engineering and legal fees are estimated to be 1,000,000 dollars. Allowing a 5 percent contingency, this gives a total construction cost of \((99,360,000 + 200,000 + 1,000,000) \times 1.05\) or 105,588,000 dollars. On the basis of an 8 percent interest rate and a 50-year life for the tank farm, the annual cost of interest and capital recovery will be \(0.0817 \times 105,588,000\) or 8,627,000 dollars. Assuming a tank size of 160 feet in diameter by 50 feet high (7,500,000 gallons), 132 tanks will be needed to store 993,600,000 gallons. If a tank spacing of 200 feet is assumed, the land area required for the tank farm will be 122 acres. Assuming land acquisition at 10,000 dollars
per acre, the annual interest charge on bonds to purchase land will be \(122 \times 10,000 \times 0.08\) or 98,000 dollars. Annual operating and maintenance costs are estimated to be 1 percent of the construction cost, \(105,588,000 \times 0.01\) or 1,056,000 dollars. This gives a total annual cost of 8,627,000 + 98,000 + 1,056,000 or 9,781,000 dollars to store 993,600,000 gallons of water in surface tanks.

5.3 Storage in Saline Aquifer

As an alternate to tanks, consider underground storage in a saline aquifer having the properties given in Table 5.1.

<table>
<thead>
<tr>
<th>Table 5.1--Storage Aquifer Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aquifer Thickness: 100 ft</td>
</tr>
<tr>
<td>Aquifer Permeability: 400 gpd/ft² (20 darcies)</td>
</tr>
<tr>
<td>Aquifer Storativity: 10⁻⁴</td>
</tr>
<tr>
<td>Aquifer Porosity: 0.30</td>
</tr>
<tr>
<td>Longitudinal Dispersivity Coefficient: 1.0 cm</td>
</tr>
<tr>
<td>Coefficient of Molecular Diffusion: 10⁻⁶ cm²/sec</td>
</tr>
<tr>
<td>Static Water Level: land surface</td>
</tr>
<tr>
<td>Depth to Roof of Aquifer: 800 ft</td>
</tr>
<tr>
<td>Native Water Density: 1.0087 (gm/cc) (8,000 ppm TDS)</td>
</tr>
<tr>
<td>Native Water Viscosity: 1.0 cp</td>
</tr>
</tbody>
</table>

Assume a well field configuration as shown in Figure 5.1. The required production rate of each well will be \(10,800,000 \div (1440 \times 5)\) or 1500 gpm. The injection rate for each well will be 1000 gpm. The wells will have
Figure 5.1 Assumed Well Field Configuration for Cost Comparison.
18-inch diameter casing with 100 ft of 12-inch stainless steel screen that is surrounded by a 3-inch gravel wall. The total depth of each well from ground surface to the bottom of the screen will be 900 ft. In addition to the pump, motor, piping, valves, etc., normally associated with a water well, each well will be equipped with the following: (1) a piping manifold that will allow bypassing of the production string so the well can be used for injection, (2) flow control regulators that will accurately control the injection and production rates, and (3) instrumentation to monitor and record the rate and pressure fluctuations and the changes in water quality as injection or production proceeds. The water to be injected will arrive at the well field at a pressure of 40 psi, have a density of 1.0 gm/cc, and a viscosity of 1.0 cp. The additional pressure needed to inject the water at the specified rates will be produced by a single booster pump for the entire well field. In addition to all the previously mentioned equipment, it will be necessary to have a water-treating facility for chlorination and pH adjustment of the produced water before it is reintroduced into the distribution system. The well field will require a land area of 8 acres.

Using the computational procedures described in Chapter III, it was found that it will be necessary to inject into well No. 1 for 71 days at 1000 gpm before the lagging edge of the mixed zone passes the outer ring of
wells. This will give a cushion water volume of 1000 x 1440 x 71 or 102,240,000 gallons. The cost of this volume of water is considered as part of the capital cost of the system. At the end of 71 days, injection will begin in all five wells at 1000 gpm per well. Again using the computational procedure described in Chapter III, it was found that if fresh water is injected in all five wells at 1000 gpm per well for 156 days, allowed to stand for 117 days, and then produced at 1500 gpm per well until breakthrough occurs at the outer ring of wells, the volume produced at breakthrough will be 995,944,000 gallons. This exceeds the required production of 993,600,000 gallons, therefore the procedure should be adequate to supply the required water since subsequent cycles will have better recoveries. Hence, the maximum water loss per cycle will be 

\[(156 \times 1440 \times 1000 \times 5) - 993,600,000 \text{ or } 129,600,000 \text{ gallons. The cost of this water will be considered as an operating cost.}\]

Using the Theis equation (Theis, 1935) to determine the pressure changes that will be encountered during injection, it was found that a head of 140 ft will have to be produced by the booster pump in order to inject at the specified rates. The motor horsepower required by the booster pump will be \[(5 \times 1000 \times 140) \div (3960 \times 0.80) \text{ or 220 horsepower. The drawdown during production will be approximately 325 ft. The horsepower required to lift the water 325 ft at a rate of 1500 gpm and produce a surface} \]
pressure of 40 psi will be \( (1500 \times [325 + 92]) \div (3960 \times 0.80) \) or 200 horsepower. Each well will require a 200 horsepower motor.

The electrical power required to inject the cushion water will be \( ([220 \div 5] \times 0.746 \times 71 \times 24) \div 0.90 \) or 63,000 Kw-Hr. The cost of this power is considered as part of the capital cost of installing the system. The power required during a normal injection half-cycle will be \( (220 \times 0.746 \times 156 \times 24) \div 0.90 \) or 683,000 Kw-Hr. The cost of this power is an operating expense. The power required during a normal production half-cycle will be \( (200 \times 5 \times 0.746 \times 92 \times 24) \div 0.90 \) or 1,830,000 Kw-Hr. The cost of this power is an operating expense.

The total capital cost of installing the well field is shown in Table 5.2 On the basis of an 8 percent interest rate and a 25-year life for the well field the annual cost of interest and capital recovery will be \( 0.0937 \times (1,236,000 - 80,000) \) or 108,000 dollars. The annual cost of interest for land purchase will be \( 80,000 \times 0.08 \) or 6,000 dollars. The annual cost of electrical power will be \( (683,000 + 1,830,000) \times 0.015 \) or 38,000 dollars. The annual cost for water losses will be \( 129,600 \times 0.05 \) or 7,000 dollars. Other annual operating and maintenance costs are estimated to be 1 percent of the total capital cost less the costs of land and the hydrogeological survey, hence, these costs will be \( (1,236,000 - 80,000 - 250,000) \times 0.01 \) or 9,000 dollars. The total annual cost
TABLE 5.2--Capital Costs of Installing Well Field

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Hydrogeological Survey</td>
<td>$250,000</td>
</tr>
<tr>
<td>b) Land (8 acres @ $10,000/acre)</td>
<td>80,000</td>
</tr>
<tr>
<td>c) Wells (5 wells @ $75,000 each)</td>
<td>375,000</td>
</tr>
<tr>
<td>d) Motor and pump for wells ($20,000 per well)</td>
<td>100,000</td>
</tr>
<tr>
<td>e) Accessories, flow regulators, valves,</td>
<td>50,000</td>
</tr>
<tr>
<td>instrumentation, etc., for wells ($10,000 per well)</td>
<td></td>
</tr>
<tr>
<td>f) Injection booster pump</td>
<td>25,000</td>
</tr>
<tr>
<td>g) Water treatment facility</td>
<td>50,000</td>
</tr>
<tr>
<td>h) Cushion water (102,240,000 gal @ 5¢ per 1000 gal)</td>
<td>5,000</td>
</tr>
<tr>
<td>i) Electric power to inject cushion water (63,000 Kw-Hr @ 1.5¢ per Kw-Hr)</td>
<td>1,000</td>
</tr>
<tr>
<td>j) Engineering and legal fees (25% of items c through g)</td>
<td>150,000</td>
</tr>
<tr>
<td>k) Contingency (20% of items c, d, e, f, g, and j)</td>
<td>150,000</td>
</tr>
<tr>
<td>Total Capital Cost</td>
<td>$1,236,000</td>
</tr>
</tbody>
</table>
of storing 993,600,000 gallons of fresh water in the saline aquifer is $108,000 + 6,000 + 38,000 + 7,000 + 9,000 or 168,000 dollars.

5.4 Comparison of the Two Storage Methods

Table 5.3 summarizes the annual costs of the two methods of storage. It can be seen that storage in the saline aquifer has an overwhelming economic advantage (58 to 1) when compared to surface storage in steel tanks. Also, surface storage uses 122 acres of land that can subsequently be used for no other purpose than a tank farm, while underground storage in the saline aquifer requires an area of only 8 acres and this area can simultaneously be used for other purposes such as recreational facilities or a parking lot, since most of the structures are beneath the land surface.

TABLE 5.3--Summary of Annual Costs for Tank Storage and Saline Aquifer Storage

<table>
<thead>
<tr>
<th>Annual Cost</th>
<th>Storage Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tanks</td>
</tr>
<tr>
<td>Interest &amp; Capital Recovery</td>
<td>$8,627,000</td>
</tr>
<tr>
<td>Interest on Land</td>
<td>98,000</td>
</tr>
<tr>
<td>Power</td>
<td>--</td>
</tr>
<tr>
<td>Water Losses</td>
<td>--</td>
</tr>
<tr>
<td>Operation and Maintenance</td>
<td>1,056,000</td>
</tr>
<tr>
<td>Totals</td>
<td>$9,781,000</td>
</tr>
</tbody>
</table>
CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

On the basis of the results obtained from this investigation, the following conclusions are drawn:

1. The recovery of fresh water stored in a saline aquifer using a well field can be predicted using the computational procedure presented in this dissertation. The well field must by symmetrical and must be operated so that the injected bubble of fresh water remains essentially circular.

2. The computational procedure predicts the experimentally determined recovery efficiencies for multiple well systems within 10 percent.

3. The predicted recovery efficiencies are invariably smaller than the observed recovery efficiencies.

4. The experimental work showed: (a) the recovery efficiency of the storage process improves as the number of cycles of operation increases, and (b) the larger the density difference between the injected and native fluids, the lower the recovery efficiency.

5. Storage of fresh water in a saline aquifer by means of a well field has a tremendous economic advantage.
when compared to surface storage of an equal volume of water in tanks.

6. The method used to determine the longitudinal dispersivity coefficient of the miniaquifer can be readily adapted to field use.

6.2 Recommendations

Recommendations for further study on the storage of fresh water in saline aquifers are:

1. The computational procedure proposed in this dissertation should be expanded by including the effects of the following field conditions on the recovery efficiency of the storage process:
   a. Aquifer dip
   b. Unequal viscosity ratios between the injected and native fluids.
   c. Pre-existing ground-water movement in the storage aquifer.

2. Experimental and theoretical investigations should be undertaken to:
   a. Determine the rate of gravitational segregation between miscible fluids for conditions where the dimensionless group, $\psi$, is greater than 1 (see Fig. 2.1).
   b. Develop a more elegant mathematical description of gravitational segregation for a radial system than that presented in this dissertation.
NOMENCLATURE

\( c_i = \) concentration of injected fluid at any radius and time.

\( c_0 = \) initial concentration of injected fluid.

\( c_n = \) concentration of native fluid at any radius and time.

\( D = \) coefficient of molecular diffusion of fluids in porous medium. \((\text{cm}^2/\text{sec})\)

\( \text{erfc}(\xi) = \) complementary error function of \( \xi \)

\[
\text{erfc}(\xi) = \frac{2}{\sqrt{\pi}} \int_\xi^\infty e^{-w^2} \, dw
\]

\( F = \) a dimensionless factor dependent on viscosity ratio. \((F = 1.0 \text{ for a ratio of one})\)

\( g = \) acceleration due to gravity. \((\text{cm/sec}^2)\)

\( h = \) aquifer thickness. \((\text{cm})\)

\( k = \) intrinsic permeability of aquifer. \((\text{cm}^2 \text{ in Equation 2.7, darcies in Equation 4.1})\)

\( k_H = \) horizontal intrinsic permeability. \((\text{cm}^2)\)

\( k_V = \) vertical intrinsic permeability. \((\text{cm}^2)\)

\( P = \) pressure. \((\text{atm})\)

\( Q = \frac{q}{2\pi h \phi}. \) \((\text{cm}^2/\text{sec})\)

\( q = \) volumetric flow rate. \((\text{cm}^3/\text{sec})\)

\( R = \) radius of injected fluid at any time \( t \), assuming no mixing or gravitational segregation. \((\text{cm})\)

\( r = \) radius. \((\text{cm})\)

\( S = \) density gradient. \((\text{gm/cm}^4)\)
\[ t = \text{time. (sec)} \]

\[ 2XL = \text{projection of the 50 percent concentration line on the horizontal for a linear system. (cm)} \]

\[ 2XR = \text{projection of the 50 percent concentration line on the horizontal for a radial system. (cm)} \]

\[ \alpha = \text{longitudinal dispersivity coefficient of porous medium. (cm)} \]

\[ \Delta \rho = \text{density difference between injected and native fluids. (gm/cc)} \]

\[ \theta = \text{the angle that the 50 percent concentration line makes with respect to the vertical.} \]

\[ \mu = \text{viscosity of the native fluid. (centipoise)} \]

\[ \bar{\mu} = \text{average viscosity of the injected and native fluids. (poise)} \]

\[ \phi = \text{aquifer porosity. (fraction)} \]

\[ \psi = \left[ \frac{k \cdot g \cdot \Delta \rho \cdot t}{\bar{\mu} \cdot \phi \cdot h} \right] \left[ \frac{(\bar{\mu})^{2/3} \cdot S}{(\Delta \rho)^{5/3} \cdot g^{1/3}} \right]^{1/2} \]
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Kumar, A., 1968, Dispersion and gravity segregation of miscible fluids in porous media for stratified radial flow systems, M.S. Thesis, Dept. of Petroleum Engineering, Louisiana State University, Baton Rouge.


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APPENDIX A

DERIVATION OF EQUATIONS

A.1 Derivation of Equation 2.3

Starting with Equation 2.2:

\[
\frac{c_i}{c_0} = \frac{1}{2} \text{erfc} \left[ \frac{r^2/2 - Qt}{(4/3 \alpha R^3 + D/Q R^4)^{1/2}} \right] \ldots (2.2)
\]

Where:

\(c_i\) = concentration of injected fluid at radius, \(r\), and time, \(t\). (volume fraction)
\(r\) = radius. (cm)
\(R\) = radius of injected fluid at time \(t\), assuming no mixing or gravitational segregation. (cm)
\(Q = q/(2\pi h\phi)\) (cm\(^2\)/sec)
\(q\) = volumetric flow rate. (cc/sec)
\(h\) = aquifer thickness. (cm)
\(\phi\) = aquifer porosity. (fraction)
\(D\) = coefficient of molecular diffusion. (cm\(^2\)/sec)
\(\alpha\) = longitudinal dispersivity coefficient of porous medium. (cm)
\(\text{erfc}\) = complementary error function.

Note that:

\[q \cdot t = \pi R^2 h\phi \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (A.1)\]
Hence:
\[ \frac{q \cdot t}{\pi h \phi} = R^2 \quad \ldots \quad (A.2) \]

Dividing both sides by 2:
\[ \frac{q}{2 \pi h \phi} \cdot t = \frac{R^2}{2} \quad \ldots \quad (A.3) \]

Therefore:
\[ Q \cdot t = \frac{R^2}{2} \quad \ldots \quad (A.4) \]

Solving for R:
\[ R = \sqrt{2 \cdot Q \cdot t} \quad \ldots \quad (A.5) \]

Substituting Equations A.4 and A.5 into Equation 2.2:
\[ \frac{c_i}{c_o} = \frac{1}{2} \operatorname{erfc} \left[ \frac{r^2/2 - R^2/2}{\left[ 4/3 \alpha (2 \cdot Q \cdot t)^{3/2} + D \left( \frac{2 \cdot Q \cdot t}{q} \right)^2 \right]^{1/2}} \right] \quad (A.6) \]

Or:
\[ \frac{c_i}{c_o} = \frac{1}{2} \operatorname{erfc} \left[ \frac{r^2 - R^2}{2 \sqrt{f(t)}} \right] \quad \ldots \quad (A.7) \]

Where:
\[ f(t) = 4/3 \alpha (2 \cdot Q \cdot t)^{3/2} + D \left( \frac{2 \cdot Q \cdot t}{q} \right)^2 \]

Note that Equation A.7 is identical to Equation 2.3.
A.2 Derivation of Equation 2.4

Starting with Equation 2.3:

\[
\frac{c_i}{c_0} = \frac{1}{2} \text{erfc} \left( \frac{r^2 - R^2}{2\sqrt{f(t)}} \right) \quad \ldots \ldots \ldots \ldots \quad (2.3)
\]

Note that:

\[
\frac{c_n}{c_0} = 1 - \frac{c_i}{c_0}
\]

Hence:

\[
\frac{c_n}{c_0} = 1 - \frac{1}{2} \text{erfc} \left( \frac{r^2 - R^2}{2\sqrt{f(t)}} \right) \quad \ldots \ldots \ldots \ldots \quad (A.8)
\]

Multiplying through by 2:

\[
\frac{2c_n}{c_0} = 2 - \text{erfc} \left( \frac{r^2 - R^2}{2\sqrt{f(t)}} \right) \quad \ldots \ldots \ldots \ldots \quad (A.9)
\]

Rearranging:

\[
\frac{2c_n}{c_0} = 1 + \left\{ 1 - \text{erfc} \left( \frac{r^2 - R^2}{2\sqrt{f(t)}} \right) \right\} \quad \ldots \ldots \ldots \quad (A.10)
\]

Recall the identities:

\[
\text{erfc} (\xi) = 1 - \text{erf} (\xi) \quad \ldots \ldots \ldots \ldots \quad (A.11)
\]

\[
\text{erf} (\xi) = 1 - \text{erfc} (\xi) \quad \ldots \ldots \ldots \ldots \quad (A.12)
\]

\[
\text{erf} (-\xi) = -\text{erf} (\xi) \quad \ldots \ldots \ldots \ldots \quad (A.13)
\]
Using Equation A.12, note that Equation A.10 can be written as:

\[
\frac{2c_n}{c_0} = 1 + \text{erf} \left[ \frac{r^2 - R^2}{2\sqrt{f(t)}} \right] \quad \ldots \ldots \ldots \ldots \quad (A.14)
\]

Using Equation A.13, note that Equation A.14 can be written as:

\[
\frac{2c_n}{c_0} = 1 - \text{erf} \left[ \frac{R^2 - r^2}{2\sqrt{f(t)}} \right] \quad \ldots \ldots \ldots \ldots \quad (A.15)
\]

Using Equation A.11, note that Equation A.15 can be written as:

\[
\frac{2c_n}{c_0} = \text{erfc} \left[ \frac{R^2 - r^2}{2\sqrt{f(t)}} \right] \quad \ldots \ldots \ldots \ldots \quad (A.16)
\]

Dividing through by 2:

\[
\frac{c_n}{c_0} = \frac{1}{2} \text{erfc} \left[ \frac{R^2 - r^2}{2\sqrt{f(t)}} \right] \quad \ldots \ldots \ldots \ldots \quad (A.17)
\]

Note that Equation A.17 is identical to Equation 2.4.
APPENDIX B

COMPUTER PROGRAMS FOR CALCULATING RECOVERY EFFICIENCIES

The three computer programs listed in the following pages are for predicting the recovery efficiencies of the storage process for one, two, and three cycle operation of a single well system. The programs are in FORTRAN IV language and are written for use on an IBM 360/65 system.

A list of the required input data is presented at the beginning of each program. Following this is a complete list of all the variable names used in the program along with their definitions.

To illustrate the manner in which the programs have to be modified for use with a multiple well system, a well field pattern similar to that shown in Figure 7b will be assumed. The operating procedure would be as follows:

1. Inject into the center well until the lagging edge of the mixed zone passes the outer ring of wells. (2) Inject into all five wells until the desired quantity is injected.
2. Allow the injected water to stand until needed.
3. Produce all five wells until breakthrough occurs at the outer ring of wells, at which time production from the well field is stopped. Subsequent cycles are made with injection beginning in all five wells simultaneously.
As stated in Chapter III it is assumed that all injection and production takes place through the center well of the pattern. The programs listed in the following pages are for single well systems and it is assumed that during any half-cycle the rate during that half-cycle remains constant. To use the programs for the operating procedure outlined above provisions would have to be made to allow a rate change during the first injection half-cycle. This can be accomplished as follows:

1) Change statement 21 to read:

   21 READ(5,13000)QR1GM,QR1AGM,QR2GM

Where:

   QR1GM  = Injection rate in center well until mixed zone passes outer ring of wells. (gpm)
   QR1AGM = Combined injection rate of all five wells. (gpm)
   QR2GM  = Combined production rate of all five wells. (gpm)

2) Immediately following statement 22 add the statement:

   READ(5,15100)TIMDAY

Where:

   TIMDAY = Time of injection in center well until the mixed zone passes the outer ring of wells and injection begins in all five wells. (days)

3) Change statement 24 to read:

   24 WRITE(6,19000)QR1GM,QR1AGM,QR2GM

4) Immediately following statement 51 add the statement:

   QR1A=QR1AGM*CGMCCS
Where:

\[ Q_{R1A} = \text{Combined injection rate of all five wells.} \quad (\text{cc/sec}) \]

5) Immediately following statement 57 add the statement:

\[ \text{TIMSEC} = \text{TIMDAY} \times \text{CFDSEC} \]

Where:

\[ \text{TIMSEC} = \text{Time of injection in center well until mixed zone passes outer ring of wells and injection begins in all five wells.} \quad \text{(sec)} \]

6) Immediately following statements 151 and 191 add the statements:

\[ \text{TCHECK} = \text{TRT} - \text{TIMSEC} \]

\[ \text{IF} (\text{TCHECK} \geq 0.0) \text{QR1} = \text{QR1A} \]

Where:

\[ \text{TCHECK} = \text{A time check to see if time of injection has reached or exceeded TIMSEC.} \quad \text{(sec)} \]

7) Change format statement 13000 to read:

\[ 13000 \text{ FORMAT}(3F12.0) \]

8) Immediately following format statement 15000 add the format statement:

\[ 15100 \text{ FORMAT}(1F12.0) \]

9) Make the following changes in the continuation statements of format statement 19000:

\[ 3 \quad 11X, \text{"RATE FOR FIRST STEP"}, 35X, F14.8/\]

\[ 4 \quad 11X, \text{"RATE FOR SECOND STEP"}, 34X, F14.8/\]

\[ 5 \quad 9X, \text{"PRODUCTION RATE FOR FIRST PRODUCTION HALF-CYCLE"}, 9X, F14.8/\]

The above has shown how the programs can be modified to take care of one rate change in the first injection half-cycle. If there is more than one rate change in the
first injection half-cycle or if there are rate changes in any subsequent half-cycle, either injection or production, they can be handled in a similar manner.

