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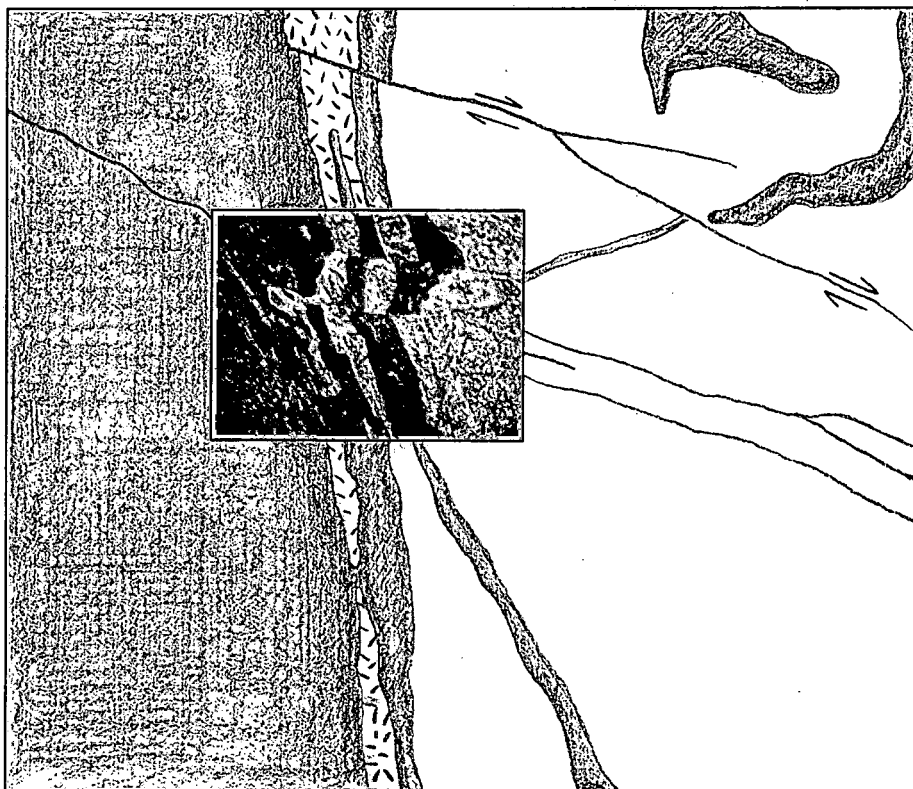
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NAGRA - DOE  
COOPERATIVE  
PROJECT REPORT

# Prematurely Terminated Slug Tests



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*Kenzi Karasaki*

July 1990

Swiss National Cooperative for  
the Storage of Nuclear Waste  
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NDC-11

## **Prematurely Terminated Slug Tests**

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July 1990

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## Preface

This report is one of a series documenting the results of the Nagra-DOE Cooperative (NDC-I) research program in which the cooperating scientists explore the geological, geophysical, hydrological, geochemical, and structural effects anticipated from the use of a rock mass as a geologic repository for nuclear waste. This program was sponsored by the U. S. Department of Energy (DOE) through the Lawrence Berkeley Laboratory (LBL) and the Swiss Nationale Genossenschaft für die Lagerung radioaktiver Abfälle (Nagra) and concluded in September 1989. The principal investigators are Jane C. S. Long, Ernest L. Majer, Karsten Pruess, Kenzi Karasaki, Chalon Carnahan and Chin-Fu Tsang for LBL and Piet Zuidema, Peter Blümling, Peter Hufschmied and Stratis Vomvoris for Nagra. Other participants will appear as authors of the individual reports. Technical reports in this series are listed below.

1. Determination of Fracture Inflow Parameters with a Borehole Fluid Conductivity Logging Method by Chin-Fu Tsang, Peter Hufschmied, and Frank V. Hale (NDC-1, LBL-24752).
2. A Code to Compute Borehole Fluid Conductivity Profiles with Multiple Feed Points by Frank V. Hale and Chin-Fu Tsang (NDC-2, LBL-24928; also NTB 88-21).
3. Numerical Simulation of Alteration of Sodium Bentonite by Diffusion of Ionic Groundwater Components by Janet S. Jacobsen and Chalon L. Carnahan (NDC-3, LBL-24494).
4. P-Wave Imaging of the FRI and BK Zones at the Grimsel Rock Laboratory by Ernest L. Majer, John E. Peterson Jr., Peter Blümling, and Gerd Sattel (NDC-4, LBL-28807).
5. Numerical Modeling of Gas Migration at a Proposed Repository for Low and Intermediate Level Nuclear Wastes at Oberbauenstock, Switzerland by Karsten Pruess (NDC-5, LBL-25413).
6. Analysis of Well Test Data from Selected Intervals in Leuggern Deep Borehole — Verification and Application of PTST Method by Kenzi Karasaki (NDC-6, LBL-27914).
7. Shear Wave Experiments at the U. S. Site at the Grimsel Laboratory by Ernest L. Majer, John E. Peterson Jr., Peter Blümling, and Gerd Sattel (NDC-7 LBL-28808).
8. The Application of Moment Methods to the Analysis of Fluid Electrical Conductivity Logs in Boreholes by Simon Loew, Chin-Fu Tsang, Frank V. Hale, and Peter Hufschmied (NDC-8, LBL-28809).
9. Numerical Simulation of Cesium and Strontium Migration through Sodium Bentonite Altered by Cation Exchange with Groundwater Components by Janet S. Jacobsen and Chalon L. Carnahan (NDC-9, LBL-26395).
10. Theory and Calculation of Water Distribution in Bentonite in a Thermal Field by Chalon L. Carnahan (NDC-10, LBL-26058).
11. Prematurely Terminated Slug Tests by Kenzi Karasaki (NDC-11, LBL-27528).
12. Hydrologic Characterization of Fractured Rocks — An Interdisciplinary Methodology by Jane C. S. Long, Ernest L. Majer, Stephen J. Martel, Kenzi Karasaki, John E. Peterson Jr., Amy Davey, and Kevin Hestir, (NDC-12, LBL-27863).
13. Exploratory Simulations of Multiphase Effects in Gas Injection and Ventilation Tests in an Underground Rock Laboratory by Stefan Finsterle, Erika Schlueter, and Karsten Pruess (NDC-13, LBL-28810).
14. Joint Seismic, Hydrogeological, and Geomechanical Investigations of a Fracture Zone in the Grimsel Rock Laboratory, Switzerland by Ernest L. Majer, Larry R. Myer, John E. Peterson Jr., Kenzi Karasaki, Jane C. S. Long, Stephen J. Martel, Peter Blümling, and Stratis Vomvoris (NDC-14, LBL-27913).
15. Analysis of Hydraulic Data from the MI Fracture Zone at the Grimsel Rock Laboratory, Switzerland by Amy Davey, Kenzi Karasaki, Jane C.S. Long, Martin Landsfeld, Antoine Mensch, and Stephen J. Martel (NDC-15, LBL-27864).
16. Use of Integrated Geologic and Geophysical Information for Characterizing the Structure of Fracture Systems at the US/BK Site, Grimsel Laboratory, Switzerland by Stephen J. Martel and John E. Peterson Jr. (NDC-16, LBL-27912).

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## Abstract

A solution of the well response to a prematurely terminated slug test (PTST) is presented. The advantages of a PTST over conventional slug tests are discussed. A systematized procedure of a PTST is proposed, where a slug test is terminated in the midpoint of the flow period, and the subsequent shut-in data is recorded and analyzed. This method requires a downhole shut-in device and a pressure transducer, which is no more than the conventional deep-well slug testing. As opposed to slug tests, which are ineffective when a skin is present, more accurate estimate of formation permeability can be made using a PTST. Premature termination also shortens the test duration considerably. Because in most cases no more information is gained by completing a slug test to the end, the author recommends that conventional slug tests be replaced by the premature termination technique.

## **Acknowledgements**

This work was funded at Lawrence Berkeley Laboratory under U.S. Department of Energy under Contract NO. DE-AC03-76SF00098 through the Repository Technology Department, Chicago and through USGS. Much of the work is fostered through cooperation with Nagra, Nationale Genossenschaft für die Lagerung radioaktiver Abfälle. The author wishes to express special thanks to Professor Ramey of Stanford University for critical reviews and useful suggestions.

