Attachment B

AN ANALYSIS OF AIR PERMEABILITY TESTING IN BOREHOLE UZ-16, YUCCA MOUNTAIN, NEVADA

Prepared for:

The Nye County Nuclear Waster Repository Project Office

by:

Advanced Resources International, Inc.

December, 1994

ARI Advanced Resources International Inc.

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I. INTRODUCTION

This report presents an independent analysis prepared by Advanced Resources International, Inc. ("ARI") of air permeability testing conducted by the U.S. Geological Survey ("USGS") in Borehole UZ-16 at Yucca Mountain, Nevada. This analysis was prepared at the request of Mr. J.N. Stellavato of the Nye County Nuclear Waste Repository Office ("Nye County"). The main objectives of this investigation were as follows:

1. Interpret the air permeability tests conducted in wells UZ-16, NRG-6 and NRG 7/7A using state-of-the-art well test analysis methods from the oil and gas industry. The test data for NRG-6 and NRG 7/7A have not yet been provided; accordingly, this report only covers Borehole UZ-16.

2. Review the results of the USGS analysis of the same data, and discuss the merits of the USGS analysis.

3. Provide technical recommendations to the County for future testing and analysis, to aid the County in understanding and analyzing the flow system at Yucca Mountain.

Information provided for this effort consisted of an article by G.D. LeCain and J.N. Walker[1] of the USGS entitled "Results of Air Permeability Testing in a Vertical Borehole at Yucca Mountain, Nevada," published in *Radioactive Waste Management*; and a USGS data package[2] of "Air-K Permeability Data from UE-25 UZ-16 Borehole collected from 11-03-93 to 3-31-94," including ten (10) diskettes with raw sensor data and six (6) diskettes with data converted to scientific units for the various tests. In all, the USGS conducted more than 250 air injection tests in UZ-16 from November 1993 to March 1994. Their analysis included semi-log and type curve analysis, and steady-state flow analysis to evaluate permeability of the tested intervals. They noted that "pressured-squared differences" should be used instead of pressure to account for the compressible nature of air. Other assumptions they used included ideal gas behavior, isothermal flow, and negligible gravitational effects.

Data files obtained by Nye County from the USGS for the various tests contain measured pressure data for the injection zone and packed-off intervals above and below the injection interval, and temperature and relative humidity in the injection interval. Air injection rates as versus time were also included in some data files. Pressure data were reported in kilopascals, temperature in degrees Kelvin and flow rates in standard liters per minute (slpm). Handwritten daily reports and typed weekly reports contained information regarding test intervals, rates and durations.

It was assumed that the data provided by the USGS were accurate. It should be noted, however, that the test interval thickness was based on the interval between the middle packers (or between the uppermost and third packer in a few cases where the upper interval gauge recorded significant pressure increase). The actual thickness accepting flow could have been less than the assumed thickness.

For ARI's independent analysis, the pressure, temperature and flow rate data were converted into petroleum industry units for consistency with the analysis program used. Oilfield units are pounds per square inch (psia) for pressure, degrees Fahrenheit (°F) for temperature, and thousand standard cubic feet per day (Mcfd) for flow rates. Standard conditions used in the petroleum industry (14.7 psia and 60°F) differ slightly from those used by the USGS (101.3 kPa and 273.17°K), and an adjustment was made to account for this difference.

Edinburgh Petroleum Systems' *PanSystem* computer-aided well test analysis program[3] was used for ARI's analysis. *PanSystem* is one of the most sophisticated and user-friendly analysis systems commercially available. This program is based on type-curve analysis, and contains several hundred type curves that may be selected by the user. It can be used for wells with oil, gas or water flow, or combinations of oil, gas and water (multi-phase flow). Four wellbore storage models are available, and a range of reservoir boundary conditions (faults, no-flow or constant pressure boundaries). Flow geometry may be radial, linear, bilinear, or spherical. Conventional and fractured vertical wells can be analyzed, as well as horizontal wells. The program is suitable for constant rate or variable rate tests.

The most important differences between the USGS analysis and analyses with the *PanSystem* are the pressure derivative, wellbore storage and skin effect, and variable rate analysis. *PanSystem* was designed to include these factors in every analysis automatically. The USGS, however, apparently did not evaluate those factors for every test.

Based on our understanding of the objectives of the investigation, the following work plan was formulated:

1. Review USGS data to identify how many and what type of tests were run, and whether sufficient data existed to analyze the tests.
2. Convert USGS data into oil-field units, and import data into *PanSystem* for analysis.
3. Prepare analysis of selected tests to evaluate the effectiveness of the USGS methodology. The first tests reviewed were those reported in the USGS article in *Radioactive Waste Management*. Other tests would be evaluated as warranted.
4. Compare results to USGS results. Identify reasons for differences.
5. Prepare recommendations and report.

II. ANALYSIS

A. Data Review and Conversion

The initial review of the USGS report indicated 87 intervals in UZ-16 were tested, many at several injection rates, for a total of about 250 tests. The tests were mostly short-term injection tests several minutes to one hour in length, although a few tests were run overnight. Air injection rates ranged from 10 to 1000 slpm (0.5 to 54 Mcfd). The interval tested was commonly 13 feet between the middle packers. In a few instances, the gauge above or below the injection interval recorded significant pressure increase similar to that observed in the injection interval. In those cases, the USGS assumed the tested interval extended from the base of the top packer of the highest affected zone, to the top of the bottom packer of the lowest affected zone. The thermocouples recorded small changes in temperature during the tests.

Descriptive test information is summarized in Table 1. This table was prepared to show the date of the test, the file name used by the USGS, which zone(s) were tested, and the injection rates used in the test. The data on the USGS diskettes were arranged in files based on the test date. The files were formatted according to the layout listed in the USGS report on the testing. Many files contained bad data, or some alternate format; those files with bad or questionable data are noted in the remarks section of Table 1. The pressure, temperature and rate data were imported into a spreadsheet and converted into oil-field units for use with the *PanSystem*.

Additional data required for the test analysis included the following:

- Air Viscosity 0.018 cp
- Average Temperature 60°F
- Average Gas Deviation Factor (Z-factor) 1.0
- Assumed Porosity 1%
- Assumed Average Compressibility 0.067 psia^{-1}

Computed results are insensitive to probable errors in these estimates. The maximum error in air viscosity is less than 10%, and a 20° error in temperature would change the computed permeability by only a few percent. The gas deviation factor should be correct to within 1%. Errors in porosity and compressibility affect the computed skin factor and not permeability. A factor of ten change in porosity or compressibility would only change the skin factor by ±1.

Table 1: Summary Data For USGS Well Tests of UZ-16

TEST DATE	FILE NAME	FORMATION	TEST INTERVAL 1	TEST INTERVAL 2	TEST INTERVAL 3	TEST INTERVAL 4	REMARKS
Nov. 18, 1993	111893.REC	Prow Pass	1661-1674	1641-1654	1609-1622		
Nov. 29, 1993	112993.REC	Prow Pass	1609-1622 20 slpm				
Nov. 30, 1993	113093.REC	Calico Hills	1406-1419 20 and 250 slpm	1341-1354 20 slpm			
Dec. 1, 1993	120193.REC	Calico Hills	1297-1310 20 slpm				Injected overnight
Dec. 2, 1993	120293.REC	Calico Hills	1297-1310 5, 10 and 20 slpm				
Dec. 6, 1993	120693.REC	Calico Hills	1297-1310 30 slpm				Injected overnight
Dec. 7, 1993	120793.REC	---	---				No useable data in file
Dec. 14, 1993	121493.REC	Tiva Canyon	60-73 250, 500 and 750 slpm				USGS Interpretations reported in Radioactive Waste Management article.
Dec. 15, 1993	121593.REC	Tiva Canyon	70-83 250, 500 and 750 slpm				USGS Interpretations reported in Radioactive Waste Management article.
Dec. 16, 1993	121693.REC	Tiva Canyon	85-122 500, 750 and 1000 slpm	119-132 250, 500 and 750 slpm			USGS Interpretations reported in Radioactive Waste Management article.
Dec. 17, 1993	121793.REC	Topopah Springs	256-269 50, 250 and 500 slpm	271-284 250, 500 and 750 slpm	289-302 250 and 500 slpm		USGS Interpretations reported in Radioactive Waste Management article. Data for Test 1 not in file.
Dec. 20, 1993	122093.REC	Topopah Springs	453-466 50, 300 and 600 slpm				Some bad data in file
Dec. 21, 1993	122193.REC	Topopah Springs	467-480 150 and 500 slpm	511-524 150, 300 and 600 slpm	521-534 150, 300 and 600 slpm	531-544 150, 300 and 600 slpm	Test last zone at 90 slpm overnight
Dec. 22, 1993	122293.REC	----					Monitor barometric response
Dec. 27, 1993	122793.REC	----					Monitor barometric response
Jan. 3, 1994	010394.REC	Topopah Springs	541-554 150, 300 and 600 slpm	551-564 150 slpm	556-569 150 and 300 slpm		
Jan. 4, 1994	010494.REC	Topopah Springs	556-569 600 slpm	561-574 150, 300 and 600 slpm	571-584 150, 300 and 600 slpm		
Jan. 5, 1994	010594.REC	Topopah Springs	581-594 150 and 300 slpm	573-586 150 slpm	575-588 150 slpm		
Jan. 7, 1994	010794.REC	Topopah Springs	577-590 150 slpm	579-592 150 slpm			
Jan. 10, 1994	011094.REC	Topopah Springs	583-596 150 slpm	585-598 150 slpm			
Jan. 11, 1994	011194.REC	Topopah Springs	591-604 20 slpm	597-610 20, 40 and 80 slpm			
Jan. 13, 1994	011394.REC	Topopah Springs	601-614 20 and 80 slpm				
Jan. 18, 1994	011894.REC	Topopah Springs	611-624 20, 40 and 80 slpm				
Jan. 19, 1994	011994.REC	Topopah Springs	621-634 20, 50 and 80 slpm	631-644 40, 80 and 160 slpm			
Jan. 20, 1994	012094.REC	Topopah Springs	641-654 40, 80 and 160 slpm	651-664 80 slpm			
Jan. 24, 1994	012494.REC	Topopah Springs	611-624 80 slpm	641-654 80 slpm			
Jan. 25, 1994	012594.REC	----					Monitor air velocity due to barometric pressure
Jan. 27, 1994	012794.REC	----					Monitor barometric response
Jan. 31, 1994	013194.REC	Topopah Springs	655-668 20 slpm				Injected overnight at 20 slpm
Feb. 1, 1994	020194.REC	Topopah Springs	655-668 10, 15 and 20 slpm				Injected overnight at 30 slpm
Feb. 2, 1994	020294.REC	Topopah Springs	655-668 10, 20 and 30 slpm				Injected overnight at 10 slpm
Feb. 3, 1994	020394.REC	Topopah Springs	655-668 5, 8 and 10 slpm				

Table 1: Summary Data For USGS Well Tests of UZ-16 (Continued)

