WELL FIELD DESIGN IN ANISOTROPIC MEDIA FOR IN-SITU OIL SHALE MINING

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ABSTRACT

A good well field design often determines the success of an in-situ oil shale mining project. A successful well field design should consider the following essential parameters:

1. Three dimensional geohydrologic properties of the reservoir
2. Sweep efficiency of well field pattern
3. Well spacing
4. Breakthrough time and production projection

The three dimensional geohydrologic properties of a reservoir are vertical and horizontal permeabilities, leakage, storage coefficient, and vertical and horizontal boundary conditions. These geohydrologic properties can be tested in a single field test program. These properties will provide overall mass balance and fluid flow control parameters of the in-situ oil shale mining operation. The sweep efficiency of a well field pattern is a key design parameter. For isotropic conditions, a standard 5-spot pattern is preferred. For anisotropic conditions, direct line drive, staggered line drive, and marching line drive patterns are preferred. Basically, well field design patterns that can provide maximum well spacing, symmetrical sweep with least dilution and excursion are considered to be acceptable.

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INTRODUCTION

The primary objective of this paper is to apply a combination of groundwater hydraulic and reservoir engineering principles on well field design for the extraction of oil and gas from underground reservoirs (oil shale, tar sand, heavy crude and others).

The present oil shale mining practice has been emphasizing either surface retort or modify in-situ retort methods on relatively impervious oil shale material. Little attention was given to the tremendous oil shale reserve that is locked in place in the porous media which is an ideal setting for the true in-situ retort mining method.

This paper discusses the simplicity of a well field design that utilizes a combination of reservoir engineering and groundwater hydraulic principles in a very practical way. A successful well field design should consider the following essential parameters:

1. Three dimensional reservoir anisotropic hydraulic properties
2. Sweep efficiency of selected well field pattern
3. Well spacing determination
4. Breakthrough time and production projection

RESERVOIR ANISOTROPIC HYDRAULIC PROPERTIES

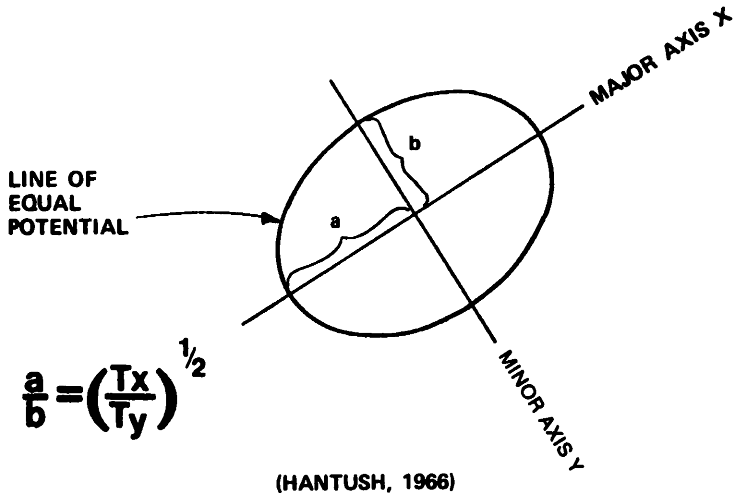
Most underground reservoirs are anisotropic due to either the depositional environment, solution channels and natural fractures or a combination of them. The oil shale containing reservoir (leached zone) in the Piceance Creek Basin displays a definite anisotropic property (Loo, et al, 1979).

The anisotropic properties of a reservoir are vertical and horizontal permeabilities and boundaries. These anisotropic properties can be tested in a single field test program (Loo, 1979). The method of reservoir analysis for horizontal anisotropic properties can be done by the Papadopulos method (1965) and the vertical permeability can be done by the Weeks method (1969).

These reservoir anisotropic properties will provide overall mass balance and govern the fluid flow control of the in-situ oil shale mining operation. For example, the orientation of the horizontal permeabilities or transmissivities will govern fluid flow underground in an elliptical pattern for anisotropic case (Figure 1). The basic hydraulic relationship was developed by Hantush (1966).

SWEEP EFFICIENCY OF SELECTED WELL FIELD PATTERN

For proper well field design, a well field pattern needs to be selected to adapt to the anisotropic properties of the reservoir. Orientation of well field and operational procedures are required to clean or sweep the dead spots for optimal production. Well completion design should be done to curb excursion and influx of native groundwater.