It should be noted that in the single well case and the multiple well case it is necessary to run the one cycle program to obtain the fluid produced during the first production half-cycle and the total number of computation intervals through the end of the first production half-cycle before the two-cycle program can be run. This procedure is necessary since these two values are input data for the two-cycle program. Similarly the two-cycle program must be run before the three-cycle program can be run.
PROGRAM TO CALCULATE THE RECOVERY EFFICIENCY OF THE PROCESS OF STORING FRESH WATER IN SALINE AQUIFERS.

PROGRAM 'CYCLE 1A' (SINGLE WELL - ONE CYCLE)

*******************************************************************************

DATA TO BE READ IN

FIRST CARD - FORMAT(6F12.0)
  ABTFT = RADIUS AT WHICH BREAKTHROUGH IS COMPUTED. (FT)
  CBT = ALLOWABLE CONCENTRATION OF NATIVE SALT WATER IN PRODUCED STREAM. (VOLUME FRACTION)
  TILIFT = INTERVAL LENGTH FOR CALCULATIONS DURING INJECTION HALF-CYCLES. (FT)
  TILPFT = INTERVAL LENGTH FOR CALCULATIONS DURING PRODUCTION HALF-CYCLES. (FT)
  RINCFT = LENGTH OF INCREMENT FOR CALCULATION OF MIXED ZONE LENGTHS. (FT)
  TINCFT = INCREMENT BY WHICH TILIFT IS INCREASED IF MIXED ZONE INTERSECTS THE LINE SOURCE DURING CALCULATIONS FOR FIRST INTERVAL OF FIRST INJECTION HALF-CYCLE. (FT)

SECOND CARD - FORMAT(5F12.0)
  MPT = AQUIFER THICKNESS. (FT)
  PLYDAR = AQUIFER PERMEABILITY. (DARCYS)
  PR = POROSITY. (FRACTION)
  ALF = LATERAL DISPERSIVITY COEFFICIENT. (CM)
  DIFMOL = COEFFICIENT OF MOLECULAR DIFFUSION. (SQ CM/S SEC)

THIRD CARD - FORMAT(5F12.0)
  VISCP1 = VISCOSITY OF THE INJECTED FRESH WATER. (CP)
  VISCP2 = VISCOSITY OF THE NATIVE SALT WATER. (CP)
  DENS1 = DENSITY OF THE INJECTED FRESH WATER. (GM/CC)
  DENS2 = DENSITY OF THE NATIVE SALT WATER. (GM/CC)
  ACNG = ACCELERATION DUE TO GRAVITY. ((CM/SEC)/SEC)

FOURTH CARD - FORMAT(2F12.0)
  OR1GN = INJECTION RATE FOR FIRST INJECTION HALF-CYCLE. (GPM)
  OR2GN = PRODUCTION RATE FOR FIRST PRODUCTION HALF-CYCLE. (GPM)

FIFTH CARD - FORMAT(1F12.0)
  PLING1 = FLUID INJECTED IN FIRST INJECTION HALF-CYCLE. (GAL)

SIXTH CARD - FORMAT(1F12.0)
  TSTD = STATIC STORAGE TIME AT THE END OF THE FIRST INJECTION HALF-CYCLE. (DAYS)

*******************************************************************************

DEFINITION OF VARIABLE NAMES USED IN PROGRAM

A1 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RUSO FOR FIRST INJECTION HALF-CYCLE. (SQ CM)
A2 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RUSO FOR FIRST PRODUCTION HALF-CYCLE. (SQ CM)
B1 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RUSO FOR FIRST INJECTION HALF-CYCLE. (SQ CM)
B2 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RUSO FOR FIRST PRODUCTION HALF-CYCLE. (SQ CM)
CFCPP = CONVERSION FACTOR. (POISE/CENTIPOISE)
CPDSCH = CONVERSION FACTOR. ((SQ CM)/DARCYS)
CPDSCH = CONVERSION FACTOR. (SEC/DAY)
CPFCTCM = CONVERSION FACTOR. (CM/FT)
CFGLCC = CONVERSION FACTOR. (CC/GAL)
CGMCCS = CONVERSION FACTOR. ((CC/SEC)/(GAL/MIN))
CONST1 = VALUE USED IN CHECKING FOR BREAKTHROUGH DURING A
PRODUCTION HALF-CYCLE.
CONST2 = VALUE USED IN CHECKING FOR BREAKTHROUGH DURING A
PRODUCTION HALF-CYCLE.
CRCEFF = CUMULATIVE RECOVERY EFFICIENCY. (FRACTION)
CVLING = CUMULATIVE VOLUME OF FLUID INJECTED. (GAL)
CVLARDG = CUMULATIVE VOLUME OF INJECTED FLUID RECOVERED. (GAL)
CVDILN = CUMULATIVE VOLUME OF FLUID INJECTED. (CC)
CVOLRD = CUMULATIVE VOLUME OF INJECTED FLUID RECOVERED. (CC)
C11 = COMPUTED CONCENTRATION AT THE RADIUS AND AT THE TIME
BEING CONSIDERED. (VOLUME FRACTION)
DG = DENSITY GRADIENT. ((GM/CC)/CM)
DN1 = A CONSTANT USED IN THE COMPUTATION OF THE DIMENSIONLESS
PARAMETER GIVEN BY EQUATION 2.7A.
DN2 = DIMENSIONLESS GROUP. SECOND GROUP ON RIGHT SIDE OF
EQUATION 2.7A.
DN2A = A CONSTANT USED IN THE COMPUTATION OF THE DIMENSIONLESS
PARAMETER GIVEN BY EQUATION 2.7A.
DNOM11 = DENOMINATOR OF ARGUMENT OF COMPLEMENTARY ERROR FUNCTION
IN EQUATION 2.5 FOR FIRST INJECTION HALF-CYCLE.
DNOMP2 = DENOMINATOR OF ARGUMENT OF COMPLEMENTARY ERROR FUNCTION
IN EQUATION 2.5 FOR FIRST PRODUCTION HALF-CYCLE.
DSDF = DENSITY DIFFERENCE BETWEEN INJECTED AND NATIVE
FLUIDS. (GM/CC)
OSC2 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RL50 FOR
FIRST PRODUCTION HALF-CYCLE. (SO CM)
FLINJ1 = FLUID INJECTED IN FIRST INJECTION HALF-CYCLE. (CC)
FLPAG2 = FLUID PRODUCED IN FIRST PRODUCTION HALF-CYCLE. (GAL)
FLPRN2 = FLUID PRODUCED IN FIRST PRODUCTION HALF-CYCLE. (CC)
H = AQUIFER THICKNESS. (CM)
I = SUBSCRIPT DESIGNATING COMPUTATION INTERVAL.
NINT1 = NUMBER OF COMPUTATION INTERVALS THRU THE END OF THE
FIRST INJECTION HALF-CYCLE.
NINT2 = NUMBER OF COMPUTATION INTERVALS THRU THE FIRST
PRODUCTION HALF-CYCLE.
PLY = AQUIFER PERMEABILITY. (SO CM)
PPP = PRODUCT OF PI, POROSITY, AND THICKNESS. (CM)
PPP1 = 2*PPP. (CM)
Q11 = TWO DIMENSIONAL FLOW RATE FOR FIRST INJECTION
HALF-CYCLE. ((50 CM)/SEC)
QP2 = TWO DIMENSIONAL FLOW RATE FOR FIRST PRODUCTION
HALF-CYCLE. ((50 CM)/SEC)
QR1 = FLOW RATE FOR FIRST INJECTION HALF-CYCLE. (CC/SEC)
QR2 = FLOW RATE FOR FIRST PRODUCTION HALF-CYCLE. (CC/SEC)
QS11 = TWO DIMENSIONAL PSEUDO FLOW RATE FOR FIRST INJECTION
HALF-CYCLE. ((50 CM)/SEC)
QSP2 = TWO DIMENSIONAL PSEUDO FLOW RATE FOR FIRST PRODUCTION
HALF-CYCLE UP TO COMPUTATION INTERVAL AT WHICH
BREAKTHROUGH CHECK IS BEING MADE. ((50 CM)/SEC)
R(1) = RADIUS OF INJECTED FLUID AT THE ITH COMPUTATION
INTERVAL ASSUMING NO MIXING OR GRAVITATIONAL
SEGREGATION. (CM)
RBT = RADIUS AT WHICH BREAKTHROUGH IS COMPUTED. (CM)
RCBT(1) = LEAST RADIUS TO A VALUE OF CONCENTRATION OF CBT FOR THE
LAST COMPUTATION INTERVAL OF THE LAST PRODUCTION
HALF-CYCLE. (CM)
RCBTFT = LEAST RADIUS TO A VALUE OF CONCENTRATION OF CBT FOR THE
LAST COMPUTATION INTERVAL OF THE LAST PRODUCTION
HALF-CYCLE. (FT)
RCEFF = CYCLE RECOVERY EFFICIENCY. (FRACTION)
RFT = RADIUS OF INJECTED FLUID AT THE ITH COMPUTATION
INTERVAL ASSUMING NO MIXING OR GRAVITATIONAL
SEGREGATION. (FT)
RINC = LENGTH OF INCREMENT USED FOR CALCULATION OF MIXED
ZONE LENGTHS. (CM)
RINJ1 = RADIUS OF INJECTED FLUID AT THE END OF THE FIRST
INJECTION HALF-CYCLE ASSUMING NO MIXING AND NO
GRAVITATIONAL SEGREGATION. (CM)
RL50 = RADIUS TO LOWER END OF 50 PERCENT CONCENTRATION
LINE. (CM)
ALSOFT = RADIUS TO LOWER END OF 50 PERCENT CONCENTRATION LINE. (FT)

ALSOII = RADIUS TO LOWER END OF 50 PERCENT CONCENTRATION LINE AT THE START OF THE FIRST PRODUCTION HALF-CYCLE. (CM)

RUS0 = RADIUS TO UPPER END OF 50 PERCENT CONCENTRATION LINE. (CM)

RUSOFT = RADIUS TO UPPER END OF 50 PERCENT CONCENTRATION LINE. (FT)

R1 = RADIUS AT WHICH CONCENTRATION IS BEING COMPUTED. ALSO INNER RADIUS OF MIXED ZONE. (CM)

R1FT = INNER RADIUS OF MIXED ZONE. (FT)

R2(I) = OUTER RADIUS OF MIXED ZONE. (CM)

R2FT = OUTER RADIUS OF MIXED ZONE. (FT)

R3 = LENGTH OF MIXED ZONE. (CM)

R3FT = MIXED ZONE LENGTH. (FT)

R4 = TILI/2. (CM)

R5 = RADIUS TO THE MIDPOINT BETWEEN R(I) AND R(I-1). (CM)

R5SQ = R5 SQUARED. (CM)

R6 = TILP/2. (CM)

SDENOM = DENOMINATOR OF ARGUMENT OF COMPLEMENTARY ERROR FUNCTION IN EQUATION 2.5 USING PSEUDO RATES TO CHECK FOR BREAKTHROUGH DURING A PRODUCTION HALF-CYCLE.

TILI = INTERVAL LENGTH FOR COMPUTATIONS DURING INJECTION HALF-CYCLES. (CM)

TILP = INTERVAL LENGTH FOR COMPUTATIONS DURING PRODUCTION HALF-CYCLES. (CM)

TRT = CUMULATIVE TRAVEL TIME OF FRESH WATER-SALT WATER INTERFACE. (SEC)

TRTI = CUMULATIVE TRAVEL TIME OF INTERFACE THRU END OF FIRST INJECTION HALF-CYCLE. (SEC)

TRT2 = CUMULATIVE TRAVEL TIME OF INTERFACE THRU COMPUTATION INTERVAL AT WHICH BREAKTHROUGH CHECK IS BEING MADE. (SEC)

TST1 = STATIC STORAGE TIME AT THE END OF THE FIRST INJECTION HALF-CYCLE. (SEC)

TSP = PSEUDO TIME USED IN GRAVITATIONAL SEGREGATION CALCULATIONS. (SEC)

TSPD = PSEUDO TIME USED IN GRAVITATIONAL SEGREGATION CALCULATIONS. (DAYS)

TT = TIME OF TRAVEL ACROSS ANY COMPUTATION INTERVAL PLUS THE PSEUDO TIME FOR THAT INTERVAL. (SEC)

TTD = TIME OF TRAVEL ACROSS ANY COMPUTATION INTERVAL PLUS THE PSEUDO TIME FOR THAT INTERVAL. (DAYS)

T1 = TIME AT WHICH CONCENTRATION IS BEING COMPUTED DURING FIRST INJECTION HALF-CYCLE. ALSO CUMULATIVE TRAVEL TIME OF INTERFACE THRU END OF FIRST INJECTION HALF-CYCLE. (SEC)

T2 = TIME AT WHICH CONCENTRATION IS BEING COMPUTED DURING FIRST PRODUCTION HALF-CYCLE. (SEC)

TII = TIME OF TRAVEL ACROSS ANY COMPUTATION INTERVAL. (SEC)

TIDD = TIME OF TRAVEL ACROSS ANY COMPUTATION INTERVAL. (DAYS)

VIS = MEAN VISCOSITY OF INJECTED AND NATIVE FLUIDS. (POISE)

RISCP = RESIDUAL SVU密度 OF INJECTED AND NATIVE FLUIDS. (CP)

VOLNR = TOTAL VOLUME OF INJECTED FLUID NOT RECOVERED. (CC)

X = VALUE OF DIMENSIONLESS PARAMETER GIVEN BY EQUATION 2.7A.

XL(I) = HORIZONTAL PROJECTION OF 50 PERCENT CONCENTRATION LINE FOR LINEAR GEOMETRY. (CM)

XLFT = HORIZONTAL PROJECTION OF 50 PERCENT CONCENTRATION LINE FOR LINEAR GEOMETRY. (FT)

XR(I) = HORIZONTAL PROJECTION OF 50 PERCENT CONCENTRATION LINE FOR RADIAL GEOMETRY. (CM)

XRFT = HORIZONTAL PROJECTION OF 50 PERCENT CONCENTRATION LINE FOR RADIAL GEOMETRY. (FT)

XX = ARGUMENT OF COMPLEMENTARY ERROR FUNCTION FOR EQUATION 2.6.

YL(I) = RATIO OF HORIZONTAL PROJECTION OF 50 PERCENT CONCENTRATION LINE TO AQUIFER THICKNESS FOR LINEAR GEOMETRY.
C YR(I) = RATIO OF HORIZONTAL PROJECTION OF 90 PERCENT
C CONCENTRATION LINE TO AQUIFER THICKNESS FOR RADIAL
C GEOMETRY.

*************************************************************************

C DIMENSION R1(1000), R2(1000), YL(1000), XL(1000), XR(1000), RCBT(1000)

C PART 1 - READING DATA

20 READ(5,10000) RBTFT, CBTT, TILIFT, TILPFT, RINCFT, TINCFT
READ(5,10000) HFT, PLYDAR, PR, ALF, DIFNOL
READ(5,12000) VISCP1, VISCP2, DENS1, DENS2, ACNG
21 READ(5,13000) ORIG1, OR2GN
READ(5,14000) FLING1
22 READ(5,15000) TSSTD

C CALCULATION OF DENSITY DIFFERENCE AND MEAN VISCOSITY OF FLUIDS

DSDF = ABS(DENS1 - DENS2)
VISCP = (VISCP1 + VISCP2)/2.0

C PART 2 - PRINTING DATA

WRITE(6,16000) HFT, PLYDAR, PR, ALF, DIFNOL
WRITE(6,17000) VISCP1, VISCP2, VISCP
WRITE(6,18000) DENS1, DENS2, DSDF, ACNG
24 WRITE(6,19000) ORIG1, OR2GN
WRITE(6,20000) FLING1
WRITE(6,21000) TSSTD

C WRITE(6,22000)

30 TILIFT = TILIFT + TINCFT
GOTO 50

C PART 3 - CONSTANTS AND CONVERSION FACTORS

*************************************************************************

50 CFFFTCH=30.8801
CFDSCH=0.987E-08
CFLCCS=3785.434
CGMCCS=63.0906
CFSOSEC=86400.0
CFCPP=0.01
RBT=RBTFT*CFFFTCH
RINC=RINCFT*CFFFTCH
H=HFT*CFFFTCH
PPP=3.14159265
PPP=3.14159265
PLY=PLYDAR*CFDSCH
FLING1=FLING1*CFLCCS
51 ORIG=ORIG1*CGMCCS
52 OR2=OR2GN*CGMCCS
57 TSSTD=TSSTD*CFDSEC
VIS=VISCP*CFCPP
DM1=(PLY*ACNG*DSDF)/(PR*VIS1)
DM2=VIS*0.6667/(DSDF*1.001*ACNG**0.3333)
PART 4 - CALCULATIONS FOR FIRST INJECTION HALF-CYCLE

CALCULATIONS OF INTERVALS AND RADIUS OF INJECTION

\[ R_{INJ1} = \text{SQRT} \left( \frac{FLINJ1}{PPP} \right) \]
\[ N_{INT} = \frac{R_{INJ1}}{TILI} \]

CALCULATION OF MIXED ZONE DUE TO DIFFUSION AND DISPERSION

\[ I = 1 \]
\[ \text{TTR} = 0.0 \]
\[ R(I) = TILI \]

61 \[ R5 = R(I) - RA \]
62 \[ R50 = R5 * R5 \]
63 \[ R1 = R5 - RINC \]
64 \[ T1 = PPP * R50 / OR1 \]
65 \[ Q11 = OR1 / PPP1 \]
66 \[ DNOM1 = 2.05 * \text{SQRT}(1.333 * \text{ALF} * (2.000110 * T1)^001.5 + \text{DIFMOL} * (2.000110 * T1)^002) \]
67 \[ /Q11 \]
70 \[ XX = (R500 - R1 * OR1) / DNOM11 \]
71 \[ CI1 = \text{ERFC}(XX) / 2.0 \]
72 \[ IF(C11 < 0.5) \]
73 \[ 80 \]
74 \[ R2(I) = R1 \]
75 \[ GOTO110 \]
76 \[ 100 \]
77 \[ R1 = R1 - RINC \]
78 \[ IF(R1 < 30.0) \]
79 \[ 70 \]
80 \[ R1 = R1 + RINC \]
81 \[ GOTO70 \]
82 \[ 120 \]
83 \[ IF(C11 < 0.5) \]
84 \[ 130 \]
85 \[ R1 = R1 + RINC \]
86 \[ GOTO70 \]
87 \[ 160 \]
88 \[ R3 = R1 - R2(I) \]
89 \[ R1FT = R1 / CFFTCH \]
90 \[ R2FT = R2(I) / CFFTCH \]
91 \[ R3FT = R3 / CFFTCH \]

CALCULATION OF INTERFACE PROJECTION DUE TO GRAVITY SEGREGATION

\[ IF(1-I) = 0.750, 150, 190 \]

150 \[ DG = DSD / R3 \]
151 \[ DM2 = DM2A * DG \]
152 \[ T11 = PPP * R(1) * OR1 \]
153 \[ TRT = TRT + T11 \]
154 \[ X = DM1 * T11 + DM2 * 0.5 \]
155 \[ IF(X < 0.1) \]
156 \[ 160 \]
157 \[ YL(I) = 0.795 + 12.523 * X - 4.019 * X * 2 \]
158 \[ GOTO180 \]
159 \[ 175 \]
160 \[ YL(I) = 6.5 + 2.0 * X \]
161 \[ XL(I) = YL(I) * 0.8 \]
162 \[ XLP = XL(I) / CFFTCH \]
163 \[ T10 = T11 / CFDSEC \]
164 \[ T5P = 0.0 \]
165 \[ YTD = T11D \]
166 \[ GOTO290 \]
167 \[ 190 \]
168 \[ DG = DSD / R3 \]
169 \[ DM2 = DM2A * DG \]
170 \[ T11 = PPP * ABS(R(I) * OR1 - R(1) * OR2) / OR1 \]
171 \[ TRT = TRT + T11 \]
172 \[ IF(YL(I) < 2.0) \]
173 \[ 195, 198, 200 \]
195 X=YL(I-1)/20.0
GOTO215
200 IF(YL(I-1)-6.0)205,210,210
205 X=1.4993-SORT(172.1873-19.2784*YL(I-1))/9.6392
GOTO215
210 X=(YL(I-1)-6.5)/2.0
215 TSP=X/(DH1*DH2*9.5)
220 TT=TT1+TSP
IF(I-NINT1)220,230,330
230 TT=TT+TST1
240 X=DH1*TST2*9.5
IF(X<0.1)250,250,255
250 YL(I)=20.0*X
GOTO270
255 IF(X>1.0)250,250,265
260 YL(I)=0.7950+12.5230*X-4.8196*X**2
GOTO270
265 YL(I)=6.5+2.0*X
270 XL(I)=YL(I)*H
XLFT=XL(I)/CFFTCM
TID1=TT/CFDSEC
TSPD=TSP/CFDSEC
TTO=TT/CFDSEC
GOTO300