TEST DATE	FILE NAME	FORMATION	TEST INTERVAL 1	TEST INTERVAL 2	TEST INTERVAL 3	TEST INTERVAL 4	REMARKS
Feb. 7, 1994	020794.REC	Topopah Springs	6[illegible]1 684 10, 60, 95, 250 and 500 slp				
Feb. 8, 1994	020894.REC	Topopah Springs	671-684 600 and 1000 slpm	679-692 300, 600 and 900 slpm	691-704 900, 1200 and 1500 slpm	705-718 900, 1200 and 1500 slpm	Some bad data in file
Feb. 9, 1994	020994.REC	Topopah Springs	713-726 750, 900 and 1050 slpm	722-735 750, 900 and 1050 slpm	731-744 750, 900 and 1050 slpm	749-762 750, 1050 and 1200 slpm	
Feb. 10, 1994	021094.REC	Topopah Springs	767-780 300, 450 and 900 slpm	781-794 90, 150 and 450 slpm	791-804 90, 150 and 250 slpm	801-814 90, 150 and 250 slpm	Considerable bad data in file
Feb. 14, 1994	021494.REC	Topopah Springs	811-824 90, 150 and 250 slpm	822-835 90, 150 and 500 slpm	831-844 150, 300 and 600 slpm		Considerable bad data in file
Feb. 15, 1994	021594.REC	Topopah Springs	841-854 300, 600 and 750 slpm	849-862 600, 750 and 900 slpm	861-874 300, 450 and 600 slpm		
Feb. 16, 1994	021694.REC	Topopah Springs	869-882 300, 450 and 600 slpm	881-894 300, 450 and 600 slpm	896-909 300, 450 and 600 slpm		
Feb. 22, 1994	022294.REC	Topopah Springs	906-919 150, 250 and 300 slpm	921-934 150, 300 and 450 slpm	931-944 300, 600 and 1000 slpm		
Feb. 23, 1994	022394.REC	Topopah Springs	939-952 450, 1200 and 1500 slpm	949-962 900, 1200 and 1500 slpm	958-971 900, 1200 and 1500 slpm		
Feb. 24, 1994	022494.REC	Topopah Springs	971-984 90, 300 and 600 slpm	981-994 150, 300 and 450 slpm			
Feb. 28, 1994	022894.REC	Topopah Springs	991-1004 150, 300 and 450 slpm	1001-1014 60, 90 and 150 slpm			
Mar. 1, 1994	030194.REC	Topopah Springs	1011-1024 90, 150 and 300 slpm				
Mar. 2, 1994	030294.REC	Topopah Springs	1021-1034 150, 250 and 375 slpm				
Mar. 3, 1994	030394.REC	Topopah Springs	1031-1044 150, 250 and 375 slpm	1046-1059 150, 300 and 600 slpm	1061-1074 300, 600 and 750 slpm	1091-1104 150, 300 and 450 slpm	
Mar. 7, 1994	030794.REC	Topopah Springs	1076-1089 150, 225 and 300 slpm	1181-1194 30, 40 and 60 slpm			
—		Calico Hills	1251-1264 10 slpm				Injected overnight at 10 slpm
Mar. 8, 1994	030894.REC	Calico Hills	1251-1264 Pressure bleed-off				Not a pressure falloff test.
Mar. 9, 1994	030994.REC	Calico Hills	1341-1354 15 slpm				Injected overnight at 15 slpm
Mar. 10, 1994	031094.REC	Calico Hills	1341-1354 8 and 15 slpm				Considerable bad data in file
Mar. 14, 1994	031494.REC	Calico Hills	1421-1434 20 slpm				Bad data in file; injected overnight at 20 slpm
Mar. 15, 1994	031594.REC	Calico Hills	1421-1434 30 slpm				Bad data in file; injected overnight at 30 slpm
Mar. 16, 1994	031694.REC	Calico Hills	1421-1434 30 slpm (cont.)				Bad data in file; injected overnight at 30 slpm
Mar. 17, 1994	031794.REC	Prow Pass	1631-1644 40 slpm; 35 psi				Bad data in file; Test designed "to determine if skin damage present"
Mar. 21, 1994	032194.REC	Prow Pass	1631-1644 10 slpm				Bad data in file; injected overnight at 10 slpm
Mar. 22, 1994	032294.REC	Prow Pass	1631-1644 6, 8 and 10 slpm				Bad data in file; injected overnight at 20 slpm
Mar. 23, 1994	032394.REC	Prow Pass	1631-1644 10, 15 and 20 slpm				Bad data in file; injected overnight at 30 slpm
Mar. 24, 1994	032494.REC	Prow Pass	1631-1644 10, 20 and 30 slpm				
Mar. 28, 1994	032894.REC	Calico Hills	1297-1310 10 slpm				Injected overnight at 10 slpm USGS interpretations reported in Radioactive Waste Management article.
Mar. 29, 1994	032994.REC	Calico Hills	1297-1310 30 slpm				Injected overnight at 30 slpm USGS interpretations reported in Radioactive Waste Management article.
Mar. 30, 1994	033094.REC	Calico Hills	1297-1310 30 slpm (cont.)				USGS interpretations reported in Radioactive Waste Management article.
Mar. 31, 1994	033194.REC	Calico Hills	1297-1310 Falloff				USGS interpretations reported in Radioactive Waste Management article.

Based on data provided in USGS Weekly Operations Reports.

B. Tiva Canyon Test, 60-73'

The first test selected for analysis was that of the Tiva Canyon zone from 60 to 73 feet in depth, which was the first test listed in the USGS *Radioactive Waste Management* article. The Tiva Canyon interval from 60 to 73 feet depth (18.3-22.3 m) was tested on Dec. 14, 1993. Initially, 50 slpm (2.7 Mcfd) was attempted, but the pressure response was negligible at that rate, so the rate was increased to 250 slpm (13 Mcfd). This rate was held for 4 minutes, after which injection was halted for 13 minutes. In the second injection period, 500 slpm (27 Mcfd) was injected for 9 minutes. Subsequently, 750 slpm (40 Mcfd) was injected for 8 minutes. The pressure response observed during the test is shown in **Figure 1**. As seen from this graph, the pressure increased by approximately 0.3 psi during the first injection period, 0.9 psi during the second injection period, and 1.5 psi in the final injection period. The falloff response was not monitored.

The first analysis step normally used in modern well test interpretation is a plot of the change in pressure (or pressure-squared) versus flow time on log-log paper[4] (such as **Figure 2**). The pressure response is compared to a family of type curves, which are computed pressure responses for various reservoir and well properties. At early times, pressure data follow a unit slope (45° line), which indicates wellbore storage[3-6]. For radial flow in the reservoir, with wellbore storage and skin, the pressure follows the wellbore storage response (45° line), and then smoothly flattens out to follow a nearly horizontal line. The *PanSystem* also computes the pressure derivative response. The pressure derivative type curves have a characteristic hump, and then bend over and reach a stabilized level. The proper semi-log straight line occurs after the derivative reaches its stabilized level[3-6].

As seen on **Figure 2**, the derivative curve never stabilized, so semi-log analysis would be incorrect. The type curve match suggested a permeability (k) of 200000 millidarcies (md) or 200 darcies ($200\text{x}10^{-12}$ m^2), a skin factor (S) of +134, and an effective wellbore storage constant (C_s) of 2.7 bbl/psi. The large wellbore storage and skin factor preclude accurate permeability determination with such a short test. To achieve one log cycle of stabilized derivative response, injection should have been continued for 1 hour or more. The wellbore storage constant was computed from the unit slope line (so the data were effective in evaluating the wellbore storage), and the shape of the derivative curve is diagnostic of a high skin factor, but the test was not long enough for accurate permeability determination. In simplistic terms, the test evaluated the capacity of the well to hold air, and not the formation permeability. The type curve match for the higher rate tests had similar results (Figures 3 and 4).

The interpretation was not materially changed by using pressure-squared differences (Figure 5). The pressure-squared method partially corrects for changes in compressibility at different pressure. The variance between the actual pressure and the computed pressure was probably due to minor changes in injection rate during the test, or to finite skin. The type curves assume that the skin or damage in a well occurs in an infinitesimally thin layer around the well, but in reality, the skin may extend several inches or feet into the rock. *PanSystem* contains additional type curves for finite skin, but these were not used because they would not change the basic problem that the test was not run long enough for stabilized flow into the formation to be reached. Figure 6 is a semi-log plot of the observed response at 750 slpm (40 Mcfd) injection; the correct semi-log straight line on this plot would not occur until after more than 1 hour of injection. (In the petroleum industry, semi-log plots of flow period data are known as MDH plots. They are essentially the same as the Cooper and Jacob plots used by hydrologists.)

Tests that do not reach a stabilized derivative are notoriously inaccurate for permeability evaluation. Figure 6 contains the simulated response for a permeability of 210 darcies. For illustration, a similar match was computed for a different permeability (400 darcies) and skin factor (+190), as shown in Figure 7. The simulated results in Figures 6 and 7 were nearly identical, which is typical when trying to analyze a test that was run for too short a period.

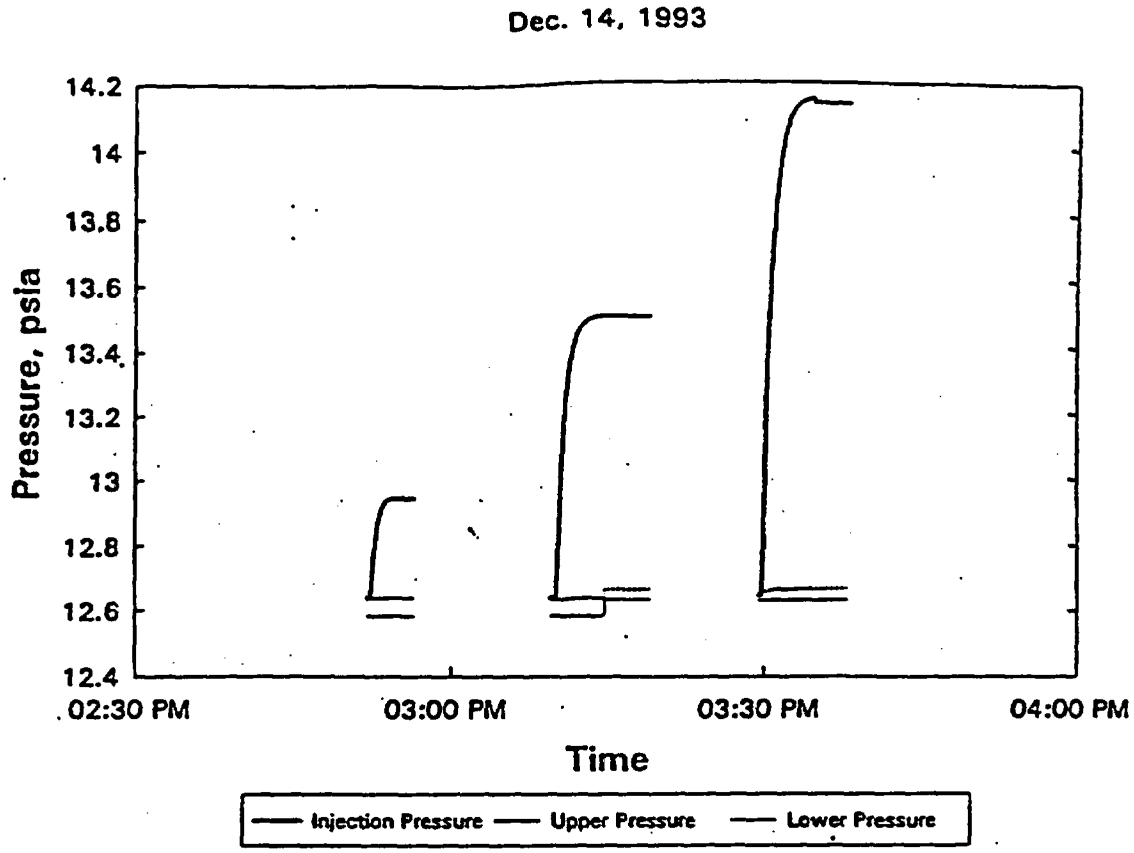


Figure 1: Test of Tiva Canyon 60-73'