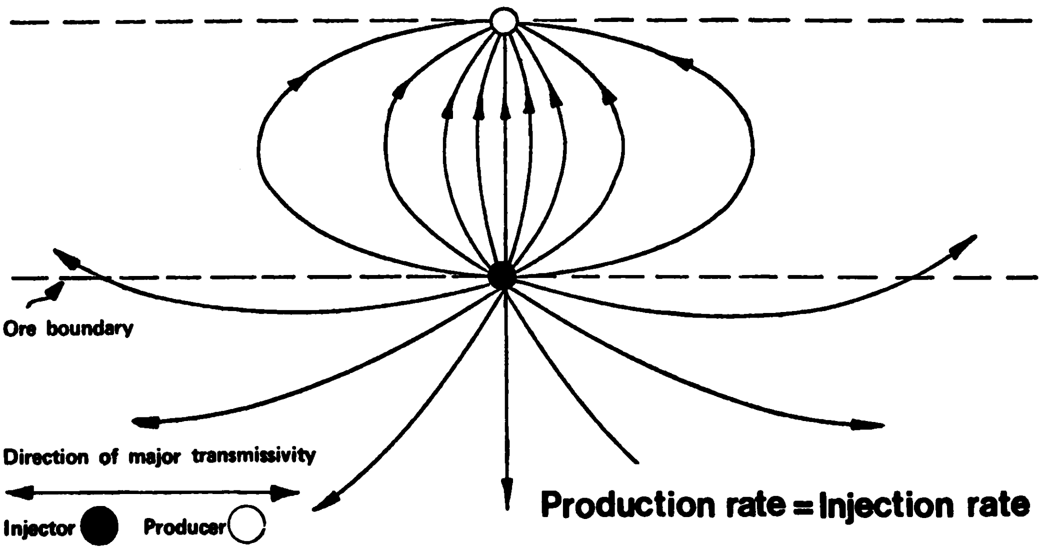


$$\frac{a}{b}=\left(\frac{Tx}{Ty}\right)^{1/2}$$

(HANTUSH, 1966)

AQUIFER ANISOTROPY PROPERTY

FIGURE 1



FLUID FLOW PATTERN
WHEN INJECTOR & PRODUCER ALIGNMENT PERPENDICULAR
TO THE DIRECTION OF MAJOR TRANSMISSIVITY

FIGURE 2

A series of well field simulations was done and display the serious problem of improper orientation of wells versus the anisotropy orientation (see Figures 2 and 3). The problem can be easily corrected by working with the preferred flow direction rather than against it (see Figure 4). Previous studies done by Caudle (1960), Laudrum (1960) and Mortada (1961) all showed similar results. It is obvious that a well field pattern should be in an elongated form when anisotropic conditions exist (see Figure 5). The elongated types of well field patterns are direct line drive and staggered line drive.

Well completion technology is also of great importance to curb excursion of injection fluid and influx of native groundwater (see Figure 6). It can be handled by proper well shielding completion particularly at the peripheral wells in the well field (see Figure 7).

In most of the well field patterns shown in Figure 5, after the flooding operation there are usually spots or areas in the field not swept properly by the injection fluid called "dead spot" (see Figures 8, 9, 10 and 11) for various popular patterns. The marching line drive, as shown in Figure 12, will effectively eliminate these spots or better the sweep efficiency.

WELL SPACING DETERMINATION

The number of wells in a well field pattern often decides the economics of a well field operation. It is recommended that well spacing should be maximized to minimize the wells required for operation.

The maximum allowable well spacing can be determined by a field test program to detect the temperature profile between injector and producer (see Figure 13). By knowing the location of the critical temperature front and the fluid flow velocity at that location, the maximum allowable well spacing can be determined readily (see Figures 14, 15 and 16).

BREAKTHROUGH TIME AND PRODUCTION PROJECTION

For proper well field management, breakthrough time and period of production need to be estimated. For a well field situation with an equal number of injectors and producers, the first order maximum breakthrough time can be determined by the following equations:

For fully penetration well field,

$$T_B = \frac{\pi a\, b\, h \theta}{2Q}$$

T_B is breakthrough time

a and b are the axes of an elliptical cylinder and a is the long side of the ellipse aligning the injector and producer

h is the thickness of the reservoir

θ is the average effective porosity of the reservoir

Q is the rate of injection or production assuming equal rates

Note: the ratio of a to b can be determined by the square root of the contrast of major to minor horizontal permeability or transmissivity (Hantush, 1966) and see Figure 1.

For partially penetration well field with wells completed and perforated in the same horizon in the reservoir,

$$T_B = \frac{4/3\ \pi\ a\, b\, c\, \theta}{2Q}$$

a, b and c are the axes of an ellipsoid. The axis a is the long side of the ellipsoid aligning the injector and the producer. The axis c is measured from the mid-point of the perforated interval vertically.

Note: the ratio of a to b to c can be found by the square root contrast of the major and the minor horizontal permeabilities and the vertical permeability.

For other applications, such as vertical sweep, the breakthrough time determination has to be done on a case-by-case basis depending on the distance between injector and producer at different horizon and the 3-dimensional permeabilities of the reservoir.

