# RESERVOIR ENGINEERING STUDIES OF THE TRAVALE-RADICONDOLI RESERVOIR

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## 1. INTRODUCTION

Initial reservoir engineering studies of the Travale-Radicondoli steamfield in the Larderello region of Italy were begun in late 1976, with the ultimate objective of estimating energy reserves. Research centered on pressure transient (well test) studies. Reasonable success was attained in studying mathematical models of the reservoir in an attempt to duplicate the pressure buildup behavior of Travale Well 22 as observed in the field. A well interference test[1] was later designed and implemented, involving Well T-22 as the test well, and seven other nearby observation wells. Results of analysis of the test appeared to be conclusive. They indicated the direction of the main fracture in the reservoir which is penetrated by Well T-22, the steam flow pattern in the reservoir, and that the reservoir can be represented by a parallelepiped model.

Following this study, it was believed that a better concept of the Travale reservoir structure and the flow behavior of its fluids could be developed through analysis of the pressure-production history of Well T-22 over a period of two years and seven months, beginning just after construction of a power plant in 1973.

## 2. METHODOLOGY

The data available (Fig. 1) consist of a long wellhead pressure history from July 1973 to July 1975. During this period, flowrates, wellhead temperatures, and noncondensable gas composition were recorded once a month. By means of this information, bottomhole pressures were calculated.