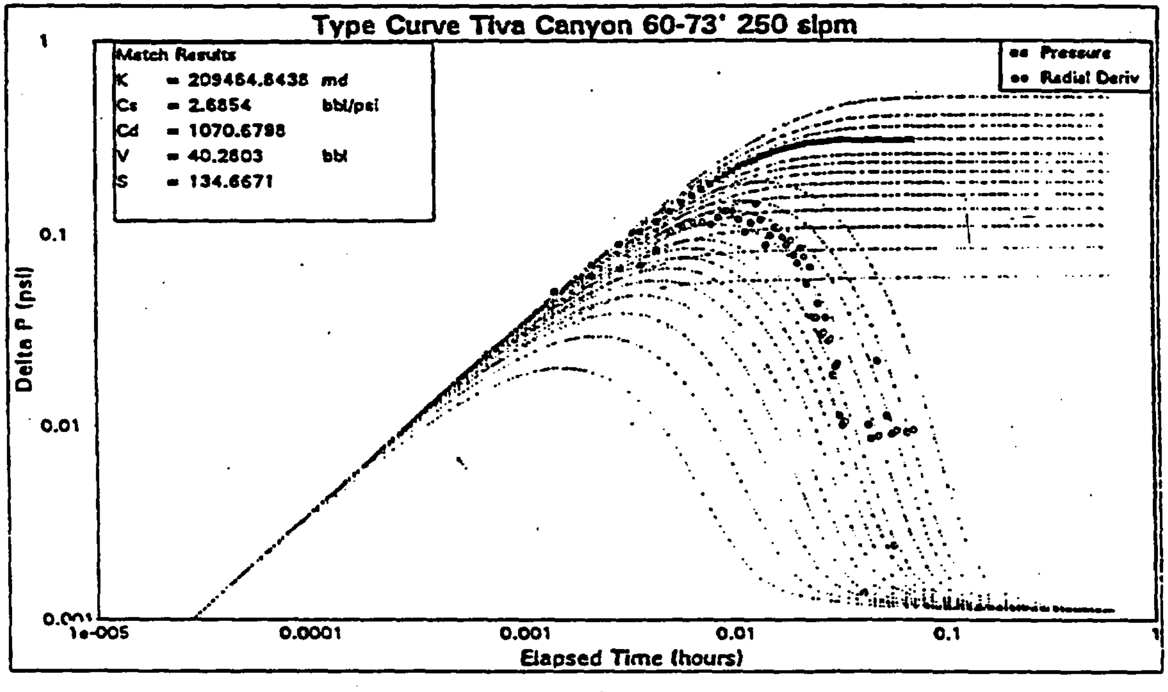


Figure 2: Type Curve Tiva Canyon 60-73' 250 slpm

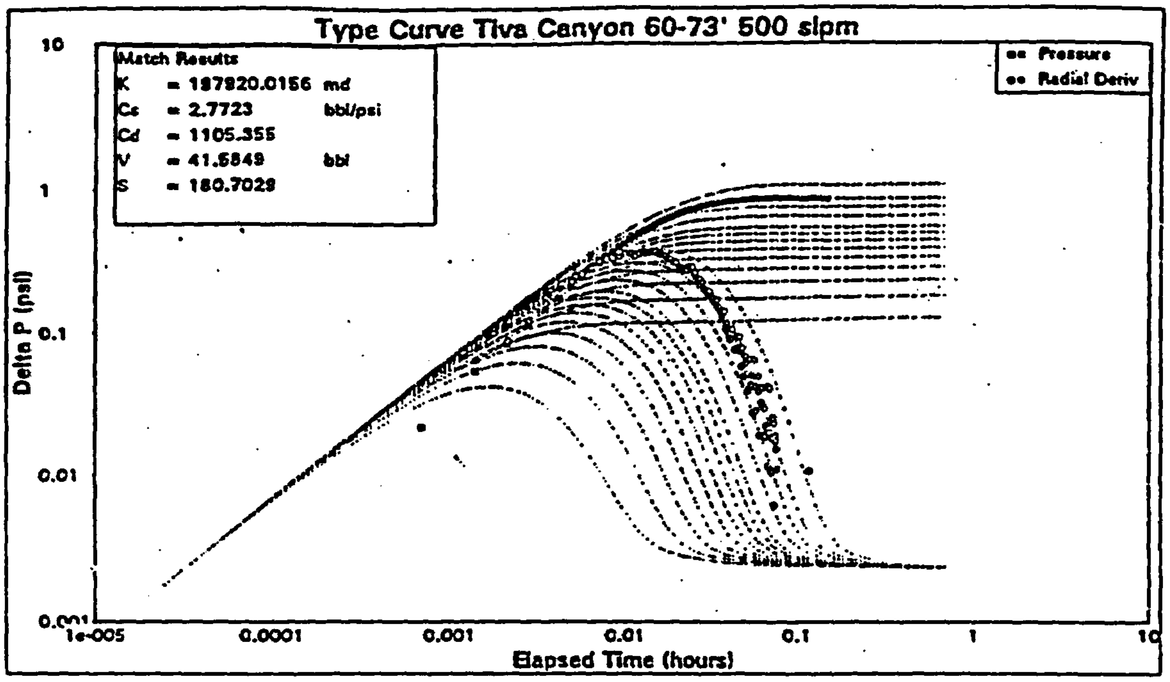


Figure 3: Type Curve Tiva Canyon 60-73' 500 slpm

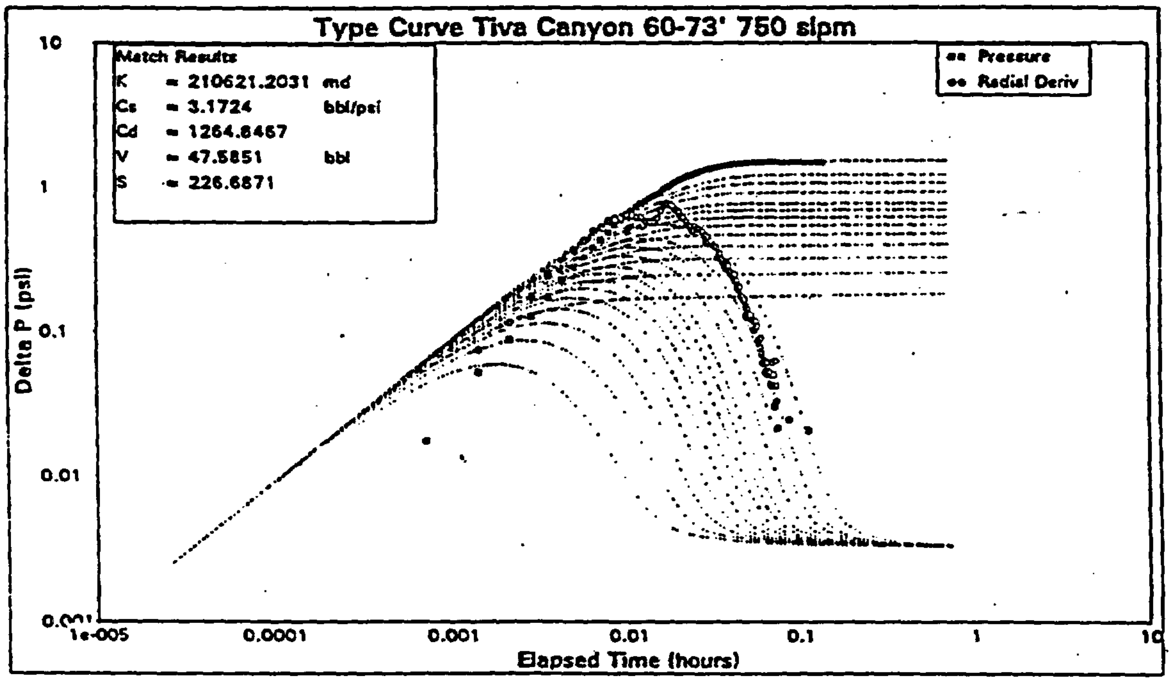


Figure 4: Type Curve Tiva Canyon 60-73' 750 slpm

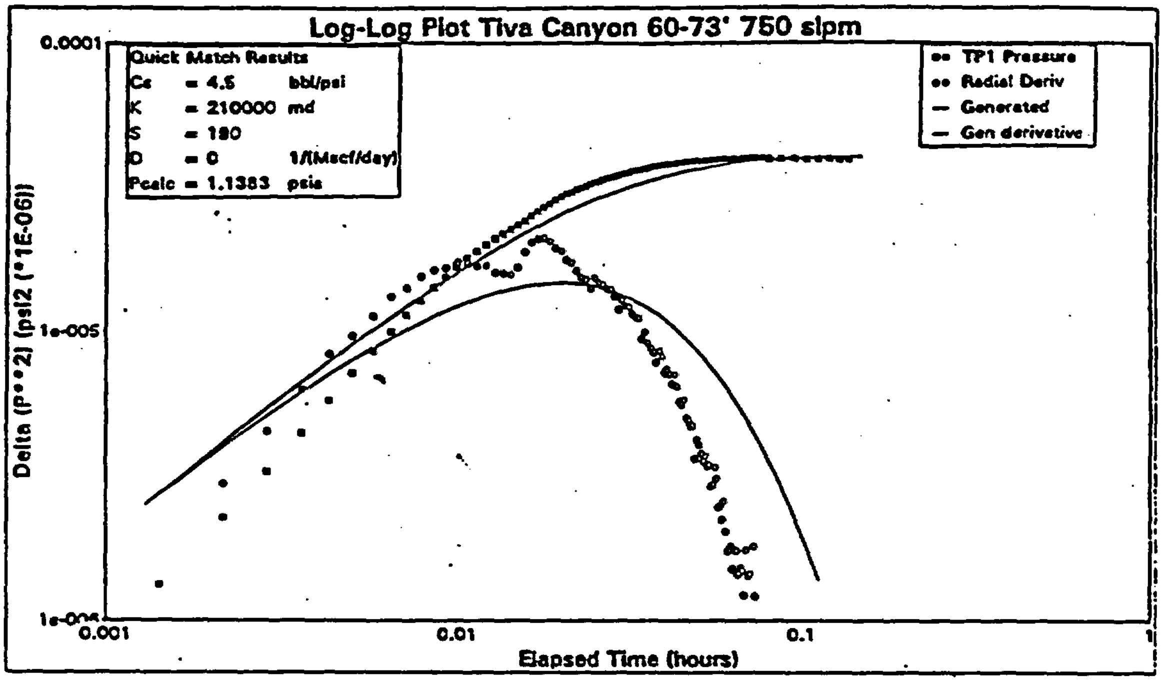


Figure 5: Log-Log Plot Tiva Canyon 60-73' 750 slpm

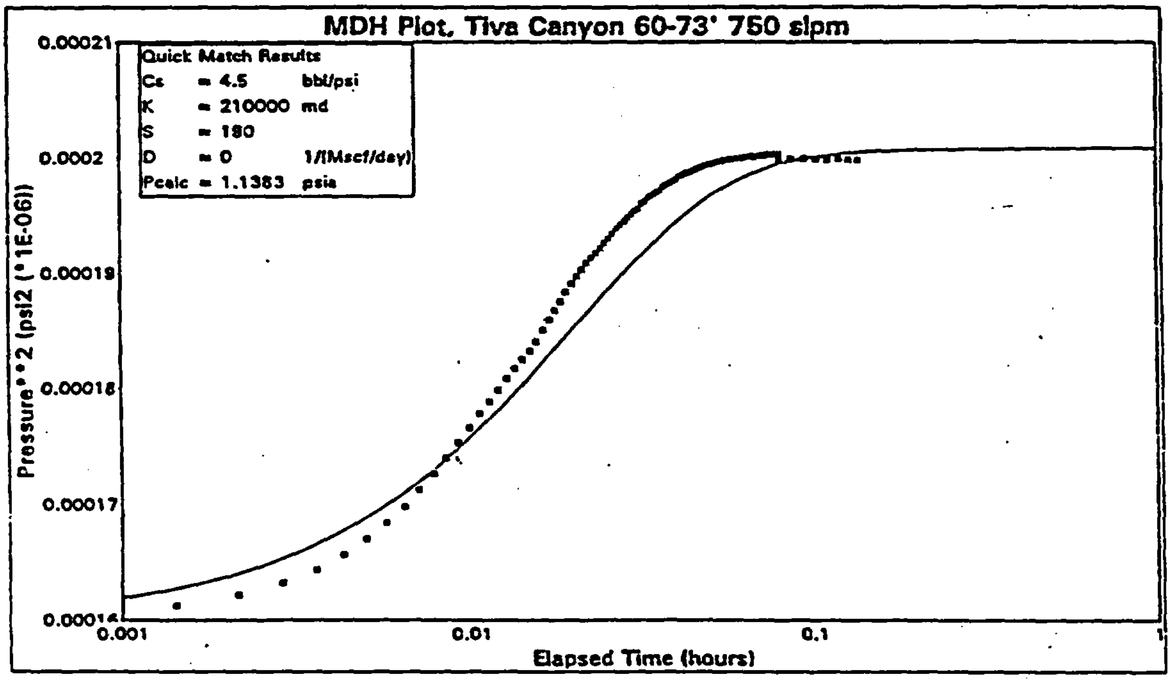


Figure 6: MDH Plot Tiva Canyon 60-73' 750 slpm (210 D)

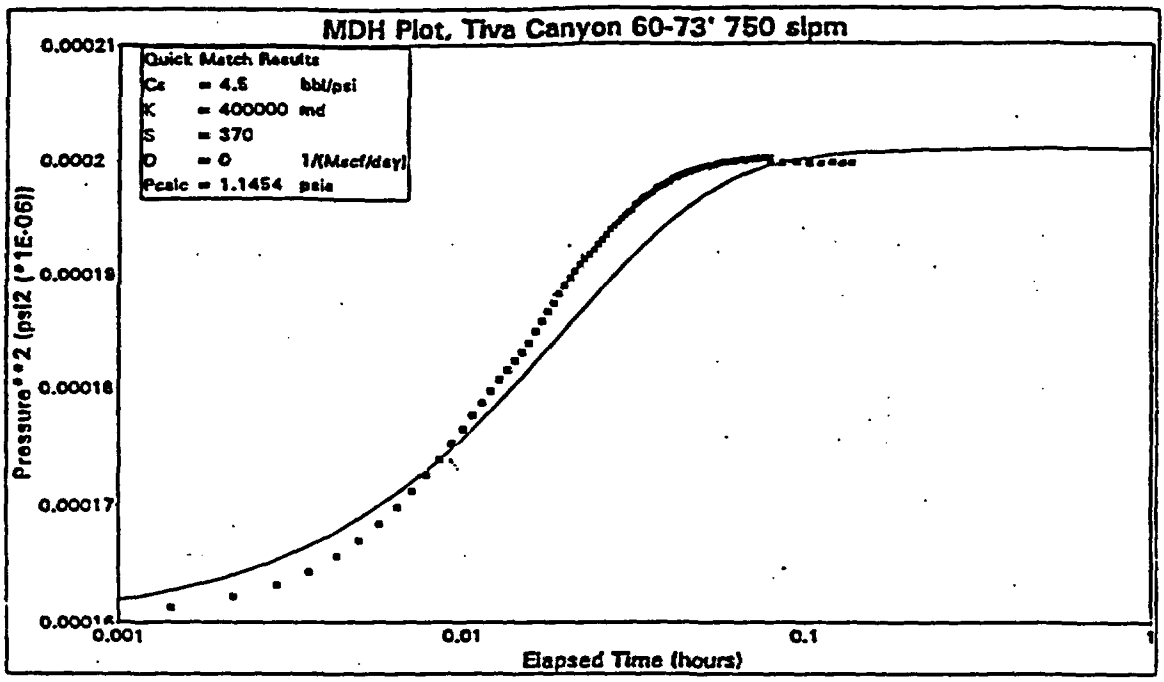
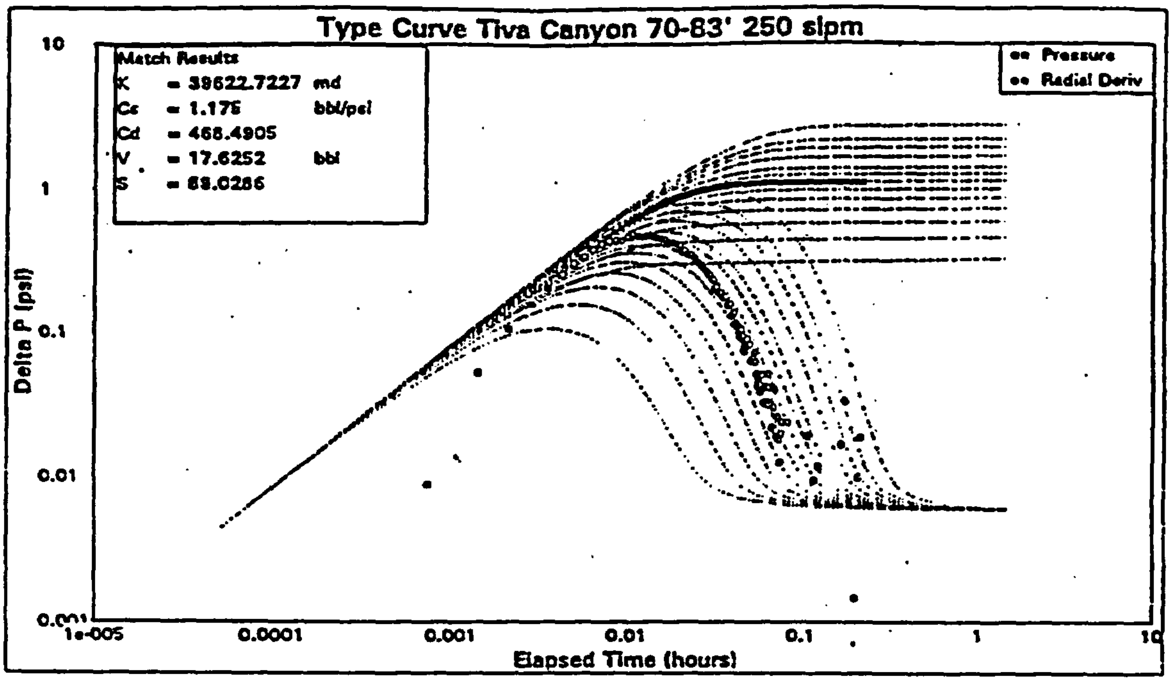