It is important to note that the breakthrough time determination mentioned above can be used as first order approximation only. The complications of high temperature, viscosity change, porosity change, permeability change, short cut flow paths within reservoir, pressure changes, and multi-phase fluid flow are not being considered. These complications need to be further understood and resolved before any prediction model or production projection can be done. Computer simulation model to be used as a prediction tool should be calibrated with field performance data considering all of the above-mentioned complications.

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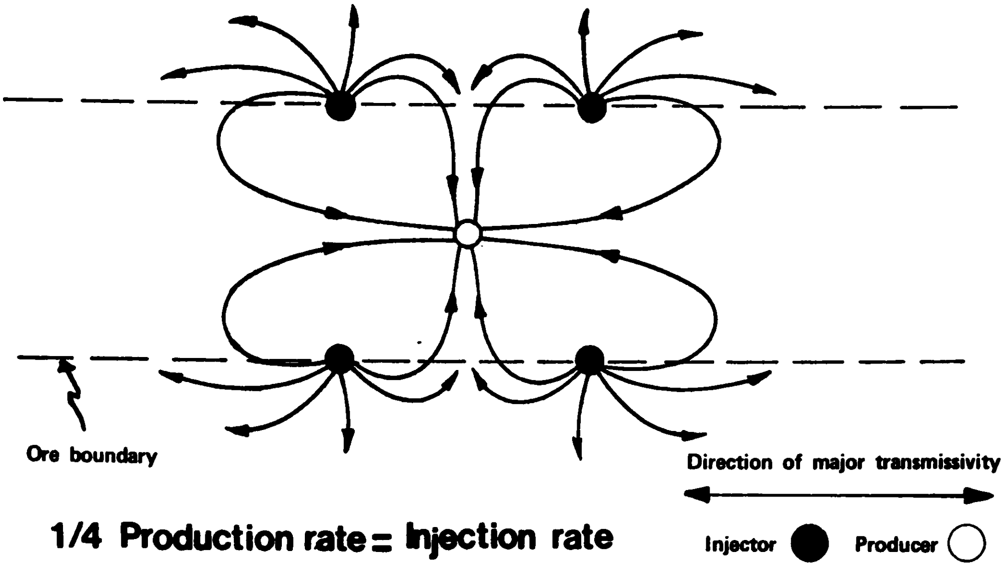
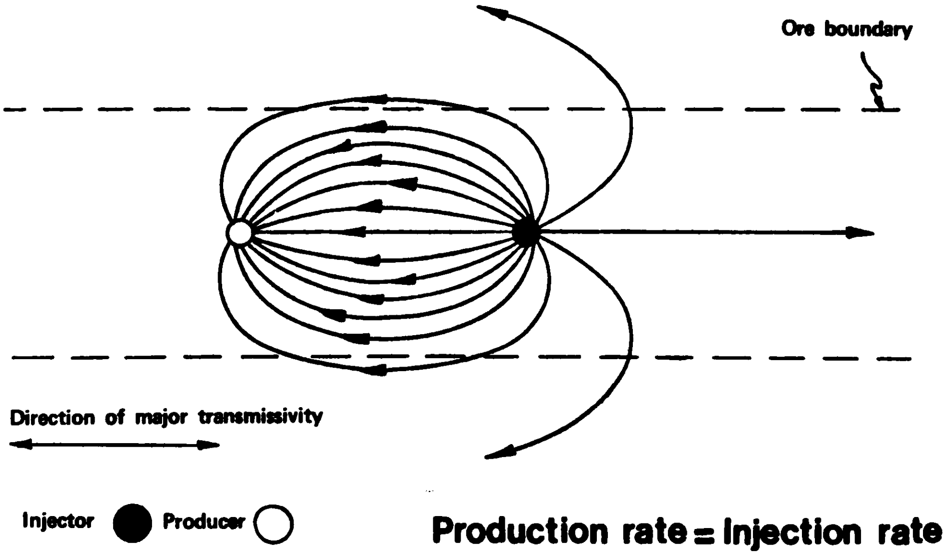