## 1.0. Introduction

Slug tests are relatively easy and inexpensive to perform. For this reason, they are widely used for estimating aquifer parameters. However, when a skin is present, it is very difficult to distinguish the permeability of the formation from that of the skin. Because of the transient nature of the induced boundary condition at the wellbore under slug tests, the result obtained by type-curve matching represents an unknown average of the permeability of the skin and the formation.

Skin-like conditions can occur naturally with the presence of heterogeneity in rocks. They are especially pronounced in fractured rocks, where fractures are the main conduits for groundwater. In such rocks, the flow parameters of the fractures near the borehole can be quite different from those of the overall network of fractures. Any single fracture can present a highly heterogeneous permeability. Therefore, slug tests alone are not generally recommended for estimating flow parameters in these systems. However, sometimes the economic advantages outweigh the above mentioned disadvantages and slug tests may be the only practical tests.

This paper proposes a PTST method, a systematized test procedure and analysis method of drillstem tests (DST's). The method allows one to obtain a better estimate of the flow parameters from slug tests when skin is present. Furthermore, the duration of the test can be shortened by up to an order of magnitude compared to a slug test carried all the way to the stabilization. In the modified procedure, it is proposed that the interval be shut-in after 50% of the initial slug is injected followed by monitoring of the recovery. A Drillstem test (DST) is a familiar petroleum terminology (van Poolen, 1961; Edwards and Shryock, 1974). However, to the author's knowledge, none has proposed a systematic DST procedure with a prescribed shut-in level. This paper presents a solution to this boundary value problem through the use of Duhamel's theorem and suggests an analysis method using the regular normalized head vs. time semilog plot and

Horner plot (Horner, 1951). An example is shown to demonstrate that the method successfully yields the formation permeability even with the presence of skin.

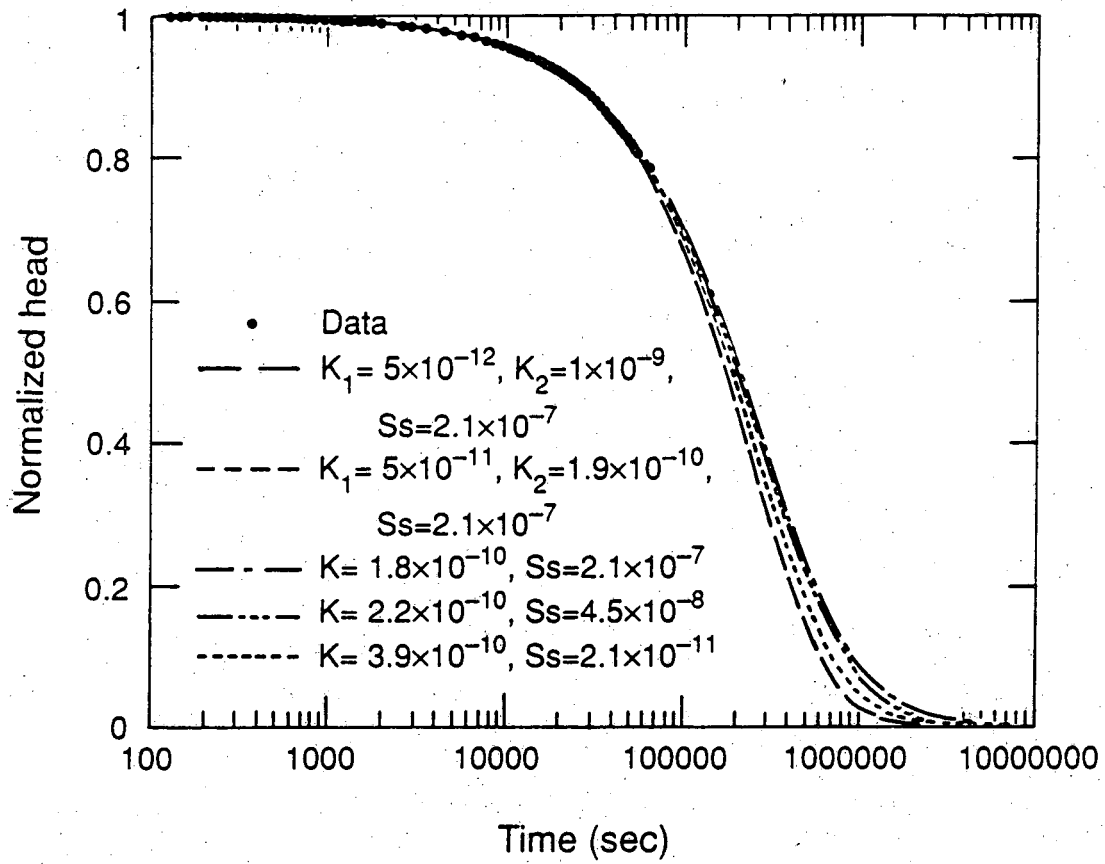
## 2.0. Background

Cooper, Bredehoeft and Papadopoulos (1967) presented a solution for the change in water level for a finite radius well subjected to a slug test in a homogeneous medium. They showed that the instantaneous line-source solution proposed by Ferris and Knowles (1954) is valid only for very late time. Cooper et al. obtained the solution from the analogous heat transfer problem in Carslaw and Jaeger (1946). Several workers have since investigated various slug test problems. The effect of skin on observed fluid levels was studied by Ramey and Agarwal (1972), and Ramey et al. (1975), and more recently by Faust and Mercer (1984), Moench and Hsieh (1985) and Sageev (1986). Moench and Hsieh found that for parameters that are often encountered in open well tests the solution is practically identical to that of infinitesimal skin presented by Ramey et al. They also pointed out that because the type curves are nearly identical shapes it is not possible to accurately estimate the transmissivity. Wang et al. (1977) studied cases where tight fractures intersect the wellbore. Barker and Black (1983) and Dougherty and Babu (1984) presented a solution for slug tests in a double porosity medium. Black and Barker (1987) discussed interpretation-based errors of slug tests and other single-hole hydraulic tests. They suggested an analysis method for slug tests where the 50 percent equilibration time and the gradient at the time are used. Karasaki et. al. (1988) extended slug test solutions to various geometries. They also cautioned that slug tests suffer non-uniqueness problems to a greater extent than other well tests.

For infinitesimally thin skin, the shapes of the head versus time curves are nearly identical to those without skin (Ramey et al., 1975). Therefore, either the skin factor or the formation storativity must be known a priori to estimate the transmissivity. For finite radius skin, certain combinations of flow parameters have a characteristic curve shape (Moench and Hsieh, 1985). However, in most cases the curves are again indistinguishable from those without skin. Figure

2.1 shows an example where slug test data can be fit to different combinations of skin and formation transmissivities. The curves were obtained by using the solution presented by Moench and Hsieh (1985). As can be seen from Figure 2.1, slug tests exhibit nonuniqueness in the presence of skin for most cases. Thus, the results obtained by type-curve matching must be treated with caution if the presence of skin is suspected.

As opposed to the flow period data, buildup/fall-off data are in general less obscured by skin effects. The Horner-plot can be used for buildup data. Pressure is plotted as a function of  $\frac{t_p + \Delta t}{\Delta t}$ , where  $t_p$  is the flow duration and  $\Delta t$  is the time after shut-in. Formation transmissivity can be estimated from the slope of the straight line section of the curve. Fall-off/buildup data of a prematurely terminated slug test (PTST), which are essentially a drillstem test (DST), are commonly analyzed by using this method (Ammann, 1960). Correa and Ramey (1987,1988) presented the first rigorous solution to the DST problem by using a unit step function to express a time dependent inner boundary condition (Correa and Ramey, 1986), where non-constant flow rate prior to shut-in is accounted for. In the next section, another solution of the same problem is presented using a different solution method, namely, the time convolution method or Duhamel's theorem.



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Figure 2.1. Non-unique fits of type curves to slug test data.