Figure 7: MDH Plot Tiva Canyon 60-73' 750 slpm (400 D)

C. Tiva Canyon Test, 70-83'

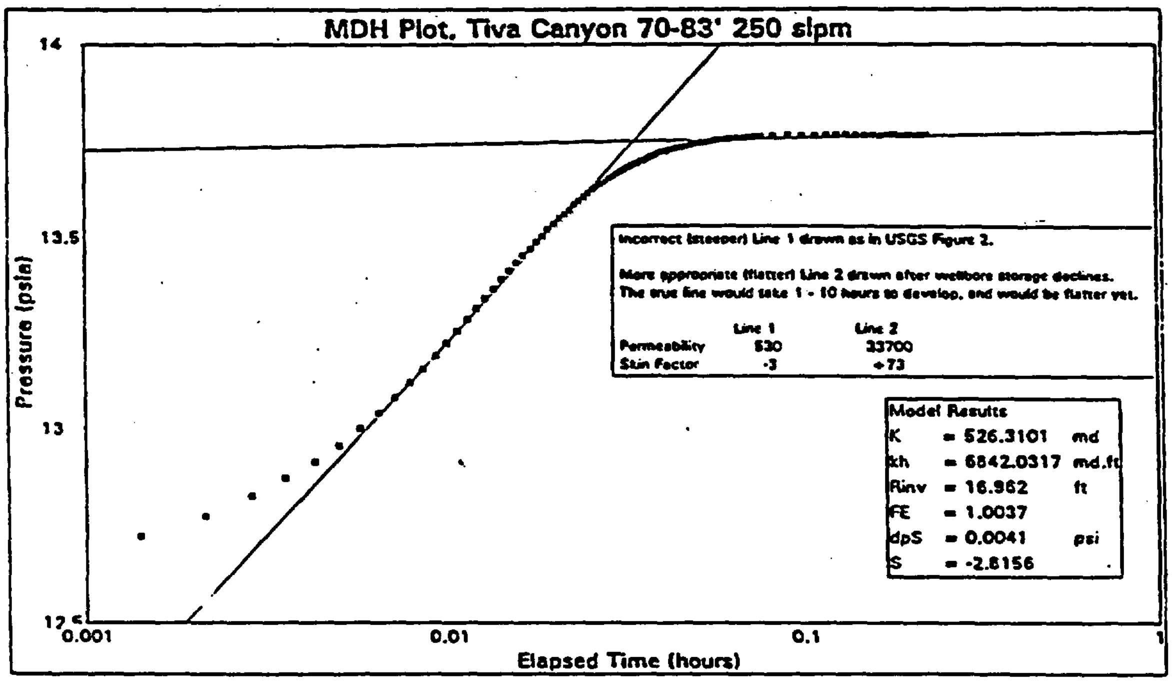
Tests of the Tiva Canyon Member from 70 to 83 feet (21.3-25.3 m) were conducted by the USGS on Dec. 15, 1993. The type curve match for an injection rate of 250 slpm (13 Mcfd) is shown in Figure 8. It is possible that the derivative after 0.1 hours of injection may have been approaching stabilization; if so, a semi-log analysis would be feasible. A semi-log analysis of the 250 slpm response is presented in Figure 9. Two straight lines were drawn on Figure 9. The first line drawn corresponds to the location of the line drawn by the USGS in Figure 2 of their *Radioactive Waste Management* paper. Based on the derivative analysis, the proper semi-log line should be asymptotic to the late time data instead, leading to a computed permeability of 34 darcies (34000 md) instead of 530 md. The USGS computed a permeability of $5.8\text{x}10^{-13}$ m^2 from their semi-log analysis of this test, or 580 millidarcies. Thus, they used the earlier data for their straight line, which was a response to wellbore storage and not formation permeability.

However, it is doubtful whether the derivative was stable. The derivative response is computed from the measured pressures, and is subject to computation error and inherent errors because of gauge resolution. Examination of the response of this zone to other injection rates, such as Figure 10 for 750 slpm, suggests the derivative probably had not stabilized, and therefore any interpretation of the USGS tests of this zone are subject to the same uncertainties as the first test reviewed.



Match Results
K = 38622.7227 md
Cs = 1.175 bbl/psi
Cd = 468.4905
V = 17.6252 bbl
S = 68.0286

Figure 8: Type Curve Tiva Canyon 70-83' 250 slpm



Incorrect (steeper) Line 1 drawn as in USGS Figure 2.

More appropriate (flatter) Line 2 drawn after wellbore storage declines. The true line would take 1 - 10 hours to develop, and would be flatter yet.

	Line 1	Line 2
Permeability	530	33700
Skin Factor	-3	+73

Model Results
K = 526.3101 md
kh = 6842.0317 md.ft
Rinv = 16.962 ft
FE = 1.0037
dpS = 0.0041 psi
S = -2.8156

Figure 9: MDH Plot Tiva Canyon 70-83' 250 slpm

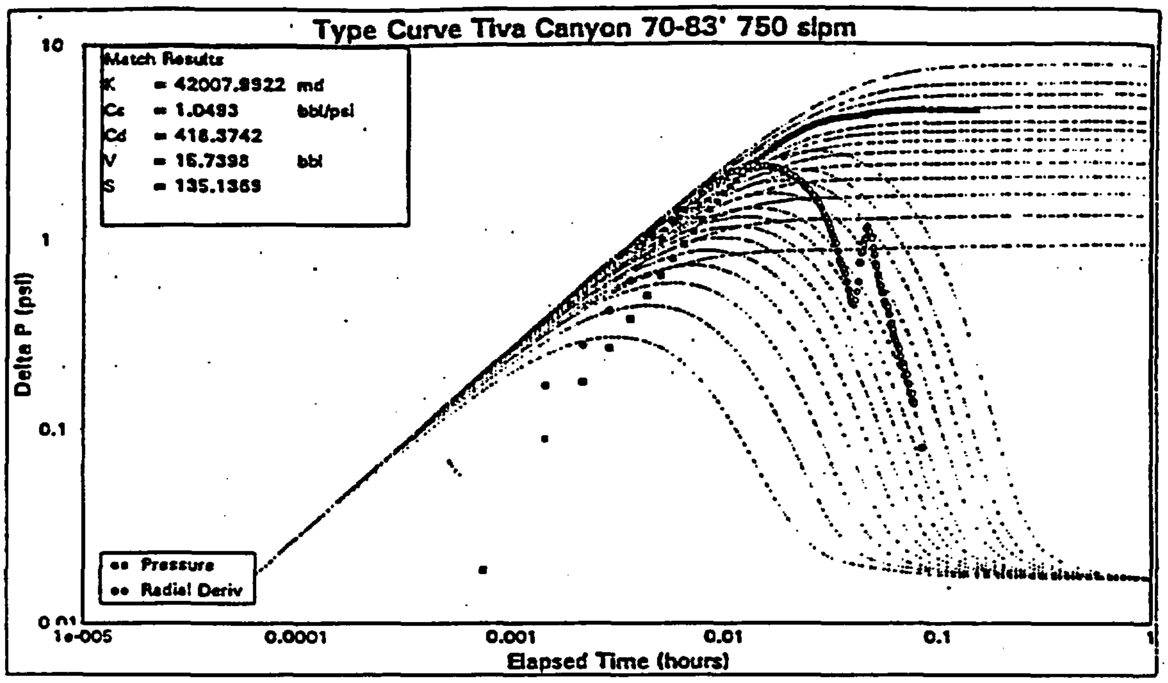


Figure 10: Type Curve Tiva Canyon 70-83' 750 slpm

D. Tiva Canyon Test, 85-122'

It had become apparent that many of the tests conducted by the USGS were not sufficiently long to get beyond the influence of wellbore storage and skin. Several other tests were analyzed to assess the likelihood of the first tests evaluated being exceptional, or part of a general pattern.

The Tiva Canyon was tested from 85 to 122 feet depth (25.9-37.2 m) on Dec. 16, 1993. This test was selected for review because it was also analyzed by the USGS, and it had a longer test interval, which would normally correspond to a larger wellbore constant. A type curve plot is presented in Figure 11 for the highest injection rate (1000 slpm or 54 Mcfd) used for this interval. The match shown in Figure 11 was for 125 darcies permeability and a skin factor of +19. The indicated wellbore storage constant was 45 bbl/psi. An alternate match is shown in Figure 12 for about the same storage constant, but much higher permeability and skin. It was concluded that the test was not run long enough to determine permeability accurately.

E. Tiva Canyon Test, 119-132'

Figure 13 contains a type curve plot for the Tiva Canyon test from 119 to 132 feet (36.3-40.2 m) conducted on Dec. 16, 1993. No derivative stabilization was observed, and it was therefore concluded that the test was not run long enough to determine permeability.

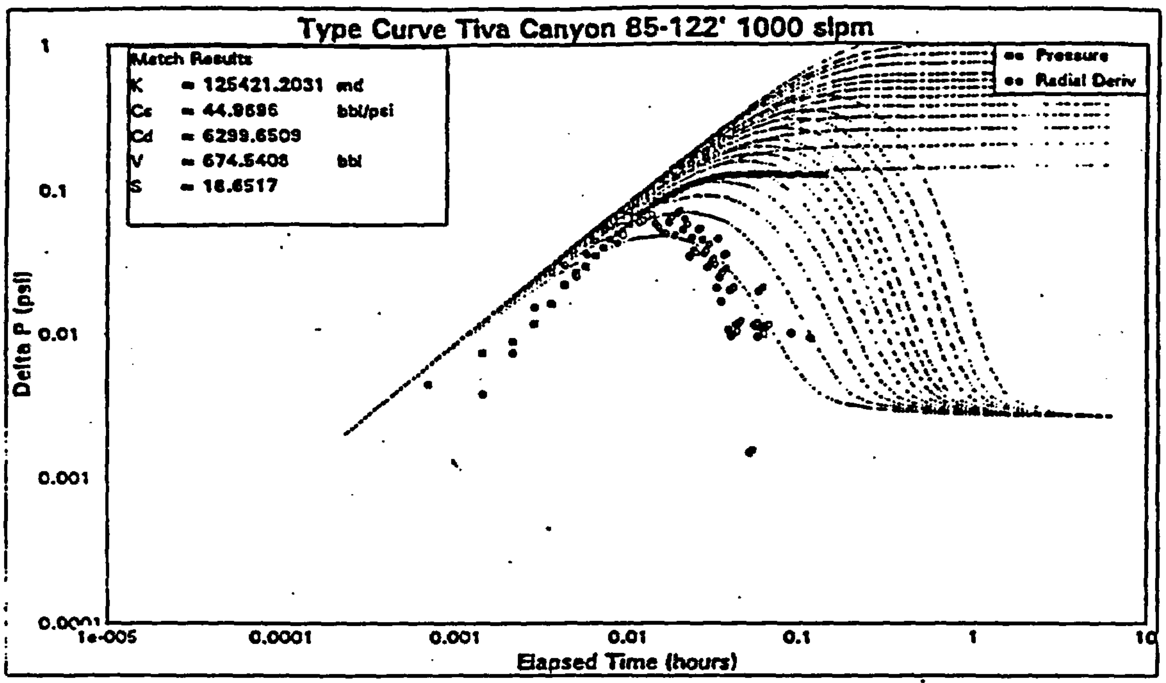


Figure 11: Type Curve Tiva Canyon 85-122' 1000 slpm (125 D)