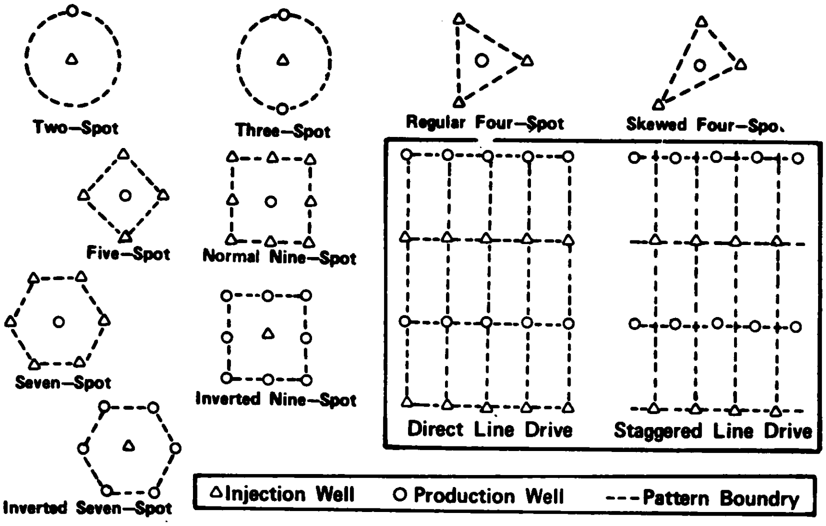
FLUID FLOW PATTERN
OF A 'STANDARD FIVE-SPOT' CONFIGURATION

FIGURE 3



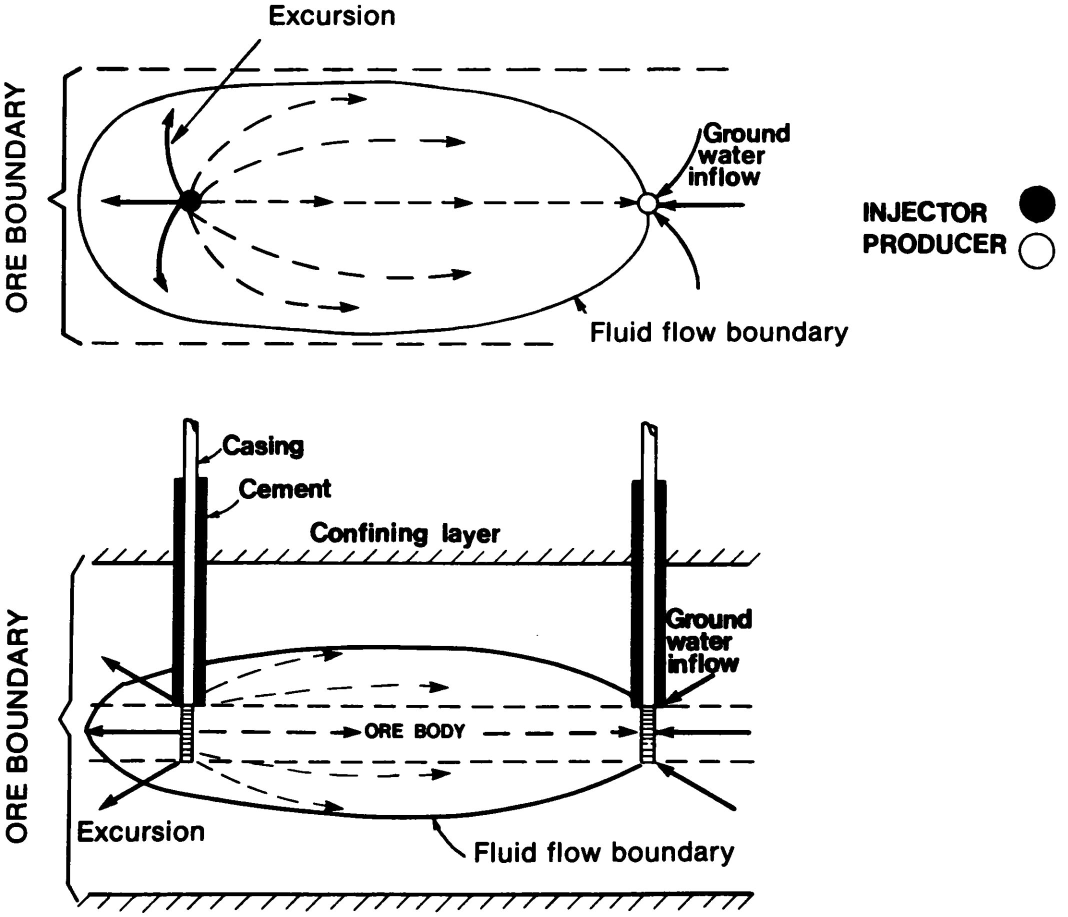
FLUID FLOW PATTERN
WHEN INJECTOR & PRODUCER ALIGNMENT PARALLEL
TO THE DIRECTION OF MAJOR TRANSMISSIVITY

