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# CHIMNEY PERMEABILITY DATA ANALYSIS

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### ABSTRACT

Analysis of atmospheric response data from three nuclear chimneys, DH3, DH5 and DH6, has been made using two different analytical solutions. A simple one-dimensional linearized model is used to predict the pressure response at depth in a chimney to surface pressure variations. Comparison of computed and measured downhole pressure histories shows a good fit over times of up to 25 days for all three chimneys. Assuming a nominal value of 1/3 for porosity, the permeability in darcies is computed to be 63 for DH3, 12 for DH5 and 57 for DH6.

### INTRODUCTION

Knowledge of the permeability of earth and stemming media to gases is important in the study of containment in nuclear device tests. Several field experiments have been conducted to determine permeabilities of undisturbed (in situ) earth material.[1-5] Laboratory tests to evaluate stemming permeabilities have also been conducted.[6,7]

Beginning in 1972, field measurements have been made of pressure response at depth in chimneys using the varying atmospheric pressures as a driving source.[8] The idea is to use a simple mathematical model and simulate the expected pressure response with different values of permissivity (permeability divided by porosity, $K/\varepsilon$) to find a reasonable fit with the measured response.[9-11] The permissivity values of various chimneys are needed in calculations of the gas flow from nearby detonations as well as in general problems of long-term seepage.

### DISCUSSION

#### Mathematical Model

The simplest mathematical model to describe the pressure response at depth in the chimney is that for linearized, one-dimensional, isothermal compressible gas flow in a uniform porous media.[12]

$$\frac{\partial P}{\partial t} = (\alpha)\,\frac{\partial^2 P}{\partial x^2}$$

where

P = pressure,

t = time,

x = distance,

$\alpha$ = pressure diffusivity.

The pressure diffusivity is the analog of thermal diffusivity in the transient heat conduction equation, and is related to the permeability and porosity of the porous media

$$\alpha = \frac{K\overline{P}}{\varepsilon\mu}$$

where

K = permeability,

$\varepsilon$ = porosity,

$\mu$ = viscosity of gas,

$\overline{P}$ = mean pressure of gas.

Some of the initial calculations[9,10] using the above model were done using TRUMP,[13] a heat-transfer code. The large number of data points coupled with the long-time requirements restricted the number of computer runs made, but a permissivity ($K/\varepsilon$) value for the first chimney data analysis was bracketed within a factor of 4.

We attempted to collect and analyze later chimney data using correlation methods assuming periodic behavior of surface pressure patterns.[11] This method was faster than the finite difference TRUMP calculation. Although the permissivity values calculated by the amplitude dampening and time lag methods did not always agree, the value was bracketed within a factor of 2.

## Semi-Infinite Chimney Solution

Our latest analysis technique involves a closed-form solution to the linearized equation applied in finite steps approximating the surface forcing function[14] using the principle of superposition.

For the case of a semi-infinite chimney, the solution for a step change at the surface is*

$$\frac{P - P_0}{\Delta P} = \text{ERFC}\left[\left(\frac{x^2}{4\alpha t}\right)^{1/2}\right]$$

where

$P_0$ = initial pressure,

$\Delta P$ = step change in pressure,

ERFC = complimentary error function.

The surface-forcing function may be approximated by a series of step changes at equal time increments,

*See p. 63, Ref. 14.

$$P_{SF}(t) = P_{SF0} + \sum_{\tau=1}^{M} (\Delta P_{SF})_\tau$$

where

$P_{SF}$ = surface pressure,

$P_{SF0}$ = initial surface pressure,

$\Delta t$ = time increment between data points,

$t = M\Delta t$,

$M$ = number of data points at time t.

The complete solution is given by

$$P(t) - P_0 = \sum_{\tau=1}^{M} (\Delta P_{SF})_\tau \ \mathrm{ERFC}\left\{\left[\frac{x^2}{4\alpha(M + 1 - \tau)\Delta t}\right]^{1/2}\right\}.$$

## Composite Finite Chimney, Semi-Infinite Earth

Following the above reasoning, the solution is given by*

$$P(t) - P_0 = \sum_{\tau=1}^{M} (\Delta P_{SF})_\tau \left\{\sum_{n=0}^{\infty} \beta^n \left[\mathrm{ERFC}\left[\frac{(2n + XL)^2L^2}{4\alpha(M + 1 - \tau)\Delta t}\right]^{1/2} - \beta\left(\mathrm{ERFC}\left[\frac{(2n + 2 - XL)^2L^2}{4\alpha(M + 1 - \tau)\Delta t}\right]^{1/2}\right)\right]\right\}$$

where

$L$ = length of finite chimney,

$XL$ = fraction of depth in chimney, X/L,

$\beta = \frac{\sigma - 1}{\sigma + 1}$,

$\sigma = \sqrt{\frac{(\varepsilon K)\text{earth}}{(\varepsilon K)\text{chimney}}}$.

For no flow at the chimney-earth interface, $\sigma = 0$, $\beta = -1$. For earth and chimney with equal ($\varepsilon K$) values, $\sigma = 1$ and $\beta = 0$. This reduces to the semi-infinite case given above ($\beta^n = 1$ for $\beta$, $n = 0$).

## Computer Solution

A computer program, ERFC (6600 or 7600) was written to compute the downhole response given the surface pressure history using either of the above two solutions. The complimentary error function values are generated using a special subroutine written for use by high-speed digital computers.[15]

*See p. 319, Ref. 14.

The composite solution above is more complicated than the semi-infinite geometry solution, but the infinite series has required no more than 20 to 30 terms to converge to ($\leq 10^{-10}$) change for most of our runs, and the time requirements are thus not significantly longer.

The predicted and measured downhole pressure histories are plotted with the average values of the last 24-hr period matched. This is done for several reasons. Some of the measured data show a small cyclic (24-hr) nature due probably to temperature sensitivity of the barometric instruments. Averaging over 24 hr eliminates this bias. Matching the two pressure histories at some point in the data segment eliminates difficulties in accounting for shifts due to temperature difference in different parts of the sensing hose which extends from the surface to depth in the chimney. The end of the data segment is chosen since the initial part of the computed values is influenced greatly by the initial conditions in the chimney. The effect of different initial condiions is to shift the early time history in relation to this later time value, and is dependent on the value of $(\alpha/X^2)$. In the worst case, the effect is about 2 or 3 days' out of a total of 13 to 15 days' sampling.