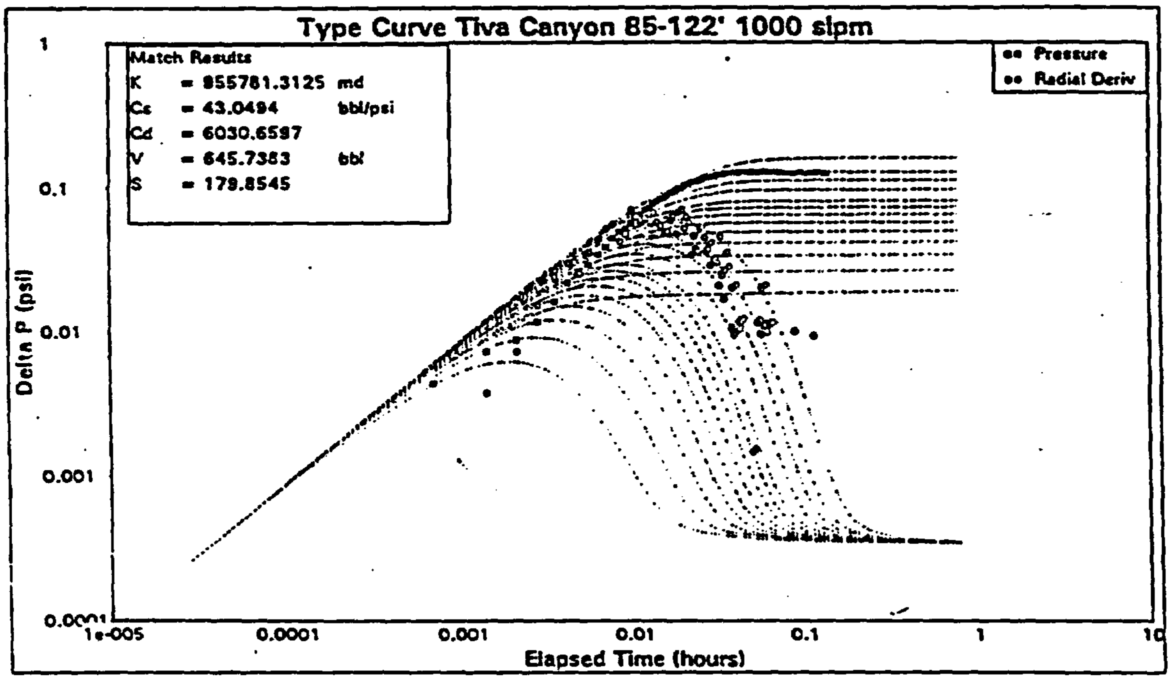


Figure 12: Type Curve Tiva Canyon 85-122' 1000 slpm (956 D)

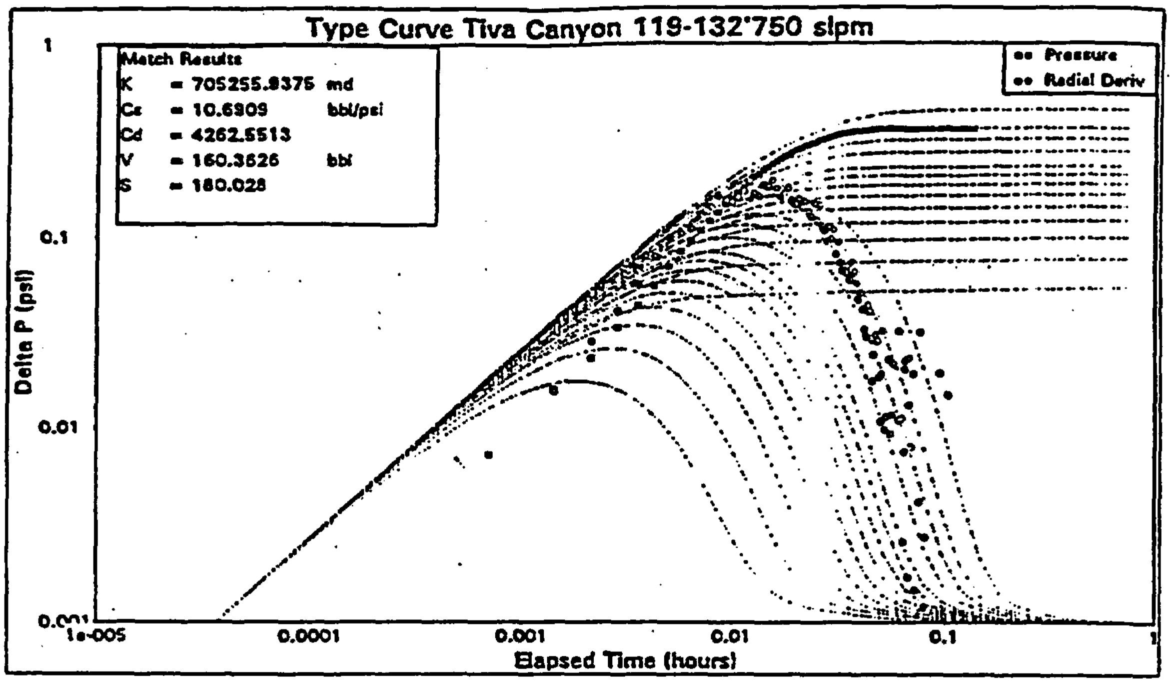


Figure 13: Type Curve Tiva Canyon 119-132' 750 slpm

F. Calico Hills Test, 1297-1310'

Because the short duration tests were not useful for permeability determination, a longer flow test was examined. The Calico Hills interval from 1297 to 1310 feet depth (395.4-399.4 m) was tested from March 28-31, 1994. Initially, injection was at 10 slpm (0.5 Mcfd), and the pressure rose to 40 psia and then dropped back to about 35 psia (see Figure 14). After about a day of injection, the well was vented for a short time. Injection at 30 slpm (1.6 Mcfd) was commenced, during which pressure remained relatively stable.

The pressure "hump" during injection at 10 slpm was unusual. In their *Radioactive Waste Management* article, the USGS attributed such humps to water drainage in the formation. Such an explanation is probably correct, although it would be more accurate to refer to the process as water displacement by the injected gas. Two-phase flow with varying fluid saturations leads to a much more complex set of flow equations, in that the gas and water saturations in the reservoir continuously change. The amount of change depends on unknown or poorly known relative permeability and dynamic capillary pressure relationships. The analysis of injection tests with these additional complicating factors would require numerical simulation. Without a pressure falloff response to better evaluate the skin effect, such an analysis would be meaningless. Any inferences regarding capillary pressure relationships based on pressure data from such tests should be considered unreliable, because of saturation gradients (and possible saturation discontinuities) varying with distance and time during such a test.

The response to 30 slpm (1.6 Mcfd) injection was more stable. The log-log plot of the pressure response (Figure 15) shows a different response than the other tests. The pressure followed a unit slope (wellbore storage) for almost an hour, but remained nearly flat after that. This response resulted from the unusual operational procedures. After injecting at 10 slpm for a day, the USGS vented the well before resuming injection. By venting the well, they allowed the wellbore to depressure at an extremely rapid rate, and the test interval produced back at a high (but unmeasured) rate. The pressure transient introduced by venting did not remove all the air that had been injected previously, which after a day of injection was stored mostly in the formation by compression to higher pressure, and not just in the well. After injecting for a short period, the volume produced during venting had been replaced, and thus the pressure flattened out. Without a measurement of the rate of venting, and without a proper pressure and derivative response to match, the second injection period data could not be analyzed.

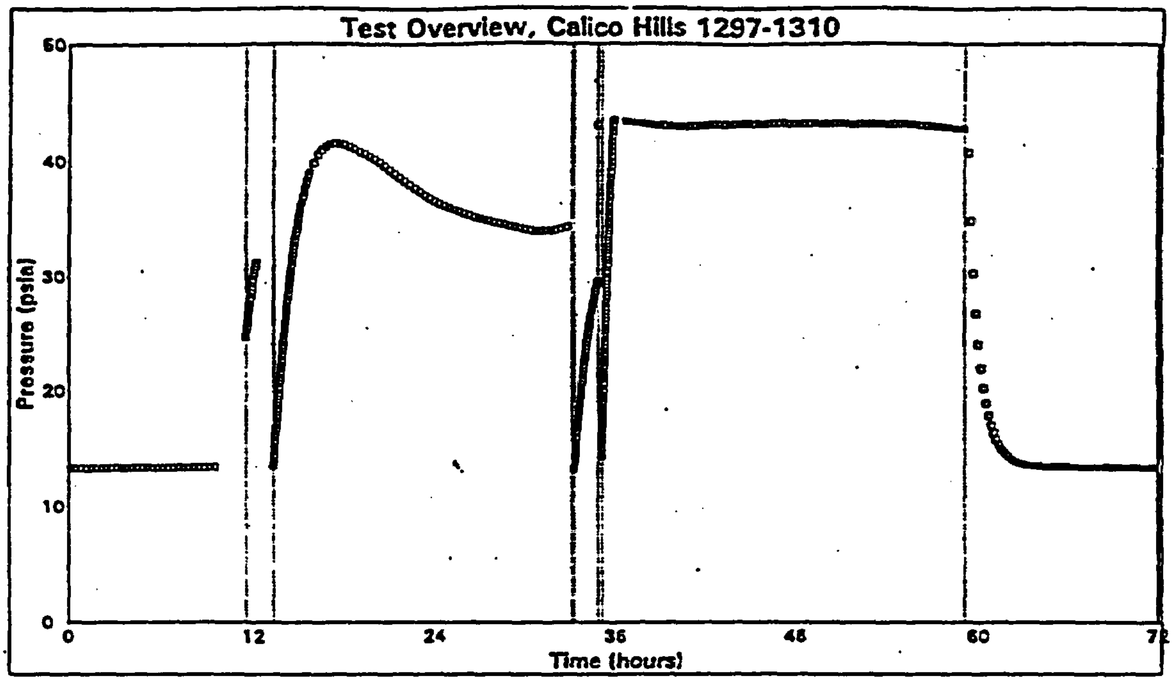


Figure 14: Test Overview Calico Hills 1297-1310'

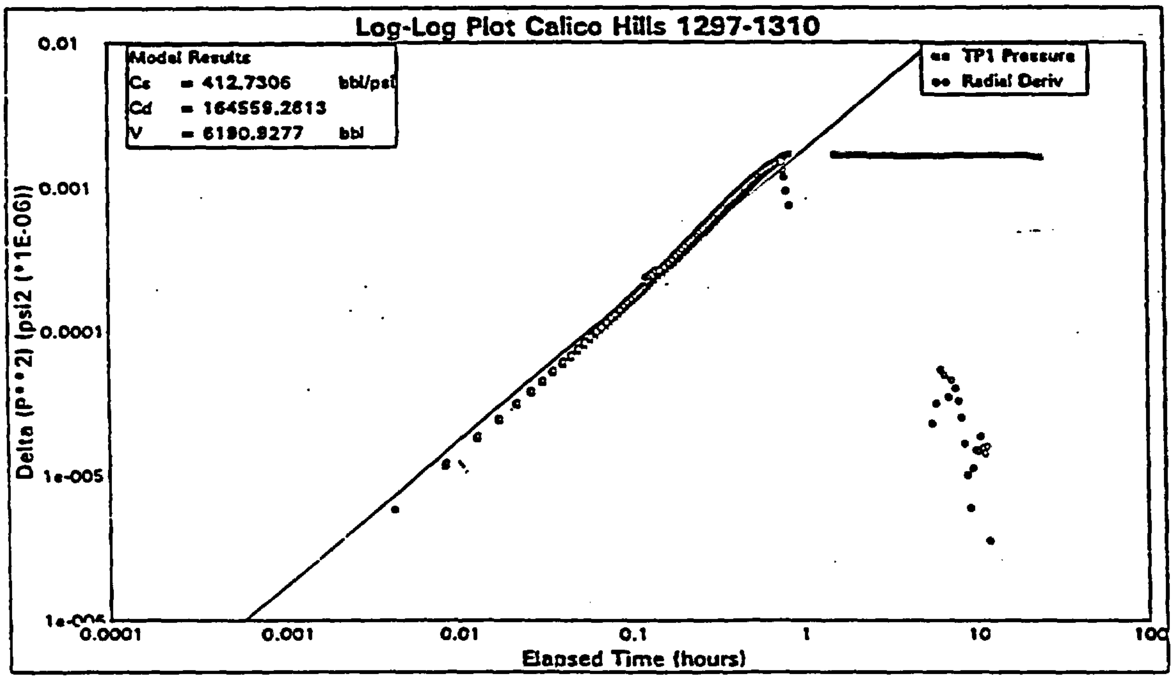


Figure 15: Log-Log Plot Calico Hills 1297-1310'

III. DISCUSSION

A. Comparison to USGS Interpretation

The analysis presented here differs significantly from the USGS interpretation. Based on current technology for well test analysis, every test examined in detail suffered from defects that prevented accurate evaluation of permeability or skin factor. The other tests were also short duration tests, or had two-phase flow (the "hump" in the pressure response). Therefore, it appears that none of the 250 tests run by the USGS in Borehole UZ-16 are suitable for analysis.