FIGURE 4



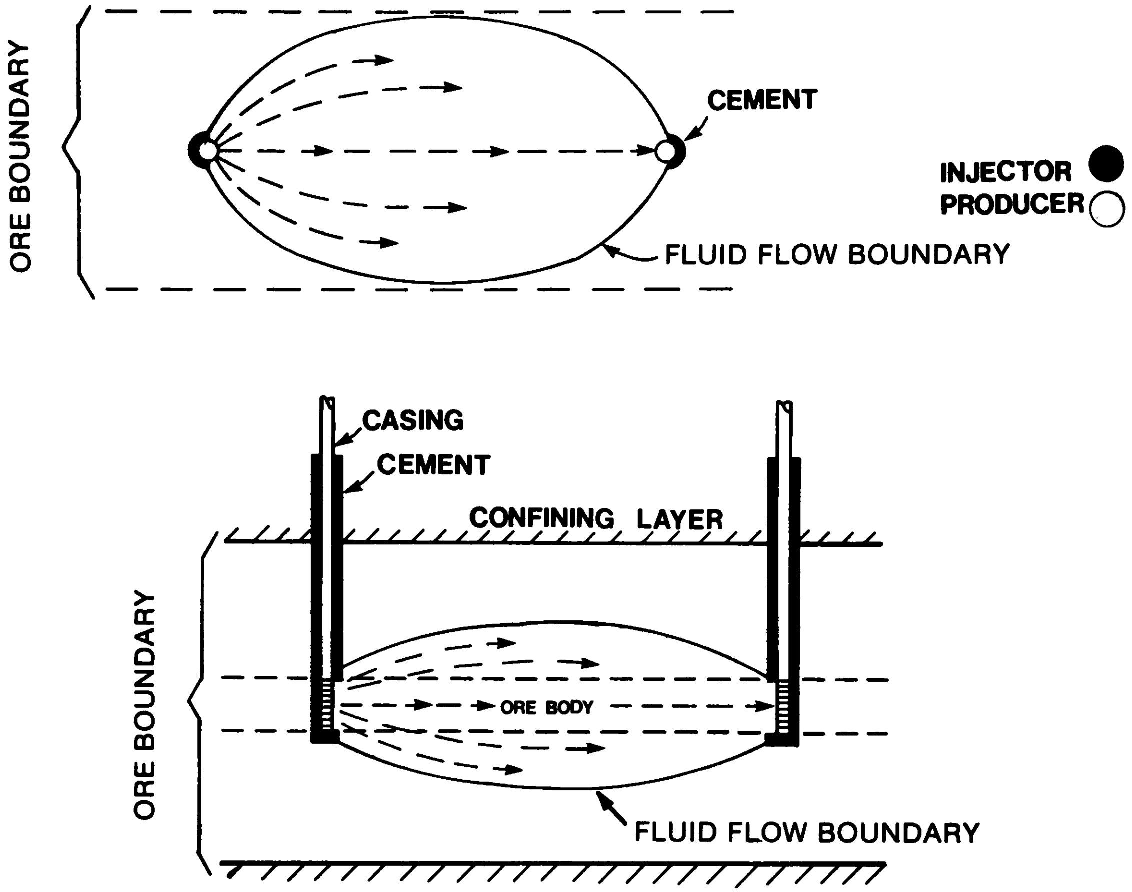
VARIOUS FLOODING PATTERNS
ADAPTED FROM CRAIG, 1971