### 3.0. Theory

The boundary condition for premature termination of slug test at  $t_D = \tau$  can be expressed in a dimensionless form as:

$$\frac{1}{\alpha(t_D)} \cdot \frac{dh_{wD}}{dt_D} = \frac{\partial h_D}{\partial r_D}, \quad (3.1)$$

and

$$\alpha(t_D) = \begin{cases} \alpha_1 = \frac{2\pi r_w^2 S}{C_{w1}} (0 < t_D < \tau) \\ \alpha_2 = \frac{2\pi r_w^2 S}{C_{w2}} (t_D > \tau). \end{cases} \quad (3.2)$$

Here  $h_{wD}$  is the normalized fluid level in the well,  $h_D$  is the normalized head in the system,  $t_D$  is the dimensionless time,  $\frac{Tt}{Sr_w^2}$ , and  $r_D$  is the dimensionless radius,  $r/r_w$ . The wellbore storage  $C_w$

changes from that of the open well to that of the closed interval at the termination of a slug test. Specifically,  $C_{w1} = \pi r_c^2$  and  $C_{w2} = \rho_w g V_w c_{sys}$ , where  $r_c$  is the radius of the delivery pipe,  $\rho_w$  is the density of water,  $g$  is the acceleration of gravity, and  $V_w$  is the volume of water in the shut-off section, and  $c_{sys}$  is the system compressibility. It is this time-dependent coefficient that makes a straightforward Laplace transform solution method difficult. Correa and Ramey (1986) presented a way to handle this problem using a unit step function and new operational rules. In this paper a different approach is sought. First the flow rate at the well is solved as a function of time for the usual slug test boundary conditions. Then this transient flow rate is used as the inner boundary condition of a controlled variable-rate injection/pumping test. Duhamel's theorem is employed to solve for the pressure at the well with time-dependent flow rate. This is done through a time-convolution of the flow rate with the solution for a unit injection rate. Premature termination of



the test can be formulated by dividing the time integration into parts: before and after the shut-in. In the following section the above procedure is more closely examined.

Duhamel's theorem as described in Carslaw and Jaeger (1946) states that if  $F(r,t)$  represents the head distribution in response to a constant unit injection, the solution  $h(r,t)$ , when the injection rate is a function of time,  $\phi(t)$ , is given by

$$h(r,t) = \int_0^t \phi(\lambda) \frac{\partial}{\partial t} F(r,t-\lambda) d\lambda. \quad (3.3)$$

In a homogeneous, confined aquifer  $F(r,t)$  is the solution given by van Everdingen and Hurst (1949), which can be written in a dimensionless form as:

$$F(r_D, t_D) = \frac{2}{\pi_0} \int_0^\infty \frac{(1-e^{-\mu^2 t_D}) [J_1(\mu) Y_0(\mu r_D) - Y_1(\mu) J_0(\mu r_D)] d\mu}{\mu^2 [J_1^2(\mu) + Y_1^2(\mu)]}. \quad (3.4)$$

The flow rate at the sandface  $\phi(t_D)$  can be obtained by taking a time derivative of the solution in Cooper et al. (1967) at  $r_D = 1$ :

$$h_D(r_D, t_D) = \frac{2}{\pi_0} \int_0^\infty e^{-\mu^2 t_D} \frac{\{J_0(\mu r_D) \cdot \Psi(\mu) - Y_0(\mu r_D) \cdot \Phi(\mu)\}}{\Phi^2(\mu) + \Psi^2(\mu)} \cdot d\mu \quad (3.5)$$

$$\phi(t_D) = \frac{1}{\alpha} \frac{dh_{wD}}{dt_D} = -\frac{4}{\pi^2} \int_0^\infty e^{-\mu^2 t_D} \cdot \frac{\mu d\mu}{[\Phi^2(\mu) + \Psi^2(\mu)]}, \quad (3.6)$$

where  $h_{wD}(t_D) = h_D(1, t_D)$ , and

$$\Phi(\mu) = \mu J_0(\mu) - \alpha J_1(\mu). \quad (3.7)$$

$$\Psi(\mu) = \mu Y_0(\mu) - \alpha Y_1(\mu). \quad (3.8)$$

Evaluating (3.4) at  $r_D = 1$  and using the identity:

$$J_1(\mu) Y_0(\mu) - Y_1(\mu) J_0(\mu) = \frac{2}{\pi \mu}, \quad (3.9)$$

and substituting into (3.3) with (3.6) yields the solution for fluid level at the well equivalent to

that given by Cooper et al.(1967).

$$h_{wD}(t_D) = - \frac{16}{\pi^4} \int_0^{t_D} \left[ \int_0^{\infty} \frac{e^{-\mu^2 \lambda} \mu d\mu}{[\Phi^2(\mu) + \Psi^2(\mu)]} \int_0^{\infty} \frac{(1 - e^{-\mu^2(t_D - \lambda)}) d\mu}{\mu^3 [J_1^2(\mu) + Y_1^2(\mu)]} \right] d\lambda \quad (3.10)$$

Van Everdingen and Hurst (1949) used the same transient rate-time convolution method to obtain their original presentation of the storage problem. As it is the solution is of little use because it is much more complex than Cooper et al.'s. However, premature termination of injection/withdrawal can be easily formulated by breaking up the integration into two time domains. For termination at time  $\tau$ , the equation, therefore, can be expressed as:

$$h_{wD}(t_D) = - \frac{16}{\pi^4} \int_0^{\tau} \left[ \int_0^{\infty} \frac{e^{-\mu^2 \lambda} \mu d\mu}{[\Phi^2(\mu, \alpha_1) + \Psi^2(\mu, \alpha_1)]} \int_0^{\infty} \frac{(1 - e^{-\mu^2(t_D - \lambda)}) d\mu}{\mu^3 [J_1^2(\mu) + Y_1^2(\mu)]} \right] d\lambda \\ - \frac{16}{\pi^4} \int_{\tau}^{t_D} \left[ \int_0^{\infty} \frac{e^{-\mu^2 \lambda} \mu d\mu}{[\Phi^2(\mu, \alpha_2) + \Psi^2(\mu, \alpha_2)]} \int_0^{\infty} \frac{(1 - e^{-\mu^2(t_D - \lambda)}) d\mu}{\mu^3 [J_1^2(\mu) + Y_1^2(\mu)]} \right] d\lambda \quad (3.11)$$

The integrands in (3.11) are very slowly converging functions and therefore it is difficult to evaluate the equation numerically. It is much easier to express them in terms of Laplace space solutions and evaluate them by numerical inversion. Hence (3.11) can be rewritten as:

$$h_{wD}(t_D) = \int_0^{\tau} L_{\lambda}^{-1} \left\{ \frac{-\sqrt{p} K_1(\sqrt{p})}{p K_0(\sqrt{p}) + \alpha_1 \sqrt{p} K_1(\sqrt{p})} \right\} \cdot L_{t_D - \lambda}^{-1} \left\{ \frac{K_0(\sqrt{p})}{\sqrt{p} K_1(\sqrt{p})} \right\} d\lambda \\ + \int_{\tau}^{t_D} L_{\lambda}^{-1} \left\{ \frac{-\sqrt{p} K_1(\sqrt{p})}{p K_0(\sqrt{p}) + \alpha_2 \sqrt{p} K_1(\sqrt{p})} \right\} \cdot L_{t_D - \lambda}^{-1} \left\{ \frac{K_0(\sqrt{p})}{\sqrt{p} K_1(\sqrt{p})} \right\} d\lambda \quad (3.12)$$

where  $p$  is the Laplace space variable and  $L^{-1}$  denotes Laplace inversion. The subscript denotes the corresponding real space variable. Here the following property of the transform is used:

$$L \left\{ \frac{\partial F(t)}{\partial t} \right\} = p L \left\{ F(t) \right\} - F(+0). \quad (3.13)$$

Throughout this study, the inversions were obtained using Stehfest's algorithm (Stehfest, 1970). Some values were cross-checked against the results obtained by using another inversion program written by Barker (1988), which is based on the algorithm introduced by Green (1955) and developed by Talbot (1979). The latter algorithm is known to be more robust.