It is disheartening to discover that so much effort was expended with such poor results. It is important to identify why these errors were made, to improve future testing and to try to avoid further problems of this type. The tests were well executed and data gathering was meticulous. The key problem was not data quality or test execution, but instead was a fundamental lack of understanding of compressible fluids and gas well testing. This probably resulted from the investigators being experienced in water well testing, instead of gas well testing.

Gas well testing is significantly different from water well testing. Gas is a compressible fluid, while water is nearly incompressible. The compressibility of air at atmospheric pressure is 0.068 psia^{-1}, which is 23,000 times as large as the compressibility of water (0.000003 psia^{-1}). Consequently, wellbore storage has a much greater effect in gas wells than in water wells, which can simply be filled with water. The poor understanding the USGS had regarding wellbore storage is shown by their conclusion that "testing above 268.3 meters showed no wellbore storage or skin effects"[1] although the log-log graphs presented here clearly have a unit slope indicative of wellbore storage.

The USGS investigators were apparently unaccustomed to dealing with skin effects, and their impact on well test response. It is commonly found in the petroleum industry that the actual pressure change observed in a well test deviates from that computed based on the wellbore size and the permeability, etc. In most cases, there is an additional pressure drop near the well that is considered a skin effect. The existence of skin effects has been documented for more than forty years[7]. A positive skin shows a well is damaged, while a negative skin factor indicates a stimulated well. Extremely large positive skins may occur in naturally fractured reservoirs, because of formation plugging with drill cuttings or from incomplete connection to the natural fracture system. High positive skins should have been expected in UZ-16, because there is almost no natural pressure available to expel cuttings from the formation back into the well. Wellbore storage also lasts for a longer time when positive skin is present[4-6].

The time required to reach the reservoir response can be estimated from the following relation[4]:

$$t = \frac{3385\,C\,(60 + 3.5\,S)}{kh/\mu},\ \textit{where}$$

t = *Time in hours*

C = *Wellbore Storage Constant in* ft^3/psi

S = *Skin Factor*

k = *Permeability in millidarcies*

h = *Net Thickness in feet*

μ = *Fluid Viscosity in centipoise*

The test should be run several times to ten times longer than the minimum test time, to provide sufficient data for accurate semi-log analysis. If the USGS had applied this relation for a wellbore storage constant of 15 ft^3/psi (2.6 bbl/psi, from the first test of the Tiva Canyon interval from 60 to 73 feet depth), a skin factor of 5 (as they assumed for the Calico Hills interpretation they reported), a permeability of 1000 md (10×10^{-13} m^2, about the average of their interpreted permeabilities), a thickness of 13 feet, and air viscosity of 0.018 cp, they would have found that 5.4 hours of injection would be needed to reach the reservoir response, instead of 4 to 8 minutes. Thus, even if their interpretations were correct, they would have had to run the tests ten to one hundred times longer than they did to get beyond the effects of wellbore storage. This is the reason gas well tests in the petroleum industry customarily have flow periods that are several hours to several days in length, after which the well is shut-in for two to four times as long as the flow period.

The high compressibility of air and wellbore storage caused the USGS steady-state calculations to be invalid. The time required to reach stabilized flow within a particular drainage area is directly proportional to the fluid compressibility (among other factors). Low pressure gas wells have such high compressibilities that weeks to years may be required before pseudo-steady state flow calculations are appropriate. Steady-state flow calculations for such wells are grossly incorrect.

High compressibility and wellbore storage also caused the USGS type curve interpretations to be in error. The USGS used the Hantush type curves, because "the transient test data from the Tiva Canyon and Topopah Spring Members best fit a type curve for a well with partial penetration and vertical leakage."[1] The pressure response looked like the Hantush curves, but was instead caused by wellbore storage. Hantush's curves were developed for groundwater flow, and did not account for wellbore storage. Several thousand type curves are available in the petroleum literature for various well and reservoir conditions. The proper type curve must be selected for the reservoir and well conditions present. By not recognizing wellbore storage, the USGS selected unsuitable type curves.

Other methods have been developed to analyze low permeability wells that have extended wellbore storage periods. Such methods include McKinley afterflow analysis, convolution, desuperposition and Chow's method. None of these methods would be appreciably than type curve analysis better for these tests.

B. Considerations for Future Testing

Future air permeability testing at Yucca Mountain can be improved in several ways, including:

1. Identifying permeable zones before testing.
2. Identifying methods to reduce skin effect.
3. Selecting tool and tubing configurations to minimize wellbore storage.
4. Running tests for longer periods, to get beyond the storage-dominated response.
5. Shutting in the well to monitor the pressure fall-off after injection.
6. Utilizing modern well test analysis methods as soon as each test is completed, to assure proper data quality and results.

Each of these concepts is examined below.

1. Identify Permeable Zones before Testing

The methodology for selecting test intervals was not explained in the USGS paper. In dealing with naturally fractured zones, permeability as a function of depth can vary by a factor of 100 or more, depending on whether or not fractures are encountered at a particular depth, and the degree of connection or plugging in those fractures. Thus, it is critical to identify the intervals that have the greatest permeability, so that they can be tested. Other zones should be tested as well for baseline information. Without this type of information, what assurance is there that the zones were adequately tested?

Identifying permeable zones generally requires either injection or production, so that flow into or out of a zone can be observed. Many techniques or tools are available for flow measurement, including temperature surveys, heat pulsing, spinners, strain gauge flowmeters, noise logs, and radioactive tracers. Some of these tools can be run while flow is occurring, while others are run after the fact.

2. Reduce Skin

Besides complicating well test interpretation, a high skin effect can reduce flow rates to negligible values. In this way, zones may have poor flow characteristics even if there is high permeability just a few inches or feet from the well. Although the skin factors computed from the previous testing are not particularly accurate, the derivative response implies high skin factors are present. The most likely causes of high skin in Borehole UZ-16 are incomplete connection between the natural fractures and the wellbore, or plugging caused by cuttings.

Well test reliability would be greatly improved if the skin factors can be reduced. Producing the well probably would not be effective in reducing skin, because of the low pressure and high skin. Injecting into the well might be effective, but more than likely would push any cuttings further back into the fractures. Pneumatic jetting also would be a possibility.

3. Minimize Wellbore Storage

The test tools and tubing string could be reconfigured to try to minimize wellbore storage. The main sources of wellbore storage are the volume in the wellbore between the packers, and the tubing string from the surface to the test assembly. The wellbore volume between the packers could be reduced by wrapping the pipe through the test interval with rubber or another material, while leaving ports or openings for air movement. The easiest way to reduce the tubing volume is to use a smaller diameter tubing. Also, if the tubing is a flexible or thin-walled material, tubing compressibility could be a factor. If so, a thicker wall diameter should help stiffen the tubing. A downhole shut-in device will substantially reduce the wellbore storage for the fall-off portion of a test, and is strongly recommended as a means to improve test reliability.

4. Run Tests for Longer Periods

Most of the USGS tests were too short to provide useful information about the formation. If wellbore storage and skin factor are reduced, it should be feasible to establish the permeability of most of the intervals to within ±20% with a 12 hour injection test, followed by a 36 hour shut-in. In lower permeability intervals, it may be necessary to extend the flow period to 24 or 48 hours, followed by a shut-in about three times as long as the flow period. The USGS reported permeabilities varied by a factor of 2½ to three times for a single interval, depending on the test rate and interpretation method they selected. Such large variability in computed permeability should not occur when the tests are run long enough, and correct interpretations are made.

By running the tests for longer periods, it should not be necessary to test every zone at multiple rates. Three or four tests with multiple rates would be worthwhile, however, to evaluate possible rate-dependent skin. The well should be shut-in between the different rates, not vented. Venting the well introduces large, unmeasured rate transients that prevent meaningful interpretations for the test periods after venting.

5. Measure Pressure Fall-off after Testing

Measuring the pressure fall-off after ceasing injection should be a mandatory part of the test procedure. Pressure behavior during injection is strongly influenced by rate variations, skin effects, rate- or stress-dependent skin, particle movement in the formation, possible two-phase flow, and a host of other complications. If one had precise information about all these factors, a correct interpretation could be obtained using only flow data. In practice, however, monitoring the shut-in pressure after flow is halted will provide more accurate results than an interpretation of the injection pressure. The reason for this is simple: when a well is shut-in, it has zero flow below the shut-in point. The only flow continuing into the formation after shut-in is the expansion of fluids stored in the wellbore, which declines rapidly with time. The skin pressure drop is directly proportional to the flow rate; once flow drops to negligible levels, the skin effect disappears, and the reservoir properties dominate the response thereafter.

A pressure fall-off would also be useful for those tests exhibiting a pressure "hump" during the flow period. This behavior was attributed by the USGS to "transient drainage of water-filled pores and/or fractures," which is a credible explanation. The changing nature of such water drainage (or, more properly, displacement) was evident during twelve hours or more of injection (see Figure 14), although the effect was apparently decreasing with time. As the saturation front moved radially into the formation, its effect should taper off. The altered saturation region should manifest itself in the pressure response as a higher gas permeability near the well, which would probably lead to a slight decrease in the apparent skin factor. In extreme cases, if the zone becomes large enough, if would lead to a higher computed permeability to gas. Compared to the injection pressure response, a fall-off response would be much less influenced by changing saturations, which would have reached a more stable level. Consequently, it should be possible to obtain reasonable estimates of permeability and skin factor using fall-off response, even if the injection response is hopelessly complicated by water displacement.

6. Use Modern Well Test Analysis Procedures

If modern well test interpretation procedures had been applied after each test, it would have been immediately evident that longer tests were needed. It is important to evaluate test results as soon as possible after the test is run, in case a retest is necessary. The acquisition of a computed-assisted well test analysis program should be considered. Although programs such as *PanSystem* are expensive, costing over $10,000, many of the shortcomings of the UZ-16 test program could have been avoided if proper test interpretation had been done. The test interpretations should be conducted by well test personnel who are experienced in gas well testing.

In future testing, all tests should have fall-offs after the injection. Log-log plots, proper type curve matching, and derivative analysis should be an integral part of every test interpretation. Semi-log and Cartesian plots should be prepared for every test, showing the simulated match. Quality of results should be emphasized over quantity: a few tests with high quality data and reliable interpretations would be far more valuable than the current state of affairs.

IV. CONCLUSIONS AND RECOMMENDATIONS

1. The USGS conducted about 250 well tests on the UZ-16 Borehole. It was impossible to determine permeability reliably from those tests, because they were too short in duration or had non-steady water displacement occurring during the test.

2. The USGS interpretations were not correct, because they did not account for wellbore storage and skin effect.

3. The tests reviewed had large wellbore storage constants (1 to 400 bbl/psi), because of the high compressibility of air. The wellbore storage constants can be accurately found from the test data.

4. Type curve matching suggests permeabilities are probably high (40 to 1000 darcies). These estimates are highly uncertain because of the short duration of the tests, and these estimates for permeability could be in error by a factor of five or more.

5. High positive skin factors were indicated by the tests (+19 to +270). The high skin factors are probably caused by incomplete connection between natural fractures and the wellbore, or by plugging with cuttings or fine particulate matter.

6. Future air permeability testing at Yucca Mountain can be improved by:
    1. Identifying permeable zones before testing.
    2. Reducing skin effect.
    3. Minimizing wellbore storage.
    4. Running longer tests.
    5. Monitoring pressure fall-off after injection.
    6. Utilizing modern well test analysis methods.

V. REFERENCES

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DISCLAIMER

ATTACHMENT A:
APPLICATION OF TYPE CURVES FOR A FINITE CYLINDRICAL SOURCE IN AN INFINITE RESERVOIR

SUMMARY

Type curves for a test interval 25 times as long as the wellbore radius were constructed using the methods described in **Attachment B**. For ease of use, the dimensionless formulae were converted to normal pressure and rate measurements using the differences in pressure-squared (P^2). These calculations were then converted to pressure changes for plotting, and a spreadsheet program for projecting test results for different test conditions was prepared. Three types of flow response were investigated: radial, spherical, and flow around a finite cylinder.

Key results of the analysis include:

1. It was not possible to determine the flow geometry for most (if not all) of the UZ-16 tests. However, the results are affected very little by the flow geometry.

2. The UZ-16 tests were characterized by large wellbore storage constants and high skin factors. Because of the short duration of the tests, relative to the length of the wellbore storage dominated period, it is not possible to accurately determine the flow regime, the exact permeability, or the exact skin factor.

3. New type curves have been developed that can be used for air-k test analysis. With the new curves, better tests can be designed that will determine the flow geometry, permeability and skin within acceptable accuracy. Downhole shut-ins and pressure falloffs will be necessary for this purpose.