FIGURE 5



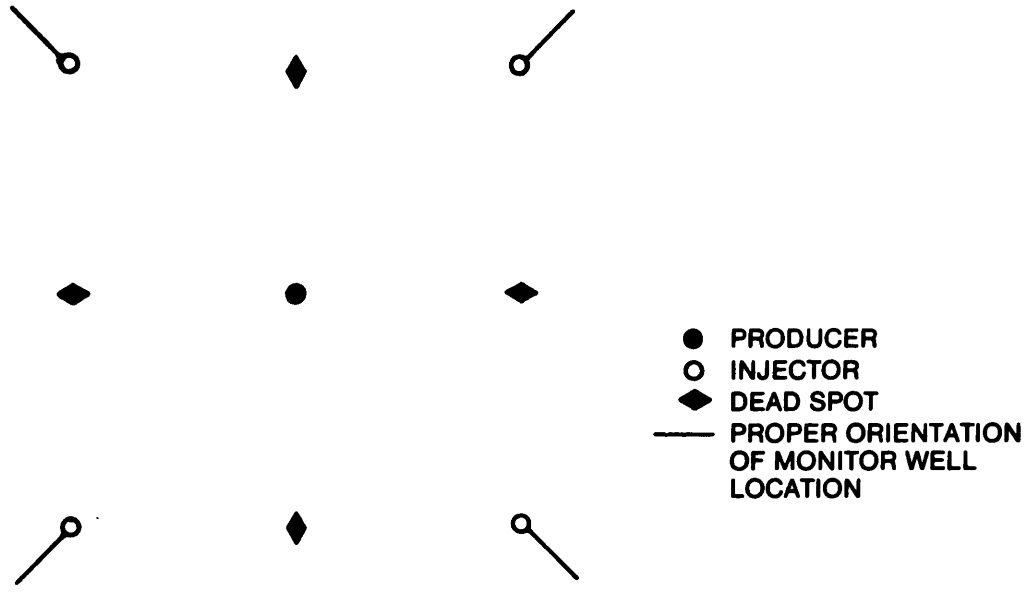
EXCURSION AND GROUNDWATER INFLOW
OF CONVENTIONAL WELL FIELD
COMPLETION

FIGURE 6



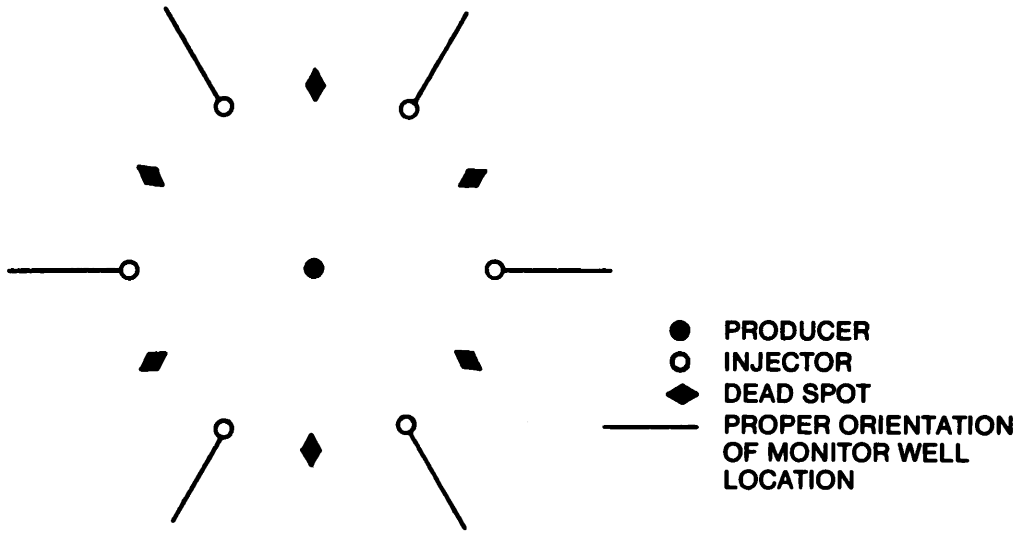
CONTROL OF EXCURSION AND
GROUNDWATER INFLOW OF WELL FIELD

FIGURE 7



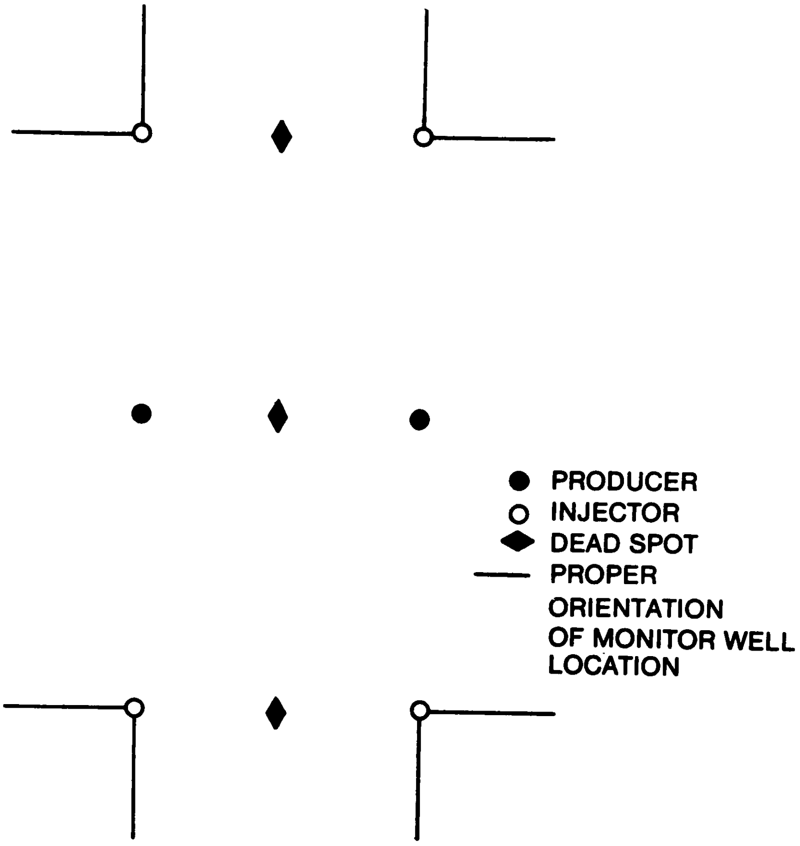
5-SPOT PATTERN

FIGURE 8



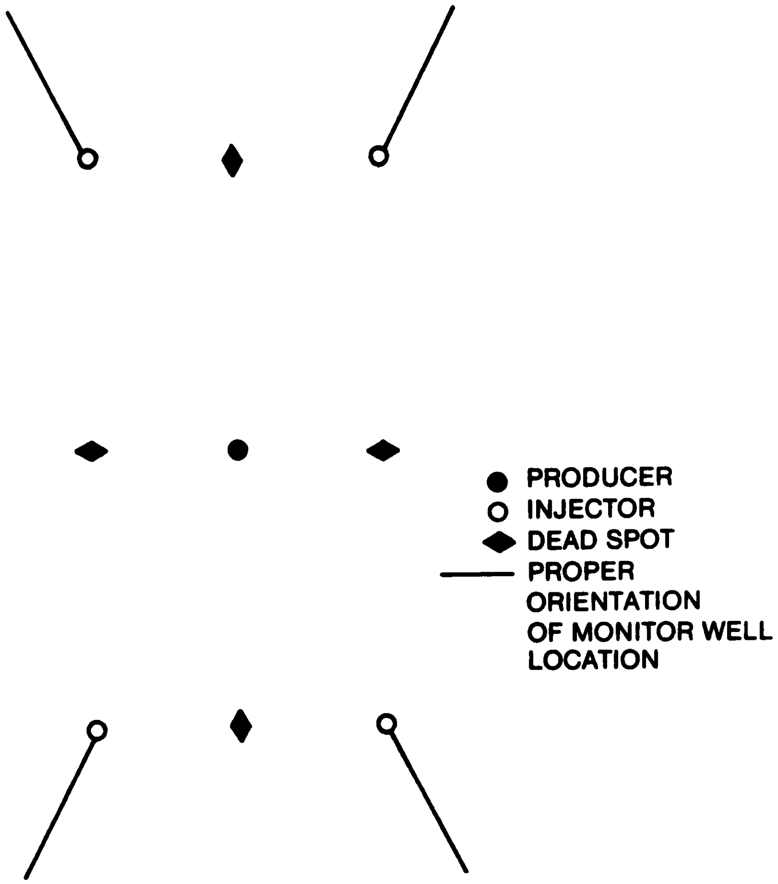