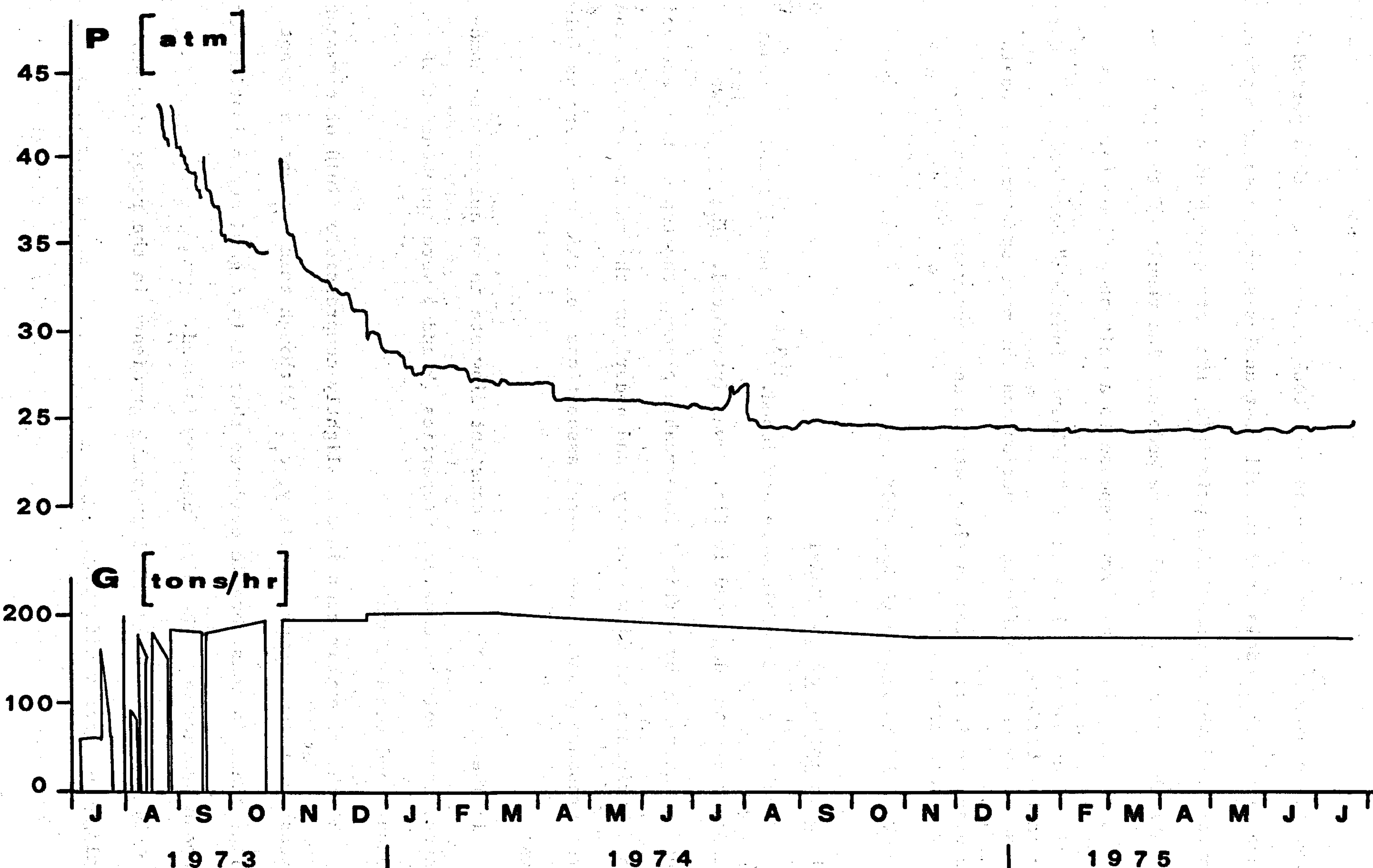


FIG. 1 - Wellhead pressure history

Flowrate changes and many shut-ins also took place during this period. Since almost all models used in well test analysis are based on constant flowrate and the superposition principle, the data have been processed to make them comparable with these models. The result of this processing is the pressure drawdown response to a unit step flowrate. This idealized drawdown will be named "influence function" hereinafter.[6] Comparison between the influence function and the most appropriate models can disclose information on flow pattern and reservoir parameters.

## 3. PARALLELEPIPED INTERPRETATION

### 3.1 Description of the Model

Parallelepiped models were developed.[2,3,4] A parallelepiped reservoir such as that depicted in Fig. 2 was introduced. The system was bounded laterally by vertical impermeable planes, the top of the reservoir was a horizontal no-flow boundary, and underlying the reservoir was a constant pressure plane. The general assumptions for this model are as follows:

1) The well produced at a constant flowrate in an anisotropic homogeneous reservoir of constant properties (k and $\phi$ were independent of pressure and temperature).

2) The reservoir contained a slightly compressible fluid of constant viscosity, $\mu$, and compressibility, $c_t$. Although this assumption is not valid, there is considerable evidence that it is a good approximation for gaseous systems when the m(p) function is used.

3) There were only small pressure gradients in the reservoir, and negligible gravity effects.