One verification of the solution is to test whether the solution by Cooper et al. can be reproduced when  $\alpha_1 = \alpha_2$ , i.e., for no termination case. Figure 3.1 demonstrates that this is indeed the case: two solutions are identical in a semilog plot.

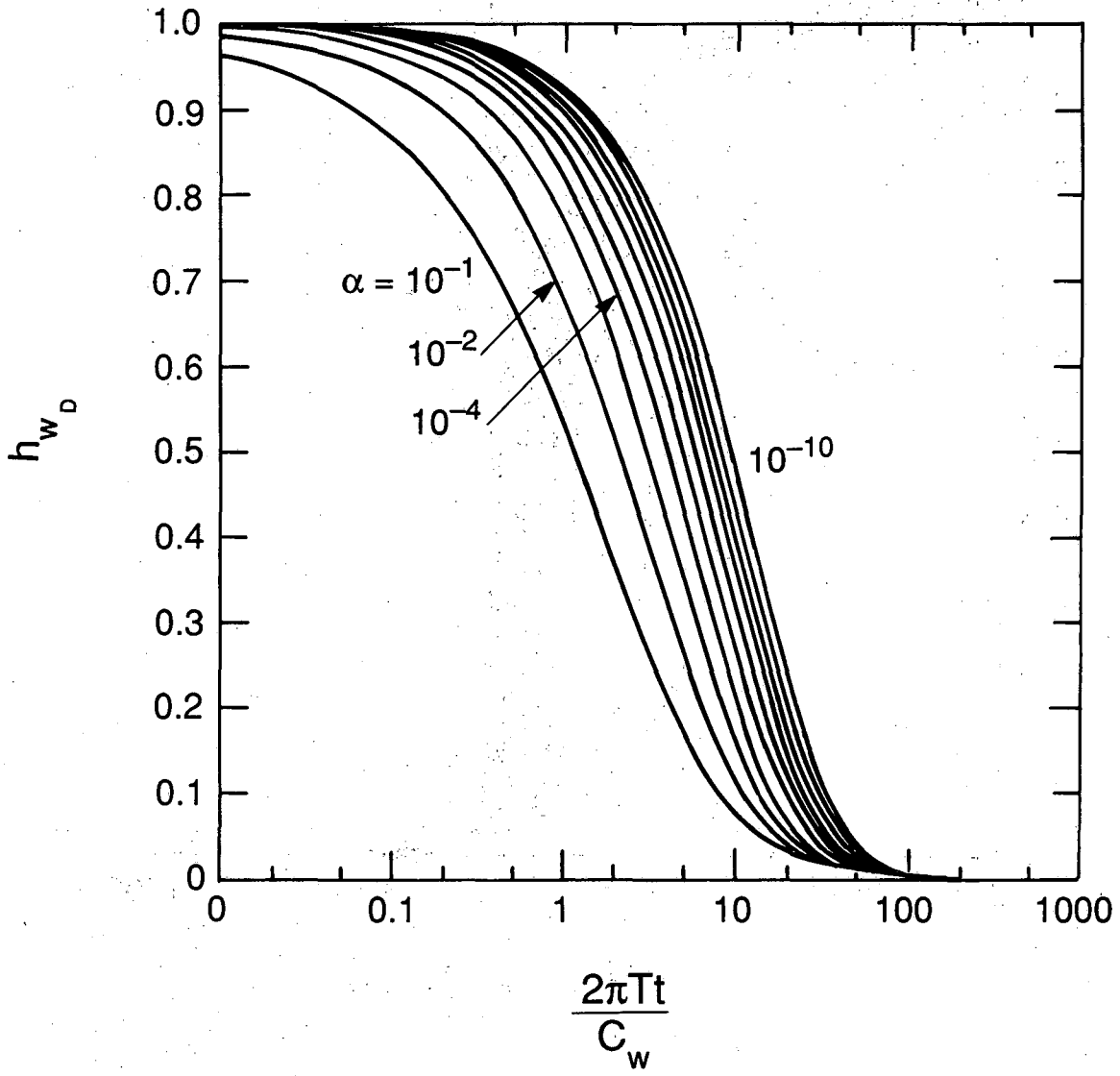
For premature termination of open hole slug test, the wellbore storage typically declines by several orders of magnitude between before and after shut-in, i.e.,  $\alpha_1 \ll \alpha_2$ . Therefore, the second term on the right hand side of (3.12) can be neglected for most cases of premature termination. Physically, this means that the flow into the interval after shut-in is negligibly small. Figure 3.2 shows the termination at 50 percentile for various values of  $\alpha_1$ . It must be noted that the time needed for completion of the test is shortened by up to one order of magnitude. This is a significant saving of time and cost especially in light of the fact that by completing the slug test to the end is unlikely to yield more information for the reason discussed previously.

Figure 3.2 is not very useful in analyzing the falloff/recovery portion of the test. However, if  $\frac{h_{wD}}{q_{av}}$  is plotted against  $\frac{t_D}{t_D - \tau}$ , i.e., in a Horner plot, the curves for different  $\alpha$  collapse to a narrow range except for relatively large  $\alpha$  as can be seen in Figure 3.3.  $q_{av}$  is the average flow rate in a dimensionless form over the flow period and can be expressed as:

$$q_{av} = \frac{1 - h_{wD}(\tau)}{\tau \alpha} \quad (3.14)$$

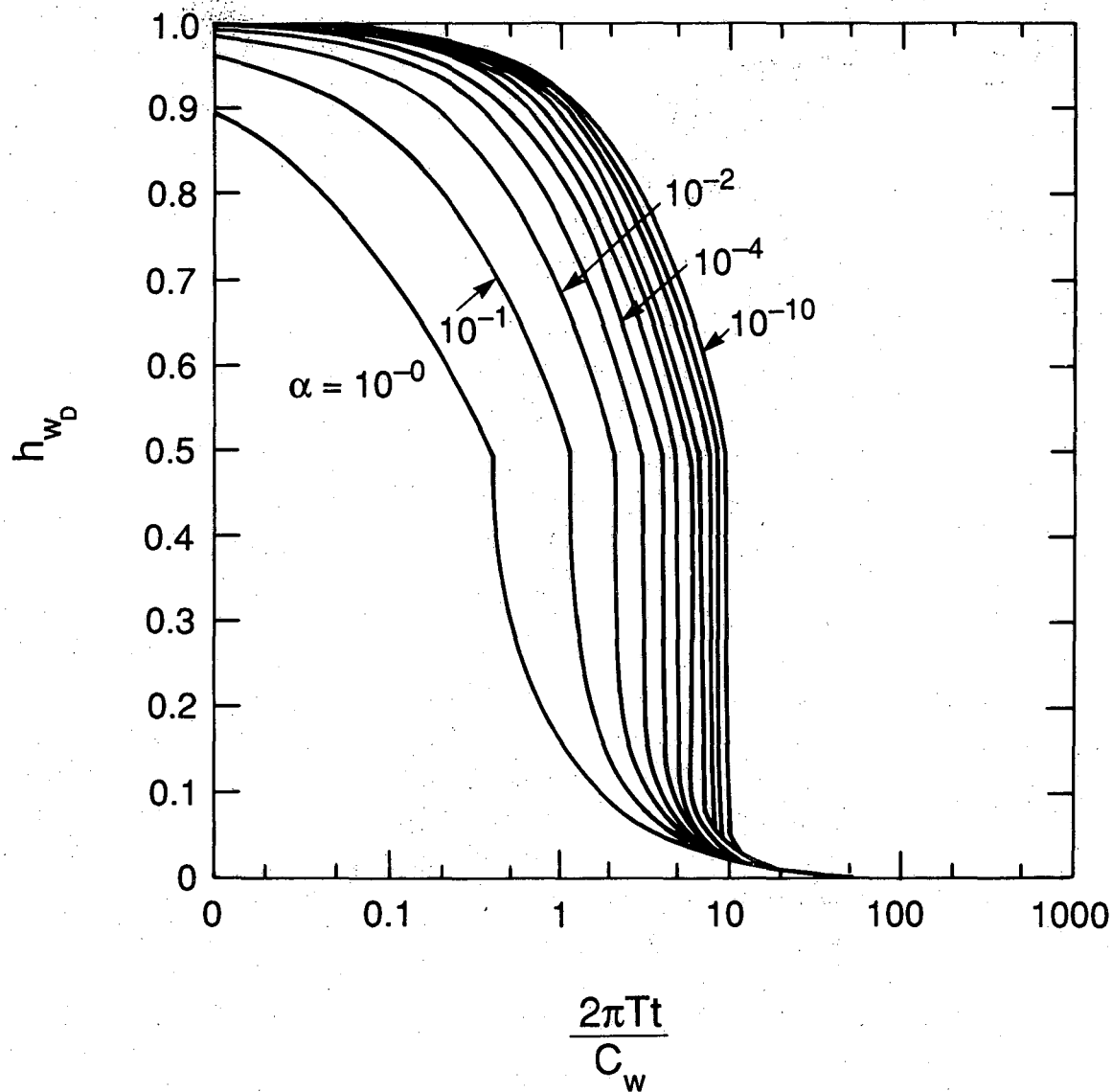
Figure 3.3 also shows the curve for fall-off/recovery after a constant rate injection/production at  $q_{av}$ . The straight line portion of the theoretical curve has a slope of 1.15 per log cycle. It should be noted that most curves converge to a single one as  $\frac{t_D}{t_D - \tau}$  approaches to unity, i.e., for large  $t_D$ .