USE OF THE SOURCE FUNCTION RELATIONS

After the pressure response functions were determined, as described in **Attachment B**, they were used to calculate specific test responses for various cases. These were then examined to determine whether any general principles or insights could be discovered.

PREPARATION OF TYPE CURVES

Using the same methodology, the dimensionless pressure response was computed for varying skin factors and wellbore storage constants. The calculated responses have numerous similarities and differences. In all cases, the pressure reaches a stabilized level, but the response for a skin factor of zero (**Figure 2**) has a distinctly different shape than that for positive skin factors (**Figures 3-5**). The stabilized pressure level reached also depends on the skin factor, with an increase that is proportional to the skin factor (P_D approaches $S+0.15670$ for $h/r_w = 25$). The derivative curves for positive skin factor all have similar shapes, with characteristic "humps," after which the derivative follows the zero skin response.

The effect of varying the length of the test interval was also examined. If the test interval were twice as long, a slightly longer stabilized slope was observed prior to declining according to ideal spherical flow, but otherwise the results were very similar. This would also apply if the test interval were the same length, and the horizontal permeability were four times the vertical permeability (also known as directional, or anisotropic permeability). The same methodology can also be used to compute type curves for other test intervals.

THE GENERAL TYPE CURVES

Based on the results with various skin factors and storage constants, general type curves were developed. Separate type curves were needed for the zero skin and positive skin cases because of the different shapes. The positive skin results were normalized by dividing both the dimensionless pressure and dimensionless time by the stabilized pressure level reached, to simplify application.

The general type curve for skin equal to zero is presented in **Figure 6**. For zero skin, any "hump" that develops is gentle and has limited height. The shape of the zero skin pressure response is very distinctive, and is substantially different from that of the positive skin cases.

The general type curve for positive skins is presented in **Figure 7**. This curve indicates the shape of the pressure response will be very similar for any positive skin and storage constant, which implies any analysis based solely on the stable pressure will be unable to distinguish between different skin factors. The derivative curve, however, is more definitive. The

Figure 4: Response Functions

Skin = 10; Cd = 0, 1, 10, 100, 1000

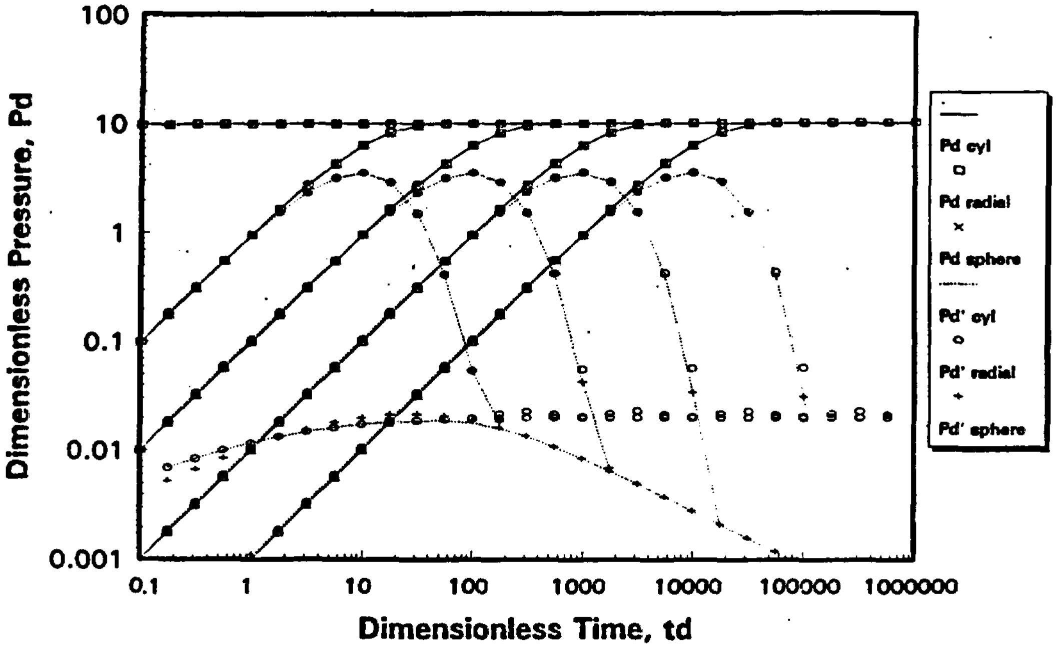


Figure 5: Response Functions

Skin = 100; Cd = 0, 1, 10, 100, 1000

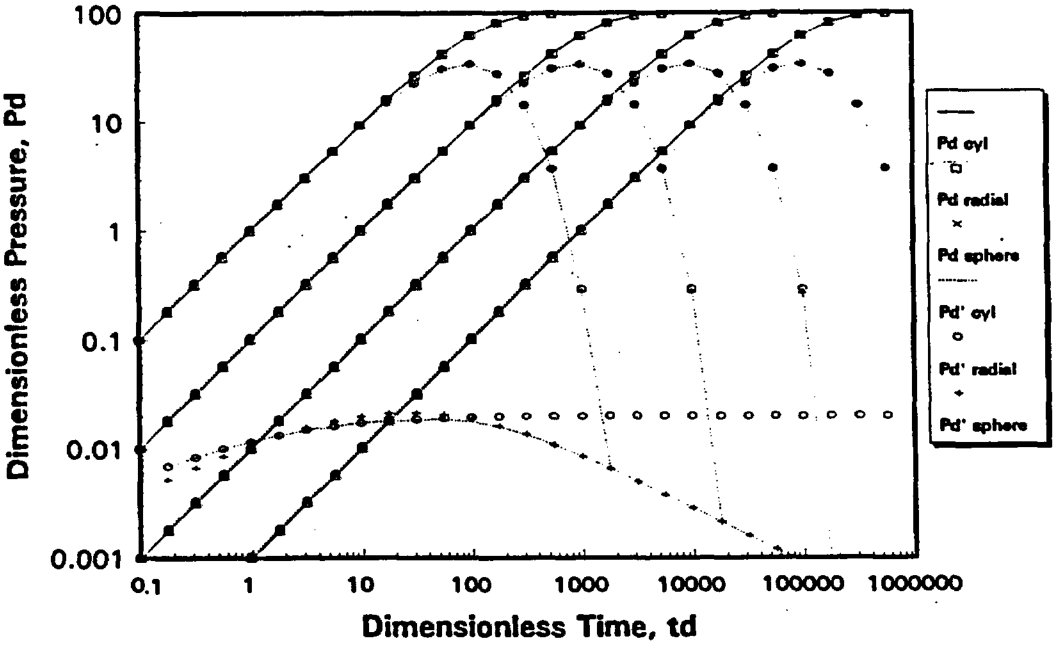


Figure 7: Type Curve for Skin > 0

Finite Cylinder, h/rw = 25

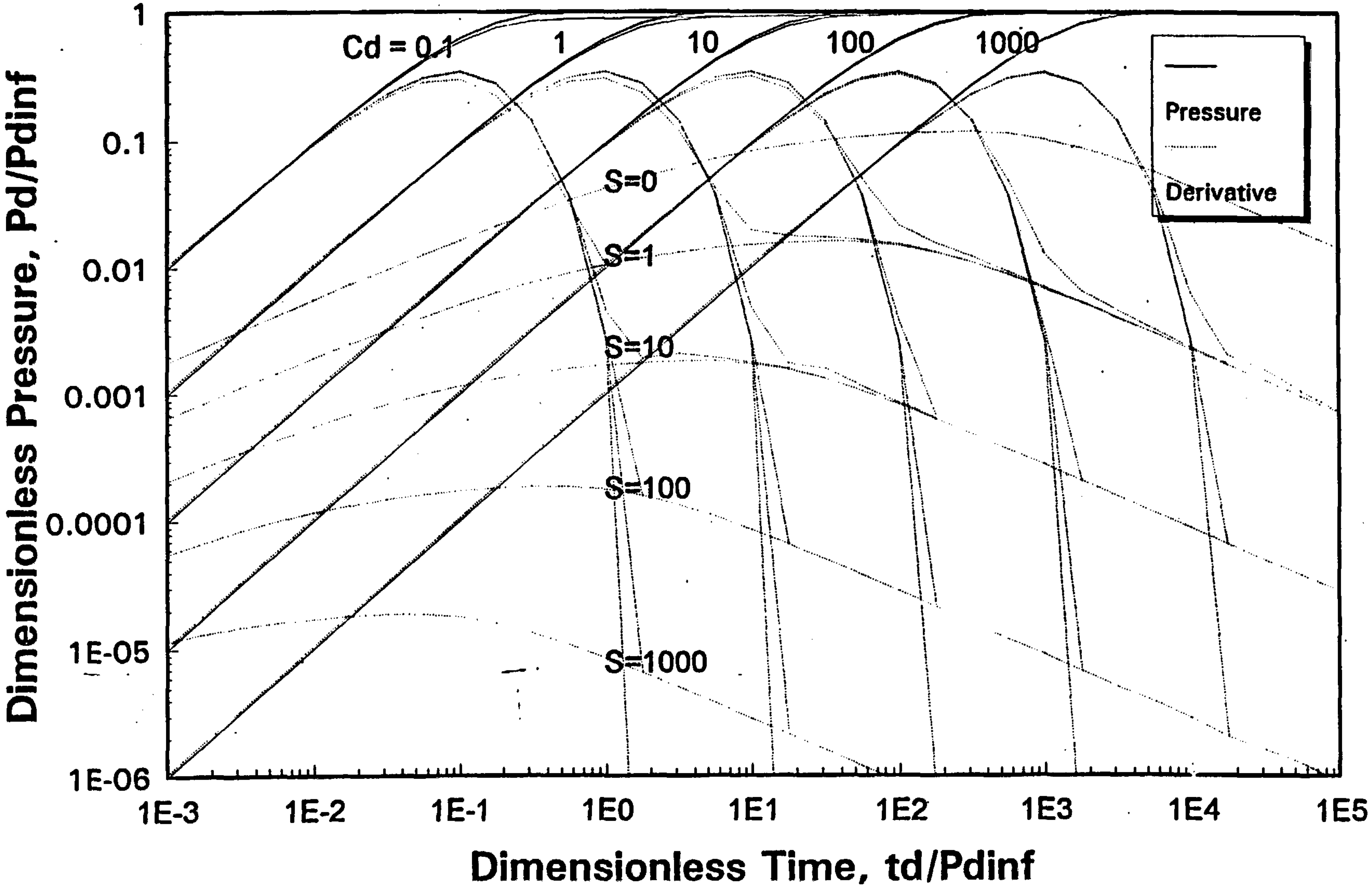


Figure 9: Computed Well Test Results

k=39600 md, S=90, Cs=1.2, q=13 Mcfd

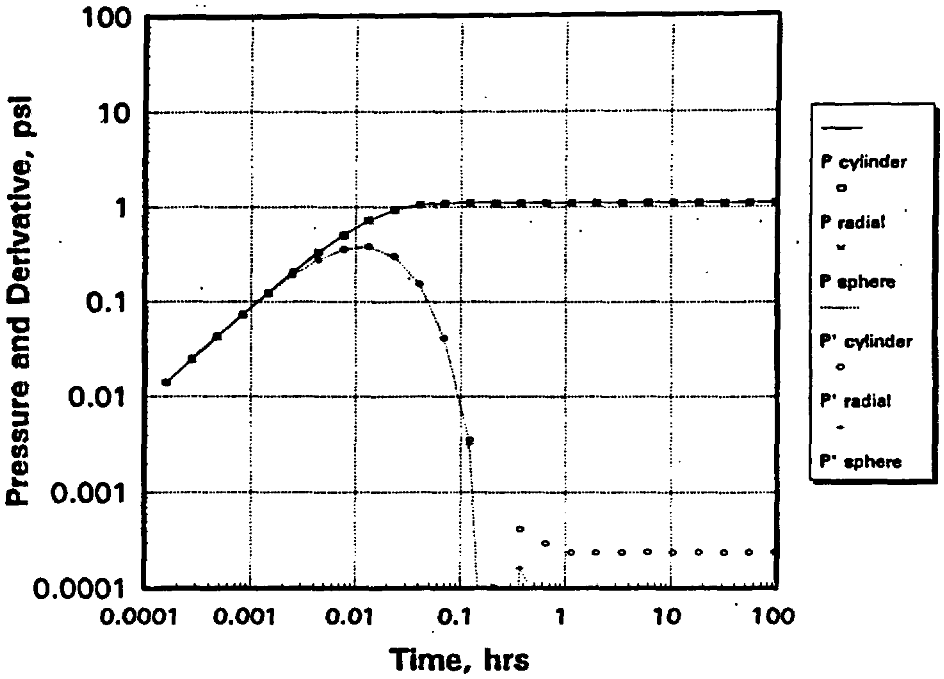
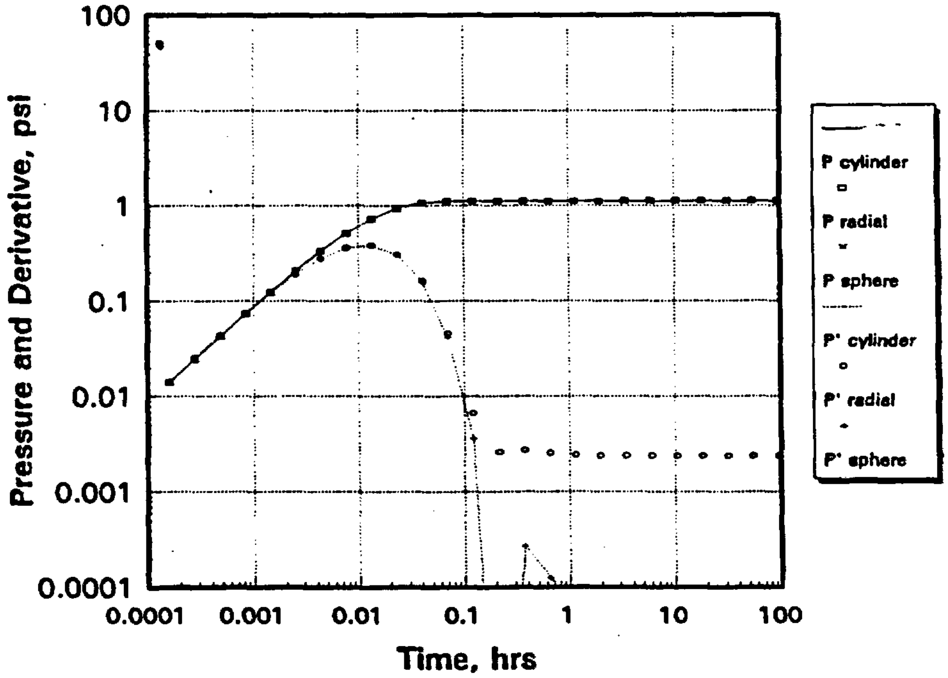