C
APPROXIMATION TO RADIAL GEOMETRY
C
290 RUSO=R(I)+XL(I)/2.0
RLSO=R(I)-XL(I)/2.0
IF(RLSO<0.350,310,310
300 A1=3.142(R(I-1)+XR(I-1))/2.0**2-R(I-1)**2)
B1=3.142(R(I-1)**2-R(I-1)+XR(I-1))/2.0**2)
RUSO=SORT(3.142(R(I-1)+XR(I-1))/3.142*(XL(I)-XL(I-1))/2.0)
RLSO=SORT(3.142(R(I-1)+XR(I-1))-B1)/3.142-(XL(I)-XL(I-1))/2.0
310 XR(I)=RUSO-RLSO
YR=XR(I)/H
RUSOFT=RUSO/CFFTCM
RLSOFT=RLSO/CFFTCM
XRFT=XR(I)/CFFTCM
RFT=R(I)/CFFTCM
C
PRINTING COMPUTATIONS FOR FIRST INJECTION HALF-CYCLE
C
WRITE(6,23000)I,RF1,RF2,RF3
WRITE(6,24000)1,DM1,DM2,DG,X
WRITE(6,25000)I,TID1,TSPD,TTO,YL(I),XLFT
WRITE(6,26000)I,RUSOFT,GLSOFT,XRFT,YR,RF1
C
I=I+1
IF(I-NINT1)320,320,330
320 R(I)=R(I-1)+TIL1
GOTO61
330 TRT1=TRT
RLSO1=RLSO
GSL=(RLSO1+RLSO1)/1.20*TRT1
CONST1=2.0*GSL1*TRT1)**1.5
CONST2=2.0*GSL1*TRT1)**2/GSL1
C
PART 5 - CALCULATIONS FOR FIRST PRODUCTION HALF-CYCLE
C
WRITE(6,27000)
C
CALCULATION OF MIXED ZONE DUE TO DIFFUSION AND DISPERSION
C
340 R(I)=R(I-1)-TILP
IF(R(I))550,590,345
CALCULATION OF INTERFACE PROJECTION DUE TO GRAVITY SEGREGATION

\[
\begin{align*}
&346 \text{ R5=R}(1)+R6 \\
&\text{R5SO=R5+R5} \\
&\text{RI=R5-RINC} \\
&T1=\text{PPP}R((\text{INT1})**2/QR1) \\
&T2=\text{T1}+\text{PPP}R((\text{INT1})**2-RSSO)/QR2 \\
&Q2=\text{QR2}/\text{PPP} \\
&\text{DNOMP2}=2.000QRT(1.333+\text{ALP}(\text{2.000P2*T2})*1.5-(\text{2.000P2*T1})*1.5+2.000P2*T1)*1.5 \\
&1 \quad 0 \quad 0 \quad 1 \quad 0 \quad 1 \quad + \text{DIFFHOLE}(\text{2.000P2*T2})*1.52/\text{QR2}-(\text{2.000P2*T1})*1.52 \\
&2 \quad /\text{QR2}(\text{2.000INT1)**2/QR1}) \\
&350 \text{ XX=(R5SO-R1*RI)/DNOMP2} \\
&\text{CII=ERFC}(\text{XX}/2.0) \\
&\text{IF(CII<0.9)} \text{360, 360, 400} \\
&360 \text{ IF(CII<0.93)} \text{370, 370, 380} \\
&370 \text{ R2(RI)=RI} \\
&\text{G0T0390} \\
&380 \text{ RI=R1-RINC} \\
&\text{1F(R1)} \text{550, 350, 350} \\
&390 \text{ RI=R5+RINC} \\
&\text{G0T0350} \\
&400 \text{ IF(CII<0.97)} \text{410, 420, 420} \\
&410 \text{ R1=R1+RINC} \\
&\text{G0T0350} \\
&420 \text{ R3=R1-R2(RI)} \\
&\text{R1FT+R1/CFPTCHM} \\
&\text{R2FT=R2(RI)/CFPTCHM} \\
&\text{R3FT=R3/CFPTCHM} \\

C C APPROXIMATION TO RADIAL GEOMETRY

\[
\begin{align*}
&A2=3.1420((R(1)-1)+XR(1-1)/2.0)**2-R(1-1)**2 \\
&B2=3.1420((R(1)-1)**2-(R(1)-1)-XR(1-1)/2.0)**2 \\
&DSC2=3.1420R(1)**2-B2 \\
&\text{IF(DSC2)} \text{550, 550, 550} \\
&520 \text{ RL50=SORT(DSC2)**3.142)}-(XL(1)-XL(1-1))/2.0 \\
&\text{IF(RL50)} \text{550, 550, 530} \\
&530 \text{ RUSO=SORT((3.1420R(1)**2+A2)**3.142/(XL(1)-XL(1-1))/2.0} \\

C C CHECKING FOR BREAKTHROUGH
PARCING-CNTP.ADA

PART 6 - CALCULATION OF RECOVERY EFFICIENCY

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PRINTING COMPLETED FOR FIRST PRODUCTION MEL-CYCLE

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G01020

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PART 7 - FORMAT STATEMENTS

10000 FORMAT(6F12.0)
11000 FORMAT(5F12.0)
12000 FORMAT(5F12.0)
13000 FORMAT(2F12.0)
14000 FORMAT(1F12.0)
15000 FORMAT(1F12.0)
16000 FORMAT(1H1,35X,DATAgabe,36X,----- ///,6X, 'POROUS MEDIUM' ///
  1 9X,'THICKNESS OF THE MEDIUM (FT)' ,30X,F12.0///
  2 9X,'PERMEABILITY OF THE MEDIUM (DARCIES)' ,22X,F12.0///
  3 9X,'POROSITY OF THE MEDIUM (FRACTION)' ,25X,F12.0///
  4 9X,'LONGITUDINAL DISPERSIVITY OF THE MEDIUM (CM)' ,14X,F12.0///
  5 9X,'COEFFICIENT OF MOLECULAR DIFFUSION (30 CH/SEC)' ,12X,F12.0///
)
17000 FORMAT(6X,'FLUID PROPERTIES' ///,6X, 'VISCOSITY OF THE FLUIDS (CP)' ///
  1 9X,'VISCOSITY OF THE INJECTED FLUID' ,27X,F12.0///
  2 9X,'VISCOSITY OF THE NATIVE FLUID' ,29X,F12.0///
  3 9X,'MEAN VISCOSITY OF THE TWO FLUIDS' ,26X,F12.0///
)
18000 FORMAT(6X,'DENSITY OF THE FLUIDS (GM/CC)' ///
  1 9X,'DENSITY OF THE INJECTED FLUID' ,29X,F12.0///
  2 9X,'DENSITY OF THE NATIVE FLUID' ,31X,F12.0///
  3 9X,'DENSITY DIFF. BETWEEN THE FLUIDS' ,26X,F12.0///
  4 6X,'ACCELERATION DUE TO GRAVITY (CM/SEC/SEC)' ,19X,F12.0///
)
19000 FORMAT(6X,'OPERATING CONDITIONS' ///
  1 6X,'INJECTION AND PRODUCTION RATES (GAL/MIN)' ///
  2 9X,'INJECTION RATE FOR FIRST INJECTION HALF-CYCLE' ,8X,F14.0///
  3 9X,'PRODUCTION RATE FOR FIRST PRODUCTION HALF-CYCLE' ,8X,F14.0///
20000 FORMAT(6X,'VOLUME OF FLUID INJECTED OR PRODUCED (GALLONS)' ///
  1 9X,'FLUID INJECTED IN FIRST INJECTION HALF-CYCLE' ,4X,F20.8///
)
21000 FORMAT(6X,'TIME OF STATIC STORAGE (DAYS)' ///
  1 9X,'AT THE END OF FIRST INJECTION HALF-CYCLE' ,18X,F13.8///
)
22000 FORMAT(1H1,41X,'CALCULATIONS FOR FIRST INJECTION HALF-CYCLE' ///
  1 42X,'----------------------------------------------- ///
)
23000 FORMAT(1X,'I=' ,13.5X,'R1FT=' ,E15.8,3X,'R2FT=' ,E15.8,3X,'R3FT=' ,E15.8///
  1 E15.8)
24000 FORMAT(1X,'I=' ,13.6X,'D41=' ,E15.8,6X,'D2M=' ,E15.8,5X,'DG=' ,E15.8,5X,'D1=' ,E15.8///
  1 E15.8)
25000 FORMAT(1X,'I=' ,13.5X,'P11D=' ,E15.8,5X,'TPD=' ,E15.8,4X,'TDD=' ,E15.8///
  1 E15.8,3X,'YL=' ,E15.8,3X,'XLFT=' ,E15.8///
)
26000 FORMAT(1X,'I=' ,13.7X,'RUSOF=' ,E15.8,3X,'RUSOF=' ,E15.8,3X,'RXOF=' ,E15.8,4X///
  1 E15.8,3X,'VR=' ,E15.8,4X,'VRP=' ,E15.8///
)
27000 FORMAT(1H1,41X,'CALCULATIONS FOR FIRST PRODUCTION HALF-CYCLE' ///
  1 42X,'----------------------------------------------- ///
)
32000 FORMAT(1H1,40X,'CALCULATION OF RECOVERY EFFICIENCY' ///
  1 47X,'----------------------------------------------- ///
)
33000 FORMAT(1X,'I=' ,13.4X,'RBF=' ,E15.8,5X,'CB=' ,E15.8,3X///
  1 'RBF=' ,E15.8///
)
34000 FORMAT(1X,'I=' ,13.3X,'FLR=' ,E15.8,3X,'CCEFF=' ,E15.8,3X///
  1 'CCEFF=' ,E15.8///
)
C
1300 STOP END
PROGRAM TO CALCULATE THE RECOVERY EFFICIENCY OF THE PROCESS OF STORING FRESH WATER IN SALINE AQUIFERS.

PROGRAM 'CYCLE 2A' (SINGLE WELL - TWO CYCLES)

*******************************************************************************

DATA TO BE READ IN

FIRST CARD - FORMAT(6F12.0)
   RBTFT = RADIUS AT WHICH BREAKTHROUGH IS COMPUTED. (FT)
   CBT  = ALLOWABLE CONCENTRATION OF NATIVE SALT WATER IN PRODUCED STREAM. (VOLUME FRACTION)
   TILIFT = INTERVAL LENGTH FOR CALCULATIONS DURING INJECTION HALF-CYCLES. (FT)
   TILPFT = INTERVAL LENGTH FOR CALCULATIONS DURING PRODUCTION HALF-CYCLES. (FT)
   RINCFT = LENGTH OF INCREMENT FOR CALCULATION OF MIXED ZONE LENGTHS. (FT)
   TINCFT = INCREMENT BY WHICH TILIFT IS INCREASED IF MIXED ZONE INTERSECTS THE LINE SOURCE DURING CALCULATIONS FOR FIRST INTERVAL OF FIRST INJECTION HALF-CYCLE. (FT)

SECOND CARD - FORMAT(5F12.0)
   HPT  = AQUIFER THICKNESS. (FT)
   PLYDA = AQUIFER PERMEABILITY. (DARCYS)
   PR   = POROSITY. (FRACTION)
   ALF  = LONGITUDINAL DISPERSIVITY COEFFICIENT. (CM)
   DIFNOL = COEFFICIENT OF MOLECULAR DIFFUSION. ((SO CM)/SEC)

THIRD CARD - FORMAT(5F12.0)
   VISCP1 = VISCOSITY OF THE INJECTED FRESH WATER. (CP)
   VISCP2 = VISCOSITY OF THE NATIVE SALT WATER. (CP)
   DENS1 = DENSITY OF THE INJECTED FRESH WATER. (GM/CC)
   DENS2 = DENSITY OF THE NATIVE SALT WATER. (GM/CC)
   ACNG = ACCELERATION DUE TO GRAVITY. ((CM/SEC)/SEC)

FOURTH CARD - FORMAT(4F12.0)
   QIRGM = INJECTION RATE FOR FIRST INJECTION HALF-CYCLE. (GPM)
   QR2GM = PRODUCTION RATE FOR FIRST PRODUCTION HALF-CYCLE. (GPM)
   QR3GM = INJECTION RATE FOR SECOND INJECTION HALF-CYCLE. (GPM)
   QR4GM = PRODUCTION RATE FOR SECOND PRODUCTION HALF-CYCLE. (GPM)

FIFTH CARD - FORMAT(3F12.0)
   FLING1 = FLUID INJECTED IN FIRST INJECTION HALF-CYCLE. (GAL)
   FLPRG2 = FLUID PRODUCED IN FIRST PRODUCTION HALF-CYCLE. (GAL)
   FLNG3 = FLUID INJECTED IN SECOND INJECTION HALF-CYCLE. (GAL)

SIXTH CARD - FORMAT(2F12.0)
   TST1D = STATIC STORAGE TIME AT THE END OF THE FIRST INJECTION HALF-CYCLE. (DAYS)
   TST2D = STATIC STORAGE TIME AT THE END OF THE SECOND INJECTION HALF-CYCLE. (DAYS)

SEVENTH CARD - FORMAT(113)
   NINT2 = NUMBER OF COMPUTATION INTERVALS THRU THE FIRST PRODUCTION HALF-CYCLE.

*******************************************************************************

DEFINITION OF VARIABLE NAMES USED IN PROGRAM

   A1 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RU50 FOR FIRST INJECTION HALF-CYCLE. (SO CM)
   A2 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RU50 FOR FIRST PRODUCTION HALF-CYCLE. (SO CM)
A3 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RUSO FOR
SECOND INJECTION HALF-CYCLE. (SO CM)
A4 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RUSO FOR
SECOND PRODUCTION HALF-CYCLE. (SO CM)
B1 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RLSO FOR
FIRST INJECTION HALF-CYCLE. (SO CM)
B2 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RLSO FOR
FIRST PRODUCTION HALF-CYCLE. (SO CM)
B3 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RLSO FOR
SECOND INJECTION HALF-CYCLE. (SO CM)
B4 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RLSO FOR
SECOND PRODUCTION HALF-CYCLE. (SO CM)
CFCPP = CONVERSION FACTOR. (POISE/CENTIPOISE)
CDFSEC = CONVERSION FACTOR. ((SO CM)/DARCY)
CFPDSEC = CONVERSION FACTOR. (SEC/DAY)
CFPTCM = CONVERSION FACTOR. (CM/FT)
CFPLCC = CONVERSION FACTOR. (CC/GAL)
CGMCCS = CONVERSION FACTOR. ((CC/SEC)/(GAL/MIN))
CONST1 = VALUE USED IN CHECKING FOR BREAKTHROUGH DURING A
PRODUCTION HALF-CYCLE.
CONST2 = VALUE USED IN CHECKING FOR BREAKTHROUGH DURING A
PRODUCTION HALF-CYCLE.
CRCCEF = CUMULATIVE RECOVERY EFFICIENCY. (FRACTION)
CVLING = CUMULATIVE VOLUME OF FLUID INJECTED. (GAL)
CVRDQG = CUMULATIVE VOLUME OF INJECTED FLUID RECOVERED. (GAL)
CVL1N = CUMULATIVE VOLUME OF FLUID INJECTED. (CC)
CVRAD = CUMULATIVE VOLUME OF INJECTED FLUID RECOVERED. (CC)
C11 = COMPUTED CONCENTRATION AT THE RADIUS AND AT THE TIME
BEING CONSIDERED. (VOLUME FRACTION)
DG = DENSITY GRADIENT. ((GM/CC)/CM)
DM1 = A CONSTANT USED IN THE COMPUTATION OF THE DIMENSIONLESS
PARAMETER GIVEN BY EQUATION 2.7A
DM2 = DIMENSIONLESS GROUP. SECOND GROUP ON RIGHT SIDE OF
EQUATION 2.7A.
DM2A = A CONSTANT USED IN THE COMPUTATION OF THE DIMENSIONLESS
PARAMETER GIVEN BY EQUATION 2.7A.
DNUM1 = DENOMINATOR OF ARGUMENT OF COMPLEMENTARY ERROR FUNCTION
IN EQUATION 2.5 FOR FIRST INJECTION HALF-CYCLE.
DNUM3 = DENOMINATOR OF ARGUMENT OF COMPLEMENTARY ERROR FUNCTION
IN EQUATION 2.5 FOR SECOND INJECTION HALF-CYCLE.
DNUMPR = DENOMINATOR OF ARGUMENT OF COMPLEMENTARY ERROR FUNCTION
IN EQUATION 2.5 FOR FIRST PRODUCTION HALF-CYCLE.
DNUM4 = DENOMINATOR OF ARGUMENT OF COMPLEMENTARY ERROR FUNCTION
IN EQUATION 2.5 FOR SECOND PRODUCTION HALF-CYCLE.
DSDF = DENSITY DIFFERENCE BETWEEN INJECTED AND NATIVE
FLUIDS. (GM/CC)
DSG4 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RLSO FOR
SECOND PRODUCTION HALF-CYCLE. (SO CM)
FLINJ1 = FLUID INJECTED IN FIRST INJECTION HALF-CYCLE. (CC)
FLINJ3 = FLUID INJECTED IN SECOND INJECTION HALF-CYCLE. (CC)
FLPRG4 = FLUID PRODUCED IN SECOND PRODUCTION HALF-CYCLE. (GAL)
FLPRN2 = FLUID PRODUCED IN FIRST PRODUCTION HALF-CYCLE. (CC)
FLPRN4 = FLUID PRODUCED IN SECOND PRODUCTION HALF-CYCLE. (CC)
H = AQUIFER THICKNESS. (CM)
I = SUBSCRIPT DESIGNATING COMPUTATION INTERVAL.
NINT = INTERMEDIATE VALUE USED IN CALCULATING THE NUMBER OF
COMPUTATION INTERVALS.
NINT1 = NUMBER OF COMPUTATION INTERVALS THRU THE END OF THE
FIRST INJECTION HALF-CYCLE.
NINT2 = NUMBER OF COMPUTATION INTERVALS THRU THE SECOND
INJECTION HALF CYCLE.
NINT4 = NUMBER OF COMPUTATION INTERVALS THRU THE SECOND
PRODUCTION HALF-CYCLE.
PLY = AQUIFER PERMEABILITY. (SO CM)
PPP = PRODUCT OF PI, POROSITY, AND THICKNESS. (CM)
PPP1 = 2*PPP. (CM)
Q11 = TWO DIMENSIONAL FLOW RATE FOR FIRST INJECTION
HALF-CYCLE. ((SO CM)/SEC)
Q13 = TWO DIMENSIONAL FLOW RATE FOR SECOND INJECTION
HALF-CYCLE. ((SO CM)/SEC)
C QP2 = TWO DIMENSIONAL FLOW RATE FOR FIRST PRODUCTION
   HALF-CYCLE. ((150 CM)/SEC)
C QP4 = TWO DIMENSIONAL FLOW RATE FOR SECOND PRODUCTION
   HALF-CYCLE. ((150 CM)/SEC)
C OR1 = FLOW RATE FOR FIRST INJECTION HALF-CYCLE. (CC/SEC)
C OR2 = FLOW RATE FOR FIRST PRODUCTION HALF-CYCLE. (CC/SEC)
C OR3 = FLOW RATE FOR SECOND INJECTION HALF-CYCLE. (CC/SEC)
C OR4 = FLOW RATE FOR SECOND PRODUCTION HALF-CYCLE. (CC/SEC)
C OS11 = TWO DIMENSIONAL PSEUDO FLOW RATE FOR FIRST INJECTION
   HALF-CYCLE. ((150 CM)/SEC)
C OS13 = TWO DIMENSIONAL PSEUDO FLOW RATE FOR SECOND INJECTION
   HALF-CYCLE. ((150 CM)/SEC)
C OS2 = TWO DIMENSIONAL PSEUDO FLOW RATE FOR FIRST PRODUCTION
   HALF-CYCLE. (CM)
C OS4 = TWO DIMENSIONAL PSEUDO FLOW RATE FOR SECOND PRODUCTION
   HALF-CYCLE UP TO COMPUTATION INTERVAL AT WHICH
   BREAKTHROUGH CHECK IS BEING MADE. ((50 CM)/SEC)
C R(I) = RADIUS OF INJECTED FLUID AT THE ITH COMPUTATION
   INTERVAL ASSUMING NO MIXING OR GRAVITATIONAL
   SEGREGATION. (CM)
C RBT = RADIUS AT WHICH BREAKTHROUGH IS COMPUTED. (CM)
C RCBT(I) = LEAST RADIUS TO A VALUE OF CONCENTRATION OF CBT FOR THE
   LAST COMPUTATION INTERVAL OF THE LAST PRODUCTION
   HALF-CYCLE. (CM)
C RCBTF = LEAST RADIUS TO A VALUE OF CONCENTRATION OF CBT FOR THE
   LAST COMPUTATION INTERVAL OF THE LAST PRODUCTION
   HALF-CYCLE. (FT)
C RCEFF = CYCLE RECOVERY EFFICIENCY. (FRACTION)
C RFT = RADIUS OF INJECTED FLUID AT THE ITH COMPUTATION
   INTERVAL ASSUMING NO MIXING OR GRAVITATIONAL
   SEGREGATION. (FT)
C RINC = LENGTH OF INCREMENT USED FOR CALCULATION OF MIXED
   ZONE LENGTHS. (CM)
C RN3 = RADIUS OF INJECTED FLUID AT THE END OF THE FIRST
   INJECTION HALF-CYCLE ASSUMING NO MIXING AND NO
   GRAVITATIONAL SEGREGATION. (CM)
C RN7 = RADIUS OF INJECTED FLUID AT THE END OF THE SECOND
   INJECTION HALF-CYCLE ASSUMING NO MIXING AND NO
   GRAVITATIONAL SEGREGATION. (CM)
C RL50 = RADIUS TO LOWER END OF 50 PERCENT CONCENTRATION
   LINE. (CM)
C RL50FT = RADIUS TO LOWER END OF 50 PERCENT CONCENTRATION
   LINE. (FT)
C RL5011 = RADIUS TO LOWER END OF 50 PERCENT CONCENTRATION
   LINE AT THE START OF THE FIRST PRODUCTION HALF-CYCLE. (CM)
C RL50I2 = RADIUS TO LOWER END OF 50 PERCENT CONCENTRATION
   LINE AT THE START OF THE SECOND PRODUCTION HALF-CYCLE. (CM)
C RL50P1 = RADIUS TO LOWER END OF 50 PERCENT CONCENTRATION
   LINE AT THE START OF THE SECOND INJECTION HALF-CYCLE. (CM)
C RUS0 = RADIUS TO UPPER END OF 50 PERCENT CONCENTRATION
   LINE. (CM)
C RUS0FT = RADIUS TO UPPER END OF 50 PERCENT CONCENTRATION
   LINE. (FT)
C R1 = RADIUS AT WHICH CONCENTRATION IS BEING COMPUTED. ALSO
   INNER RADIUS OF MIXED ZONE. (CM)
C R1FT = INNER RADIUS OF MIXED ZONE. (FT)
C R2(I) = OUTER RADIUS OF MIXED ZONE. (CM)
C R2FT = OUTER RADIUS OF MIXED ZONE. (FT)
C R3 = LENGTH OF MIXED ZONE. (CM)
C R3FT = MIXED ZONE LENGTH. (FT)
C R4 = TIL1/2. (CM)
C R5 = RADIUS TO THE MIDPOINT BETWEEN R(I) AND R(I-1). (CM)
C RSSQ = R5 SQUARED. (50 CM)
C R6 = TILP/2. (CM)
C SDENOM = DENOMINATOR OF ARGUMENT OF COMPLEMENTARY ERROR FUNCTION
   IN EQUATION 2-5 USING PSEUDO RATES TO CHECK FOR
   BREAKTHROUGH DURING A PRODUCTION HALF-CYCLE.
C TIL1 = INTERVAL LENGTH FOR COMPUTATIONS DURING INJECTION
   HALF-CYCLES. (CM)
TILP = INTERVAL LENGTH FOR COMPUTATIONS DURING PRODUCTION
HALF-CYCLES. (CM)
TRT = CUMULATIVE TRAVEL TIME OF FRESH WATER-SALT WATER
INTERFACE. (SEC)
TRT1 = CUMULATIVE TRAVEL TIME OF INTERFACE THRU END OF FIRST
INJECTION HALF-CYCLE. (SEC)
TRT2 = CUMULATIVE TRAVEL TIME OF INTERFACE THRU END OF FIRST
PRODUCTION HALF-CYCLE. (SEC)
TRT3 = CUMULATIVE TRAVEL TIME OF INTERFACE THRU END OF SECOND
INJECTION HALF-CYCLE. (SEC)
TRT4 = CUMULATIVE TRAVEL TIME OF INTERFACE THRU COMPUTATION
INTERVAL AT WHICH BREAKTHROUGH CHECK IS BEING
MADE. (SEC)
TST1 = STATIC STORAGE TIME AT THE END OF THE FIRST INJECTION
HALF-CYCLE. (SEC)
TST3 = STATIC STORAGE TIME AT THE END OF THE SECOND INJECTION
HALF-CYCLE. (SEC)
TSP = PSEUDO TIME USED IN GRAVITATIONAL SEGREGATION
CALCULATIONS. (SEC)
TSPD = PSEUDO TIME USED IN GRAVITATIONAL SEGREGATION
CALCULATIONS. (DAYS)
TT = TIME OF TRAVEL ACROSS ANY COMputation INTERVAL PLUS THE
PSEUDO TIME FOR THAT INTERVAL. (SEC)
TTD = TIME OF TRAVEL ACROSS ANY COMputation INTERVAL PLUS THE
PSEUDO TIME FOR THAT INTERVAL. (DAYS)
TI = TIME AT WHICH CONCENTRATION IS BEING COMPUTED DURING
FIRST INJECTION HALF-CYCLE. ALSO CUMULATIVE TRAVEL
TIME OF INTERFACE THRU END OF FIRST INJECTION
HALF-CYCLE. (SEC)
T2 = TIME AT WHICH CONCENTRATION IS BEING COMPUTED DURING
FIRST PRODUCTION HALF-CYCLE. ALSO CUMULATIVE TRAVEL
TIME OF INTERFACE THRU END OF FIRST PRODUCTION
HALF-CYCLE. (SEC)
T3 = TIME AT WHICH CONCENTRATION IS BEING COMPUTED DURING
SECOND INJECTION HALF-CYCLE. ALSO CUMULATIVE TRAVEL
TIME OF INTERFACE THRU END OF SECOND INJECTION
HALF-CYCLE. (SEC)
T4 = TIME AT WHICH CONCENTRATION IS BEING COMPUTED DURING
SECOND PRODUCTION HALF-CYCLE. (SEC)
T11 = TIME OF TRAVEL ACROSS ANY COMPUTATION INTERVAL. (SEC)
T11D = TIME OF TRAVEL ACROSS ANY COMPUTATION INTERVAL. (DAYS)
VIS = MEAN VISCOSITY OF INJECTED AND NATIVE FLUIDS. (POISE)
VISC = MEAN VISCOSITY OF INJECTED AND NATIVE FLUIDS. (CP)
VOLNR = TOTAL VOLUME OF INJECTED FLUID NOT RECOVERED. (CC)
X = VALUE OF DIMENSIONLESS PARAMETER GIVEN BY
EQUATION 2.7A.
XL(I) = HORIZONTAL PROJECTION OF 50 PERCENT CONCENTRATION
LINE FOR LINEAR GEOMETRY. (CM)
XLFT = HORIZONTAL PROJECTION OF 50 PERCENT CONCENTRATION
LINE FOR LINEAR GEOMETRY. (FT)
XR(I) = HORIZONTAL PROJECTION OF 50 PERCENT CONCENTRATION
LINE FOR RADIAL GEOMETRY. (CM)
XRFT = HORIZONTAL PROJECTION OF 50 PERCENT CONCENTRATION
LINE FOR RADIAL GEOMETRY. (FT)
XX = ARGUMENT OF COMPLEMENTARY ERROR FUNCTION FOR
EQUATION 2.5.
YL(I) = RATIO OF HORIZONTAL PROJECTION OF 50 PERCENT
CONCENTRATION LINE TO AQUIFER THICKNESS FOR LINEAR
GEOMETRY.
YR(I) = RATIO OF HORIZONTAL PROJECTION OF 50 PERCENT
CONCENTRATION LINE TO AQUIFER THICKNESS FOR RADIAL
GEOMETRY.