Alternatively, the instantaneous flow rate before shut-in,  $q_{inst}$  can be used in place of the average flow rate,  $q_{av}$ . Then  $\frac{h_{wD}}{q_{inst}}$  should be plotted against  $\frac{t_D}{t_D - \tau'}$ , where  $\tau'$  is the adjusted flow time



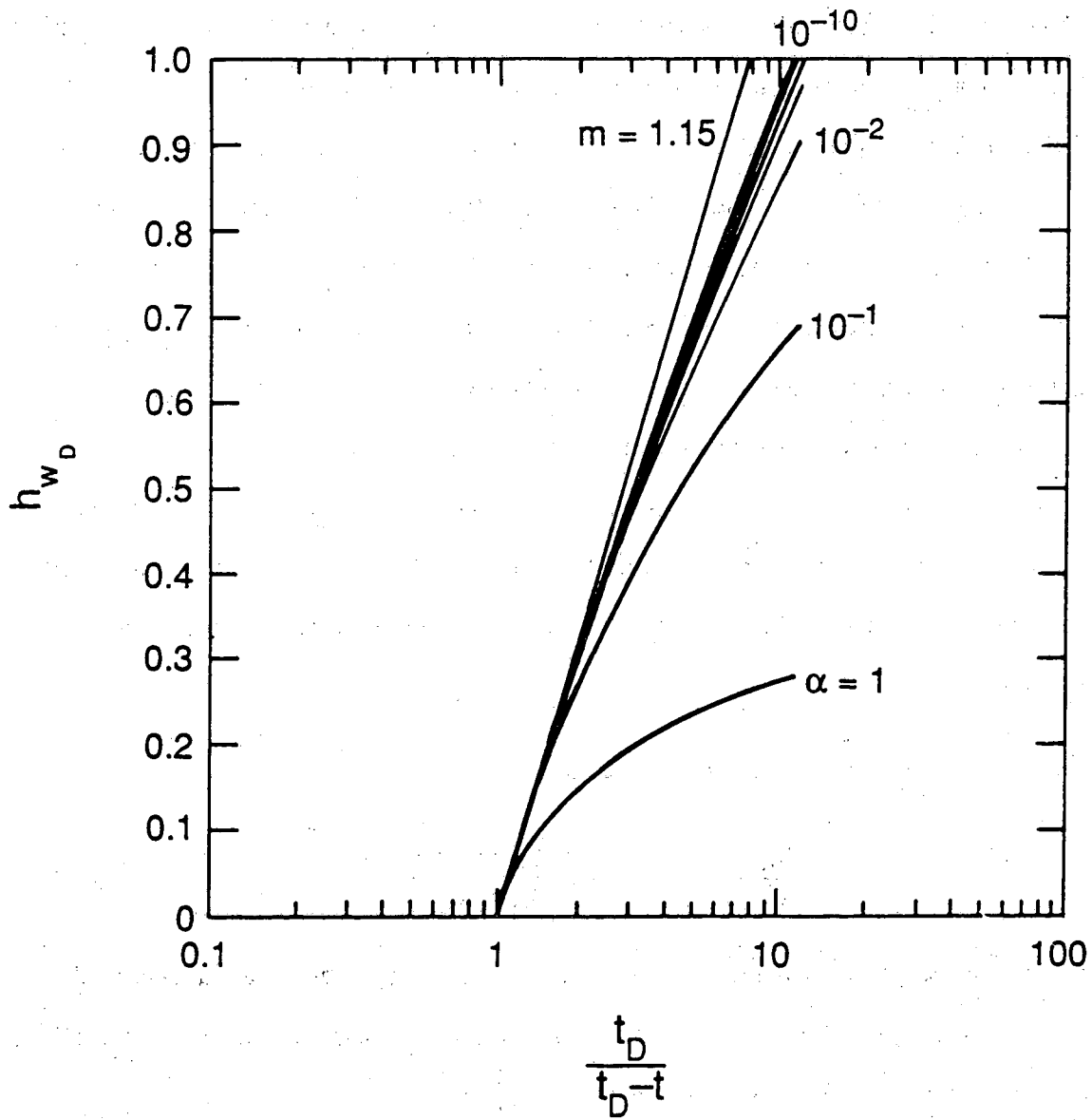
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Figure 3.1. Cooper et al. type curves and those by evaluating (3.12).



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Figure 3.2. Termination at 50 percentile for various values of  $\alpha_1$ .



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Figure 3.3. Horner plot of a PTST and a constant flow test data.

obtained by dividing the cumulative volume by  $q_{inst}$ . Although a slightly better result can be obtained by using  $q_{inst}$ , a method using  $q_{av}$  is developed here, because  $q_{av}$  is easier to estimate than  $q_{inst}$  and the subsequent analysis is simpler. Figure 3.4 compares fall-off/recovery curves after shut-in at various percentile completion for  $\alpha = 1 \times 10^{-6}$ . A straight line with a slope of 1.15 is also shown. From the figure it is evident that the longer the flow period is the farther the curves deviate from the slope of 1.15. At first sight therefore it appears that it is better to shut-in at the early stage of a slug test. However, the shorter the flow period is, the smaller the radius of influence is. Figure 3.5 is a plot of the normalized head vs. the dimensionless radius at various times during a slug test for the case of  $\alpha = 10^{-6}$ . The curves are obtained by evaluating (3.5) as a function of radius at each given head level. As can be seen in the figure, the propagation distance of the pressure pulse is a function of the head level in the well, which is, in effect, the amount of injected/withdrawn fluid. In this particular example, the front of  $h_D = 0.1$  reaches as far as  $r_D = 1000$  when  $h_{wD} \approx 0.5$ . However, for  $h_{wD} < 0.4$ , the front becomes weak even though the disturbed radius is larger. Therefore shut-in at a 50 percentile head level seems to be a reasonable value.