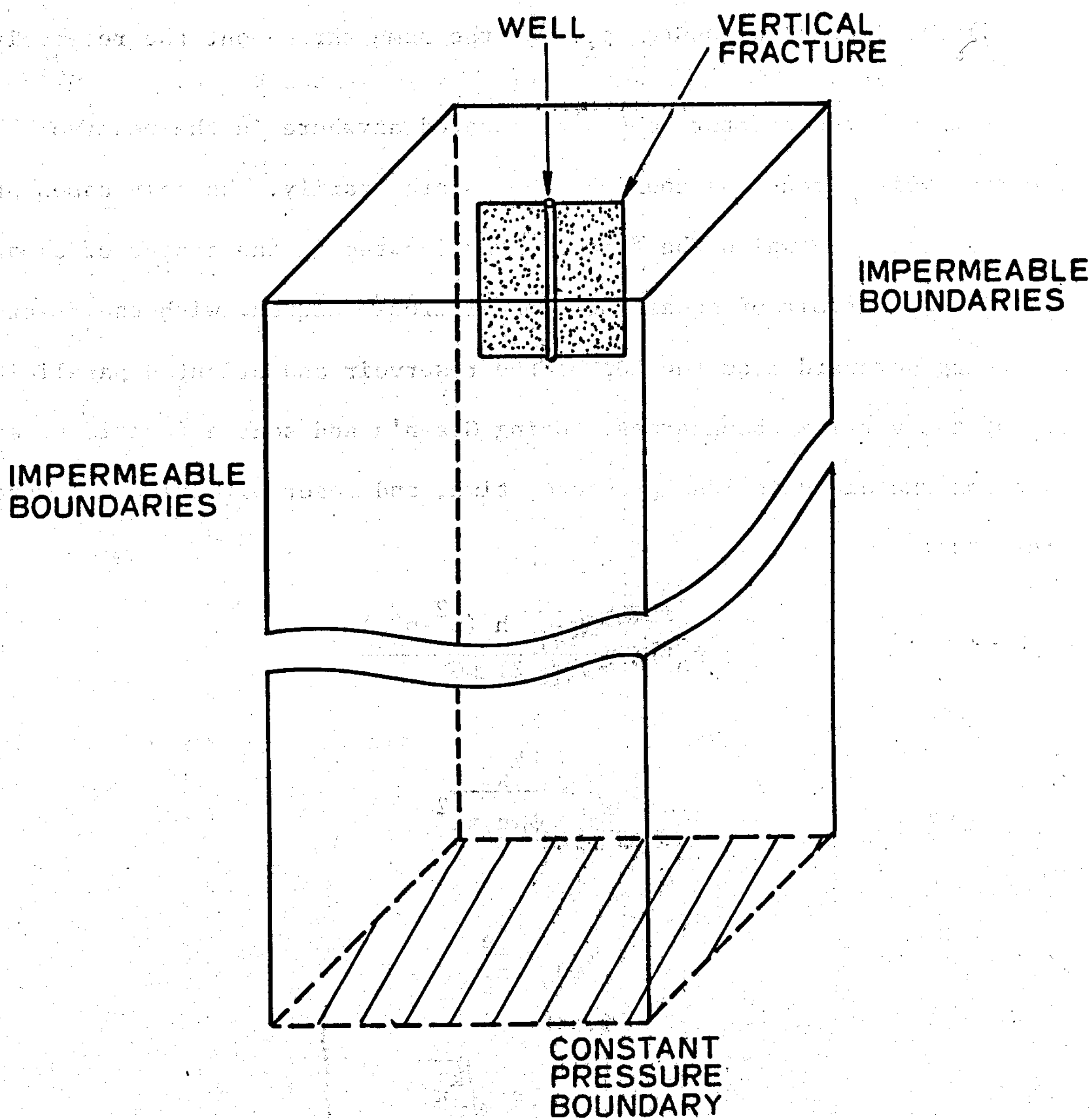


FIG. 2 - Parallelepiped model for a well intersected by a partially penetrating vertical fracture

4) Well fluid production was via a vertical fracture which partially penetrated the reservoir. The top of the fracture could be located at any elevation, and the fracture could extend to any depth.

5) The initial pressure, $p_i$, was the same throughout the reservoir.

Although the fracture could be located anywhere in the reservoir and the reservoir dimensions could be chosen arbitrarily, the only cases studied were those in which the fracture was located in the center of a parallelepiped reservoir of square horizontal cross-section, with the fracture extending downward from the top of the reservoir and oriented parallel to two of the vertical boundaries. Using Green's and source functions, equations of the dimensionless pressure, time, and reservoir thickness were presented:

$$p_D = \frac{\pi M \sqrt{k_x k_y}\, h\, (p_i^2 - p_{wf}^2)}{R\, ZT\, \mu G} \qquad (1)$$

$$t_{Dx_f} = \frac{k_x t}{\phi \mu c_t x_f^2} \qquad (2)$$

$$\left.\begin{aligned} x_{eD} &= \frac{x_e}{x_f} \\ y_{eD} &= \frac{y_e}{x_f}\sqrt{\frac{k_x}{k_y}} \\ h_D &= \frac{h}{x_f}\sqrt{\frac{k_x}{k_z}} \end{aligned}\right\} \qquad (3)$$

A computer program was written to calculate the pressure drop at any point in the system at any dimensionless time, $t_{Dx_f}$. Several runs were made by considering different values of dimensionless formation thickness, $h_D$, fracture penetration ratio, $x_e/x_f$, and dimensionless fracture height, $h_f/x_f$. The dimensionless formation thickness varied from 2 to 20, the fracture penetration from 2 to 10, and the dimensionless fracture height was assumed to be unity.