## RESULTS

We have applied the solution to data from three chimneys, DH3,[8] DH5,[11] and DH6.[16] The depths of the chimneys and downhole measurements are given in Fig. 1 for idealized chimney conditions. The recorded surface and downhole pressure histories are given in Figs. 2-4. We have not bothered to transcribe the raw voltage data to psia since the relative comparison between computed and measured pressures is the same in either case. Ten volts corresponds to a pressure differential of 30 mm Hg (0.58 psia). The absolute pressure is 12.2 psia plus the differential. The time interval between data points is 3 hr for DH3 and 1.5 hr for DH5 and DH6.

In Figs. 5-12 we show comparisons of computed and measured downhole pressures for the three chimneys. The difference between the semi-infinite and composite no-flow solution cases is not really significant except for perhaps DH6 (Figs. 9-12) and even here gives a value of $(L^2/4\alpha\Delta t)$ within a factor of 2. In Figs. 5-8 we show the best fit obtained for different $(L^2/4\alpha\Delta t)$ values. The sensitivity of the fit to different values of $(L^2/4\alpha\Delta t)$ is shown in Figs. 9-12 where the $(L^2/4\alpha\Delta t)$ is varied over a range of about two.

The effect of the unknown initial condition is insignificant after about 9 hr for DH3, 88 hr for DH5, and 44 hr for DH6 [solving for t such that $(X^2/\alpha t) \sim 1$].

For test purposes, the DH3 and DH5 data were also run using a modified TRUMP[13] program. The runs agreed closely with the composite no-flow solutions as expected. With 100 nodes, the runs took about 5-6 min on the 7600 for one value of $(L^2/4\alpha\Delta t)$. The runs using ERFC took less than 1 min for five values of $(L^2/4\Delta t)$. For our purposes where only one position is needed, the use of a finite difference code such or TRUMP is not time-efficient (the TRUMP run has pressure values for 100 positions available during its

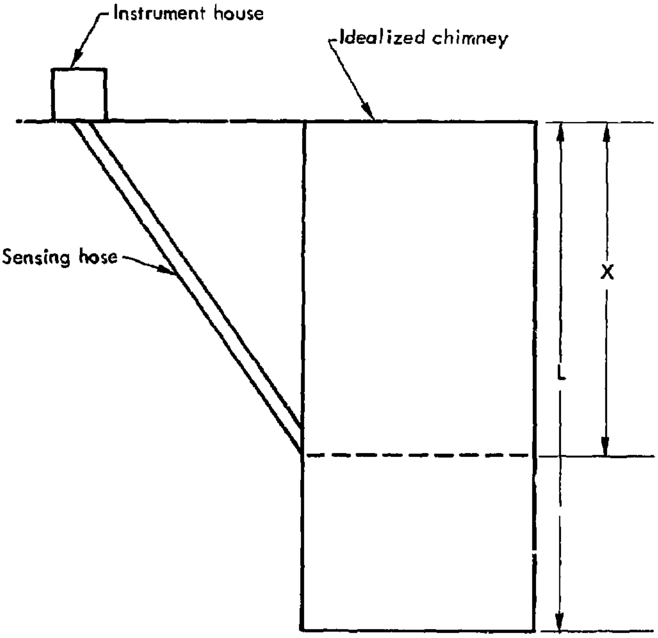


Fig. 1. Schematic of idealized chimney conditions.

| | DH3 | DH5 | DH6 |
|---|---|---|---|
| L (meters) | 265 | 400 | 500 |
| X (meters) | 165 | 216 | 340 |

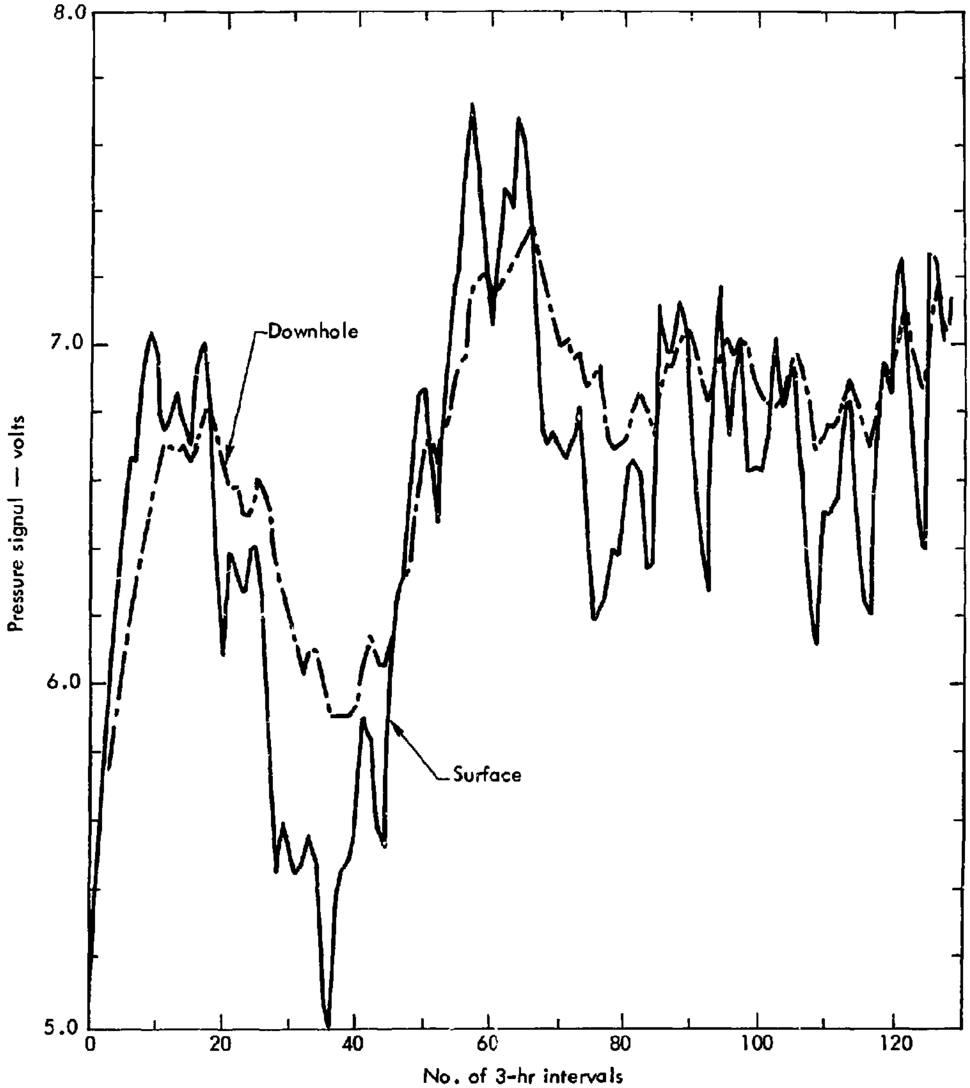


Fig. 2. Surface and downhole pressure versus time for DH3.