*******************************************************************************
**Part 1 - Reading Data**

```
DIMENSION R(1000), R2(1000), YL(1000), XL(1000), XR(1000), ACB(1000)
```

20 READ(5, 10000, END=1380) RBTFT, CBT, TILIFT, TILPT, RINCFT, TINCFT
21 READ(5, 11000) RFT, PLYDAR, PR, ALF, DIFMOL
22 READ(5, 12000) VISCPI, VISCPI2, DENS1, DENS2, ACNG
23 READ(5, 13000) OR1GM, OR2GM, OR3GM, OR4GM
24 READ(5, 14000) PLING1, PLING2, PLING3
25 READ(5, 15000) TST1D, TST3D
26 READ(5, 15200) NINT2

**Part 2 - Printing Data**

```
CALCULATION OF DENSITY DIFFERENCE AND MEAN VISCOSITY OF FLUIDS

DSDP = ABS(DENS1 - DENS2)
VISC = (VISCPI + VISCPI2) / 2.0
```

**Part 3 - Constants and Conversion Factors**

```
PART 3 - CONSTANTS AND CONVERSION FACTORS

50 CFFTCN = 30.4801
CFDSCH = 0.987E-08
CFGLCC = 3785.434
CGMCCS = 63.0906
CFDESEC = 86400.0
CFCU = 0.01
RBT = RBTFT * CFFTCN
RINC = RINCFT * CFFTCN
H = HFT * CFFTCN
PPP = 3.1416 * PR * H
PPP1 = 2.0 * PPP
PLY = PLYDAR * CFDSCH
PLING1 = PLING1 * CFGLCC
PLING2 = PLING2 * CFGLCC
PLING3 = PLING3 * CFGLCC
```