All cases exhibited a unique one-half slope straight line for small values of time. This behavior was caused by the linear flow behavior in the vicinity of the fracture. At large values of time, the wellbore pressure drop stabilized, indicating steady-state flow in the system. Figures 2 and 3 show that over a large region of the graph, the curves for pressure response at a fractured well in a parallelepiped reservoir were similar in slope to the infinite conductivity vertical fracture solution for an infinite reservoir.

### 3.2 Data Manipulation and Type-Curve Matching

The first major task was to manipulate the physical data. First, since there were no accurate pressure data during the initial 47 days, a widely practiced method of averaging was used. All cumulative production prior to the 47th day was added and then divided by the last flowrate (150 tons/hour). Thus a "pseudo" time of roughly 16 days was obtained. This has theoretical basis in superposition in time, as can be found in Horner and other sources. Therefore, "day zero" in the long drawdown data is day 16. The second "data manipulation" concerned the three shutdowns that appear on the data. Since no pressure data were collected during the shutdown, they were "hand smoothed." A simple influence function,

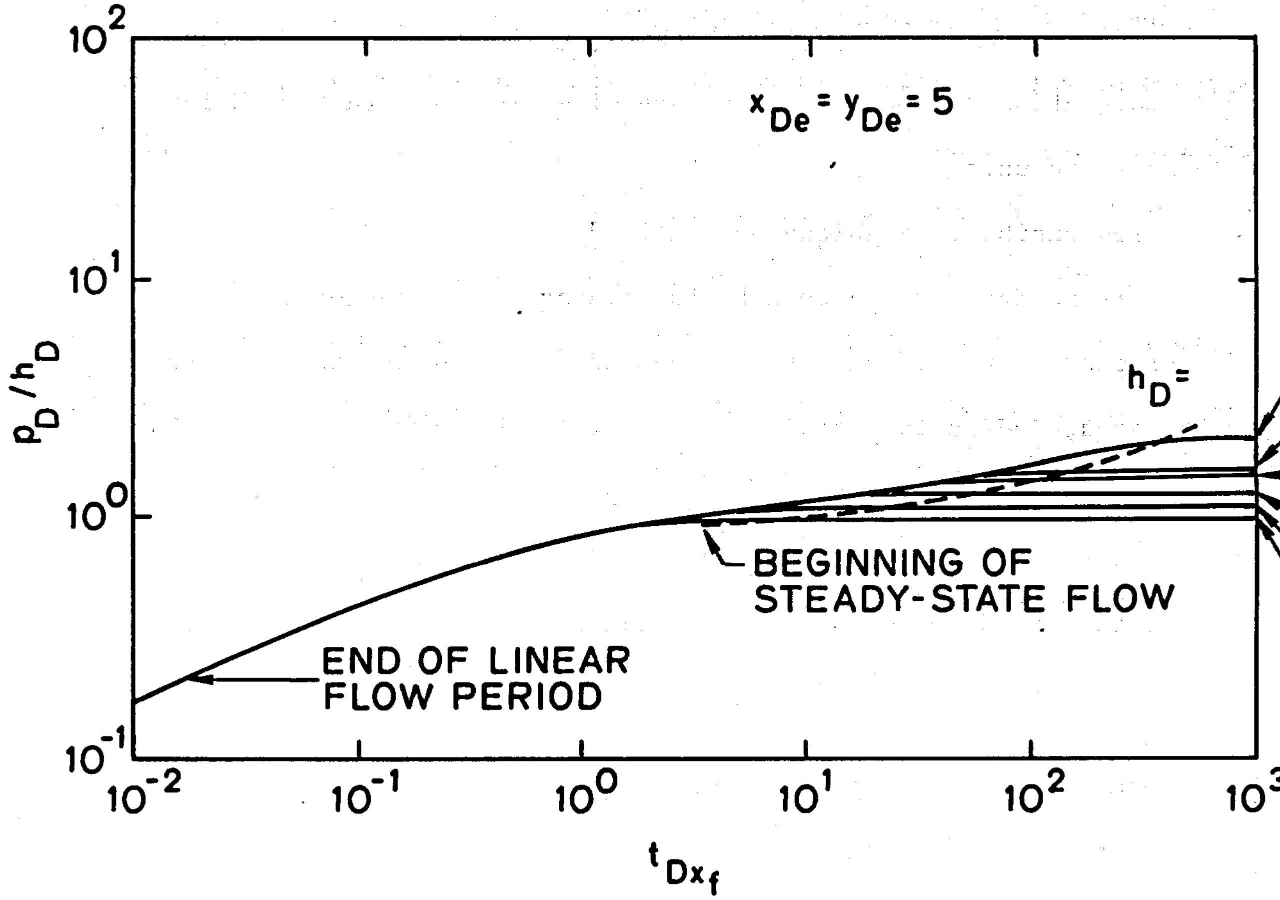


FIG. 3 - Log $p_D/h_D$ vs log $t_{Dx_f}$ for a fractured well in a parallelepiped reservoir ($x_e/x_f$=5).

$\Delta p^2/q$, was used. The graph appears on Fig. 4. A Cartesian graph was used to show the influence function (bottomhole pressures were used throughout the calculations).

The next task was to graph the influence function on log-log paper, matched on a type-curve prepared for a "parallelepiped reservoir" penetrated by a vertical fracture (Fig. 5). Several interim calculations were done in order to facilitate the type-curve matching. If the parallelepiped assumptions are to be accepted, then the flattening of the pressure curve that appears on Fig. 5 should be interpreted as the result of boiling subformation water. This breakpoint appears to be about day 475. The type-curve matching resulted in the following set of points:

$$x_{eD} = x_e/x_f = 5$$

$$\Delta p^2/q = 10$$

$$p_D/h_D = 0.94$$

$$t = 100 \text{ days}$$

$$t_{Dx_f} = 8$$

$$h_D = 9$$

$$y_{eD} = 5$$

From $x_{eD} = 5$, $y_{eD} = 5$, and their definition, we obtain:

$$k_x = k_y$$

Since the reservoir lateral extent is known (1 km in each direction), then:

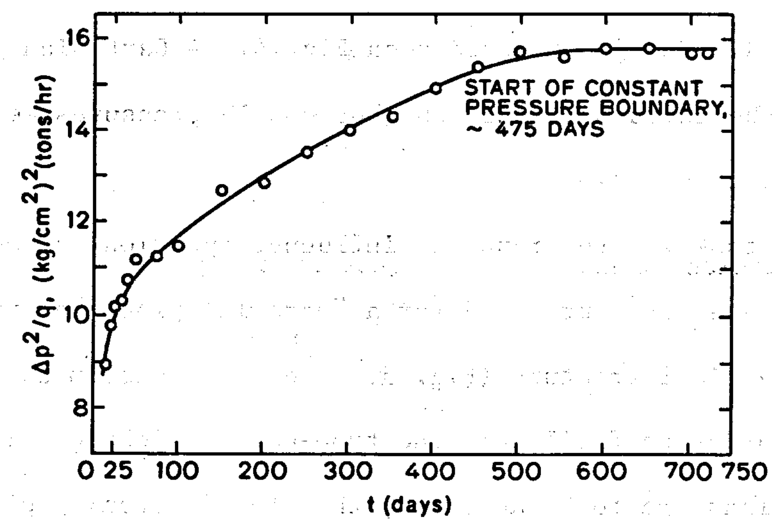


FIG. 4 - Cartesian graph of drawdown of T-22.