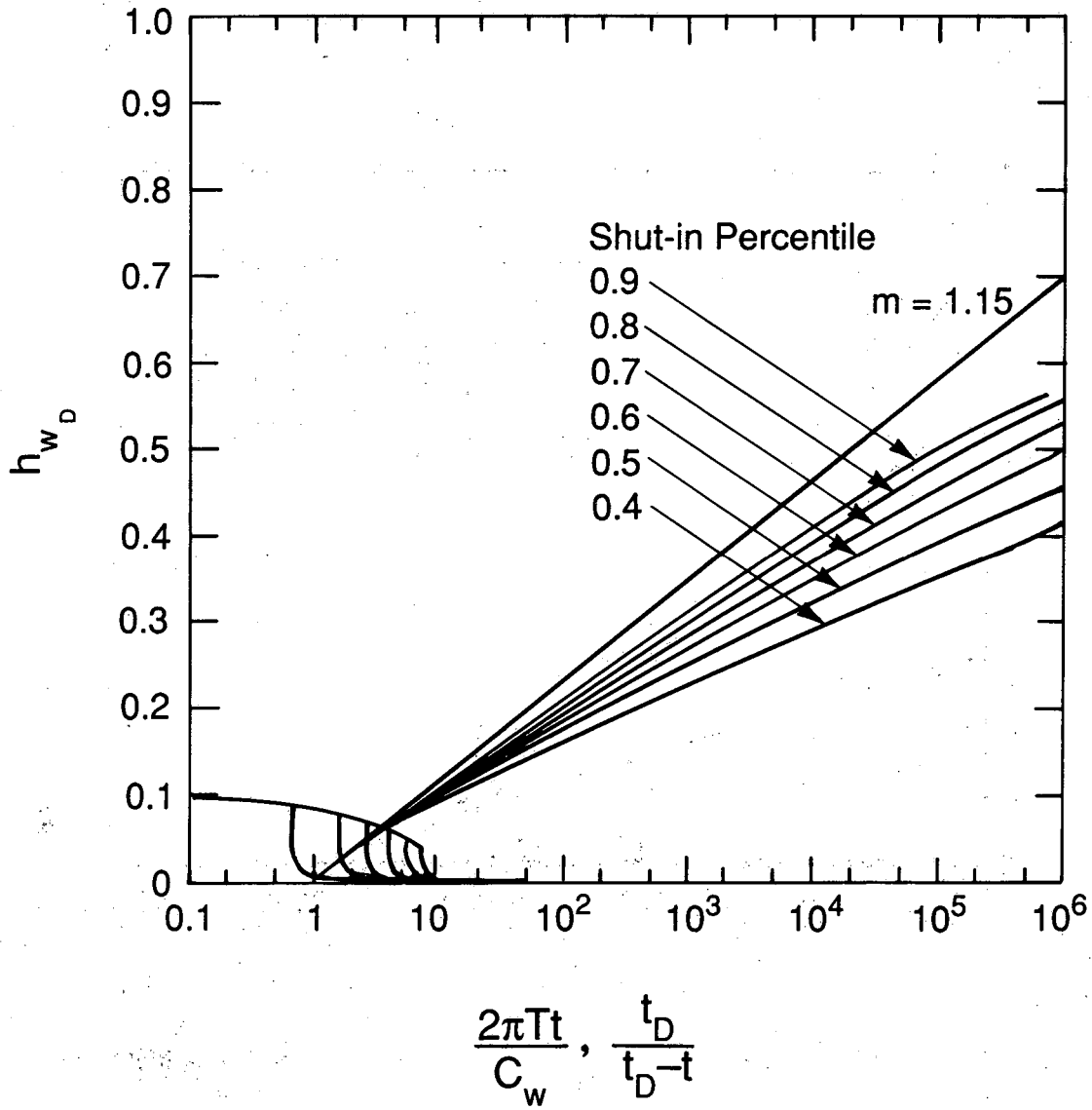
Using (3.14),  $\frac{h_{wD}}{q_{av}}$  can be expressed in a dimensional form as:

$$\frac{h_{wD}}{q_{av}} = \frac{h_{wD}\tau\alpha}{1-h_{wD}(\tau)} = \frac{2\pi T t_t (h-h_i)}{(h_0-h_t)C_w l} \quad (3.15)$$

where the subscript  $t$  denotes the shut-in time. Horner analysis assumes that  $h_{wD}/q_{av} = 1.15 \cdot \log t_D / (t_D - \tau)$ . Therefore, from the slope  $m$  of the  $h$  vs.  $t/(t-t_i)$  plot, the permeability can be calculated by using the following relation:

$$K = \frac{1.15(h_0-h_t)C_w l}{2\pi m b t_t} \quad (3.16)$$

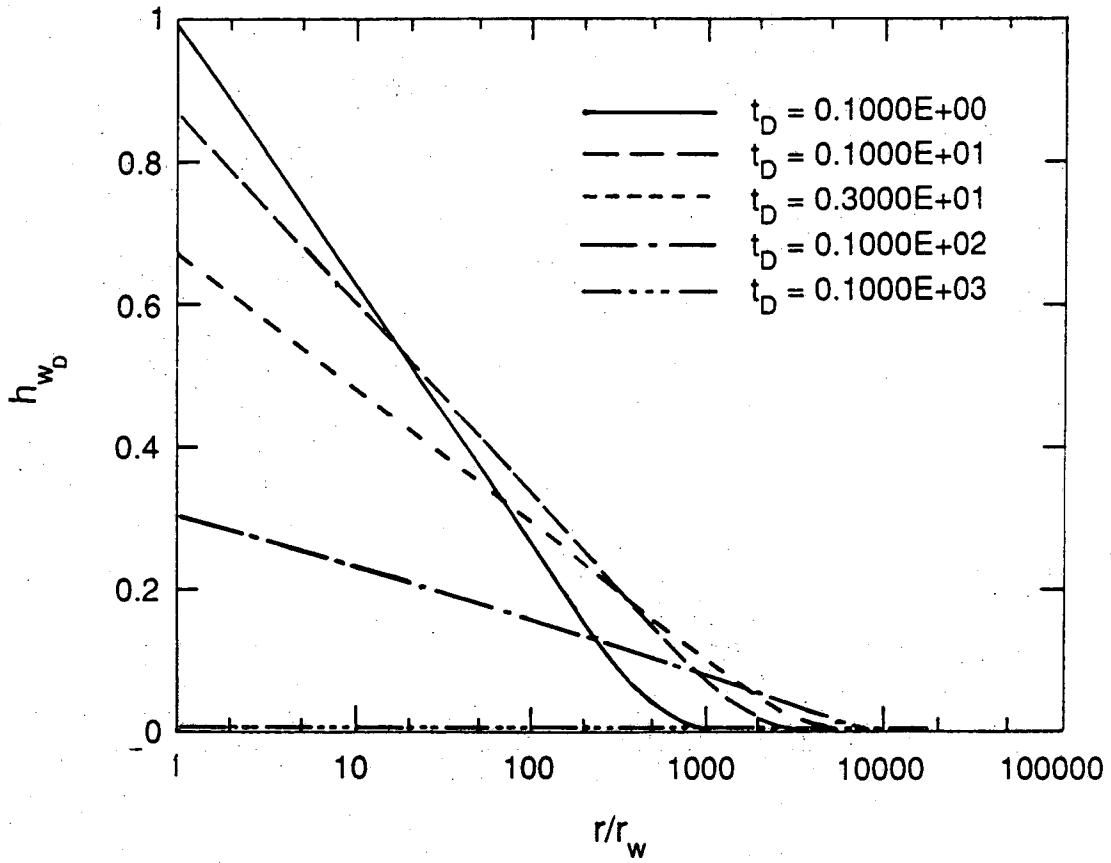
However, as pointed out earlier, the Horner plot of a PTST data does not always have a slope of 1.15. As can be seen in Figure 3.3, for large  $\alpha$  or for  $t_D/(t_D - \tau) \gg 1$ , the curves deviate from the slope of 1.15. In some cases tests cannot be run long enough to achieve  $t/(t-t_i) \approx 1$ . Alternative to (3.16), the following equation can be used.



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Figure 3.4. PTST's shut-in at various percentile completion for  $\alpha = 1 \times 10^{-6}$ .





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Figure 3.5. Normalized head vs. dimensionless radius at various times for  $\alpha = 10^{-6}$ .

$$K = \frac{(h_0 - h_i) C_w h_{wD} / q_{av}(10)}{2\pi b t_i (h_{10} - h_i)}, \quad (3.17)$$

where  $h_{10}$  denotes the head at  $t/(t-t_i) = 10$ . The values for  $h_{wD}(3.10)$  can be obtained from Figure 3.3 for 50 percentile termination case. For other values, (3.12) must be used. In most cases, however, using  $h_{wD}(10) \approx 1.0$  yields satisfactory results. Specifically, for 50 percentile termination case, (3.17) can be further simplified to:

$$K = \frac{(h_0 - h_i) C_w}{4\pi b t_i (h_{10} - h_i)}. \quad (3.18)$$

It is recommended that type curves in Figure 3.2 be used to estimate the  $\alpha$  value first. If the value is more than  $10^{-2}$ , (3.17) should be used. Otherwise, (3.18) can be used with 90 per cent accuracy for most cases.