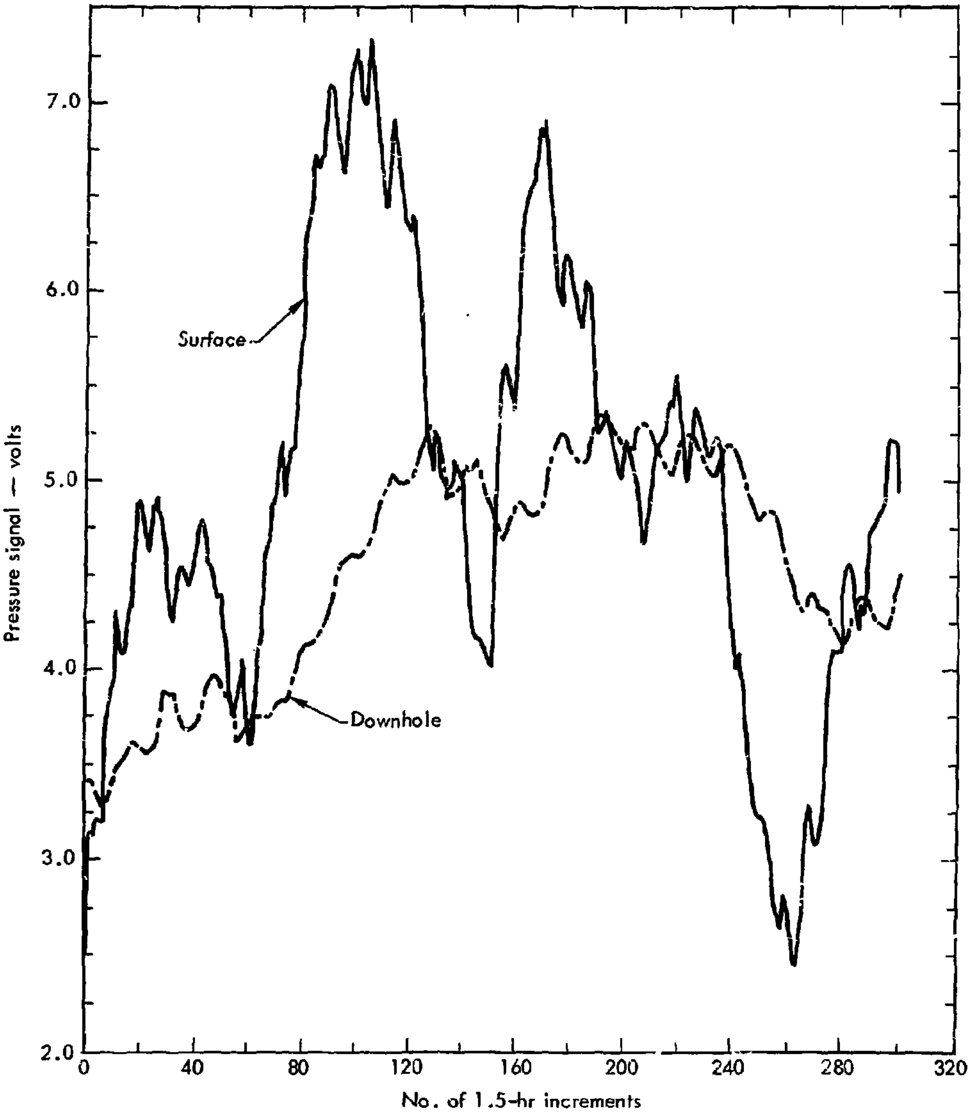


Fig. 3. Surface and downhole pressure versus time for DH5.