7-SPOT PATTERN

FIGURE 9



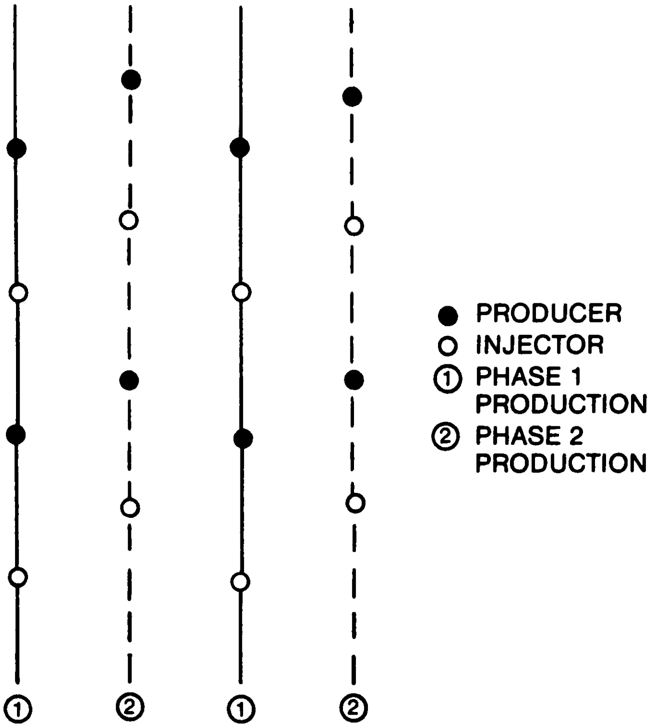
DIRECT LINE DRIVE PATTERN

FIGURE 10



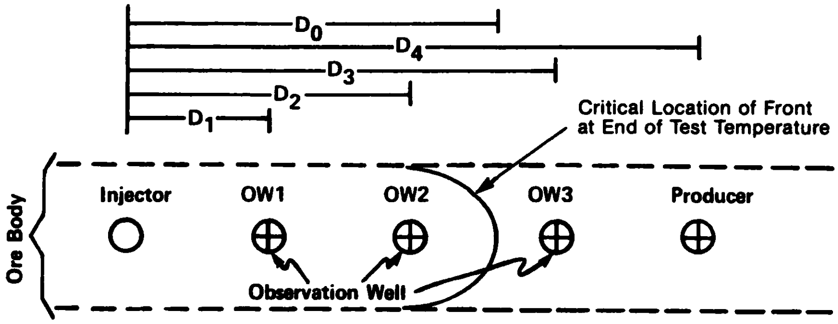
STAGGERED LINE DRIVE PATTERN

FIGURE 11



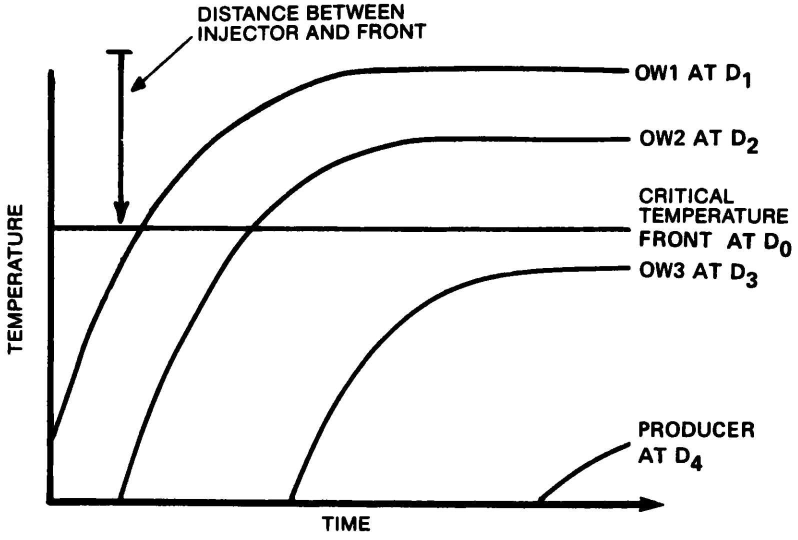
MARCHING LINE DRIVE

FIGURE 12



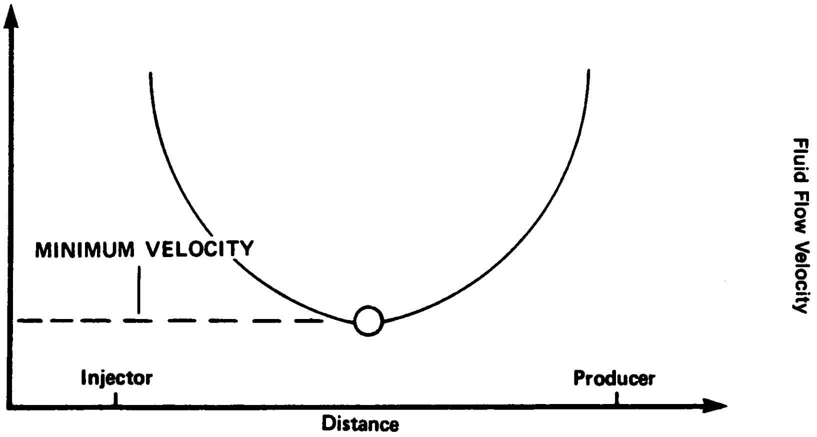
TEST PROGRAM ON