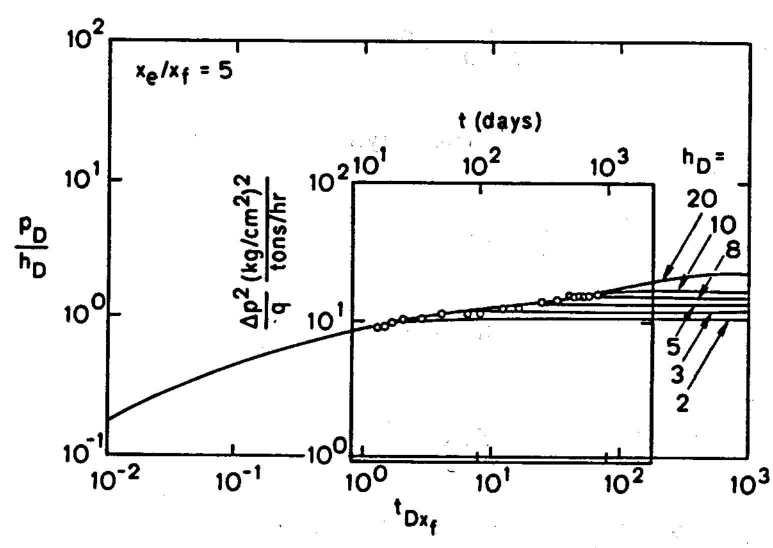


FIG. 5 - Type-curve matching of T-22 drawdown data. Type-curve for a parallelepiped reservoir with a vertical fracture.

$$x_e = 500 \text{ m}$$

$$x_f = 100 \text{ m}$$

From the definition of the dimensionless pressure:

$$\frac{p_D}{h_D} = \frac{\pi M \sqrt{k_z k_y}\ x_f}{RzT\mu} \ \frac{(p_i^2 - p_{wf}^2)}{G}$$

and substituting the known variables:

$$(k_z k_y)^{1/2} = 3.34 \times 10^{-2} \text{ darcy} \tag{4}$$

From the definition of dimensionless time:

$$t_{Dx_f} = \frac{k_x t}{\phi \mu c_t x_f^2}$$

and substituting the known variables:

$$\frac{k_y}{\phi} = \frac{k_x}{\phi} = 7 \times 10^{-2} \text{ darcy} \tag{5}$$

Combining Eqs. 4 and 5 and remembering that $k_x = k_y$, we obtain two equations:

$$\frac{k_x^2 k_z}{\phi} = 7.8 \times 10^{-5} \text{ darcy}^3 \tag{6-a}$$

$$\sqrt{\frac{k_z}{k_x}} \cdot \phi = 0.47 \tag{6-b}$$

Combining Eqs. 5 and 6-b, then:

$$\phi k_z = 1.5\text{x}10^{-2} \text{ darcy}$$

Introducing the definitions of $h_D$ in Eq. 6-b:

$$\frac{h}{h_D} \phi = 47.7 \text{ m}$$

and hence:

$$h\phi = 430 \text{ m}$$

The pore volume is then:

$$V\phi = 4\, y_e x_e\, h\phi \simeq 4\text{x}10^8 \text{ m}^3$$

Another interpretation using the same match can be made by following Grant's approach[8] which considers the thermodynamics related to phase changes. He shows that for small pressure changes, the diffusion equation is still valid in the two-phase zone if $\phi c_t$ is replaced by an "effective compressibility," the value of which is on the order of 0.06 $\text{atm}^{-1}$ in this case.

Calculations have been repeated starting from Eq. 4 downwards. The main results are:

$$k_x = k_y \simeq 10^{-1} \text{ darcy}$$

$$k_z \simeq 10^{-2} \text{ darcy}$$

$$h \simeq 0.3 \text{ km}$$

$$V = 0.3 \text{ km}^3$$

## 4. AN ALTERNATE APPROACH

### 4.1 Bottomhole Pressure Calculations

Bottomhole pressure history was calculated by Rumi's method.[7] Adiabatic flow of pure steam was considered.

### 4.2 Influence Function: Calculations and Results

Using the calculated bottomhole pressure history, the drawdown due to a unit step flowrate (influence function) was calculated according to ref. 5, assuming only that the superposition in time is valid.

The influence function was calculated in terms of $(p_i^2 - p_{wf}^2)/G$. Squared p's were used because steam is considered to be a perfect gas (Figs. 6 and 7). The drawdown pressure history match based on $\Delta p^2$ is shown on Fig. 8. The calculated influence function is graphed on log-log paper on Fig. 6. A certain scatter is evident, probably due to uncertainties in the data (especially in the first period). Nonlinear phenomena in the reservoir may also invalidate the superposition principle.