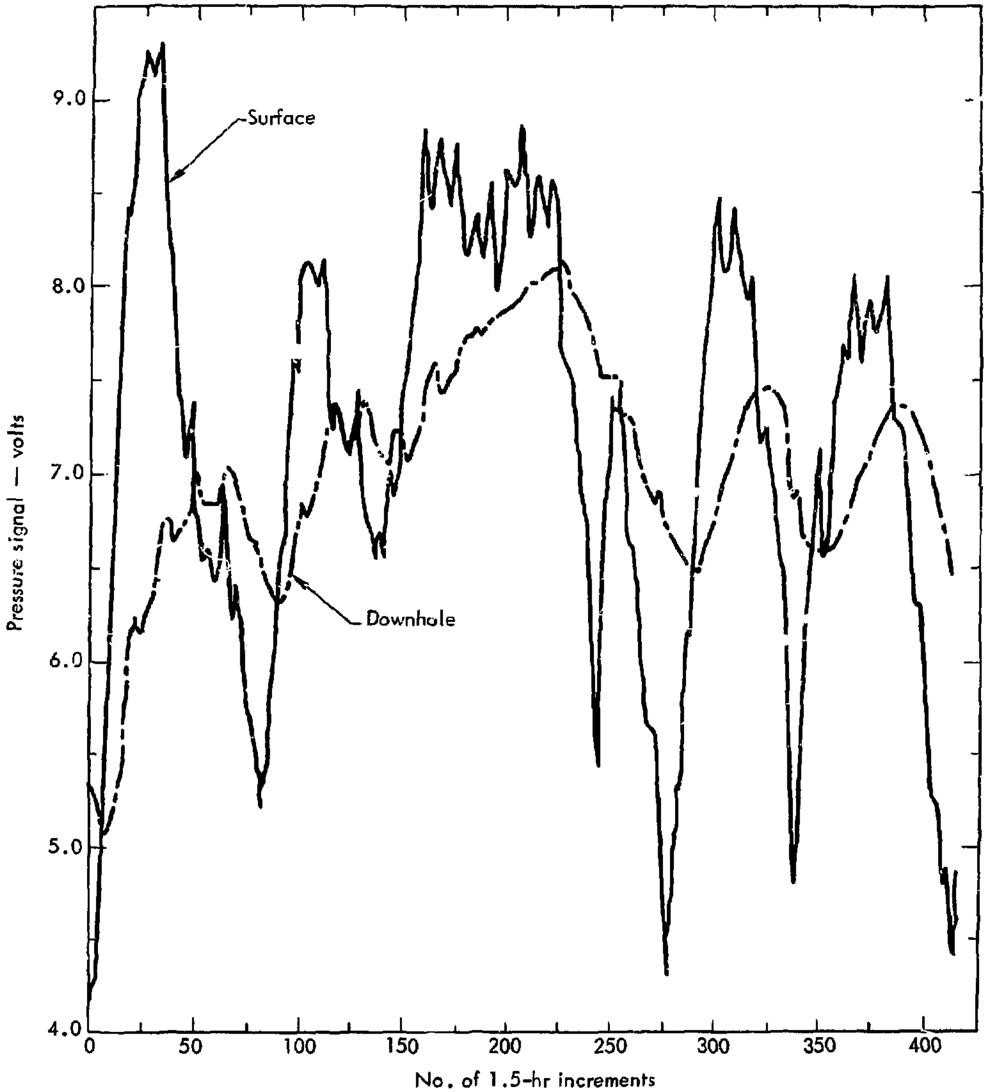


Fig. 4. Surface and downhole pressure versus time for DH6.

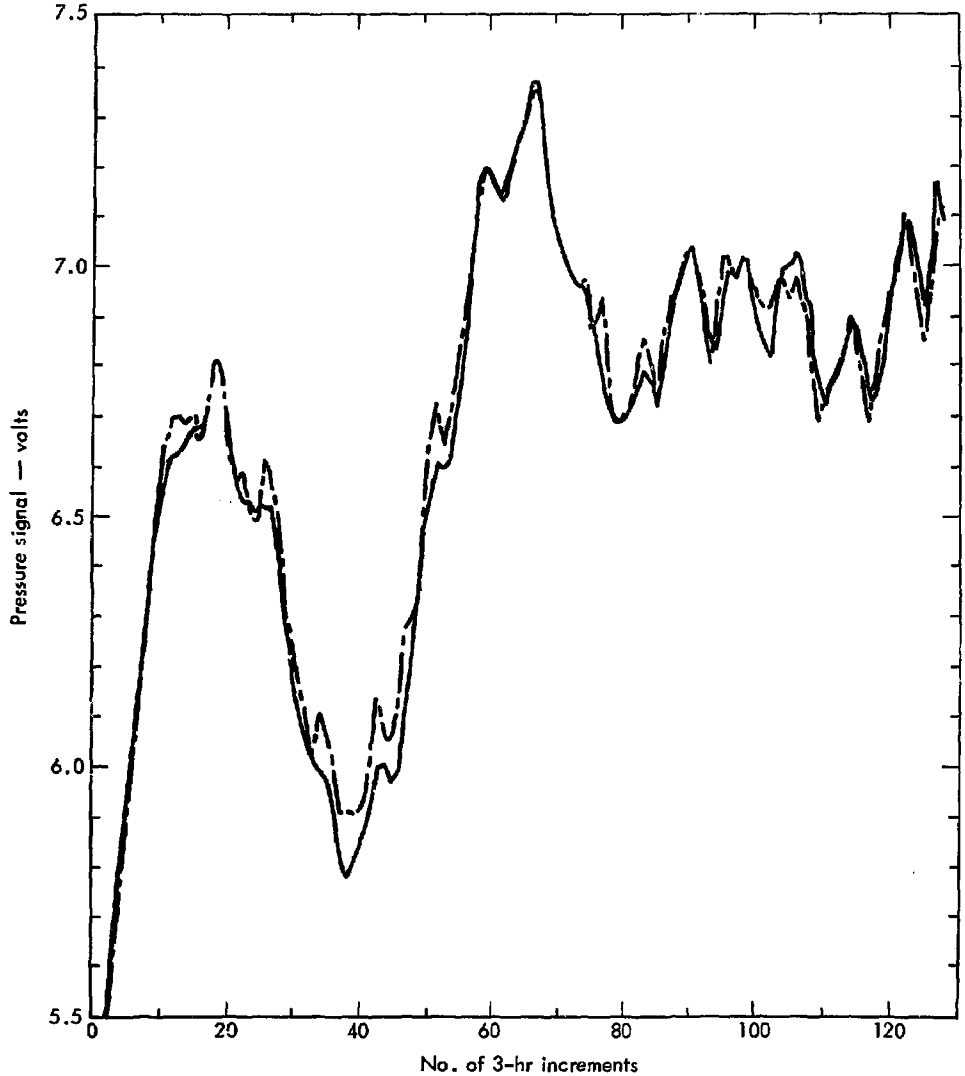


Fig. 5. Comparison of computed and measured downhole pressures for semi-infinite solution, $(L^2/4\alpha\Delta t) = 2$, for DH3.