#### 4.0. Skin

So far, it has been shown that the advantage of shutting-in a slug test prematurely is that the time duration of the test may be shortened. However, the real advantage of premature termination is realized when a skin is present. In this section a comparison will be made between a conventional slug test and its premature termination in the presence of a skin.

The Laplace domain solution for the dimensionless head in the well for a finite radius skin was presented by Moench and Hsieh (1985) and can be written as:

$$\bar{h}_{wD}(p) = \frac{K_D[\Lambda K_0(q\beta) - \Omega I_0(q\beta)]}{\Theta \Lambda - \Xi \Omega} \quad (4.1)$$

where

$$\Lambda = K_D I_0(q\beta r_{Ds}) K_1(qr_{Ds}) + \beta I_1(q\beta r_{Ds}) K_0(qr_{Ds}) \quad (4.2)$$

$$\Omega = K_D K_0(q\beta r_{Ds}) K_1(qr_{Ds}) - \beta K_1(q\beta r_{Ds}) K_0(qr_{Ds}) \quad (4.3)$$

$$\Theta = K_D p K_0(q\beta) + \alpha \beta q K_1(q\beta) \quad (4.4)$$

$$\Xi = K_D p I_0(q\beta) - \alpha \beta q I_1(q\beta) \quad (4.5)$$

$$q = \sqrt{p} \quad (4.6)$$

$$r_{Ds} = \frac{r_s}{r_w} \quad (4.7)$$

$$K_D = \frac{K}{K_s} \quad (4.8)$$

$$\beta = \sqrt{K_D \delta} \quad (4.9)$$

$$\delta = \frac{S_{ss}}{S_s} \quad (4.10)$$

The subscript s refers to the skin region. Figure 4.1 shows the corresponding flow geometry.

Following the steps similar to those that were used to obtain (3.12), by using (3.18) in (3.13) and then in (3.3), the dimensionless level in the well with termination at time  $\tau$  can be written as:

$$h_{wD}(t_D) = \int_0^{\tau} L_{\lambda}^{-1} \left\{ \frac{K_{DP}[\Lambda K_0(q\beta) - \Omega I_0(q\beta)]}{\Theta_1 \Lambda - \Xi_1 \Omega} - 1 \right\} \cdot L_{t_D - \lambda}^{-1} \left\{ \frac{K_0(\sqrt{p})}{\sqrt{p} K_1(\sqrt{p})} \right\} d\lambda$$

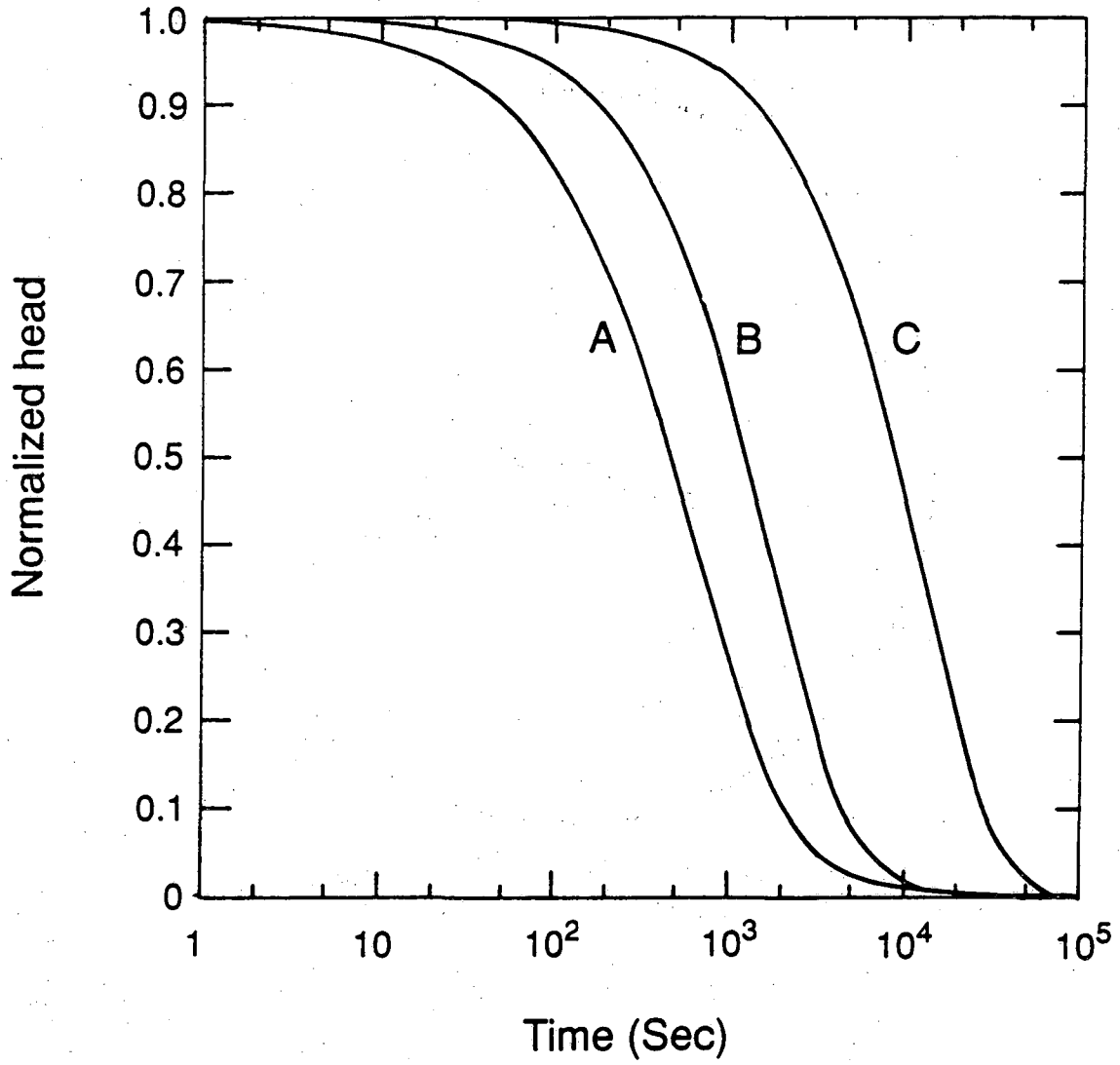
$$+ \int_{\tau}^{t_D} L_{\lambda}^{-1} \left\{ \frac{K_{DP}[\Lambda K_0(q\beta) - \Omega I_0(q\beta)]}{\Theta_2 \Lambda - \Xi_2 \Omega} - 1 \right\} \cdot L_{t_D - \lambda}^{-1} \left\{ \frac{K_0(\sqrt{p})}{\sqrt{p} K_1(\sqrt{p})} \right\} d\lambda \quad (4.11)$$

where the subscripts 1 and 2 on  $\Theta$  and  $\Xi$  refer to the  $\alpha$  values before and after shut-in, respectively.

To illustrate that a PTST can be used to estimate the transmissivity more accurately than a conventional slug test when a skin is present, both slug test and premature termination data are generated by evaluating (4.1) and (4.11) for sets of parameters shown in Table 4.1.