Type-curve matching has been attempted with models considering fractured reservoirs. Satisfactory matches were obtained, but reservoir parameters such as fracture height, fracture length, and reservoir volume are in contrast with the size of the known reservoir, probably because the models do not consider phase changes.

Since the interference test conducted in April 1977 revealed the presence of linear flow in the reservoir, the influence function was graphed vs the square root of time (Fig. 7) to identify a possible linear flow regime. The main portion of the data (from 45 days to 2.5 years) seems to lie on a straight line, suggesting linear flow.

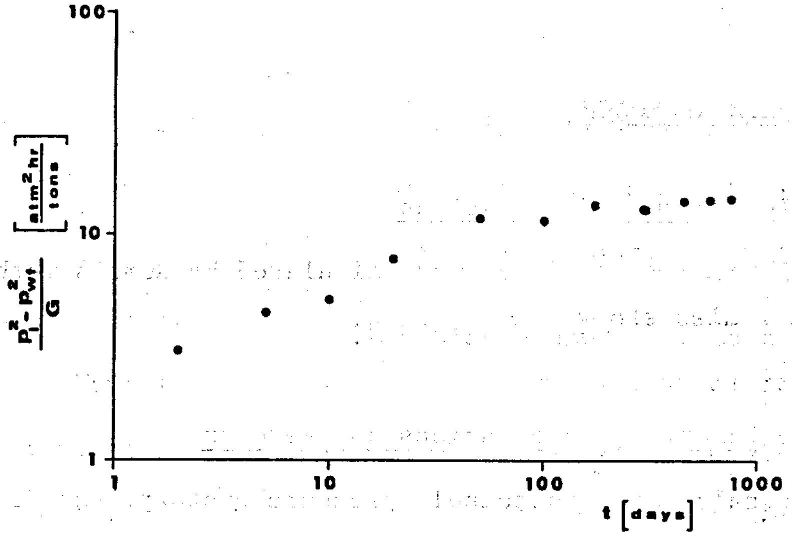


FIG. 6 - T-22 influence function.

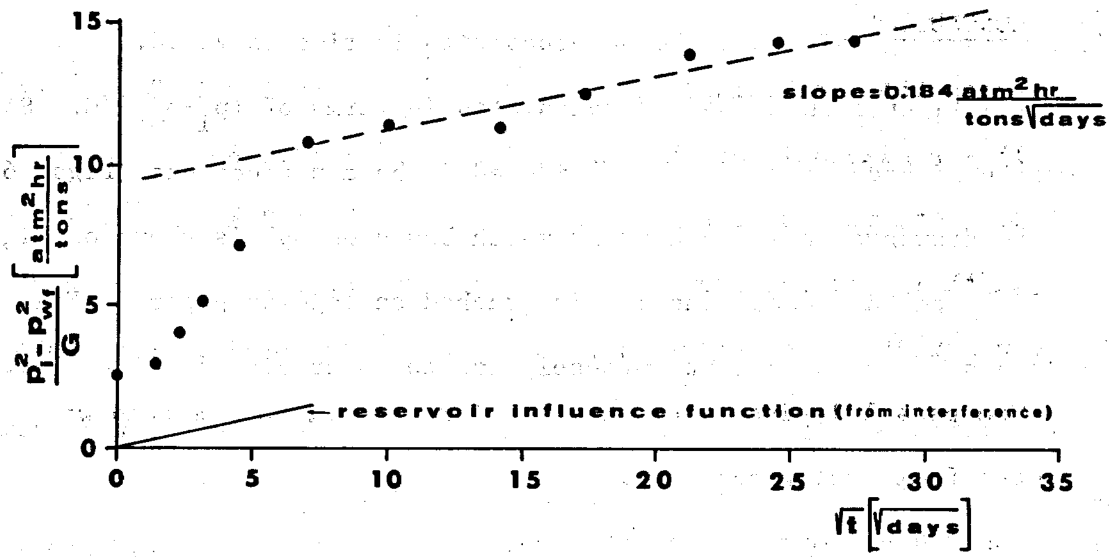


FIG. 7 - Drawdown T-22--influence function.