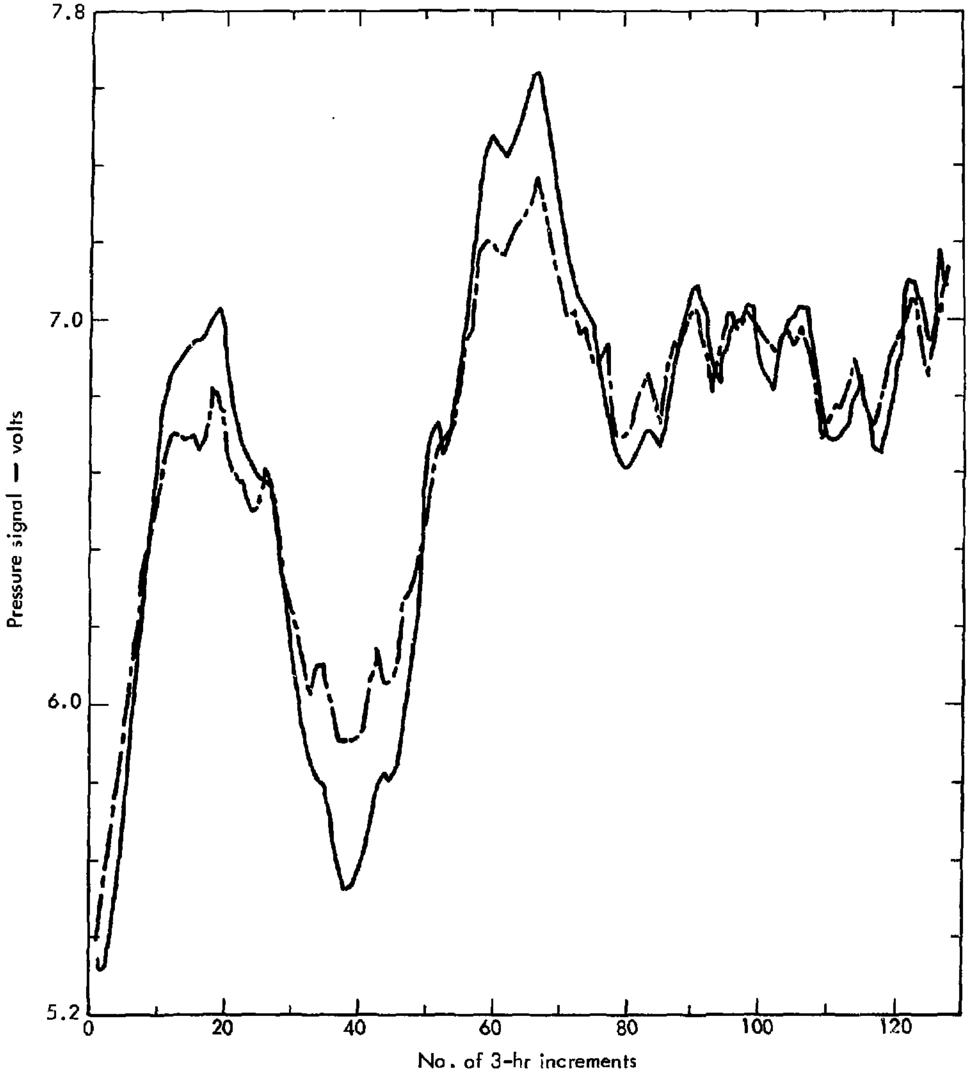


Fig. 6. Comparison of computed and measured downhole pressures for composite, no-flow solution, $(L^2/4\alpha\Delta t) = 2$, for DH3.

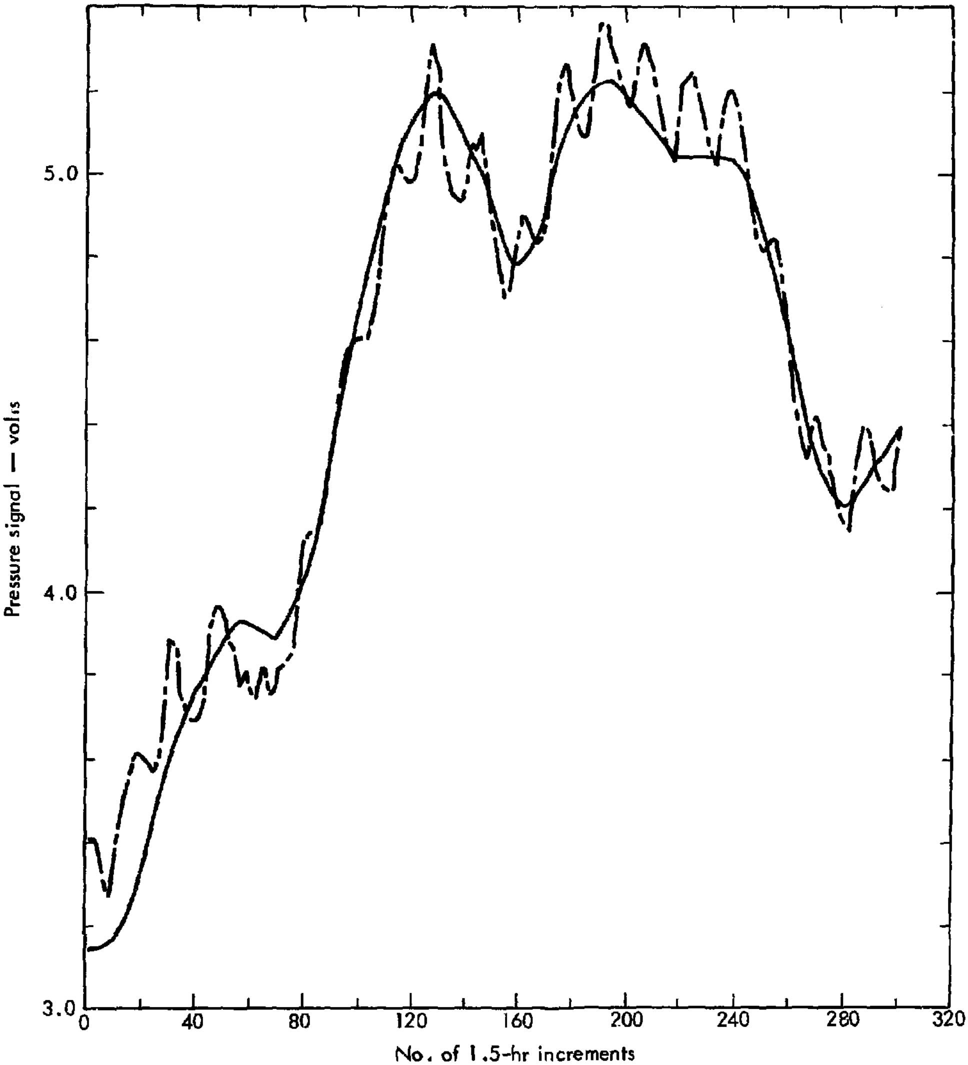


Fig. 7. Comparison of computer and measured downhole pressures for semi-infinite solution, $(L^2/4\alpha\Delta t) = 50$, for DHS.