51 OR1 = OR1GM * CGMCCS
52 OR2 = OR2GM * CGMCCS
53 OR3 = OR3GM * CGMCCS
54 OR4 = OR4GM * CGMCCS
57 TST1 = TST1D * CFDESEC
60 TST3 = TST3D * CFDESEC
61 VIS = VISCPI * CFCU
```

D21 = (PLY * ACNG * DSDP) / (PR * HH)
D22 = VIS * 0.6667 / (DSDP * OR1GM * OR2GM * OR3GM * OR4GM * 3333)
TILP = TILIFT * CFFTCN
R6 = RILP / 2.0
60 TIL1 = TILIFT * CFFTCN
R6 = TIL1 / 2.0
PART 4 - CALCULATIONS FOR FIRST INJECTION HALF-CYCLE

CALCULATIONS OF INTERVALS AND RADIUS OF INJECTION

\[ R_{INJ1} = \text{SQRT}(PLINJ1 / PPP) \]
\[ \text{RINT1} = R_{INJ1} / TILI \]

CALCULATION OF MIXED ZONE DUE TO DIFFUSION AND DISPERSION

\[ I = 1 \]
\[ \text{RT} = 0.0 \]
\[ R(1) = TILI \]
\[ 61 \quad R5 = R(1) - R4 \]
\[ R55 = R5 * R5 \]
\[ R1 = R5 - RINC \]
\[ Q1 = QRI / PPP1 \]
\[ DQUMI1 = 2.5 * \text{SQRT}(1.333 * \text{ALPFI}(2.0 * Q1 * T1) + 0.5 * \text{DFMOL}(2.0 * Q1 * T1) + 0.7) \]
\[ / Q11 \]
\[ 70 \quad XX = (R55 - R1 / R1) / DQUMI1 \]
\[ C11 = \text{ERFC}(XX) / 2.0 \]
\[ \text{IF}(C11 < 0.5) = 0.0 \]
\[ 80 \quad \text{IF}(C11 < 0.05) = 0.0 \]
\[ 90 \quad R2(1) = R1 \]
\[ \text{GOTO} \ 110 \]

\[ 100 \quad R1 = R1 - RINC \]
\[ \text{IF}(R1 < 0.3, 30, 70) \]
\[ \text{GOTO} \ 70 \]
\[ 110 \quad R1 = R1 + RINC \]
\[ \text{GOTO} \ 70 \]

\[ 120 \quad \text{IF}(C11 < 0.071) = 130, 140, 160 \]
\[ 130 \quad R1 = R1 + RINC \]
\[ \text{GOTO} \ 70 \]
\[ 140 \quad R3 = R1 - R2(1) \]
\[ \text{RIFT} = R1 / \text{CFCTCM} \]
\[ \text{R2FT} = R2(1) / \text{CFCTCM} \]
\[ \text{R3FT} = R3 / \text{CFCTCM} \]

CALCULATION OF INTERFACE PROJECTION DUE TO GRAVITY SEGREGATION

\[ \text{IF}(I - 1) = 150, 150, 190 \]
\[ 150 \quad \text{DG} = \text{DSDF} / \text{R3} \]
\[ \text{DM2} = \text{DM2A} + \text{DG} \]
\[ T11 = \text{PPP} * R(1) * 0.02 / QR1 \]
\[ 151 \quad \text{RT} = \text{RT} + T11 \]
\[ X = \text{DM1} * T11 + \text{DM2} * 0.5 \]
\[ \text{IF}(X < -1.1) = 160, 160, 165 \]
\[ 160 \quad \text{YL}(1) = 20.0 * X \]
\[ \text{GOTO} \ 180 \]
\[ 165 \quad \text{IF}(X < 0.0) = 170, 175, 175 \]
\[ 170 \quad \text{YL}(1) = 0.7959 + 12.5236 * X - 4.8196 * X^2 \]
\[ \text{GOTO} \ 180 \]
\[ 175 \quad \text{YL}(1) = 0.5 + 2.0 * X \]
\[ 180 \quad \text{XL}(1) = \text{YL}(1) * \text{H} \]
\[ \text{XLFT} = \text{XL}(1) / \text{CFCTCM} \]
\[ \text{T11D} = T11 / \text{CFDSEC} \]
\[ \text{TSPD} = 0.0 \]
\[ \text{TTO} = \text{T11D} \]
\[ \text{GOTO} \ 200 \]

\[ 190 \quad \text{DG} = \text{DSDF} / \text{R3} \]
\[ \text{DM2} = \text{DM2A} + \text{DG} \]
\[ T11 = \text{PPP} * \text{ABS}(R(1) * 0.02 - R(1 - 1) * 0.02) / QR1 \]
\[ 191 \quad \text{RT} = \text{RT} + T11 \]
\[ \text{IF}(\text{YL}(1 - 1) < 2.0195, 195, 200) \]
\[ 195 \quad X = \text{YL}(1 - 1) / 20.0 \]
\[ \text{GOTO} \ 215 \]
\[ 200 \quad \text{IF}(\text{YL}(1 - 1) < 0.5) = 205, 210, 210 \]
\[ 205 \quad X = 1.2993 * \text{SQRT}(172.1873 - 19.2754 * \text{YL}(1 - 1)) / 9.6392 \]
GOTO215

210 X=(YL1-1)-6.5)/2.0
215 TSP=X/(DM2-0.6)
220 TT=T1+TSP
230 IF(I-WINT1))260.230.330
240 X=DM1+TSP-0.5

260 YL(1)=0.798+12.538+X-4.0198+X+2
280 YL(1)=0.798+12.538+X-4.0198+X+2
280 YL(1)=0.798+12.538+X-4.0198+X+2

GO TO300

C

APPROXIMATION TO RADIAL GEOMETRY

C

200 RUSO=RI)+XL(1)/2.0
200 RBLSO=R(1)-XL(1)/2.0
GOTO300
300 AI=3.142(R1)-1)*XR(1-1)/2.0)+2-R(1)*2
BL=3.142(R1-1)*XR(1-1)/2.0)*2
RUSO=SORT(3.142(R1)*XR(1-1)/2.0)+2-R1
RBLSO=SORT(3.142(R1)*XR(1-1)/2.0)+2-R1

210 XRL(1)=RUSO-RLSO
YR=XR(1)/H
RUSOFT=RUSO/CFFTCM
RBLSOFT=RL50/CFFTCM
XRFPT=XR(1)/CFFTCM
RPT=R(1)/CFFTCM

C

PRINTING COMPUTATIONS FOR FIRST INJECTION HALF-CYCLE

C

WRITE(6,23000)1,RIFT,RIFT,RIFT
WRITE(6,24000)1,DM1,DM2,0.6,X
WRITE(6,25000)1,T11,TSP,TDD,YL(I),XLFT
WRITE(6,26000)1,RUSOFT,BL50FT,XRFPT,YR,RPT

C

I=1+1

IF(I-WINT1)320,320,330
320 R(1)=R(1-1)+TIL1
GOTO61
330 TRL1=TRT
RL50=RLSO
QSI1=RL50**RL50)/(2.0*TRT1)
CONST1=(2.0-QS11*TRT1)**1.1
CONST2=(2.0-QS11*TRT1)**2/QS11

C

PART 8 - CALCULATIONS FOR FIRST PRODUCTION HALF-CYCLE

C

WRITE(6,27000)
C

CALCULATION OF MIXED ZONE DUE TO DIFFUSION AND DISPERSION

C

340 R(1)=RI-1)+TILP
RS=R(1)+R6
RS50=RS+R5
R1=RS-RINC
TI=PPP*(R(1)+2/0R1
T2=T1+PPP*(R(1)+2-RS50)/0R2
Q2=0R2/PPP1
CALCULATION OF INTERFACE PROJECTION DUE TO GRAVITY SEGREGATION

APPROXIMATION TO RADIAL GEOMETRY

PRINTING COMPUTATIONS FOR FIRST PRODUCTION HALF-CYCLE
C 543 I=1+1
   IF(I-NINT2)340,340,560
560 TRT2=TRT
   RL501=RL50
   QSP2=(RL501*RL5011-RL501*RL5011)/2.*((TRT2-TRT1))
   CONST1=CONST1+(2.0*QSP2*TRT2)**1.5-(2.0*QSP2*TRT1)**1.5
   CONST2=CONST2+(2.0*QSP2*TRT2)**2/QSP2-(2.0*QSP2*TRT1)**2/QSP2
C C
PART 6 - CALCULATIONS FOR SECOND INJECTION HALF-CYCLE
C
C
WRITE(6,28000)
C
CALCULATION OF INTERVALS AND RADIUS OF INJECTION
C
RINJ3=SORI((FLINJ1-FL1*R4+FLINJ3)/PPP)
NINT1=(RINJ3-R(NINT2))/TILI
NINT3=NINT2+NINT
C
CALCULATION OF MIXED IONIC DUE TO DIFFUSION AND DISPERSION
C
580 R(I)=R(I-1)+TILI
   R5=R(I)-R4
   R550=R5+R5
   R1=R5-RINC
   T2=T1+PPP*(R(NINT1)**2-R(NINT2)**2)/QR2
   T3=T2+PPP*(R550-R(NINT2)**2)/QR3
   Q13=QR3/PPP
   QMON1=2.0*SORI(1.333A.F6((2.0001363)**1.5-(2.0001363)**1.5+2.0
   1+0.0P2*TRT)**1.5-(2.0001161)**1.5+0.01161)**1.5+DIFNLQ.*
   2*(2.0001363)**2/G13-(2.0001363)**2/G13+(2.000P2*TRT)**2/QP
   3-(2.000P2*TRT)**2/QP+(2.0001161)**2/G11)
590 XX=(R550-R*1/DP)/QMON1
   CI=ERFC(XX)/2.*6
   IF(C1=-0.6)+GO0,600,640
600 IF(C1=-0.03)+GO0,610,620
610 R2(I+1)=R1
620 GOTO630
630 R1=R1-RINC
   GOTO590
640 IF(C1=-0.97)+GO0,650,660
650 R1=R1-RINC
   GOTO590
660 R3=R1-R2(I)
   R1PR=R1/CFPHCM
   R2PR=R2(I)/CFPHCM
   R3PR=R3/CFPHCM
C
CALCULATION OF INTERFACE PROJECTION DUE TO GRAVITY SEGREGATION
C
D1=D550/R3
   DM2=DM2A*DG
   T11=PPP*ABS(R(I)**2-R(I-1)**2)/QR3
661 TRT=TRT+T11
   IF(YL(I-1)-2.0)+GO0,665,665,670
665 X=YL(I-1)+GO0,665
670 IF(YL(I-1)-6.9)+GO0,675,680,660
675 X=1.2993-SORT(I12.6153-1x2700+YL(I-1))/0.6392
   GOTO665
680 X=(YL(I-1)-6.9)+GO0,685,690,660
685 TSP=X/TOSI+DG
690 T=TTI+TSP
   IF(I-NINT3)+GO0,710,700,750
APPROXIMATION TO RADIAL GEOMETRY

\[ A = 3.142 \times (R(1-1) + XR(1-1)/2.0)^{2} \times (R(1-1) - XR(1-1)/2.0)^{2} \]

\[ B = 3.142 \times (R(1-1)^{2} - (R(1-1) - XR(1-1)/2.0)^{2}) \]

\[ RUSO = SORT((3.142 \times R(1-1)^{2} + A)/3.142 + (XR(1-1) - XL(1-1))/2.0) \]

\[ RLSO = SORT((3.142 \times R(1-1)^{2} - B)/3.142 - (XR(1-1) - XL(1-1))/2.0) \]

\[ XR(1) = RUSO - RLSO \]

\[ YR = XR(1)/H \]

\[ RUSOFT = RUSO/CFFTCN \]

\[ RLSOFT = RLSO/CFFTCN \]

\[ XRFT = XR(1)/CFFTCN \]

\[ RFT = R(1)/CFFTCN \]

PRINTING COMPUTATIONS FOR SECOND INJECTION HALF-CYCLE

\[ WRITE(6,23000) I,RFT,R2FT,R3FT \]

\[ WRITE(6,24000) I,DM1,DM2,D6,X \]

\[ WRITE(6,25000) I,T1D,TSPD,TDD,YL(I)/XLF \]

\[ WRITE(6,26000) I,RUSOFT,RLSOFT,XRFT,YR,RFT \]

PART 7 - CALCULATIONS FOR SECOND PRODUCTION HALF-CYCLE

\[ WRITE(6,29000) \]

CALCULATION OF MIXED ZONE DUE TO DIFFUSION AND DISPERSION

\[ WRITE(6,29000) \]

\[ R(1-1)=R(1-1)-TILP \]

\[ IF(R(1))940.940.765 \]

\[ R5=R(1-1)+R5 \]

\[ RSSO=R5*R5 \]

\[ RI=R5-RINC \]

\[ T3=T2+P/P/R(R(NINT3)^{2} - R(NINT2)^{2})/QR3 \]

\[ T3=T3+P/P/R(R(NINT3)^{2} - RSSQ)/QR4 \]

\[ QP4=QR4/P/P1 \]

\[ DNNINF=2.0000^5QR4 \]

\[ X=(RSSO-R1+R1)/DNNINF \]

\[ IF(C11-0.5)780.780.820 \]

\[ IF(C11-0.5)790.790.880 \]
CALCULATION OF INTERFACE PROJECTION DUE TO GRAVITY SEGREGATION

\[ \text{DG} = \frac{\text{OSDF} \times R}{3} \]
\[ \text{DM} = \frac{\text{DM2A} \times \text{DG}}{\text{TI1}} \]
\[ \text{TI1} = \text{PPP} \times \text{ABS}(R(I) - R(I-1) \times 2) / \text{GR4} \]
\[ \text{TRT} = \text{RT} + \text{TI1} \]
\[ \text{TRT} = \text{RT} + \text{TI1} \]
\[ \text{IF} (\text{YL(I-1)} - 2.0 \times 645.645.645) \]
\[ \text{X} = \frac{\text{YL(I-1)}}{20.0} \]
\[ \text{GOTO} \text{685} \]
\[ \text{IF} (\text{YL(I-1)} - 0.5) \times 655.660.660 \]
\[ \text{X} = \frac{\text{YL(I-1)} - 2.0 \times 6.038 \times 2 - 6.0196 \times K}{2.0} \]
\[ \text{GOTO} \text{685} \]
\[ \text{X} = \frac{\text{YL(I-1)}}{20.0} \times 0.0 \times 6 \]
\[ \text{GOTO} \text{900} \]
\[ \text{IF} (\text{X} \times 0.0) \times 865.800.800 \]
\[ \text{X} = \frac{\text{YL(I-1)}}{20.0} \times 6.038 \times 2 - 6.0196 \times K \]
\[ \text{GOTO} \text{900} \]
\[ \text{X} = \frac{\text{YL(I-1)}}{20.0} \times 6.0 \times 2.0 \times 0 \times 6 \]
\[ \text{APPROXIMATION TO RADIAL GEOMETRY} \]
\[ \text{A} = \text{A} + 3.1421 \times (R(I-1) \times X(I-1)) / 2.0 \times (R(I-1) \times X(I-1)) \]
\[ \text{B} = \text{B} + 3.1421 \times R(I-1) \times X(I-1) / 2.0 \times (R(I-1) \times X(I-1)) \]
\[ \text{DSC4} = 3.1421 \times R(I-1) \times X(I-1) \]
\[ \text{IF} (\text{DSC4}) = 940.940.910 \]
\[ \text{RL50} = \text{SQR} \times (\text{DSC4} / 3.1421) - (\text{XL}() - \text{XL}(1) - 1) / 2.0 \times 0 \]
\[ \text{IF} (\text{RL50}) = 940.940.920 \]
\[ \text{C} \]
\[ \text{CHECKING FOR BREAKTHROUGH} \]
\[ \text{RL5050} = \text{RL50} \times \text{RL50} \]
\[ \text{OSPF} = (\text{RL50} \times \text{RL50} \times (\text{RL50} \times \text{RL50})) / 2.0 \times (\text{TRT} - \text{TRT}) \]
\[ \text{SDENOM} = 2.0 \times \text{SQR} \times (1.3335 \times (2.0 \times \text{OSPF} \times \text{TRT} - 2.0 \times \text{OSPF} \times \text{TRT})) \]
\[ \text{I} = 2 \times \text{OSPF} \times \text{CONSTR2} \]
\[ \text{R} = \text{RL50} \times \text{RINC} \]
\[ \text{IF} (\text{R} \times \text{RBT}) = 940.930.930 \]
\[ \text{XX} = (\text{RL5050} - \text{RINC}) / \text{SDENOM} \]
\[ \text{C11} = \text{ERFC} \times (XX) / 2.0 \]
\[ \text{IF} (\text{C11} \times \text{CST}) = 932.932.931 \]
\[ \text{RINC} = \text{RINC} \]
\[ \text{IF} (\text{R} \times \text{RBT}) = 940.930.930 \]
\[ \text{R} = \text{RINC} \]
\[ \text{IF} (\text{R} \times \text{RBT}) = 940.930.930 \]
\[ \text{RA}(1) = \text{RINC} \]
\[ \text{XX} = (\text{RL5050} - \text{RINC}) / 2.0 \]
PROGRAM TO CALCULATE THE RECOVERY EFFICIENCY OF THE PROCESS OF
STORING FRESH WATER IN SALINE AQUIFERS.

PROGRAM 'CYCLE 3A' (SINGLE WELL - THREE CYCLES)

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DATA TO BE READ IN

FIRST CARD - FORMAT(6F12.0)
RBFT = RADIUS AT WHICH BREAKTHROUGH IS COMPUTED. (FT)
CBT  = ALLOWABLE CONCENTRATION OF NATIVE SALT WATER IN
PRODUCED STREAM. (VOLUME FRACTION)
TILIFT = INTERVAL LENGTH FOR CALCULATIONS DURING INJECTION
       HALF-CYCLES. (FT)
TILPF = INTERVAL LENGTH FOR CALCULATIONS DURING PRODUCTION
       HALF-CYCLES. (FT)
RINCFT = LENGTH OF INCREMENT FOR CALCULATION OF MIXED ZONE
       LENGTHS. (FT)
TINCFT = INCREMENT BY WHICH TILIFT IS INCREASED IF MIXED ZONE
       INTERSECTS THE LINE SOURCE DURING CALCULATIONS FOR
       FIRST INTERVAL OF FIRST INJECTION HALF-CYCLE. (FT)

SECOND CARD - FORMAT(5F12.0)
MFT = AQUIFER THICKNESS. (FT)
PLYDAR = AQUIFER PERMEABILITY. (DARCYS)
PR = POROSITY. (FRACTION)
ALF = LONGITUDINAL DISPERSIVITY COEFFICIENT. (CM)
DIFFOL = COEFFICIENT OF MOLECULAR DIFFUSION. ((SM CM)/SEC)

THIRD CARD - FORMAT(5F12.0)
VISCP1 = VISCOSITY OF THE INJECTED FRESH WATER. (CP)
VISCP2 = VISCOSITY OF THE NATIVE SALT WATER. (CP)
DEN1 = DENSITY OF THE INJECTED FRESH WATER. (GM/CC)
DEN2 = DENSITY OF THE NATIVE SALT WATER. (GM/CC)
ACNG = ACCELERATION DUE TO GRAVITY. (CM/SEC)/SEC)

FOURTH CARD - FORMAT(6F12.0)
Q1GM  = INJECTION RATE FOR FIRST INJECTION HALF-CYCLE. (GPM)
Q2GM  = PRODUCTION RATE FOR FIRST PRODUCTION HALF-CYCLE. (GPM)
Q3GM  = INJECTION RATE FOR SECOND INJECTION HALF-CYCLE. (GPM)
Q4GM  = PRODUCTION RATE FOR SECOND PRODUCTION HALF-CYCLE. (GPM)
Q5GM  = INJECTION RATE FOR THIRD INJECTION HALF-CYCLE. (GPM)
Q6GM  = PRODUCTION RATE FOR THIRD PRODUCTION HALF-CYCLE. (GPM)

FIFTH CARD - FORMAT(5F12.0)
FLING1 = FLUID INJECTED IN FIRST INJECTION HALF-CYCLE. (GAL)
FLPRG2 = FLUID PRODUCED IN FIRST PRODUCTION HALF-CYCLE. (GAL)
FLING3 = FLUID INJECTED IN SECOND INJECTION HALF-CYCLE. (GAL)
FLPRG4 = FLUID PRODUCED IN SECOND PRODUCTION HALF-CYCLE. (GAL)
FLING5 = FLUID INJECTED IN THIRD INJECTION HALF-CYCLE. (GAL)

SIXTH CARD - FORMAT(3F12.0)
TST1D = STATIC STORAGE TIME AT THE END OF THE FIRST INJECTION
       HALF-CYCLE. (DAYS)
TST3D = STATIC STORAGE TIME AT THE END OF THE SECOND INJECTION
       HALF-CYCLE. (DAYS)
TST5D = STATIC STORAGE TIME AT THE END OF THE THIRD INJECTION
       HALF-CYCLE. (DAYS)

SEVENTH CARD - FORMAT(2I3)
NINT2 = NUMBER OF COMPUTATION INTERVALS THRU THE FIRST
       PRODUCTION HALF-CYCLE.
NINT4 = NUMBER OF COMPUTATION INTERVALS THRU THE SECOND
       PRODUCTION HALF-CYCLE.
DEFINITION OF VARIABLE NAMES USED IN PROGRAM

A1 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RUSO FOR 
FIRST INJECTION HALF-CYCLE. (SO CM)
A2 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RUSO FOR 
FIRST PRODUCTION HALF-CYCLE. (SO CM)
A3 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RUSO FOR 
SECOND INJECTION HALF-CYCLE. (SO CM)
A4 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RUSO FOR 
SECOND PRODUCTION HALF-CYCLE. (SO CM)
A5 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RUSO FOR 
THIRD INJECTION HALF-CYCLE. (SO CM)
A6 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RUSO FOR 
THIRD PRODUCTION HALF-CYCLE. (SO CM)
B1 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RLSO FOR 
FIRST INJECTION HALF-CYCLE. (SO CM)
B2 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RLSO FOR 
FIRST PRODUCTION HALF-CYCLE. (SO CM)
B3 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RLSO FOR 
SECOND INJECTION HALF-CYCLE. (SO CM)
B4 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RLSO FOR 
SECOND PRODUCTION HALF-CYCLE. (SO CM)
B5 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RLSO FOR 
THIRD INJECTION HALF-CYCLE. (SO CM)
B6 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RLSO FOR 
THIRD PRODUCTION HALF-CYCLE. (SO CM)
CFCPP = CONVERSION FACTOR. (PDISE/CENTIPOISE)
CPDSCM = CONVERSION FACTOR. ((SO CM)/DARCY)
CFDSEC = CONVERSION FACTOR. (SEC/DAY)
CFFTCM = CONVERSION FACTOR. (CM/FT)
CFPGCC = CONVERSION FACTOR. (CC/GAL)
CGMCCS = CONVERSION FACTOR. ((CC/SEC)/(GAL/MIN))
CONST1 = VALUE USED IN CHECKING FOR BREAKTHROUGH DURING A 
PRODUCTION HALF-CYCLE.
CONST2 = VALUE USED IN CHECKING FOR BREAKTHROUGH DURING A 
PRODUCTION HALF-CYCLE.
CRCFF = CUMULATIVE RECOVERY EFFICIENCY. (FRACTION)
CVLING = CUMULATIVE VOLUME OF FLUID INJECTED. (GAL)
CVLRDG = CUMULATIVE VOLUME OF INJECTED FLUID RECOVERED. (GAL)
CVOLIN = CUMULATIVE VOLUME OF FLUID INJECTED. (CC)
CVOLRD = CUMULATIVE VOLUME OF INJECTED FLUID RECOVERED. (CC)
C11 = COMPUTED CONCENTRATION AT THE RADIUS AND AT THE TIME 
BEING CONSIDERED. (VOLUME FRACTION)
DG = DENSITY GRADIENT. (GM/CC/CM)
DH1 = A CONSTANT USED IN THE COMPUTATION OF THE DIMENSIONLESS 
PARAMETER GIVEN BY EQUATION 2.7A.
DH2 = DIMENSIONLESS GROUP. SECOND GROUP ON RIGHT SIDE OF 
EQUATION 2.7A.
DH2A = A CONSTANT IN THE COMPUTATION OF THE DIMENSIONLESS 
PARAMETER GIVEN BY EQUATION 2.7A.
DNUM11 = DENOMINATOR OF ARGUMENT OF COMPLEMENTARY ERROR FUNCTION 
in EQUATION 2.5 FOR FIRST INJECTION HALF-CYCLE.
DNUM13 = DENOMINATOR OF ARGUMENT OF COMPLEMENTARY ERROR FUNCTION 
in EQUATION 2.5 FOR SECOND INJECTION HALF-CYCLE.
DNUM15 = DENOMINATOR OF ARGUMENT OF COMPLEMENTARY ERROR FUNCTION 
in EQUATION 2.5 FOR THIRD INJECTION HALF-CYCLE.
DNUMP2 = DENOMINATOR OF ARGUMENT OF COMPLEMENTARY ERROR FUNCTION 
in EQUATION 2.5 FOR FIRST PRODUCTION HALF-CYCLE.
DNUMP4 = DENOMINATOR OF ARGUMENT OF COMPLEMENTARY ERROR FUNCTION 
in EQUATION 2.5 FOR SECOND PRODUCTION HALF-CYCLE.
DNUMP6 = DENOMINATOR OF ARGUMENT OF COMPLEMENTARY ERROR FUNCTION 
in EQUATION 2.5 FOR THIRD PRODUCTION HALF-CYCLE.
DSDF = DENSITY DIFFERENCE BETWEEN INJECTED AND NATIVE 
FLUIDS. (GM/CC)
DSC6 = INTERMEDIATE VALUE USED IN COMPUTING VALUES OF RLSO FOR 
THIRD PRODUCTION HALF-CYCLE. (SO CM)
FLINJ1 = FLUID INJECTED IN FIRST INJECTION HALF-CYCLE. (CC)
FLINJ2 = FLUID INJECTED IN SECOND INJECTION HALF-CYCLE. (CC)
RBT = RADIUS AT WHICH BREAKTHROUGH IS COMPUTED. (CN)
RCBT(1) = LEAST RADIUS TO A VALUE OF CONCENTRATION OF CBT FOR THE
LAST COMPUTATION INTERVAL OF THE LAST PRODUCTION
HALF-CYCLE. (CN)
RCBTFT = LEAST RADIUS TO A VALUE OF CONCENTRATION OF CBT FOR THE
LAST COMPUTATION INTERVAL OF THE LAST PRODUCTION
HALF-CYCLE. (FT)
RCEFF = CYCLE RECOVERY EFFICIENCY. (FRACTION)
RFT = RADIUS OF INJECTED FLUID AT THE ITH COMPUTATION INTERVAL ASSUMING NO MIXING OR GRAVITATIONAL
SEGREGATION. (FT)
RINC = LENGTH OF INCREMENT USED FOR CALCULATION OF MIXED
ZONE LENGTHS. (CN)
RINJ1 = RADIUS OF INJECTED FLUID AT THE END OF THE FIRST
INJECTION HALF-CYCLE ASSUMING NO MIXING AND NO
GRAVITATIONAL SEGREGATION. (CN)

R C B T  F T  a  (.E A S T  R A O IU S  TO A V A L U E  O F  C O N C E N T R A T IO N  OF C O T  F O R  TH E
R B T  a  R A D IU S  AT H H I C H  B R E A K T H R O U G H  I S  C O M P U T E D * ( C M )
R C E F F  a  C Y C L E  R E C O V E R Y E F F I C I E N C Y *  ( F R A C T I O N )
0 S P 6  a  TW O 0 1 M E N S I O N A L P S E U D O  F L O M  N A T E  F O R  T H IR O  P R O O U C T IO N
0 S P 2  a  TWO D I M E N S IO N A L  P S E U D O  F L O M  R A T E  F O R  F I R S T  P R O O U C T IO N
0 S I S  a  TM O  D I M E N S IO N A L  P S E U D O  F L O M  R A T E  F O R  T H IR O  I N J E C T I O N
0 R S  a  F L O M  R A T E  F O R  T H IR O  P R O O U C T IO N  H A L F - C V C L E *  ( C C / S E C )
0 R A a  F L O M  R A T E  F O R  T H IR O  I N J E C T I O N  H A L F - C V C L E .  ( C C / S E C )
0 P S  a  TM O  D I M E N S IO N A L  F L O M  R A T E  FO R  T H IR O  P R O O U C T IO N
0 P E  a  TWO D I M E N S IO N A L  F L O M  R A T E  FO R  F I R S T  P R O O U C T IO N
0 I S  a  TWO D I M E N S IO N A L  F L O M  R A T E  FO R  T H IR O  IN J E C T I O N
0 1 3  ■  TWO D I M E N S IO N A L  F L O M  R A T E  FO R  S E C O N O  I N J E C T I O N
P P P I  a  2 * P P P . I C M I
H ■  A O U IF E R T H IC K N E S S * I C N >
FLP R G G  a  F L U I O  P R O O U C E O  I N  T H IR O  P R O D U C T IO N  H A L F - C V C L E *  ( G A L )
N I N T  a  N UM BER O F C O M P U T A T IO N I N T E R V A L S T H R U  T H E  T H IR O
H A L F - C V C L E .  ( ( S Q  C M ) / S E C )
H I N T S  a  N UM BER O F C O M P U T A T IO N I N T E R V A L S T H R U  T H E  E N D  O F T H E
H A L F - C V C L E .  ( ( S Q  C M ) / S E C )
F L P R N 2  a  F L U I O  P R O O U C C O  I N  F I R O T  P R O D U C T IO H  H A L F - C V C L E *  I C C I
1 ■ S U B S C R IP T D CS IG N A T  IN S  C O N F U T A T IO N I N T E R V A L *
Z O N E . E N G T H S * ( C M )
RINJ3 = RADIUS OF INJECTED FLUID AT THE END OF THE SECOND INJECTION HALF-CYCLE ASSUMING NO MIXING AND NO GRAVITATIONAL SEGREGATION. (CM)

RINJS = RADIUS OF INJECTED FLUID AT THE END OF THE THIRD INJECTION HALF-CYCLE ASSUMING NO MIXING AND NO GRAVITATIONAL SEGREGATION. (CM)

RL50 = RADIUS TO LOWER END OF 50 PERCENT CONCENTRATION LINE. (CM)

RL50FT = RADIUS TO LOWER END OF 50 PERCENT CONCENTRATION LINE. (FT)

RL50I1 = RADIUS TO LOWER END OF 50 PERCENT CONCENTRATION LINE AT THE START OF THE FIRST PRODUCTION HALF-CYCLE. (CM)

RL50I2 = RADIUS TO LOWER END OF 50 PERCENT CONCENTRATION LINE AT THE START OF THE SECOND PRODUCTION HALF-CYCLE. (CM)

RL50I3 = RADIUS TO LOWER END OF 50 PERCENT CONCENTRATION LINE AT THE START OF THE THIRD PRODUCTION HALF-CYCLE. (CM)

RL50P1 = RADIUS TO LOWER END OF 50 PERCENT CONCENTRATION LINE AT THE START OF THE SECOND INJECTION HALF-CYCLE. (CM)

RL50P2 = RADIUS TO LOWER END OF 50 PERCENT CONCENTRATION LINE AT THE START OF THE THIRD INJECTION HALF-CYCLE. (CM)

RL50 = RADIUS TO UPPER END OF 50 PERCENT CONCENTRATION LINE. (CM)

RL50FT = RADIUS TO UPPER END OF 50 PERCENT CONCENTRATION LINE. (FT)

RL80P1 = RADIUS TO UPPER END OF 80 PERCENT CONCENTRATION LINE AT THE START OF THE FIRST PRODUCTION HALF-CYCLE. (CM)

RL80P2 = RADIUS TO UPPER END OF 80 PERCENT CONCENTRATION LINE AT THE START OF THE SECOND PRODUCTION HALF-CYCLE. (CM)

RL80 = RADIUS TO UPPER END OF 80 PERCENT CONCENTRATION LINE. (CM)

R1 = RADIUS AT WHICH CONCENTRATION IS BEING COMPUTED. ALSO INNER RADIUS OF MIXED ZONE. (CM)

R1P1 = INNER RADIUS OF MIXED ZONE. (PT)

R2I1 = OUTER RADIUS OF MIXED ZONE. (CM)

R2P1 = OUTER RADIUS OF MIXED ZONE. (PT)

R3 = LENGTH OF MIXED ZONE. (CM)

R3FT = MIXED ZONE LENGTH. (FT)

R4 = TIL/2. (CM)

R5 = RADIUS TO THE MIDPOINT BETWEEN R(I) AND R(I-1). (CM)

R55Q = R5 SQUARED. (SO CM)

R6 = TILP/2. (CM)

SDENOM = DENOMINATOR IF ARGUMENT OF COMPLEMENTARY ERROR FUNCTION IN EQUATION 2.5 USING PSEUDO RATES TO CHECK FOR BREAKTHROUGH DURING A PRODUCTION HALF-CYCLE.

TIL1 = INTERVAL LENGTH FOR COMPUTATIONS DURING INJECTION HALF-CYCLES. (CM)

TILP = INTERVAL LENGTH FOR COMPUTATIONS DURING PRODUCTION HALF-CYCLES. (CM)

TRT = CUMULATIVE TRAVEL TIME OF FRESH WATER-SALT WATER INTERFACE. (SEC)

TRT1 = CUMULATIVE TRAVEL TIME OF INTERFACE THRU END OF FIRST INJECTION HALF-CYCLE. (SEC)

TRT2 = CUMULATIVE TRAVEL TIME OF INTERFACE THRU END OF FIRST PRODUCTION HALF-CYCLE. (SEC)

TRT3 = CUMULATIVE TRAVEL TIME OF INTERFACE THRU END OF SECOND INJECTION HALF-CYCLE. (SEC)

TRT4 = CUMULATIVE TRAVEL TIME OF INTERFACE THRU END OF SECOND PRODUCTION HALF-CYCLE. (SEC)

TRT5 = CUMULATIVE TRAVEL TIME OF INTERFACE THRU END OF THIRD INJECTION HALF-CYCLE. (SEC)

TRT6 = CUMULATIVE TRAVEL TIME OF INTERFACE THRU COMPUTATION INTERVAL AT WHICH BREAKTHROUGH CHECK IS BEING MADE. (SEC)

TST1 = STATIC STORAGE TIME AT THE END OF THE FIRST INJECTION HALF-CYCLE. (SEC)

TST3 = STATIC STORAGE TIME AT THE END OF THE SECOND INJECTION HALF-CYCLE. (SEC)

TST5 = STATIC STORAGE TIME AT THE END OF THE THIRD INJECTION HALF-CYCLE. (SEC)

TSP = PSEUDO TIME USED IN GRAVITATIONAL SEGREGATION CALCULATIONS. (SEC)

TSPD = PSEUDO TIME USED IN GRAVITATIONAL SEGREGATION CALCULATIONS. (DAYS)

TT = TIME OF TRAVEL ACROSS ANY COMPUTATION INTERVAL PLUS THE PSEUDO TIME FOR THAT INTERVAL. (SEC)
T0 = TIME OF TRAVEL ACROSS ANY COMPUTATION INTERVAL PLUS THE
PSEUDO TIME FOR THAT INTERVAL. (DAYS)

T1 = TIME AT WHICH CONCENTRATION IS BEING COMPUTED DURING
FIRST INJECTION HALF-CYCLE. ALSO CUMULATIVE TRAVEL
TIME OF INTERFACE THRU END OF FIRST INJECTION
HALF-CYCLE. (SEC)

T2 = TIME AT WHICH CONCENTRATION IS BEING COMPUTED DURING
FIRST PRODUCTION HALF-CYCLE. ALSO CUMULATIVE TRAVEL
TIME OF INTERFACE THRU END OF FIRST PRODUCTION
HALF-CYCLE. (SEC)

T3 = TIME AT WHICH CONCENTRATION IS BEING COMPUTED DURING
SECOND INJECTION HALF-CYCLE. ALSO CUMULATIVE TRAVEL
TIME OF INTERFACE THRU END OF SECOND INJECTION
HALF-CYCLE. (SEC)

T4 = TIME AT WHICH CONCENTRATION IS BEING COMPUTED DURING
SECOND PRODUCTION HALF-CYCLE. ALSO CUMULATIVE TRAVEL
TIME OF INTERFACE THRU END OF SECOND PRODUCTION
HALF-CYCLE. (SEC)

T5 = TIME AT WHICH CONCENTRATION IS BEING COMPUTED DURING
THIRD INJECTION HALF-CYCLE. ALSO CUMULATIVE TRAVEL
TIME OF INTERFACE THRU END OF THIRD INJECTION
HALF-CYCLE. (SEC)

T6 = TIME AT WHICH CONCENTRATION IS BEING COMPUTED DURING
THIRD PRODUCTION HALF-CYCLE. (SEC)

T10 = TIME OF TRAVEL ACROSS ANY COMPUTATION INTERVAL. (SEC)

T110 = TIME OF TRAVEL ACROSS ANY COMPUTATION INTERVAL. (DAYS)

VIS = MEAN VISCOSITY OF INJECTED AND NATIVE FLUIDS. (POISE)

VISCP = MEAN VISCOSITY OF INJECTED AND NATIVE FLUIDS. (CP)

VOLNA = TOTAL VOLUME OF INJECTED FLUID NOT RECOVERED. (CC)

X = VALUE OF DIMENSIONLESS PARAMETER GIVEN BY
EQUATION 2.7A.

XL(1) = HORIZONTAL PROJECTION OF 50 PERCENT CONCENTRATION
LINE FOR LINEAR GEOMETRY. (CH)

XLF = HORIZONTAL PROJECTION OF 50 PERCENT CONCENTRATION
LINE FOR LINEAR GEOMETRY. (FT)

XR(1) = HORIZONTAL PROJECTION OF 50 PERCENT CONCENTRATION
LINE FOR RADIAL GEOMETRY. (CH)

XRFT = HORIZONTAL PROJECTION OF 50 PERCENT CONCENTRATION
LINE FOR RADIAL GEOMETRY. (FT)

XX = ARGUMENT OF COMPLEMENTARY ERROR FUNCTION FOR
EQUATION 2.5.

YL(1) = RATIO OF HORIZONTAL PROJECTION OF 50 PERCENT
CONCENTRATION LINE TO AQUIFER THICKNESS FOR LINEAR
GEOMETRY.

YR(1) = RATIO OF HORIZONTAL PROJECTION OF 50 PERCENT
CONCENTRATION LINE TO AQUIFER THICKNESS FOR RADIAL
GEOMETRY.

*******************************************************************************

DIMENSION R(1000),RZ(1000),YL(1000),XR(1000),RCBT(1000)

PART I - READING DATA
------ ------

20 READ(5,10000,END=1300)RBTFT,RCBT,TILIFT,TILPFT,RINCFT,TINCFT
   READ(5,11000)THT,PLOYAR,PR,ALF,DIFNL
   READ(5,12000)VISCP,VISCP2,DENSI,DENSA,ACMG
21 READ(5,13000)ORGH,ORGH2,ORGH3,ORGH4,ORGH5,ORGH6
   READ(5,14000)PLING1,PLING2,PLING3,PLING4,PLING5
22 READ(5,15000)TBSTD,TSTD1,TSTD2
23 READ(5,15200)MINT2,MINT4

CALCULATION OF DENSITY DIFFERENCE AND MEAN VISCOSITY OF FLUIDS
PART 1 - PRINTING DATA

WRITE(6,16000) HFT, PLYDAT, PR, ALF, DIFMOL
WRITE(6,17000) VISCP1, VISCP2, VISCP
WRITE(6,18000) DENS1, DENS2, DSDF, ACNG
24 WRITE(6,19000) OR1GM, OR2GN, OR3GN, OR4GN, OR5GN, OR6GN
WRITE(6,20000) FLYING1, FPLR42, FPLNG3, FPLR44, FPLNG5
WRITE(6,21000) TST10, TST30, TST50

PART 2 - CONVERSION FACTORS

50 CFFTCHM=30.4801
CFDFCN=0.987E-08
CFGLCC=3785.434
CGMCSC=63.0906
CFDFSEC=86400.0
CFDP=0.01
RBT=RBTFT*CFFTCH
RINC=RINCFT*CFFTCH
H=HFT*CFFTCH
PPP=3.1416*PR*H
PPP=2.0*PPP
PLY=PLYDAT*CFDFCN
FLINJ1=FLING1*CFGLCC
FPRN2=FPRG2*CFGCCLC
FLINJ3=FLING3*CFGLCC
FPRN4=FPRG4*CFGLCC
FLINJ5=FLING5*CFGLCC

51 OR1=OR1GM*CGMCSC
52 OR2=OR2GN*CGMCSC
53 OR3=OR3GN*CGMCSC
54 OR4=OR4GN*CGMCSC
55 OR5=OR5GN*CGMCSC
56 OR6=OR6GN*CGMCSC
57 TST1=TST10*CFDFSEC
58 TST3=TST30*CFDFSEC
59 TST5=TST50*CFDFSEC
VIS=VISCP*CFCFP
DM1=(PLY*ACNG*DSDF)/(PRO*VIS)
DM2A=VIS=0.000.6667/(DSDF=1.6667*ACNG=0.3333)
TILP=TILPFT*CFFTCH
R6=TILP/2.0
60 TILI=TILIFT*CFFTCH
R4=TILI/2.0

PART 3 - CALCULATIONS FOR FIRST INJECTION HALF-CYCLE

PART 4 - CALCULATIONS OF INTERVALS AND RADIUS OF INJECTION

RINJ1=SQRT(FLINJ1/PPP)
NINT1=RINJ1/TILI
CALCULATION OF MIXED ZONE DUE TO DIFFUSION AND DISPERSION

C
I=1
TRT=0.0
R(1)=TILI
R5=R(1)-R4
R550=R5*R5
R5=R5-RINC
T1=PPP+R550/OR1
OR1=OR1/PPP
DNOM1=2.*SORT(1.333+ALPHA*2.0001+T1)*0.5+DIFMOL*2.0001+T1)/0.5

C