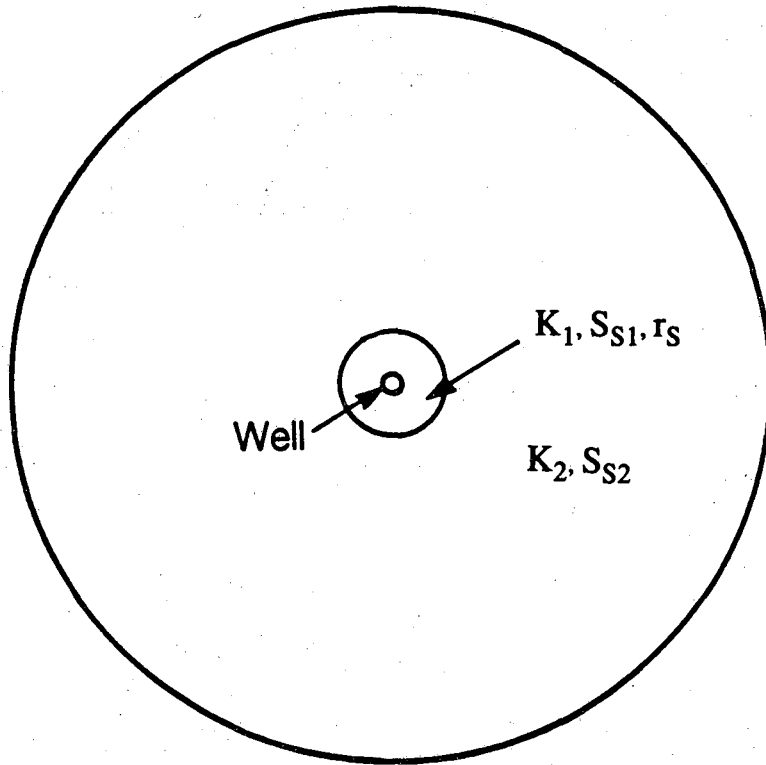
Table 4.1. Aquifer and Skin Parameters

	Case A	Case B	Case C
K	$1 \times 10^{-7}$ m/s	$1 \times 10^{-7}$ m/s	$1 \times 10^{-7}$ m/s
$S_s$	$1 \times 10^{-5}$ 1/m	$1 \times 10^{-5}$ 1/m	$1 \times 10^{-5}$ 1/m
$r_w$	0.05 m	0.05 m	0.05 m
b	10 m	10 m	10 m
$C_{w1}$	0.001 m <sup>2</sup>	0.001 m <sup>2</sup>	0.001 m <sup>2</sup>
$r_s$	0.1 m	0.1 m	0.1 m
$K_s$	$1 \times 10^{-7}$ m/s	$1 \times 10^{-8}$ m/s	$1 \times 10^{-9}$ m/s
$S_{ss}$	$1 \times 10^{-5}$ 1/m	$1 \times 10^{-5}$ 1/m	$1 \times 10^{-5}$ 1/m



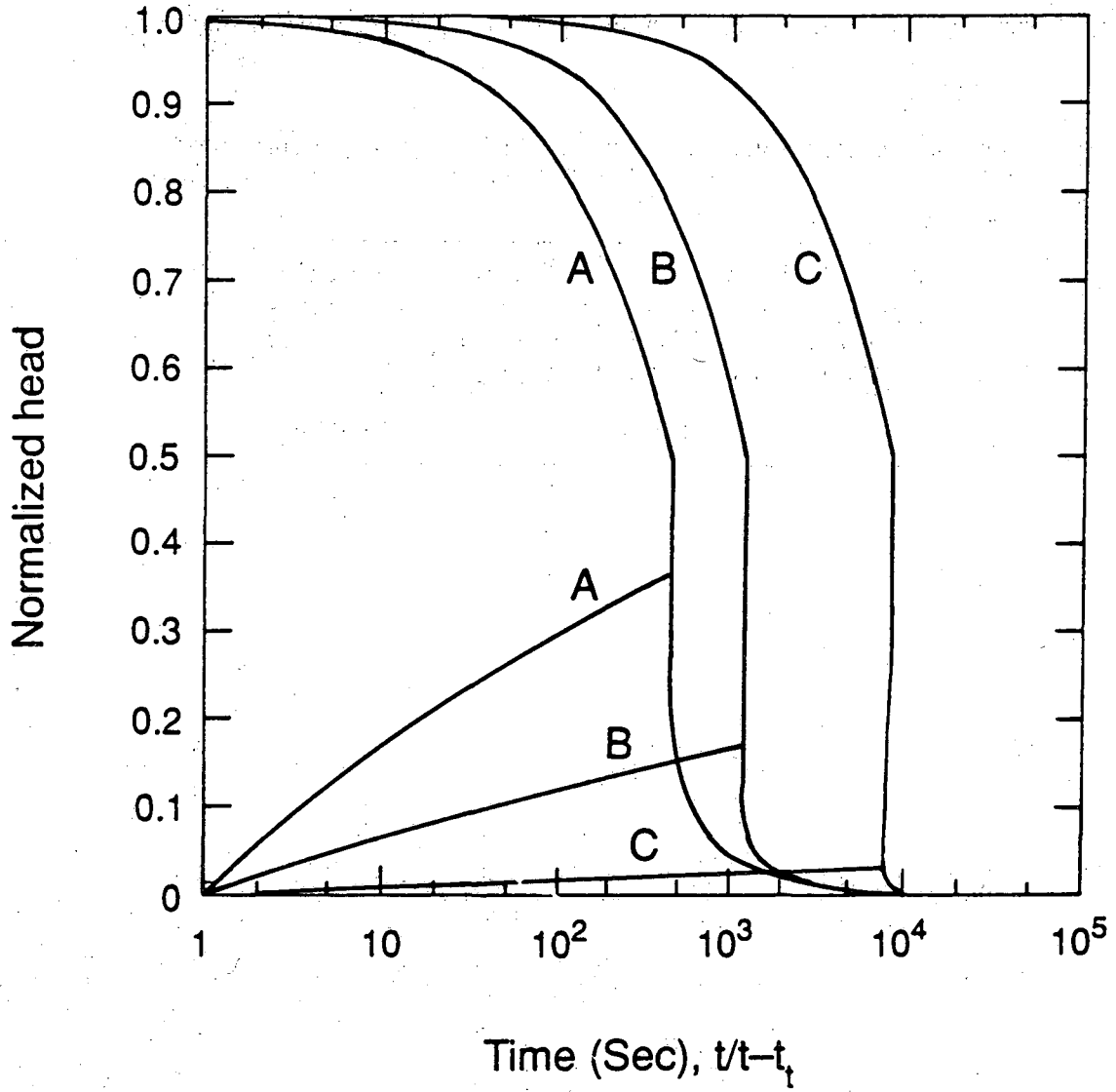
XBL 904 - 6367

Figure 4.1. A well with a finite radius skin.



XBL 907-2498

Figure 4.2. Simulated slug test data with the parameters in Table 4.1.



XBL 904 - 6368

Figure 4.3. Simulated PTST data with the parameters in Table 4.1.

Aquifer parameters are then estimated by using the type curves of Ramey et al. or Moench and Hsieh. Because these curves are nearly identical in shape, it is very difficult to find a unique match. Therefore, only a possible range of transmissivity values can be estimated. However, from the PTST data and using (3.18), the formation transmissivity can be successfully recovered.

Table 4.2 shows the comparison of the interpreted permeabilities by the two methods.

Table 4.2. Comparison of permeabilities obtained by using Ramey et al.'s curves and the DST method.

	Case A	Case B	Case C
Slug test	$1 \times 10^{-7}$ m/s	$5 \times 10^{-8}$ m/s	$1 \times 10^{-8}$ m/s
DST	$1.1 \times 10^{-7}$ m/s	$1 \times 10^{-7}$ m/s	$1.1 \times 10^{-7}$ m/s
Actual	$1 \times 10^{-7}$ m/s	$1 \times 10^{-7}$ m/s	$1 \times 10^{-7}$ m/s



## 5.0. Summary and Conclusions

In the present paper, a solution to a prematurely terminated slug test (PTST) problem was presented. A PTST is, in essence, the same as a drill stem test (DST), which is more widely known in the petroleum terminology. The author wishes to bring attention of field hydrologists to the utility of a DST. A systematized procedure of a DST was proposed, where a slug test is terminated in the midpoint of the flow period, and subsequent shut-in data are recorded and analyzed. This method requires a downhole shut-in device and a pressure transducer, which is no more than the conventional deep-well slug testing. The advantages of a DST over a conventional slug test were discussed. As opposed to a slug test, which are ineffective when a skin is present, more accurate estimate of formation permeability can be made using a DST. Premature termination also shortens the test duration considerably. Because in most cases no more information is gained by completing a slug test to the end, the author recommends that conventional slug tests be replaced by premature termination technique. It is important to note here, however, that for more accurate estimation of aquifer parameters, constant rate tests are much more favorable.

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