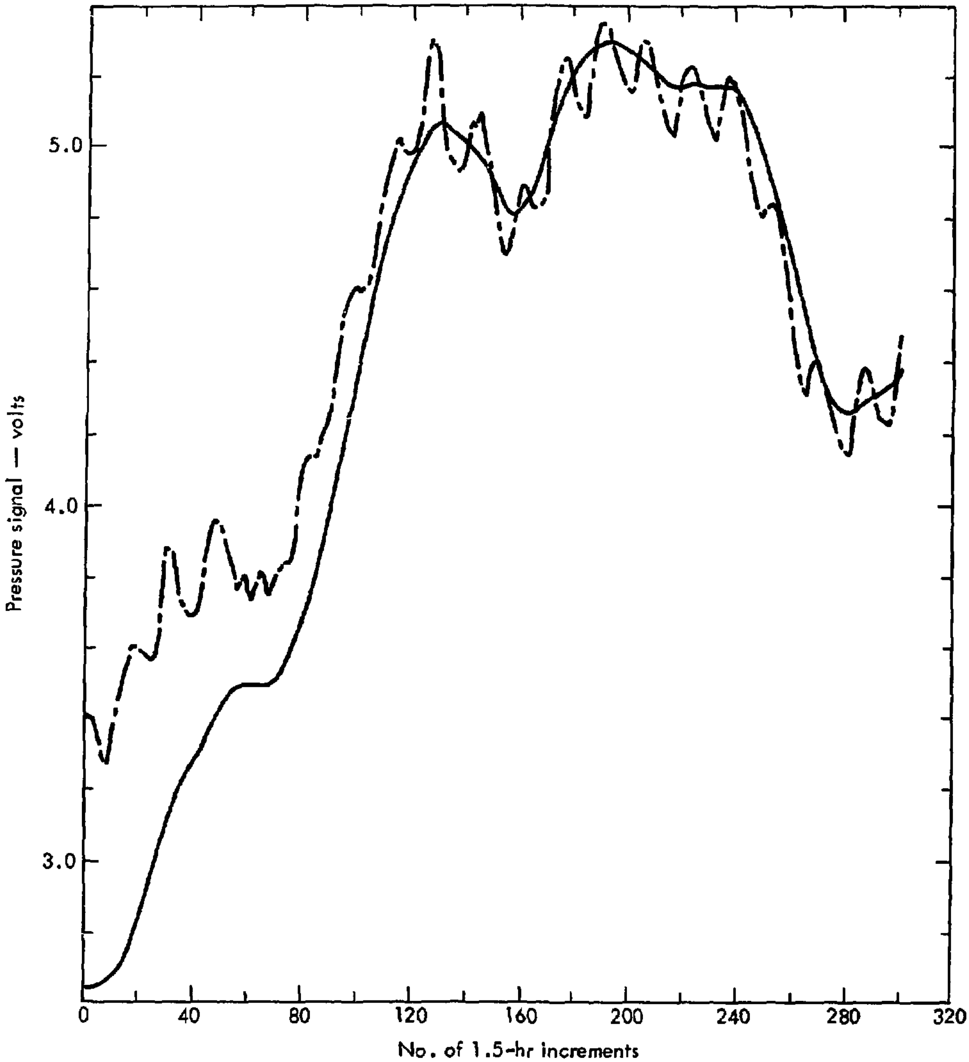


Fig. 8. Comparison of computed and measured downhole pressures for composite, no-flow solution, $(L^2/4\alpha\Delta t) = 50$, for DH5.

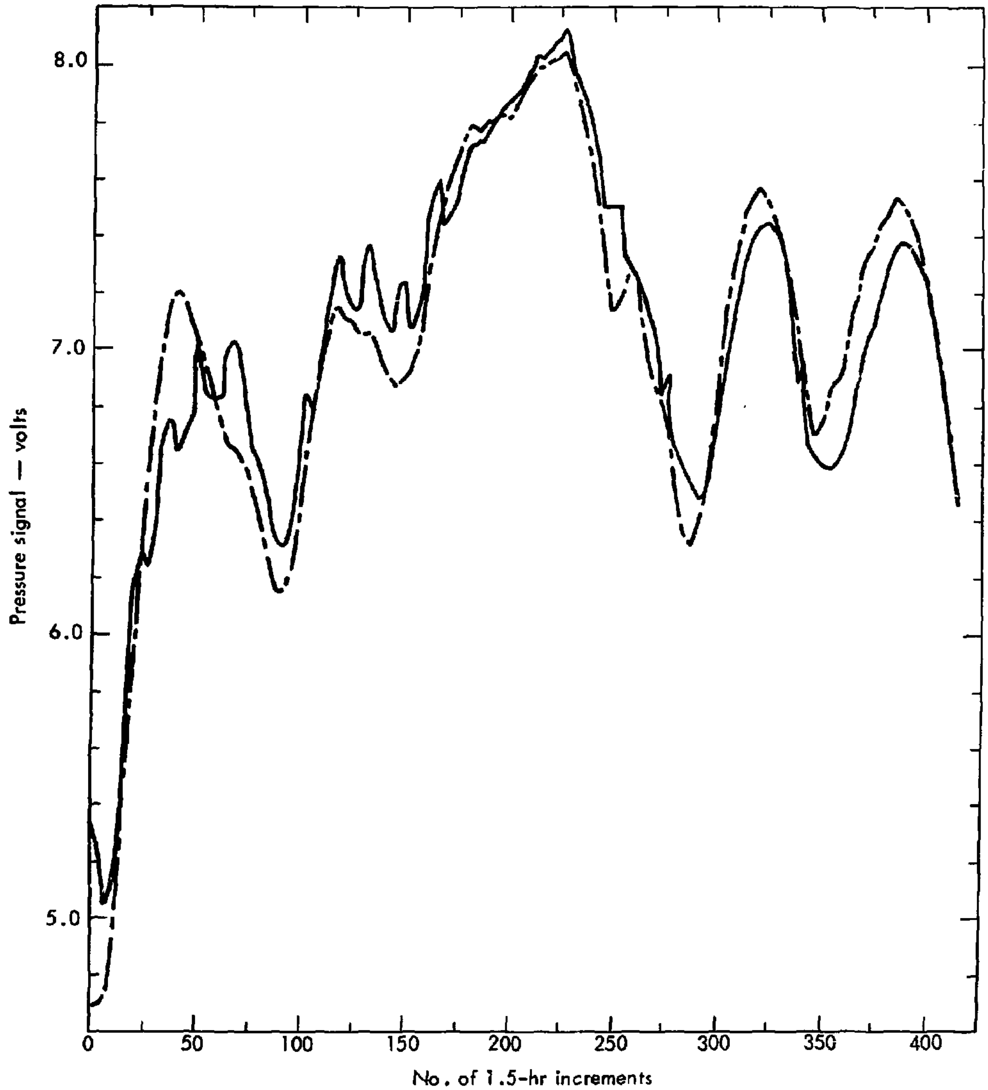


Fig. 9. Comparison of computed and measured downhole pressures for semi-infinite solution, $(L^2/4\alpha\Delta t) = 12$, for DH6.