CALCULATION OF INTERFACE PROJECTION DUE TO GRAVITY SEGREGATION

C
IF(I-1)<60,160,190
150 DG=DSOF/R3
DM2=DM2A*DG
T11=PPP*OR(I)*02/OR1
151 TRT=TRT+T11
X=DM1*T11+DM2*OR1
IF(X-0.1)<160,160,165
160 YL(I)=20.0*X
GOTO180
165 IF(X-1.0)<170,175,178
170 YL(I)=0.7958+12.523960-4.6196*X12
GOTO180
175 YL(I)=0.5+2.0*X
180 XL(I)=YL(I)*4
XLFT=XL(I)/CFFTCH
T11=T11/CFDSEC
TSPD=0.0
TTO=T11
GOT0290
190 DG=DSOF/R3
DM2=DM2A*DG
T11=PPP*ABS(R(I))*02-R(I-1)*02/OR1
191 TR=TR+T11
IF(YL(I-1)-2.0)<195,195,200
195 X=YL(I-1)/20.0
GOT0218
200 IF(YL(I-1)-6.5)<205,210,210
205 X=1.2993-SORT(172.1873-19.2784*YL(I-1))/0.6392
GOT0215
210 X=(YL(I-1)-6.5)/2.0
215 TSP=X/(DM1*DM2*0.5)
220 TT=T11+TSP
IF(T11-111)<240,230,330
230 TT=TT+TSTI
240 X=DM1*TTP+DM2*0.5
IF(X-0.1)<250,250,255
250 YL(I)=20.0*X
GOT0270
APPENDIX TO RADIAL GEOMETRY

360 ALIGN=AL(R(1-1)+XL(I-1))2.0
ALSO=AL(R(I-1)-XL(I-1))/2.0
GOT0300

PART 9 - CALCULATIONS FOR FIRST PRODUCTION HALF-CYCLE

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CALCULATION OF MIXED ZONE DUE TO DIFFUSION AND DISPERSION

370 R(I)=R(I-1)+TILP
RESQ=RESQ+RS
R1=RESQP+RINC
T1=1PP*P(NINT1)**2/QRI
T2=T1+PP*P(R(NINT1)**2-RESQ)/QRI
OPZ=OPZ+OP1
DNOMP2=2.0*SORT(t.333*P,F1(2.0GPZT1)**1.5-12.0*GPZT1)**1.5(2.0
1 0.0117/1)**1.5+10*HFNL(1,2.0GPZT1)**2/OPZ-(2.0*GPZT1)**2
2/OPZP2(2.0*G117/1)**2/OPZ)
370 IF [C11=0.03]370.370.370.
380 R(I)=R(I)-RINC
GOT0390
PRINTING COMPUTATIONS FOR FIRST PRODUCTION MULTICYCLE

APPROXIMATION TO RADIAL GEOMETRY

CALCULATION OF INTERFACE PROJECTION DUE TO GRAVITY SEPARATION

C
PART 6 - CALCULATIONS FOR SECOND INJECTION HALF-CYCLE

WRITE(6, 28000)

CALCULATION OF INTERVALS AND RADIUS OF INJECTION

RI NJ3 = SORT((FL INJ1 - FLP R42 + FL INJ3)/PPP)
NINT = (RI NJ3 - R(MINT2))/TIL1
MINT3 = MINT2 + NINT

CALCULATION OF MIXED ZONE DUE TO DIFFUSION AND DISPERSION

580 RI(I) = RI(1-1) + TIL1
RS = RI(I) - R4
RSS0 = RS + R5
R1 = RS - RINC
T2 = T1 + PPP0*(R(MINT1)**2 - R(MINT2)**2)/GR2
T3 = T2 + PPP0*(RSS0 - R(MINT2)**2)/GR3
Q13 = OR3/PPP1
DNM1 = 2.0*Q0RT(1.333 + 0.5*FF0((2.00013073)**1.5 - (2.00013073)**1.5 + (2.00013073)**1.5 + DP FQDL0)
E = ((2.00013073)**2/G13 - (2.00013073)**2/G13 + (2.00013073)**2/GP
J = 2*(2.00013073)**2/GP2 + (2.00013073)**2/GP11)

590 XX = (RSS0 - R1 + R1)/DNM13
C1 = EPSIC(XX)/2.0
IF(C11 - 0.10)600.600.640
600 IF(C11 - 0.03)610.610.620
610 RI(I) = RI
GOTO630
620 RI = RI - RINC
GOTO650
630 RI = RS + RINC
GOTO650
640 IF(C11 - 0.971600.660.660
650 RI = RI + RINC
GOTO650
660 RI = R1 - R2(I)
R1F = RI/CPFCTCN
R2F = R2/CPFCTCN
R3F = R3/CPFCTCN

CALCULATION OF INTERFACE PROJECTION DUE TO GRAVITY SEGREGATION

DG = 0.5DF/R3
DM2 = DM2A*DQ
T11 = PPP0*ABS(R(I)**2 - R(I-1)**2)/GR3
661 FRT = TRT + T11
IF(VL(I-1) - 2.01665.665.670
665 X = VL(I-1)/20.0
GOTO685
670 IF(VL(I-1) - 0.51670.680.680
675 X = 1.2993*SORT((172.1873 - 19.2704*VL(I-1)))/.6392
GOTO685
680 X = VL(I-1) - 6.5)/2.0
685 TSP = X/DM10DM2000.51
690 TT = T11 + TSP
IF(I-MINT3)710.700.750
700 TT = T11 + T3
710 X = DM10TT0DM2000.5
IF(X - 0.1)715.715.720
715 VL(I) = 20.0*OU
GOTO740
720 IF(X - 1.0)725.730.730
725 VL(I) = 0.7058 + 2.0239*X - 4.8196*X**2
GOTO740
730 VL(I) = 6.5 + 2.0*X
APPROXIMATION TO RADIAL GEOMETRY
A=3.142*(R(1.0-R(1.0))+R(1.1)+R(1.1))
B=3.142*(R(1.0-R(1.0))+R(1.1)-R(1.1))
C=3.142*(R(1.0-R(1.0))+R(1.1)-R(1.1))
D=3.142*(R(1.0-R(1.0))+R(1.1)+R(1.1))

PRINTING COMPUTATIONS FOR SECOND INJECTION HALF-CYCLE
WRITE(6,23000)I,R1FT,R2FT,R3FT
WRITE(6,24000)1,OM1,OM2,OM3
WRITE(6,25000)I,T1D,TSP,TDD,YL(I),XLFT
WRITE(6,26000)I,RUSOFT,RLSOFT,WRFT,VRFT

PRINTING COMPUTATIONS FOR SECOND PRODUCTION HALF-CYCLE
WRITE(6,29000)

CALCULATION OF MIXED ZONE DUE TO DIFFUSION AND DISPERSION

PART 7 - CALCULATIONS FOR SECOND PRODUCTION HALF-CYCLE
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WRITE(6,29000)
CALCULATION OF INTERFACE PROJECTION DUE TO GRAVITY SEGREGATION

DG=DSDF/R3
DM=DM2A*DG
TII=PPP+ABS(R(I)+0.02-R(I-1)+0.02)/DR
TR=E+TII
IF(Y(I)-1)*2+0.045, 0.045, 0.05
845 X=Y(I)-1/20.0
GOTO865
850 IF(Y(I)-1)-0.5)355, 360, 360
855 X=(Y(I)-1)-0.5)/2.0
860 TSP=X/(DM1*DM2*0.5)
870 TT=TII+TSP
X=DM1*TT*DM2*0.5
IF(X<0.1)875, 875, 880
875 Y(I)=20.0*X
GOTO900
880 IF(X<1.0)885, 890, 890
885 Y(I)=0.7956+12.5235*X-0.6196*X*X
GOTO900
890 Y(I)=6.5+2.0*X
900 XL(I)=Y(I)+XH
XLFT=XL(I)/CFFTCM
TII=TII/CFDSEC
TSPD=TSP/CFDSEC
TDD=T/D/CFDSEC

APPROXIMATION TO RADIAL GEOMETRY

A1=3.142*(R(I)-1)+XR(I-1)/2.0)*0.52-R(I-1)+0.02)
B1=3.142*(R(I)-1)+XR(I-1)/2.0)*0.52-R(I-1)+0.02)
RU0=SRTT(3.142*(R(I)+0.02-A4)+3.142*(XL(I)-XL(I-1))/2.0)
RL0=SRTT(3.142*(R(I)+0.02-A4)+3.142)*(XL(I)-XL(I-1))/2.0)
XR(I)=RU0-RL0
VR=XR(I)/H
RUF=RU0/CFFTCM
RLUF=RL0/CFFTCM
XRFT=XR(I)/CFFTCM
RF=RI(I)/CFFTCM

PRINTING COMPUTATIONS FOR SECOND PRODUCTION HALF-CYCLE

WRITE(6,23000)I,FLF,FT,RF
WRITE(6,24000)I,DM1,DM2,DM1*X
WRITE(6,25000)I XIV,TSPDI,TDD,Y(I)+XLFT
WRITE(6,26000)I,RUS,RLS0,RLS0,MAFT,VR,RF

933 I=I+1
IIF(I-NINT(I))760, 760, 950
950 TR=TR+R
RLS0P2=RLS0
QSF4=(RLS0P2+RLS0P2-RLS02*RLS0P2)/(2.0+TR4-TRT3))
CONST1=CONST1(2.0*QSF4+TR4)*1.5-(2.0*QSF4+TR4)*1.5
CONST2=CONST2(2.0*QSF4+TR4)*QSF-2.0*QSF4+TR4)*QSF/15
PART 6 - CALCULATIONS FOR THIRD INJECTION HALF-CYCLE

WRITE(6,30000)

CALCULATION OF INTERVALS AND RADIUS OF INJECTION

RINJS=SQR((FLINJ1-FLPRN2+FLINJ3-FLPRN4-FLINJ5)/PPP)
NINT=(RINJS-R(NINT4))/TILI
NINTS=NINT4+NINT

CALCULATION OF MIXED ZONE DUE TO DIFFUSION AND DISPERSION

970 R(I)=R(I-1)+TILI
R5=R(I)-R6
R5Q=R5*RS
R1=R5-RINC
T4=T3*PPP*(R(NINT3)**2-R(NINT4)**2)/QR4
T5=T4*PPP*(R5Q-R(NINT4)**2)/QR5
Q3=QR5/PPP

DLMIS=2.0*SQR(1.333+1.5*(2.0001576)**1.5-(2.0001576)**1.5+(2.0001576)**1.5-(2.0001576)**1.5)

1 G0P1020
2 T1=1.5+(2.0000000)**1.5-(2.0000000)**1.5+(2.0000000)**1.5-(2.0000000)**1.5
3 R1+RINC

1000 R2(I)=R2
G0T01020
1010 R1=R1-RINC
G0T01020
1020 R1=R5+RINC
G0T01020
1030 IF(C11<0.97)1040,1050,1060
1040 R1=R1+RINC
G0T01020
1050 R3=R1-R2(I)
R1FT=R1/CFFT
R2FT=R2(I)/CFFT
R3FT=R3/CFFT

CALCULATION OF INTERFACE PROJECTION DUE TO GRAVITY SEGREGATION

DG=D5DF/R3
DM2=DM2A*DG
T11=PPP*ABS(R(I)**2-R(I-1)**2)/QR5

1051 TR=TAT+T11
IF(YL(I-1)>2.0)1055,1056,1060
1055 X=YL(I-1)/20.0
G0T01075
1060 IF(YL(I-1)<-8.5)1065,1070,1070
1065 X=1.293555*SQR(172.1673-19.2763*YL(I-1))/0.6902
G0T01075
1070 X=(YL(I-1)-6.5)/2.0
1075 TSP=X/(DM1*DM2**0.5)
1080 T=TT+TSP
IF(I<2)1110,1120,1130
1130 X=XY1T-DM2**0.5
IF(X>-0.1)1105,1105,1110
1105 YL(I)=20.0*X
G0T01130
1110 IF(X<0.1)1115,1120,1120
1120 YL(I)=0.7958+12.8238*X-4.51956*X**2
G0T01130
\[ A_3 = 3.142 \times (R^2 - R^2) = 3.142 \times (R^2 - R^2) \]
\[ B_5 = 3.142 \times (R^2 - R^2) \]
\[ R_5 = \text{Sqrt}(3.142 \times R^2 + A_5) \]
\[ R_5 = \text{Sqrt}(3.142 \times (R^2 - R^2)) \]
\[ X_1 = R_5 - R_5 \]
\[ Y_1 = R_5 \]
\[ Z_1 = \text{Sqrt}(X_1^2 + Y_1^2) \]
\[ Z_1 = \text{Sqrt}(X_1^2 + Y_1^2) \]
\[ X_2 = \text{Sqrt}(X_1 + Y_1) \]
\[ Y_2 = \text{Sqrt}(X_1 + Y_1) \]
\[ Z_2 = \text{Sqrt}(X_2^2 + Y_2^2) \]
\[ Z_2 = \text{Sqrt}(X_2^2 + Y_2^2) \]
\[ X_3 = X_2 + Y_2 \]
\[ Y_3 = X_2 + Y_2 \]
\[ Z_3 = \text{Sqrt}(X_3^2 + Y_3^2) \]
\[ Z_3 = \text{Sqrt}(X_3^2 + Y_3^2) \]
\[ X_4 = X_3 + Y_3 \]
\[ Y_4 = X_3 + Y_3 \]
\[ Z_4 = \text{Sqrt}(X_4^2 + Y_4^2) \]
\[ Z_4 = \text{Sqrt}(X_4^2 + Y_4^2) \]
\[ X_5 = X_4 + Y_4 \]
\[ Y_5 = X_4 + Y_4 \]
\[ Z_5 = \text{Sqrt}(X_5^2 + Y_5^2) \]
\[ Z_5 = \text{Sqrt}(X_5^2 + Y_5^2) \]
\[ X_6 = X_5 + Y_5 \]
\[ Y_6 = X_5 + Y_5 \]
\[ Z_6 = \text{Sqrt}(X_6^2 + Y_6^2) \]
\[ Z_6 = \text{Sqrt}(X_6^2 + Y_6^2) \]
\[ X_7 = X_6 + Y_6 \]
\[ Y_7 = X_6 + Y_6 \]
\[ Z_7 = \text{Sqrt}(X_7^2 + Y_7^2) \]
\[ Z_7 = \text{Sqrt}(X_7^2 + Y_7^2) \]
\[ X_8 = X_7 + Y_7 \]
\[ Y_8 = X_7 + Y_7 \]
\[ Z_8 = \text{Sqrt}(X_8^2 + Y_8^2) \]
\[ Z_8 = \text{Sqrt}(X_8^2 + Y_8^2) \]
\[ X_9 = X_8 + Y_8 \]
\[ Y_9 = X_8 + Y_8 \]
\[ Z_9 = \text{Sqrt}(X_9^2 + Y_9^2) \]
\[ Z_9 = \text{Sqrt}(X_9^2 + Y_9^2) \]
\[ X_{10} = X_9 + Y_9 \]
\[ Y_{10} = X_9 + Y_9 \]
\[ Z_{10} = \text{Sqrt}(X_{10}^2 + Y_{10}^2) \]
\[ Z_{10} = \text{Sqrt}(X_{10}^2 + Y_{10}^2) \]
\[ X_{11} = X_{10} + Y_{10} \]
\[ Y_{11} = X_{10} + Y_{10} \]
\[ Z_{11} = \text{Sqrt}(X_{11}^2 + Y_{11}^2) \]
\[ Z_{11} = \text{Sqrt}(X_{11}^2 + Y_{11}^2) \]
\[ X_{12} = X_{11} + Y_{11} \]
\[ Y_{12} = X_{11} + Y_{11} \]
\[ Z_{12} = \text{Sqrt}(X_{12}^2 + Y_{12}^2) \]
\[ Z_{12} = \text{Sqrt}(X_{12}^2 + Y_{12}^2) \]
\[ X_{13} = X_{12} + Y_{12} \]
\[ Y_{13} = X_{12} + Y_{12} \]
\[ Z_{13} = \text{Sqrt}(X_{13}^2 + Y_{13}^2) \]
\[ Z_{13} = \text{Sqrt}(X_{13}^2 + Y_{13}^2) \]
\[ X_{14} = X_{13} + Y_{13} \]
\[ Y_{14} = X_{13} + Y_{13} \]
\[ Z_{14} = \text{Sqrt}(X_{14}^2 + Y_{14}^2) \]
\[ Z_{14} = \text{Sqrt}(X_{14}^2 + Y_{14}^2) \]
\[ X_{15} = X_{14} + Y_{14} \]
\[ Y_{15} = X_{14} + Y_{14} \]
\[ Z_{15} = \text{Sqrt}(X_{15}^2 + Y_{15}^2) \]
\[ Z_{15} = \text{Sqrt}(X_{15}^2 + Y_{15}^2) \]
\[ X_{16} = X_{15} + Y_{15} \]
\[ Y_{16} = X_{15} + Y_{15} \]
\[ Z_{16} = \text{Sqrt}(X_{16}^2 + Y_{16}^2) \]
\[ Z_{16} = \text{Sqrt}(X_{16}^2 + Y_{16}^2) \]
\[ X_{17} = X_{16} + Y_{16} \]
\[ Y_{17} = X_{16} + Y_{16} \]
\[ Z_{17} = \text{Sqrt}(X_{17}^2 + Y_{17}^2) \]
\[ Z_{17} = \text{Sqrt}(X_{17}^2 + Y_{17}^2) \]
\[ X_{18} = X_{17} + Y_{17} \]
\[ Y_{18} = X_{17} + Y_{17} \]
\[ Z_{18} = \text{Sqrt}(X_{18}^2 + Y_{18}^2) \]
\[ Z_{18} = \text{Sqrt}(X_{18}^2 + Y_{18}^2) \]
\[ X_{19} = X_{18} + Y_{18} \]
\[ Y_{19} = X_{18} + Y_{18} \]
\[ Z_{19} = \text{Sqrt}(X_{19}^2 + Y_{19}^2) \]
\[ Z_{19} = \text{Sqrt}(X_{19}^2 + Y_{19}^2) \]
\[ X_{20} = X_{19} + Y_{19} \]
\[ Y_{20} = X_{19} + Y_{19} \]
\[ Z_{20} = \text{Sqrt}(X_{20}^2 + Y_{20}^2) \]
\[ Z_{20} = \text{Sqrt}(X_{20}^2 + Y_{20}^2) \]
1210 IF(C11=0.97)1220,1230,1230
1220 R1=R1+RINC
GOTO1160
1230 R3=R1-R2(I)
R1FT=R1/CFFTCHM
R2FT=R2(I)/CFFTCHM
R3FT=R3/CFFTCHM
C
C CALCULATION OF INTERFACE PROJECTION DUE TO GRAVITY SEGREGATION
C
DG=DSDF/R3
DM2=DM2A+DG
T11=PPP*ABS(R(I)**2-R(I-1)**2)/OR6
TRT=TRT+T11
TRT=TRT
IF(YL(I-1)-2.0)1235,1235,1240
1235 X=YL(I-1)/20.0
GOTO1255
1240 IF(YL(I-1)-8.5)1245,1250,1250
1245 X=1.2993-SORT(172.1875-1.2784*YL(I-1))/0.6392
GOTO1255
1250 X=(YL(I-1)-6.5)/2.0
1255 TSP=X/(DM1+DM2+0.5)
1260 TR=TR+TSP
X=DM1*TSP
IF(X<0.1)1265,1265,1270
1265 YL(I)=20.0*X
GOTO1290
1270 IF(X>1.0)1275,1280,1280
1275 YL(I)=7.958+12.5230*X-4.8196*X**2
GOTO1290
1280 YL(I)=6.5+2.0*X
1290 XL(I)=YL(I)*0.4
XLFT=XL(I)/CFFTCHM
T11=111/CFDSSEC
TSPD=TSP/CFDSSEC
TTD=TT/CFDSSEC
C
C APPROXIMATION TO RADIAL GEOMETRY
C
A6=3.142*(R(I-1)+XR(I-1)/2.0)*R(I-1)**2
A6=3.142*R(I-1)**2-(R(I-1)-XR(I-1)/2.0)*R(I-1)**2
DSC6=3.142*(R(I-1)**2-B6
IF(DSC6=3.130,1330,1300
1300 RLSO=SQRT(DSC6/3.142)-(XL(I)-XL(I-1))/2.0
IF(ALSO=3.130,1330,1310
1310 RUSO=SQRT((3.142*R(I)**2+A6/3.142)+(XL(I)-XL(I-1))/2.0
C
C CHECKING FOR BREAK THROUGH
C
RL50=RL50+RL50
0SP6=(RL50+RL50+AL50)/2.06*(TRT-TRTS)
SDEN0M=2.0*SQRT(1.333*RFO((2.0*GSP6+TRT6)/0.5-(2.0*GSP6+TRTS)/0.5)
1.5+GSP6+GSP6+GSP6+GSP6+GSP6+GSP6-(2.0*GSP6+TRTS)
2)
C
R1=RL50-RINC
IF(R1-RBT)1330,1320,1320
1320 XX=(RL50-R1+R1)/SDENOM
C11=ERFC(XX)/2.0
IF(C11-CBT)1322,1322,1321
1321 R1=R1-RINC
IF(R1-RBT)1330,1320,1320
1322 RCFT(I)=R1
XR(I)=RUSO-RL50
YR=XR(I)/H
RUSOFT=RUSO/CFFTCHM
RLSOFT=RL50/CFFTCHM
XRFT=XR(I)/CFFTCHM
RFT=R(I)/CFFTCHM
C PRINTING COMPUTATIONS FOR THIRD PRODUCTION HALF-CYCLE
C
C WRITE(6,25000)1,RIFT,RF6T,RF6T
WRITE(6,24000)1,OM1,OM2,OM3
WRITE(6,25000)1,TT10,TSP,TDP,TL(1),XLFT
WRITE(6,26000)1,USR6FT,RLUSFT,XRFT,YR,RF6T
C
1323 I=I+1
GOTO1180
1330 I=I-1
NINT=I
C
C PART 10 - CALCULATION OF RECOVERY EFFICIENCY
C
C
1380 WRITE(6,32000)
C
C CVOLIN=FLINJ1+FLINJ3+FLINJ5 IF(I.GT.NINT)GOTO1360
FLPRN6=0.0
CVOLRD=FLPRN2+FLPRN4+FLPRN6
GOTO1370
1360 A6=3.142*(R(1-1)+XR(1-1)/2.0)+R(1-1)/2.0
B6=3.142*(R(1-1)-XR(1-1)-XR(1-1)/2.0)
RUS0=SQR(3.142*R(1)+2*A6)/3.142+(XL(1)-XL(1-1))/2.0
RLSO=SQR(3.142*R(1)+2*B6)/3.142-(XL(1)-XL(1-1))/2.0
VOLNR=PPP(RUS0+RUS0+RUS0+RLSO+RLSO)/3.0-(RCBT(1)+RCBT(1-1)
RBT*RB1)
FLPRN6=CVOLIN-VOLHR-FLPRN2-FLPRN6
CVOLRD=FLPRN2+FLPRN4+FLPRN6
RCBTFT=RCBT(1)/CFCTCN
WRITE(6,33000)1,RBTFT,CBT,RCBTFT
1370 RCEFF=FLPRN6/FLINJS
RCCEFF=CVOLRD/CVOLIN
FLPRG6=FLPRN6/CPGLCC
CVLING=CVOLIN/CPGLCC
CVLRDG=CVOLRD/CPGLCC
WRITE(6,34000)1,FLPRG6,RCEFF,CVLING,CVLRDG,RCCEFP
C
GOTO20
C
C PART 11 - FORMAT STATEMENTS
C
C
10000 FORMAT(6F12.0)
11000 FORMAT(5F12.0)
12000 FORMAT(5F12.0)
13000 FORMAT(5F12.0)
14000 FORMAT(5F12.0)
15000 FORMAT(3F12.0)
16000 FORMAT(2I13)
16000 FORMAT(I15,35X,'DATA'/,36X,'==='/,'6X,'POROUS MEDIUM'/,
1 9X,'THICKNESS OF THE MEDIUM (FT)*/30X,F12.0/,
2 9X,'PERMEABILITY OF THE MEDIUM (DARCIES)*/.22X,F12.0/,
3 9X,'POROSITY OF THE MEDIUM (FRACTION)*/.28X,F12.0/,
4 9X,'LONGITUDINAL DISPERSIVITY OF THE MEDIUM (CM)*14X,F12.0/,
5 9X,'COEFFICIENT OF MOLECULAR DIFFUSION (SO CM/SEC)*/12X,F12.0/)
6 )
17000 FORMAT(6X,'FLUID PROPERTIES*/,6X,'VISCOOSITY OF THE FLUIDS (CP)*/,
1 9X,'VISCOOSITY OF THE INJECTED FLUID*/.27X,F12.0/,
2 9X,'VISCOOSITY OF THE NATIVE FLUID*/.29X,F12.0/,
3 9X,'WEIGHT VISCOSITY OF THE TWO FLUIDS*/.26X,F12.0/
18000 FORMAT(8X,'DENSITY OF THE FLUIDS (GN/CM**3),
1 9X,'DENSITY OF THE INJECTED FLUID*/.29X,F12.0/,
2 9X,'DENSITY OF THE NATIVE FLUID*/.31X,F12.0/,
3 9X,'DENSIETY DIFF. BETWEEN THE FLUIDS*/.26X,F12.0/,,
4 6X,'ACCELERATION DUE TO GRAVITY (CM/SEC)/SEC)*/19X,F12.0//
**19000 FORMAT (6X, 'OPERATING CONDITIONS') /
   1 8X, 'INJECTION AND PRODUCTION RATES (GAL/MIN)' /
   2 9X, 'INJECTION RATES FOR FIRST INJECTION HALF-CYCLE' /
   3 9X, 'PRODUCTION RATE FOR FIRST PRODUCTION HALF-CYCLE' /
   4 9X, 'INJECTION RATES FOR SECOND INJECTION HALF-CYCLE' /
   5 9X, 'PRODUCTION RATES FOR SECOND PRODUCTION HALF-CYCLE' /
   6 9X, 'INJECTION RATES FOR THIRD INJECTION HALF-CYCLE' /
   7 9X, 'PRODUCTION RATES FOR THIRD PRODUCTION HALF-CYCLE' /

**20000 FORMAT (8X, 'VOLUME OF FLUID INJECTED OR PRODUCED (GALLONS)') /
   1 9X, 'FLUID INJECTED IN FIRST INJECTION HALF-CYCLE' /
   2 9X, 'FLUID PRODUCED IN FIRST PRODUCTION HALF-CYCLE' /
   3 9X, 'FLUID INJECTED IN SECOND INJECTION HALF-CYCLE' /
   4 9X, 'FLUID PRODUCED IN SECOND PRODUCTION HALF-CYCLE' /
   5 9X, 'FLUID INJECTED IN THIRD INJECTION HALF-CYCLE' /

**21000 FORMAT (8X, 'TIME OF STATIC STORAGE (DAYS)') /
   1 9X, 'AT THE END OF FIRST INJECTION HALF-CYCLE' /
   2 9X, 'AT THE END OF SECOND INJECTION HALF-CYCLE' /
   3 9X, 'AT THE END OF THIRD INJECTION HALF-CYCLE' /

**22000 FORMAT (1H1, 4X, 'CALCULATIONS FOR FIRST INJECTION HALF-CYCLE') /
   1 42X, '----------------------------------------' /

**23000 FORMAT (1X, '?', 13, 9X, 'RIFT = ', E15.6, 9X, 'R2P = ', E15.6)

**24000 FORMAT (1X, '?', 13, 6X, 'OML = ', E15.6, 9X, 'OMZ = ', E15.6, 9X, 'DG = ', E15.6, 9X = E15.6)

**25000 FORMAT (1X, '?', 13, 9X = E15.6, 9X, 'TSD = ', E15.6, 9X, 'TDD = ', E15.6)

**26000 FORMAT (1X, '?', 13, 9X = E15.6, 9X, 'RUSOFT = ', E15.6, 9X, 'RLSOF = ', E15.6, 9X = E15.6)

**27000 FORMAT (1H1, 4X, 'CALCULATIONS FOR FIRST PRODUCTION HALF-CYCLE') /
   1 42X, '----------------------------------------' /

**28000 FORMAT (1H1, 4X, 'CALCULATIONS FOR SECOND INJECTION HALF-CYCLE') /
   1 42X, '----------------------------------------' /

**29000 FORMAT (1H1, 4X, 'CALCULATIONS FOR SECOND PRODUCTION HALF-CYCLE') /
   1 42X, '----------------------------------------' /

**30000 FORMAT (1H1, 4X, 'CALCULATIONS FOR THIRD INJECTION HALF-CYCLE') /
   1 42X, '----------------------------------------' /

**31000 FORMAT (1H1, 4X, 'CALCULATIONS FOR THIRD PRODUCTION HALF-CYCLE') /
   1 42X, '----------------------------------------' /

**32000 FORMAT (1H1, 4X, 'CALCULATION OF RECOVERY EFFICIENCY') /
   1 47X, '----------------------------------------' /

**33000 FORMAT (1X, '?', 13, 9X = E15.6, 9X, 'RCT = ', E15.6, 9X = E15.6, 9X = E15.6)

**34000 FORMAT (1X, '?', 13, 9X = E15.6, 9X = E15.6, 9X = E15.6, 9X = E15.6)

C

1300 STOP
END
APPENDIX C

DESCRIPTION OF MINIAQUIFER CONSTRUCTION

The sand used for the construction of the miniaquifer was a fine-grained commercial grade blasting sand, commonly called "sugar sand," obtained from Industrial Sand and Abrasives Corporation, Port Allen, Louisiana. Three sieve analyses of the sand are shown in Table C-1.

The uniformity coefficient is defined as the ratio of the 40 percent grain size to the 90 percent grain size. The 40 percent size was 0.0068 inches and the 90 percent size was 0.0038 inches. Hence, the uniformity coefficient was 0.0068 ÷ 0.0038 or 1.79. The low value of uniformity coefficient indicates a very uniform sand, one in which the bulk of the grains are of similar size. The mean particle diameter of the sand (50 percent grain size) was found to be 0.0063 inches.

The epoxy adhesive used to consolidate the sand was Armstrong C-7 resin with 8 percent by weight of Activator A (Armstrong Products Co., Warsaw, Indiana). Mixing of the adhesive and sand was accomplished by thoroughly hand kneading the mixture for 10 to 15 minutes. The maximum batch size that could be properly mixed in the required time was approximately 3000 grams. The amount of adhesive to sand was 6 percent by weight. The working life of a
<table>
<thead>
<tr>
<th>Sieve No. (US)</th>
<th>Screen Opening (in.)</th>
<th>Analysis No. 1</th>
<th>Analysis No. 2</th>
<th>Analysis No. 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Weight Retained (gm)</td>
<td>Percent Retained</td>
<td>Cum. % Retained</td>
</tr>
<tr>
<td>30</td>
<td>0.0328</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>0.0164</td>
<td>0.4</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>50</td>
<td>0.0116</td>
<td>2.0</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>70</td>
<td>0.0082</td>
<td>42.5</td>
<td>10.7</td>
<td>11.3</td>
</tr>
<tr>
<td>100</td>
<td>0.0058</td>
<td>184.5</td>
<td>46.5</td>
<td>57.8</td>
</tr>
<tr>
<td>140</td>
<td>0.0041</td>
<td>104.6</td>
<td>26.3</td>
<td>84.1</td>
</tr>
<tr>
<td>200</td>
<td>0.0029</td>
<td>57.9</td>
<td>14.6</td>
<td>98.7</td>
</tr>
<tr>
<td>Pan</td>
<td>--</td>
<td>5.3</td>
<td>1.3</td>
<td>100.0</td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td>397.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
batch after mixing was between 90 and 120 minutes. With such a short working life, it was a physical impossibility to mix the required amount of sand-epoxy mixture, approximately 120 batches, and compact it in the mold before the epoxy began to set. It was found that if the sand-epoxy mixture was quick frozen immediately after mixing, it could be stored for as long as two weeks without any detrimental effects. When thawed, the mixture was still workable and had a working life between 60 and 90 minutes.

After each batch of sand and epoxy was thoroughly mixed, it was placed in a plastic bag and quick frozen using "dry ice" in a chest-type food freezer. The batches were placed so that there were alternating layers of dry ice and sand-epoxy mixture. Over a period of 5 days, 130 batches were mixed and frozen. On the sixth day, the frozen bags of sand-epoxy mixture were removed from the freezer. As they thawed, they were placed in a mold that was 10'3" by 5'0" by 1.5" deep. The mold consisted of a 3/4" plywood base that had been reinforced with 2 x 4's. The base of the mold had been covered by successive layers of aluminum foil and 6 mil thick polyethylene film. The purpose of the aluminum foil was to serve as a heat reflector during the curing process. The polyethylene film served as a mold release.

The sand-epoxy mixture was packed into the mold using hand tampers, placing a polyethylene film over the mold and running in place on it, and by rolling the mixture with a
4-inch diameter by 64-inch long solid stainless steel bar. The final rolling with the bar insured a smooth, uniform finish. The elapsed time from thawing of the mixture to final rolling was approximately 75 minutes.

After the sand-epoxy mixture had been placed in the mold, it was allowed to cure at room temperature for about 48 hours. A large insulated wooden curing oven was then placed over the miniaquifer and the temperature was gradually increased over a period of 24 hours to approximately 200°F. The temperature was maintained at 200°F for 24 hours and then gradually decreased to room temperature. Temperature changes were gradual to avoid shrinkage cracks.

Even though care was taken to avoid shrinkage cracks during curing, some cracking did occur at the edges of the miniaquifer. These were removed by trimming the edges using a circular, electric handsaw that was equipped with a diamond tipped blade. The dimensions of the miniaquifer after trimming were 10'0" by 4'9.5" by 1.5" thick.

All surfaces of the miniaquifer were sealed using five coats of Armstrong C-7/A epoxy. The first three coats were applied using a 7" flat/latex paint roller in order to obtain a thin coat. Use of this technique resulted in a controlled imbibition depth as the thin coating allowed the epoxy to quickly attain capillary equilibrium within the surface pores. The final two coats were much thicker than the first three and were applied using a 12" mortar trowel to evenly spread the epoxy in order to
obtain a smooth, glossy finish. Each of the five coats was allowed to cure at room temperature for at least 24 hours before the next coat was applied.

A 3/8" by 3/8" slot was cut into the miniaquifer along three of the four edges in order to produce an iso-potential at the boundaries (see Fig. 4.7). A linen-base, laminated phenolic material was used to cover the slot and to serve as base blocks for the installation of valves and fittings. Three full wells and three half wells were installed in the miniaquifer (see Fig. 4.7). Each well was equipped with a capacitance cell similar to that shown in Figure 4.5.

The miniaquifer was then tested for leaks by pressurizing it up to 5 psi with freon. An electronic halogen leak detector was then used to locate any leaks. The leaks were patched with epoxy and the epoxy allowed to cure. The miniaquifer was then pressured up to 10 psi and shut-in. After 48 hours there was no appreciable change in pressure, hence, it was concluded that all leaks had been located and patched.

In order to assure complete saturation, the pore spaces of the miniaquifer were evacuated by attaching a vacuum pump to well 1 (see Fig. 4.7) and pulling a vacuum for 72 hours. A fluid mixture containing 43.5 percent soltrol, 53.2 percent naphtha, and 3.3 percent carbon tetrachloride (percents are by volume) was then allowed to enter the miniaquifer from the isopotential. The fluid
front moved through the miniaquifer filling the evacuated pore spaces and converged to well 1. When production of the fluid started at well 1, the well was shut-in and the miniaquifer allowed to come to equilibrium. The miniaquifer was then flushed with approximately two pore volumes of fluid to dissolve any gases that came out of solution during the initial saturation.
APPENDIX D

COMPUTER PROGRAM USED IN COMPUTING THE LONGITUDINAL DISPERSIVITY COEFFICIENT OF THE MINIAQUIFER

The computer program listed in the following pages is used to calculate the concentration of native fluid in the produced stream as a function of cumulative time since injection started. The program is for one cycle only and it is assumed that no density or viscosity differences exist between the injected and native fluids. The program is in FORTRAN IV language and is written for use on an IBM 360/65 system.

A list of the required input data is presented at the beginning of the program. Following this is a complete list of all the variable names used in the program along with their definitions.
PROGRAM TO CALCULATE CONCENTRATION AT THE WELL BORE AS A FUNCTION OF CUMULATIVE TIME SINCE INJECTION STARTED. THIS PROGRAM IS FOR ONE CYCLE ONLY AND ASSUMES NO DENSITY OR VISCOSITY DIFFERENCES BETWEEN INJECTED AND NATIVE FLUIDS.

PROGRAM "CONCENT"

******************************************************************************

DATA TO BE READ IN

FIRST CARD - FORMAT(6F12.0)
OR1 = FLOW RATE FOR INJECTION HALF-CYCLE. (GPM)
OR2 = FLOW RATE FOR PRODUCTION HALF-CYCLE. (GPM)
TID = TOTAL INJECTION TIME. (DAYS)
TSD = CUMULATIVE TIME AT WHICH CONCENTRATION CALCULATIONS ARE STARTED. (DAYS)
HFT = AQUIFER THICKNESS. (FT)
PR = AQUIFER POROSITY. (FRACTION)

SECOND CARD - FORMAT(6F12.0)
ALF = LONGITUDINAL DISPERSIVITY COEFFICIENT. (CM)
DIFMOL = COEFFICIENT OF MOLECULAR DIFFUSION. (SO CM/SEC)
DELT = TIME INCREMENT FOR CONCENTRATION CALCULATIONS. (DAYS)
RWFT = WELL BORE RADIUS. (FT)

******************************************************************************

DEFINITION OF VARIABLE NAMES USED IN PROGRAM

CFPFTC = CONVERSION FACTOR. (CM/FT)
CGMCCS = CONVERSION FACTOR. ((CC/SEC)/(GAL/MIN))
CFDSEC = CONVERSION FACTOR. (SEC/DAY)
OR1 = FLOW RATE FOR INJECTION HALF-CYCLE. (CC/SEC)
OR2 = FLOW RATE FOR PRODUCTION HALF-CYCLE. (CC/SEC)
H = AQUIFER THICKNESS. (CM)
DELT = TIME INCREMENT FOR CONCENTRATION CALCULATIONS. (SEC)
RW = WELL BORE RADIUS. (CM)
T1 = TOTAL INJECTION TIME. (SEC)
T2 = CUMULATIVE TIME AT WHICH CONCENTRATION IS COMPUTED. (SEC)
T2D = CUMULATIVE TIME AT WHICH CONCENTRATION IS COMPUTED. (DAYS)
PPP = PRODUCT OF PI, POROSITY, AND THICKNESS. (CM)
PPP1 = 2*PPP1. (CM)
O11 = TWO DIMENSIONAL FLOW RATE FOR INJECTION HALF-CYCLE. (SO CM/SEC)
O12 = TWO DIMENSIONAL FLOW RATE FOR PRODUCTION HALF-CYCLE. (SO CM/SEC)
C11 = COMPUTED CONCENTRATION. (VOLUME FRACTION)
FP2 = SQUARE OF DENOMINATOR OF ARGUMENT OF COMPLEMENTARY ERROR FUNCTION.
XX = ARGUMENT OF COMPLEMENTARY ERROR FUNCTION.

******************************************************************************

READING DATA

10 READ(5,1000,END=30)OR1,OR2,TID,TSD,HFT,PR
READ(5,2000)ALF,DIFMOL,DELT,RWFT
**PRINTING DATA**