TEMPERATURE DISTRIBUTION

FIGURE 13



CRITICAL TEMPERATURE FRONT PLOT
AND ANALYSIS

FIGURE 14



VELOCITY DISTRIBUTION
BETWEEN INJECTOR AND PRODUCER

FIGURE 15

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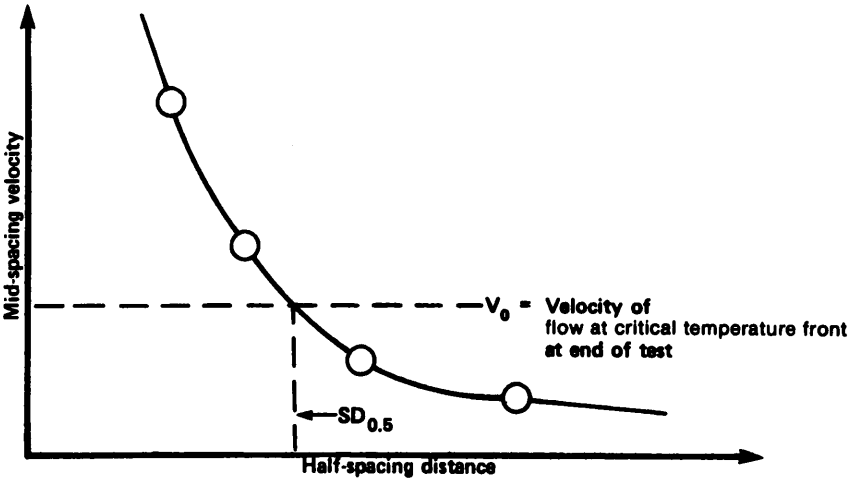

INJECTOR-PRODUCING SPACING = 2 x $SD_{0.5}$
ASSUMING MAXIMUM INJECTION & RECOVERY RATE

FIGURE 16