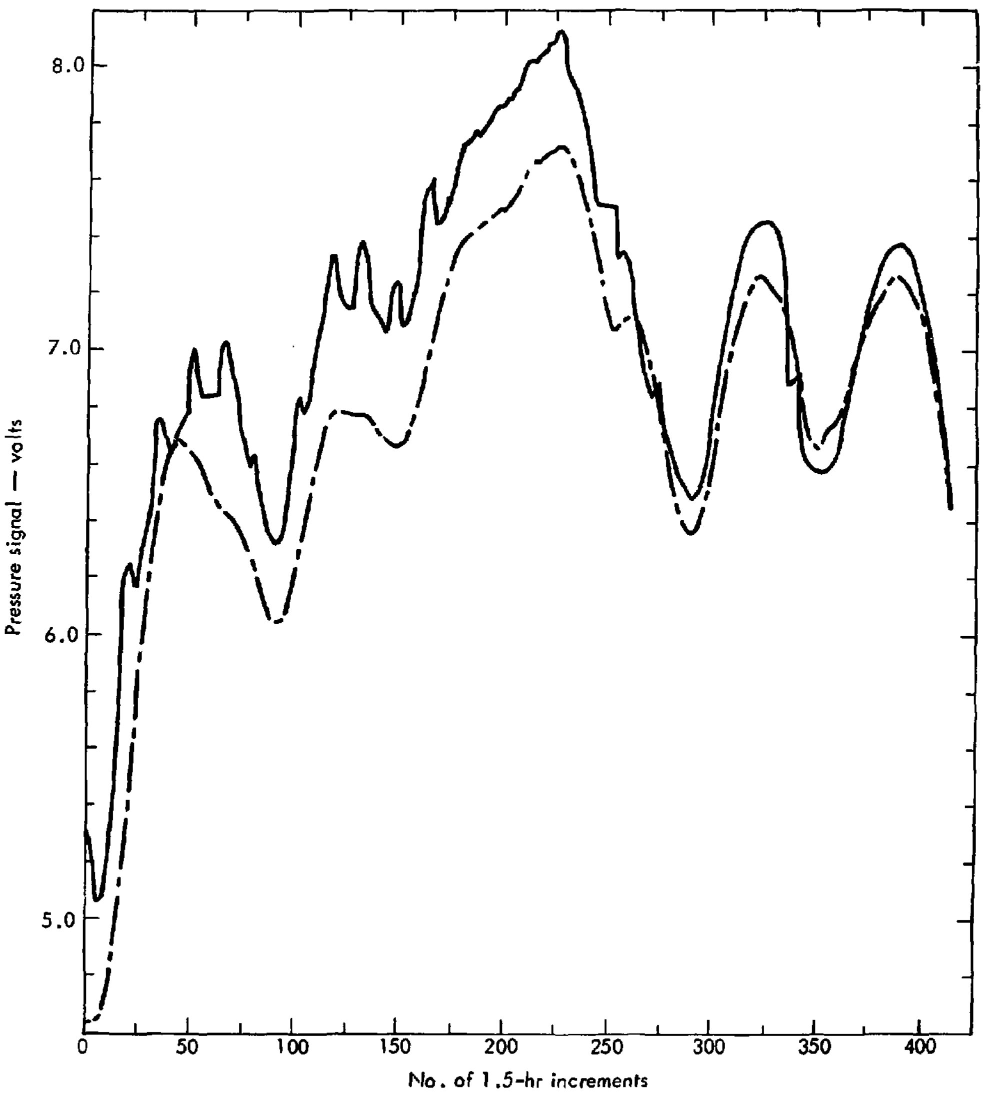


Fig. 10. Comparison of computed and measured downhole pressures for the semi-infinite solu-ion, $(L^2/4\alpha\Delta t) = 20$, for DH6.