```fortran
WRITE(6,3000) ALF,DIFNDL,RWFT,TID
WRITE(6,4000)
```

**CONSTANTS AND CONVERSION FACTORS (FIELD UNITS TO C.G.S. UNITS)**

```fortran
CFDSEC=60400.0
CFPFTCM=30.4801
CGMCCS=63.0906
DELT=DELT0*CFDSEC
MR=HFT*CFPFTCM
PPP=3.1416*PRM
PPP1=2.0*PPP
QR1=QR1H*CGMCCS
QR2=QR2H*CGMCCS
QP2=QR2/PPP1
RM=RWFT*CFPFTCM
T1=TID*CFDSEC
```

**CALCULATION OF CONCENTRATION VERSUS CUMULATIVE TIME**

```fortran
T2=TS0*CFDSEC
XX=(1-QP2-T2-T1)/(QP2+2.0+QII+T1)/PPP005.8
C11=ERFC(XX)/2.0
T2D=T2/CFDSEC
```

**PRINTING COMPUTED VALUES OF CONCENTRATION VERSUS CUMULATIVE TIME**

```fortran
WRITE(6,9000) T2D,C11
IF(C11.GT.0.99)GOTO10
T2=T2+DELT
GOTO90
```

**FORMAT STATEMENTS**

```fortran
1000 FORMAT(6F12.0)
2000 FORMAT(4F12.0)
3000 FORMAT(1H9,X,'LONGITUDINAL DISPERISIVITY COEFFICIENT (CN)','.2X,F15.8
  1 8/10X,'COEFFICIENT OF MOLECULAR DIFFUSION (SQ CN/SEC)','.2X,F15
  2 10X,'WELL BORE RADIUS (FT)','.2X,F15.8/10X
  3 *INJECTION TIME (DAYS)*/29X,F15.8//)
4000 FORMAT(32X,'CONCENTRATION PROFILE'/,.2X,'TIME'/,.2X
  1 'CONCENTRATION*/,.2X,'(DAYS)'*.2X,'(VOLUME FRACTION)'/)
5000 FORMAT(29X,F12.0,.1X,PF.8)
```