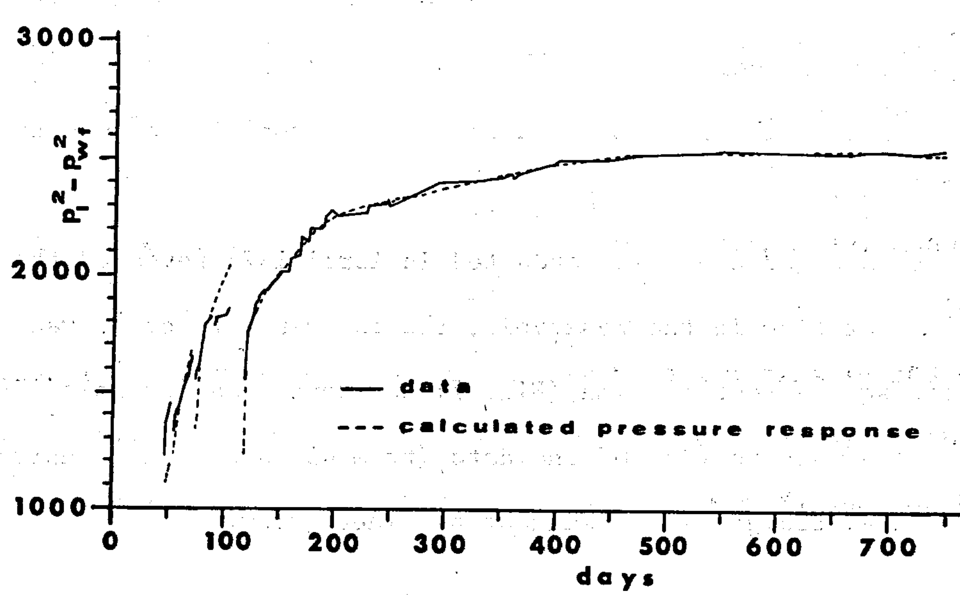


FIG. 8 - Drawdown pressure history match.

The slope of this straight line is $(0.184\ atm^2) / (t/h/\sqrt{day})$. We do not know why this line does not intersect the origin, since in linear flow, pressure drops are proportional to the square root of time.

Figure 7 also shows the result of the interference test. The two slopes appear to be the same despite the fact that different ranges of time were investigated. The earlier data are difficult to understand, but are unreliable since the flow pressure history of the first 45 days is unknown.

## 5. CONCLUSIONS

Using the parallelepiped model, two major benefits can be extracted:

1) - a diagnosis of the shape of the reservoir and

2) - the values of the directional permeabilities.

In this case unfortunately the data scatter prevents a unique match and consequently the reservoir parameters are not well determinable.

The parallelepiped model gives a larger pore volume than would be expected from geological knowledge; this observation leads to the hypothesis of phase changes with strong thermodynamic implications, as suggested by Grant.[8]

An alternate approach to the problem was also made and an "influence function" generated postulating only that the principle of superposition in time is valid. This influence function permits calculation of the pressure response for a given flow rate history independently of the type of model used.

Both the parallelepiped model and the alternate approach reveal the presence of a linear flow pattern as indicated by the interference test and buildups, but they differ from each other at later times.

## NOMENCLATURE

$c_t$ = isothermal compressibility

G = mass flowrate

h = pay thickness

$h_f$ = fracture height

k = permeability

m(p) = real gas potential

M = molecular weight

p = pressure

$p_i$ = initial pressure

$p_{wf}$ = flowing pressure

$p_{ws}$ = shut-in pressure

R = universal gas constant

T = absolute temperature

t = flowing time

$x_f$ = half-fracture length

$x_e$ = boundary location

$y_e$ = boundary location

V = reservoir bulk volume

z = gas deviation factor

$\mu$ = viscosity

$\phi$ = porosity

### Subscript

D = dimensionless

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