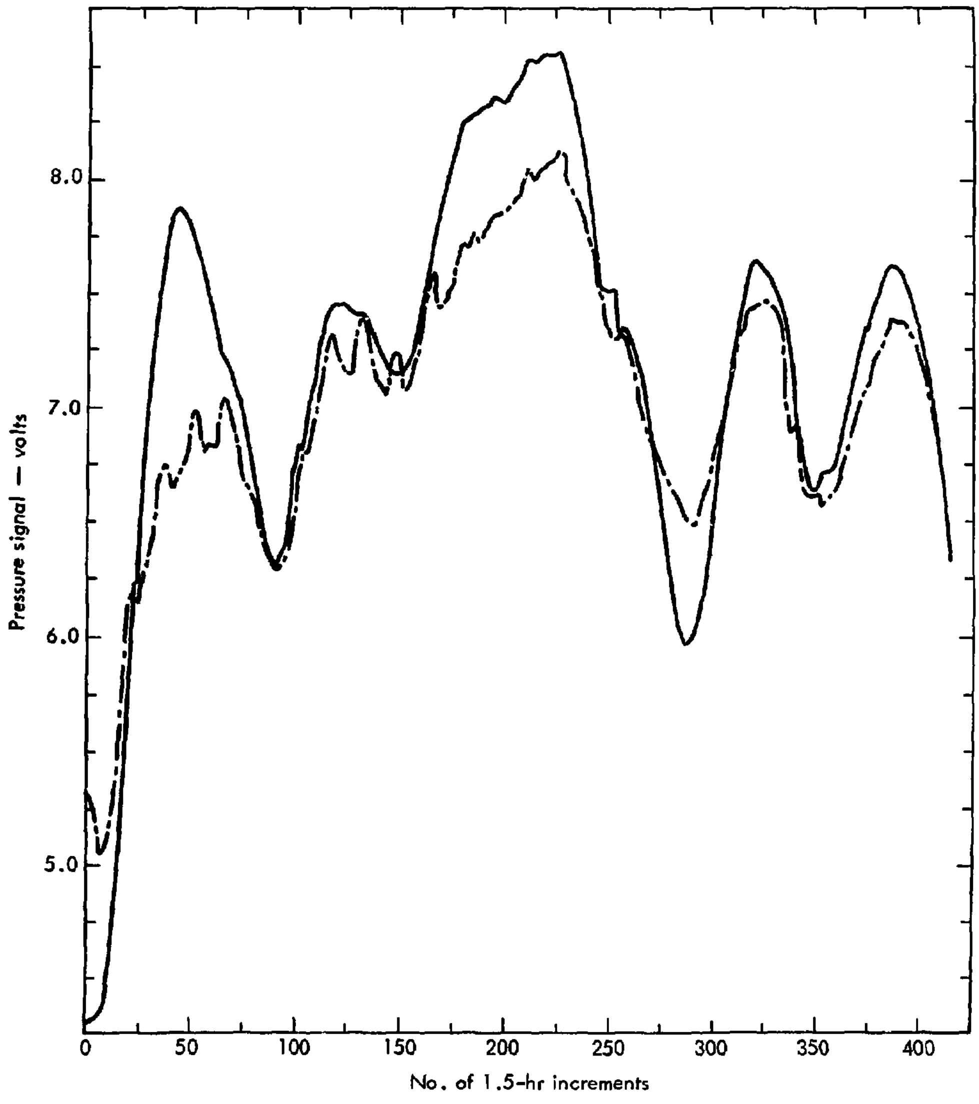


Fig. 11. Comparison of computed and measured downhole pressures for the composite, no-flow solution, $(L^2/4\alpha\Delta t) = 12$, for DH6.

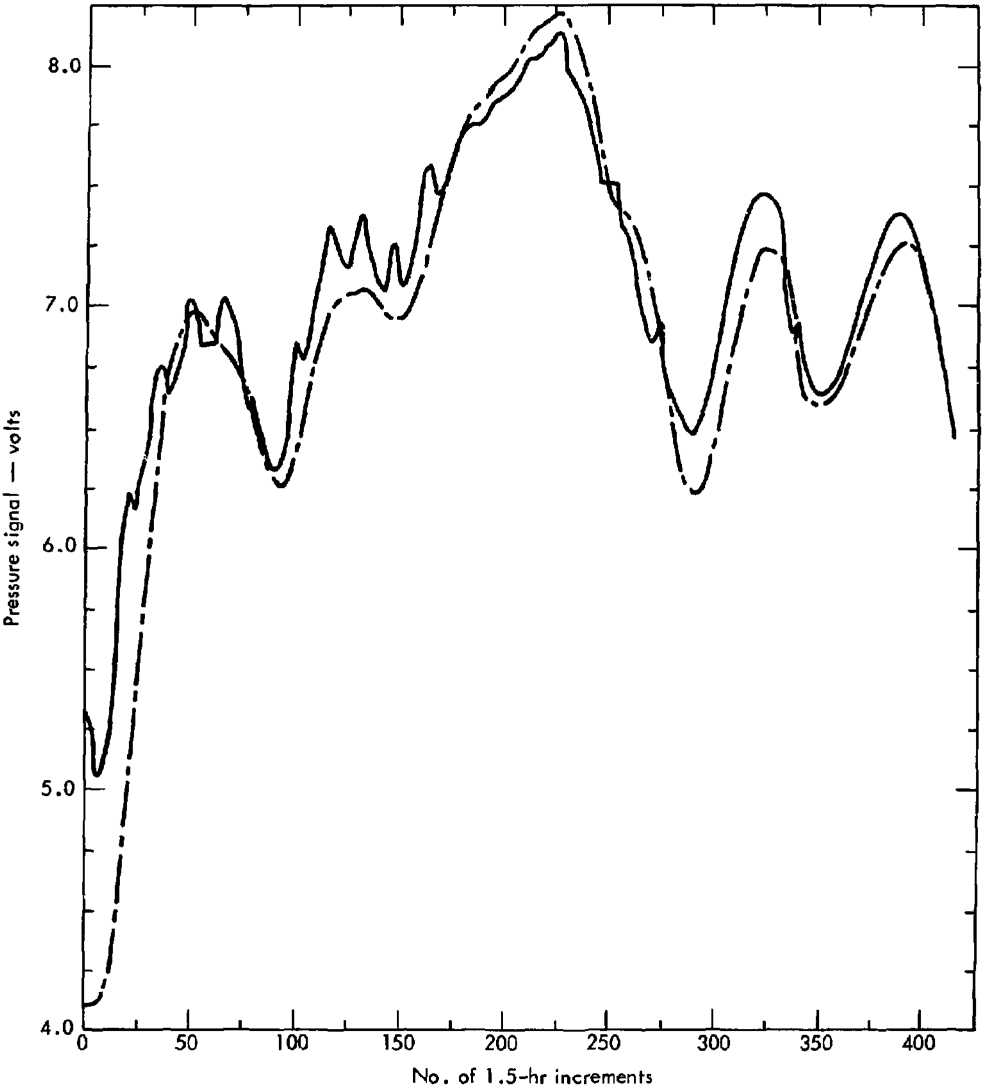


Fig. 12. Comparison of computed and measured downhole pressures for the composite, no-flow solution, $(L^2/4\alpha\Delta t) = 20$, for DH6.

calculation; if 100 different positions were calculated using ERFC, the time required would be 100 times longer than one calculation since each calculation is independent of the other).

Using the values of L from Fig. 1 and $2 \times 10^{-4}$ g/cm-sec for the nominal viscosity of air, the permissivity ($K/\varepsilon$) in $(\text{meter})^2$ of the different chimneys is calculated at $1.9 \times 10^{-10}$ for DH3, $3.5 \times 10^{-11}$ for DH5, and $1.7 \times 10^{-10}$ for DH6. For a nominal porosity of (1/3), the permeability in darcies is 63 for DH3, 12 for DH5, and 57 for DH6.

## CONCLUSIONS

Calculations of downhole pressure response to atmospheric pressure change have been made with two analytical solutions. The fit over times as long as 25 days between the computed and measured downhole pressures is very good. The fact that three different chimneys with different properties all showed reasonable fits indicates that the simple one-dimensional linearized model adequately represents the experimental situation. The differences between the semi-infinite and composite, no-flow solutions are not enough at this point to show one superior to the other.

The use of the analytical solutions is more efficient in computer time usage compared to finite difference codes since only one position is needed for our data analysis comparisons.

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