```fortran
30 STOP
END
```
APPENDIX E

RESULTS OF EXPERIMENTAL RUNS MADE TO VERIFY THE MATHEMATICAL MODEL

The following tables summarize the laboratory data that have been obtained during this investigation and in a previous investigation (Kumar, 1968) on the feasibility of storing fresh water in saline aquifers. Also tabulated are the recovery efficiencies predicted for the various experimental runs using the computational procedure proposed in this paper. In this investigation and that by Kumar, breakthrough was when the produced stream contained 3 percent native fluid.

Tables E-1 through E-4 summarize the data obtained during this investigation. Since the miniaquifer used in this investigation is one-half of a full system, the tabulated values of rates and volumes are one-half of those for a full system.

Tables E-5 and E-6 summarize the data Kumar obtained using a 45° sector of a radial system. The physical properties of the system were: thickness = 7.65 cm, porosity = 0.255, permeability = 6.90 darcies, longitudinal dispersivity coefficient = 0.04 cm, and wellbore radius = 0.4 cm. Note that since this system was one-eighth of a full system, the tabulated values of rates and
volumes are one-eighth of those for a full system.

The descriptions of the Run Types listed in the tables are:

**Run Type 1A**: Fluid was injected into the center well of the system for a predetermined length of time. This was the injection half-cycle. The injected fluid was then produced through the center well until breakthrough occurred. This was the production half-cycle. If static storage of the injected bubble was to be included in the run, this took place between the end of the injection half-cycle and the beginning of the production half-cycle. The steps outlined above constituted one complete cycle.

**Run Type 1B**: Same as Type 1A except continued for two complete cycles.

**Run Type 1C**: Same as Type 1A except continued for three complete cycles.

**Run Type 2A**: Fluid was injected into well 1 (see Fig. 4.7 for well locations) for a predetermined length of time. This was the injection half-cycle. During the production half-cycle fluid was withdrawn through wells 1, 3, and 5 until breakthrough occurred in either well 3 or 5. At that time wells 3 and 5 were shut-in. This concluded the first step of the production half-cycle. Production through well 1 continued until breakthrough occurred. This concluded the production half-cycle. If static storage of the injected bubble was to be included in the run this took place between the end of the injection half-cycle and the
beginning of the production half-cycle. The steps outlined above constituted one complete cycle.

Run Type 2C: Same as Type 2A except continued for three complete cycles.

Run Type 3C: Fluid was injected into well 1 until the front passed wells 3 and 5. This concluded the first step of the injection half-cycle. Injection was then started in wells 3 and 5, with injection continuing in well 1, and continued until the desired volume had been injected. This completed the injection half-cycle. During the production half-cycle fluid was withdrawn through wells 1, 3, and 5 until breakthrough occurred in either well 3 or 5. At that time wells 3 and 5 were shut-in. This concluded the first step of the production half-cycle. Production through well 1 continued until breakthrough occurred. This concluded the production half-cycle. If static storage of the injected bubble was to be included in the run, this took place between the end of the injection half-cycle and the beginning of the production half-cycle. The steps outlined above constituted the first cycle. The run was continued for three complete cycles.

Run Type 4C: Fluid was injected into well 1 until the front passed wells 3 and 5. This concluded the first step of the first injection half-cycle. The water injected in this step is termed "cushion water." Injection was then started in wells 3 and 5, with injection continuing in well 1, and continued until the desired volume had been
injected. This completed the injection half-cycle. During the production half-cycle, fluid was withdrawn through wells 1, 3 and 5 until breakthrough occurred in either well 3 or 5. This concluded the production half-cycle. If static storage of the injected bubble was to be included in the run, this took place between the end of the injection half-cycle and the beginning of the production half-cycle. Two additional cycles were carried out in a manner similar to the steps described above except that the first step of the first injection half-cycle was excluded in the two additional cycles.

Run Type 5B: Fluid was injected into the center well of the system for a predetermined length of time. This was the first injection half-cycle. The injected fluid was then produced through the center well but production was stopped short of breakthrough. This concluded the first production half-cycle and the first full cycle. The process was repeated for a second cycle except that during the second production half-cycle production continued until breakthrough occurred. If static storage was to be included in the run, it took place between the end of an injection half-cycle and the beginning of a production half-cycle. Kumar utilized Run Type 5B for his two-cycle experiments.
### TABLE E-1 Data for Single Well Injection and Single Well Production

<table>
<thead>
<tr>
<th>RUN NUMBER</th>
<th>TA</th>
<th>TC</th>
<th>TB</th>
<th>IC</th>
<th>TC</th>
<th>TA</th>
<th>IC</th>
<th>TA</th>
<th>IC</th>
<th>16</th>
<th>17</th>
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<tr>
<td>Run Type</td>
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<td>C</td>
<td>C</td>
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<td>A</td>
<td>A</td>
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<td>A</td>
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<td>A</td>
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</table>

#### FLUID PROPERTIES

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<th>6</th>
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<th>11</th>
<th>12</th>
<th>14</th>
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<th>17</th>
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#### FIRST CYCLE

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<td>Volume Injected (cc)</td>
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<td>5170.</td>
<td>5174.</td>
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134
### TABLE E-1 (continued)

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### TABLE E-2 Data for Single Well Injection and Multiple Well Production

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<td>Cum. Recovery Eff. (%)</td>
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**SECOND CYCLE (continued)**

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<td>Value of D'loss Group B.D.T.</td>
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| FIRST CYCLE | | |
| Cum. Recovery Eff. (%) | 90 | 90 |
| Experimental | 82 | 82 |
| Computed | | |
| Value of D'loss Group B.D.T. | 0.631 | 0.631 |

<p>| THIRD CYCLE | | |
| Injection Rate (cc/min) | 10.288 | 10.288 |
| Volume Injected (cc) | 8181. | 6181. |
| Static Storage (min) | 7.000 | 7.000 |
| First Production Rate (cc/min) | 10.288 | 10.288 |
| Volume Produced (cc) | 3600. | 3600. |
| Step Recovery Eff. (%) | 74 | 74 |
| Experimental | 64 | 64 |
| Computed | 74 | 74 |
| Cycle Recovery Eff. (%) | (S) | 76 |
| Experimental | 76 | 76 |
| Computed | | |
| Cum. Recovery Eff. (%) | (S) | 76 |
| Experimental | 76 | 76 |
| Computed | | |
| Value of D'loss Group B.D.T. | 0.799 | 0.799 |
| Volume Produced (cc) | 1403. | 1403. |
| Step Recovery Eff. (%) | 74 | 74 |
| Experimental | 64 | 64 |
| Computed | 74 | 74 |
| Cum. Recovery Eff. (%) | 74 | 74 |
| Experimental | 64 | 64 |
| Computed | 74 | 74 |
| Value of D'loss Group B.D.T. | 0.652 | 0.652 |</p>
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### TABLE E-3 Data for Multiple Well Injection and Multiple Well Production

#### FLUID PROPERTIES

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<td>Visc. of Nat. Fluid (cp)</td>
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<tr>
<td>Mean Viscosity (cp)</td>
<td>0.945</td>
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<td>Density of Inj. Fluid (gm/cc)</td>
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<tr>
<td>Density of Nat. Fluid (gm/cc)</td>
<td>0.783</td>
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<td>Density Difference (gm/cc)</td>
<td>0.009</td>
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#### FIRST CYCLE

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<tr>
<td>Second Injection Rate (cc/min)</td>
<td>20.115</td>
</tr>
<tr>
<td>Static Storage (min)</td>
<td>0.00</td>
</tr>
<tr>
<td>First Production Rate (cc/min)</td>
<td>20.115</td>
</tr>
<tr>
<td>Volume Produced (cc)</td>
<td>3755.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Recovery Eff. (%)</th>
<th>Experimental</th>
<th>Computed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step Recovery</td>
<td>75</td>
<td>63</td>
</tr>
<tr>
<td>Cum. Recovery Eff. (%)</td>
<td>75</td>
<td>63</td>
</tr>
<tr>
<td>Value of D'less Group O B.T.</td>
<td>0.396</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rate or Volume</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Second Production Rate (cc/min)</td>
<td>4.023</td>
</tr>
<tr>
<td>Volume Produced (cc)</td>
<td>768.0</td>
</tr>
<tr>
<td>Cycle Recovery Eff. (%)</td>
<td>15</td>
</tr>
<tr>
<td>Cum. Recovery Eff. (%)</td>
<td>90</td>
</tr>
<tr>
<td>Value of D’less Group O B.T.</td>
<td>0.472</td>
</tr>
</tbody>
</table>

#### SECOND CYCLE

<table>
<thead>
<tr>
<th>Rate or Volume</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Injection Rate (cc/min)</td>
<td>4.023</td>
</tr>
<tr>
<td>Second Injection Rate (cc/min)</td>
<td>20.115</td>
</tr>
<tr>
<td>Static Storage (min)</td>
<td>0.00</td>
</tr>
<tr>
<td>First Production Rate (cc/min)</td>
<td>20.115</td>
</tr>
<tr>
<td>Volume Produced (cc)</td>
<td>3984.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Recovery Eff. (%)</th>
<th>Experimental</th>
<th>Computed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step Recovery</td>
<td>79</td>
<td>71</td>
</tr>
<tr>
<td>Cum. Recovery Eff. (%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### SECOND CYCLE (continued)

<table>
<thead>
<tr>
<th>Recovery Eff. (%)</th>
<th>Experimental</th>
<th>Computed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle Recovery Eff. (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cum. Recovery Eff. (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Value of D’less Group O B.T.</td>
<td>0.769</td>
<td></td>
</tr>
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</table>

#### THIRD CYCLE

<table>
<thead>
<tr>
<th>Rate or Volume</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Injection Rate (cc/min)</td>
<td>4.023</td>
</tr>
<tr>
<td>Second Injection Rate (cc/min)</td>
<td>20.115</td>
</tr>
<tr>
<td>Static Storage (min)</td>
<td>0.00</td>
</tr>
<tr>
<td>First Production Rate (cc/min)</td>
<td>20.115</td>
</tr>
<tr>
<td>Volume Produced (cc)</td>
<td>4036.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Recovery Eff. (%)</th>
<th>Experimental</th>
<th>Computed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step Recovery</td>
<td>80</td>
<td>75</td>
</tr>
<tr>
<td>Cum. Recovery Eff. (%)</td>
<td>88</td>
<td>79</td>
</tr>
<tr>
<td>Value of D’less Group O B.T.</td>
<td>0.973</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rate or Volume</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Second Production Rate (cc/min)</td>
<td>4.023</td>
</tr>
<tr>
<td>Volume Produced (cc)</td>
<td>973.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Recovery Eff. (%)</th>
<th>Experimental</th>
<th>Computed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle Recovery Eff. (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cum. Recovery Eff. (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Value of D'less Group O B.T.</td>
<td>1.015</td>
<td></td>
</tr>
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</table>
### TABLE E-4 Data for Multiple Well Injection and Multiple Well Production

<table>
<thead>
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<th>RUN NUMBER</th>
<th>10</th>
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<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FLUID PROPERTIES</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visc. of Inj. Fluid (cp)</td>
<td>0.949</td>
<td>0.922</td>
<td>0.926</td>
</tr>
<tr>
<td>Visc. of Hot. Fluid (cp)</td>
<td>0.942</td>
<td>0.925</td>
<td>0.927</td>
</tr>
<tr>
<td>Mean Viscosity (cp)</td>
<td>0.945</td>
<td>0.923</td>
<td>0.927</td>
</tr>
<tr>
<td>Density of Inj. Fluid (gm/cc)</td>
<td>0.793</td>
<td>0.860</td>
<td>0.860</td>
</tr>
<tr>
<td>Density of Hot. Fluid (gm/cc)</td>
<td>0.783</td>
<td>0.784</td>
<td>0.784</td>
</tr>
<tr>
<td>Density Difference (gm/cc)</td>
<td>0.010</td>
<td>0.076</td>
<td>0.076</td>
</tr>
<tr>
<td><strong>FIRST CYCLE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First Injection Rate (cc/min)</td>
<td>4.023</td>
<td>4.023</td>
<td>4.023</td>
</tr>
<tr>
<td>Volume Injected (cc)</td>
<td>1006.</td>
<td>1341.</td>
<td>1341.</td>
</tr>
<tr>
<td>Second Injection Rate (cc/min)</td>
<td>20.115</td>
<td>20.115</td>
<td>20.115</td>
</tr>
<tr>
<td>Volume Injected (cc)</td>
<td>5029.</td>
<td>5029.</td>
<td>5029.</td>
</tr>
<tr>
<td>Static Storage (min)</td>
<td>0.</td>
<td>0.</td>
<td>280.</td>
</tr>
<tr>
<td>Production Rate (cc/min)</td>
<td>20.115</td>
<td>20.115</td>
<td>20.115</td>
</tr>
<tr>
<td>Volume Produced (cc)</td>
<td>4600.</td>
<td>4020.</td>
<td>3566.</td>
</tr>
<tr>
<td>Cycle Recovery Eff. (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental</td>
<td>91</td>
<td>80</td>
<td>71</td>
</tr>
<tr>
<td>Computed</td>
<td>78</td>
<td>78</td>
<td>72</td>
</tr>
<tr>
<td>*Cum. Recovery Eff. (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental</td>
<td>76</td>
<td>63</td>
<td>66</td>
</tr>
<tr>
<td>Computed</td>
<td>65</td>
<td>62</td>
<td>57</td>
</tr>
<tr>
<td>Value of O‘less Group B.T.</td>
<td>0.463</td>
<td>2.045</td>
<td>2.592</td>
</tr>
<tr>
<td><strong>SECOND CYCLE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection Rate (cc/min)</td>
<td>20.115</td>
<td>20.115</td>
<td>20.115</td>
</tr>
<tr>
<td>Volume Injected (cc)</td>
<td>5029.</td>
<td>5029.</td>
<td>5029.</td>
</tr>
<tr>
<td>Static Storage (min)</td>
<td>0.</td>
<td>0.</td>
<td>280.</td>
</tr>
<tr>
<td>Production Rate (cc/min)</td>
<td>20.115</td>
<td>20.115</td>
<td>20.115</td>
</tr>
<tr>
<td>Volume Produced (cc)</td>
<td>4663.</td>
<td>4429.</td>
<td>3913.</td>
</tr>
<tr>
<td>Cycle Recovery Eff. (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental</td>
<td>97</td>
<td>86</td>
<td>78</td>
</tr>
<tr>
<td>Computed</td>
<td>86</td>
<td>85</td>
<td>78</td>
</tr>
<tr>
<td>*Cum. Recovery Eff. (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental</td>
<td>86</td>
<td>74</td>
<td>66</td>
</tr>
<tr>
<td>Computed</td>
<td>75</td>
<td>72</td>
<td>66</td>
</tr>
<tr>
<td>Value of O‘less Group B.T.</td>
<td>0.645</td>
<td>2.766</td>
<td>3.769</td>
</tr>
<tr>
<td><strong>THIRD CYCLE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection Rate (cc/min)</td>
<td>20.115</td>
<td>20.115</td>
<td>20.115</td>
</tr>
<tr>
<td>Volume Injected (cc)</td>
<td>5029.</td>
<td>5029.</td>
<td>5029.</td>
</tr>
<tr>
<td>Static Storage (min)</td>
<td>0.</td>
<td>0.</td>
<td>280.</td>
</tr>
<tr>
<td>Production Rate (cc/min)</td>
<td>20.115</td>
<td>20.115</td>
<td>20.115</td>
</tr>
<tr>
<td>Volume Produced (cc)</td>
<td>5015.</td>
<td>4568.</td>
<td>4476.</td>
</tr>
<tr>
<td>Cycle Recovery Eff. (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental</td>
<td>100</td>
<td>91</td>
<td>89</td>
</tr>
<tr>
<td>Computed</td>
<td>89</td>
<td>86</td>
<td>80</td>
</tr>
<tr>
<td>*Cum. Recovery Eff. (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental</td>
<td>90</td>
<td>79</td>
<td>73</td>
</tr>
<tr>
<td>Computed</td>
<td>79</td>
<td>76</td>
<td>70</td>
</tr>
<tr>
<td>Value of O‘less Group B.T.</td>
<td>0.810</td>
<td>3.404</td>
<td>4.806</td>
</tr>
</tbody>
</table>

*All cumulative recovery efficiencies were computed with the "cushion water" volume included.*
TABLE E-5  Data for Single Well Operation  
(Kumar, 1968)

<table>
<thead>
<tr>
<th>FLUID PROPERTIES</th>
<th>RUN 2</th>
<th>RUN 3</th>
<th>RUN 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visc. of Inj. Fluid (cp)</td>
<td>0.833</td>
<td>0.801</td>
<td>0.656</td>
</tr>
<tr>
<td>Visc. of Nat. Fluid (cp)</td>
<td>0.781</td>
<td>0.647</td>
<td>0.571</td>
</tr>
<tr>
<td>Mean Viscosity (cp)</td>
<td>0.807</td>
<td>0.724</td>
<td>0.614</td>
</tr>
<tr>
<td>Density of Inj. Fluid (gm/cc)</td>
<td>0.765</td>
<td>0.765</td>
<td>0.751</td>
</tr>
<tr>
<td>Density of Nat. Fluid (gm/cc)</td>
<td>1.129</td>
<td>0.957</td>
<td>0.823</td>
</tr>
<tr>
<td>Density Difference (gm/cc)</td>
<td>0.364</td>
<td>0.192</td>
<td>0.072</td>
</tr>
</tbody>
</table>

FIRST CYCLE

| Injection Rate (cc/min) | 74.843 | 22.857 | 6.000 |
| Static Storage (min)    | 14.500 | 13.333 | 121.000 |
| Production Rate (cc/min)| 95.124 | 50.455 | 6.000 |
| Volume Produced (cc)    | 2933.  | 1850.  | 168.  |
| Cycle Recovery Eff. (%) | 65     | 58     | 9     |
| Cum. Recovery Eff. (%)  | 62     | 52     | 31    |
| Value of D'less Group 0 B.T. | 0.388 | 0.526 | 0.844 |
### TABLE E-6 Data for Single Well Operation (Kumar, 1968)

<table>
<thead>
<tr>
<th>RUN NUMBER</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLUID PROPERTIES</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visc. of Inj. Fluid (cp)</td>
<td>0.799</td>
<td>0.729</td>
</tr>
<tr>
<td>Visc. of Nat. Fluid (cp)</td>
<td>0.656</td>
<td>0.592</td>
</tr>
<tr>
<td>Mean Viscosity (cp)</td>
<td>0.728</td>
<td>0.661</td>
</tr>
<tr>
<td>Density of Inj. Fluid (gm/cc)</td>
<td>0.764</td>
<td>0.761</td>
</tr>
<tr>
<td>Density of Nat. Fluid (gm/cc)</td>
<td>0.870</td>
<td>0.805</td>
</tr>
<tr>
<td>Density Difference (gm/cc)</td>
<td>0.106</td>
<td>0.044</td>
</tr>
<tr>
<td>FIRST CYCLE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection Rate (cc/min)</td>
<td>63.000</td>
<td>89.714</td>
</tr>
<tr>
<td>Volume Injected (cc)</td>
<td>3150.</td>
<td>3140.</td>
</tr>
<tr>
<td>Static Storage (min)</td>
<td>20.167</td>
<td>20.000</td>
</tr>
<tr>
<td>Production Rate (cc/min)</td>
<td>66.250</td>
<td>70.667</td>
</tr>
<tr>
<td>Volume Produced (cc)</td>
<td>1325.</td>
<td>2120.</td>
</tr>
<tr>
<td>SECOND CYCLE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Injection Rate (cc/min)</td>
<td>72.422</td>
<td>86.333</td>
</tr>
<tr>
<td>Volume Injected (cc)</td>
<td>1545.</td>
<td>2590.</td>
</tr>
<tr>
<td>Static Storage (min)</td>
<td>20.167</td>
<td>13.333</td>
</tr>
<tr>
<td>Production Rate (cc/min)</td>
<td>73.489</td>
<td>78.912</td>
</tr>
<tr>
<td>Volume Produced (cc)</td>
<td>2250.</td>
<td>2900.</td>
</tr>
<tr>
<td>Cum. Recovery Eff. (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experimental</td>
<td>76</td>
<td>88</td>
</tr>
<tr>
<td>Computed</td>
<td>70</td>
<td>78</td>
</tr>
<tr>
<td>Value of D'less Group @ B.T.</td>
<td>0.253</td>
<td>0.139</td>
</tr>
</tbody>
</table>
VITA

Water Richard Whitehead, the son of Velma D. and Richard A. Whitehead, was born August 29, 1937, in Lake Charles, Louisiana. He was graduated from Forest Hill High School, Forest Hill, Louisiana, in June 1955. In September of that year, he entered Southwestern Louisiana Institute (now the University of Southwestern Louisiana), Lafayette, Louisiana, from which he received the Bachelor of Science degree in Civil Engineering in May of 1960. He was immediately employed by the U.S. Forest Service as a Civil Engineer. After four months with the U.S. Forest Service he entered active military service in September of 1960. Upon release from active military service in March of 1961, he accepted a position with the Louisiana Department of Highways as an Assistant District Laboratory Engineer. In September of 1962 he resigned from the Department and entered the Graduate School of Louisiana State University in Baton Rouge, from which he received the Master of Science degree in Civil Engineering in May of 1964. In June 1964, he joined the General Engineering Division of the Ethyl Corporation where he held positions from Design Engineer to Head of the Civil Engineering Group. In June of 1970, he resigned from the Ethyl Corporation and returned to Louisiana State University to begin work toward
the Doctor of Philosophy degree in Civil Engineering.

He is married to the former Marjorie Smith of McCall, Mississippi. They are the parents of four daughters: Cheryl (16), Kathi (14), Cynthia (9), Lynette (7); and one son, Daryl (12).
EXAMINATION AND THESIS REPORT

Candidate: Walter R. Whitehead

Major Field: Civil Engineering

Title of Thesis: Storage of Fresh Water in Saline Aquifers Using a Well Field.

Approved:

[Signatures]

Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

[Signatures]

Date of Examination: July 2, 1974