Figure 10: Computed Well Test Results

k=3960 md, S=8.9, Cs=1.2, q=13 Mcfd



The other UZ-16 tests suffered from similar defects: the tests were too short to observe the derivative break-over to the spherical flow response, or had other problems (multi-phase flow, variable rates, etc.). A key observation is the length of the steep derivative periods observed indicate high skin factors, so any analysis assuming zero skin would be incorrect.

METHODS TO IMPROVE TESTING

With several simple modifications, test results can be greatly improved. Positive skin should be expected in most tests at Yucca Mountain, because of flow convergence toward the well and incomplete connection to the natural fracture system. With this in mind, the applicable type curve will generally be **Figure** 7. The most definitive results will be obtained from **Figure** 7 if the derivative response reaches the limiting spherical flow form (the less steep region) before a slope of -½ is reached. For this to happen, wellbore storage should be minimized. The best way to accomplish this is to shut in the well following injection with a downhole shut-in tool. With downhole shut-ins, the wellbore storage constant should be reduced by a factor of 10 to 100 times, compared to the previous tests. In this manner, good results should be attainable with tests as short as 10 minutes to 2 hours in duration. Surface read-out (SRO) gauges will improve test quality by reducing the number of tests that are run for too short a period.

Downhole shut-ins have the added benefit of improving the accuracy of the derivative calculation. The derivative response is a critical element in accurate type curve analysis. Small rate variations during the injection portion of the test can cause substantial inaccuracies in the computed derivative. With a shut-in (falloff), the rate is decisively set a known value -- zero. The type curves should be applicable as long as an essentially stable pressure was reached during the injection portion of the test; otherwise, desuperposition or deconvolution should be used to remove the effect of the initial flow period. The equivalent time approach should not be applied, inasmuch as flow will not generally be transient, radial flow.

Once the spherical derivative is reached, the permeability can be computed from the spherical flow, zero skin derivative response, since the same limiting derivative form is reached regardless of the skin factor or wellbore storage. Thus, accurate interpretations are possible as long as the test is run long enough, and data are accurate enough, that the limiting derivative response is clearly defined.

$$\begin{aligned} \bar{u} &= \frac{e^{-\sqrt{s}\sqrt{R^2+(z-z')^2}}}{4\pi\sqrt{R^2+(z-z')^2}} \\ &= \frac{1}{2\pi^2}\int_0^{\infty}\cos[\xi(z-z')]\,K_0[\eta R]\,d\xi \end{aligned} \tag{2}$$

$$\begin{aligned} \textit{where } \eta &= \sqrt{\xi^2+s} \\ R^2 &= x^2 + y^2 \\ &= r^2 + r^2 - 2rr'\cos[\theta-\theta'] \end{aligned}$$

In this instance, we wish to consider a test condition where the well is packed off above and below the test interval. In this case, it is necessary that:

$$\left(\frac{\partial P}{\partial r}\right)_{r=a} = 0 \tag{3}$$

where a is the wellbore radius. The solution v to the problem was determined by setting $v=u+w$, where u is the infinite reservoir solution above, and w is a function chosen to offset the flow at the well caused by u. The Addition Theorem for modified Bessel functions was used to select w (Carslaw and Jaeger, p. 377):

$$\begin{aligned} K_0[\eta R] &= \sum_{n=-\infty}^{\infty}\cos[n(\theta-\theta')]I_n[\eta r]K_n[\eta r'] \quad \textit{for } r<r' \\ &= \sum_{n=-\infty}^{\infty}\cos[n(\theta-\theta')]I_n[\eta r']K_n[\eta r] \quad \textit{for } r>r' \end{aligned} \tag{4}$$

Considering that the source function is needed <u>in</u> the reservoir, it was assumed that $r<r'$. The K_0 portion of w was then equal to:

$$\begin{aligned} \left(\frac{\partial K_0[\eta R]}{\partial r}\right)_{r=a} &= \sum_{n=-\infty}^{\infty}\cos[n(\theta-\theta')]\,\eta\, I_n'[\eta a]K_n[\eta r'] \\ &= -\left(\frac{\partial \bar{w}}{\partial r}\right)_{r=a} \end{aligned} \tag{5}$$

$$\textit{so } \bar{w} = -\sum_{n=-\infty}^{\infty}\cos[n(\theta-\theta')]\frac{I_n'[\eta a]}{K_n'[\eta a]}K_n[\eta r]K_n[\eta r']$$

and the source function response for an instantaneous point source in a reservoir with an

$$\frac{1}{h}\int_{-h/2}^{+h/2}\cos[\xi(z-z')]\,dz' = \left(-\frac{\sin[\xi(z-z')]}{\xi h}\right)_{-h/2}^{+h/2}$$

$$= \frac{2}{\xi h}\cos[2\xi z]\sin[\xi h],\quad \textit{so} \tag{9}$$

$$\overline{v_{cyl}} = \frac{2}{\pi h}\int_0^{\infty}\sin[\xi h]\cos[2\xi z]\frac{K_0[\eta r]}{K_1[\eta]}\frac{d\xi}{\eta\xi}$$

In the special case with the source and response at the well, $z=0$ and $r_D=1$, the dimensionless wellbore pressure response for a continuous, finite cylindrical source in Laplace domain was found to be:

$$\overline{F} = \frac{2}{\pi h s}\int_0^{\infty}\sin[\xi h]\frac{K_0[\eta]}{K_1[\eta]}\frac{d\xi}{\eta\xi} \tag{10}$$

Note that the pressure response is a function of the dimensionless source length h, and the Laplace domain variable s. (As is usual, the instantaneous source relation was divided by s to obtain the response to a continuous source.) **Equation 10** is the basic relation for the pressure response in Laplace domain for the continuous, finite cylindrical wellbore, in the absence of any bed boundaries.

LIMITING FORM FOR EARLY TIME

The asymptotic formulae for K_0 and K_1 Bessel functions were used to estimate the response at early time (large s), as follows:

$$\eta = \sqrt{\xi^2+s} = \sqrt{s},\ \textit{for large } s,\ \textit{so}$$

$$\overline{F} \sim \frac{2}{\pi h s}\frac{K_0[\sqrt{s}]}{\sqrt{s}K_1[\sqrt{s}]}\int_0^{\infty}\sin[\xi h]\frac{d\xi}{\xi} \tag{11}$$

$$= \frac{1}{h}\frac{K_0[\sqrt{s}]}{s^{3/2}K_1[\sqrt{s}]}$$

The latter relation is the same as the response for a finite diameter well for one-dimensional, radial (cylindrical) flow (Sabet, p. 407), thereby demonstrating that flow initially is radial. (P_D is normally defined in the petroleum industry based on the formation thickness; but in this case, it was defined based on the wellbore radius. Hence, the term $1/h$ is present in **Equation 11**.)

The first three terms of the series were directly computed, and Euler acceleration was applied to the remaining terms. Using this technique, the series was computed to 10-digit accuracy with 20 terms of the series.

Wellbore storage and skin effect were incorporated in the standard fashion (Sabet, 1991 and Raghavan, 1994). Let *f(t)* be the response function for a continuous cylindrical source, as would be obtained for example by inverting **Equation 10**. The interplay between the unit response function, the skin effect and wellbore storage are then determined as follows:

$$\begin{aligned}
q_D &= \left(r_D \frac{\partial P_D}{\partial r_D} \right)_{r_d=1}, \quad \textit{the sandface rate} \\
P_D &= \int_0^{t_D} F'[t_D - \tau_D]\, q[\tau_D]\, d\tau_D, \quad \textit{the pressure convolution integral} \\
P_{wD} &= P_D - S \left(r_D \frac{\partial P_D}{\partial r_D} \right)_{r_D=1}, \quad \textit{the skin effect at the sandface} \\
&\left(-r_D \frac{\partial P_D}{\partial r_D} \right)_{r_D=1} + C_D \frac{dP_{wD}}{dt_D} = 1, \quad \textit{the wellbore storage condition}
\end{aligned} \tag{15}$$

Such relations as these are generally not used directly, because of the complexity of the convolution integral. In Laplace domain, these relations are considerably simpler:

$$\begin{aligned}
\overline{q_D} &= -\left(r_D \frac{d\overline{P_D}}{dr_D} \right)_{r_D=1}, \quad \textit{the rate condition} \\
\overline{P_D} &= s\, \overline{F}\, \overline{q}, \quad \textit{the pressure convolution integral} \\
\overline{P_{wD}} &= \overline{P_D} - S \left(r_D \frac{d\overline{P_D}}{dr_D} \right)_{r_D=1}, \quad \textit{the skin effect at the sandface} \\
&\left(-r_D \frac{d\overline{P_D}}{dr_D} \right)_{r_D=1} + s\, C_D \overline{P_{wD}} = \frac{1}{s}, \quad \textit{the wellbore storage condition}
\end{aligned} \tag{16}$$

The Laplace domain equations were rearranged to determine the response at the well including the effects of wellbore storage and skin:

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Draft

Attachment C

ADVANCED RESOURCES INTERNATIONAL

May 8, 1995

Mr. Nick Stellavato
Nye County Nuclear Waste Repository Project Center
P. O. Box 675
Mercury NV 89023

RE: New Type Curves for UZ-16 Well Tests

Dear Nick:

Per our discussion following the ARI letter of February 24, 1995, we have prepared new type curves for design and analysis of air-k tests, such as those conducted by the U.S.G.S. in Borehole UZ-16. The key finding from this analysis is that the flow regime (whether radial, spherical, or transitional) has little effect on well tests in these types of zones. The test results are most strongly affected by *wellbore storage and skin*, and the UZ-16 results show clear indications of both effects.

Methods for improving tests at Yucca Mountain are presented, based on the new type curves. These curves show the pressure transient test response for a thick interval with a short test interval (a finite cylindrical source). The use and derivation of the type curves is documented in the attachments to this letter.

I hope these results will help to clear up any lingering concerns regarding the flow regime of the tests, etc., and I would be glad to discuss this material with you or the USGS once you have had a chance to review it.

Sincerely,

Dave

ADVANCED RESOURCES INTERNATIONAL, INC.
Dave O. Cox, Vice President

DOC:wp

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ADVANCED RESOURCES INTERNATIONAL, INC.
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ATTACHMENT A:
APPLICATION OF TYPE CURVES FOR A FINITE CYLINDRICAL SOURCE IN AN INFINITE RESERVOIR

SUMMARY

Type curves for a test interval 25 times as long as the wellbore radius were constructed using the methods described in **Attachment B.** For ease of use, the dimensionless formulae were converted to normal pressure and rate measurements using the differences in pressure-squared (P^2). These calculations were then converted to pressure changes for plotting, and a spreadsheet program for projecting test results for different test conditions was prepared. Three types of flow response were investigated: radial, spherical, and flow around a finite cylinder.

Key results of the analysis include:

1. It was not possible to determine the flow geometry for most (if not all) of the UZ-16 tests. However, the results are affected very little by the flow geometry.

2. The UZ-16 tests were characterized by large wellbore storage constants and high skin factors. Because of the short duration of the tests, relative to the length of the wellbore storage dominated period, it is not possible to accurately determine the flow regime, the exact permeability, or the exact skin factor.

3. New type curves have been developed that can be used for air-k test analysis. With the new curves, better tests can be designed that will determine the flow geometry, permeability and skin within acceptable accuracy. Downhole shut-ins and pressure falloffs will be necessary for this purpose.

USE OF THE SOURCE FUNCTION RELATIONS

After the pressure response functions were determined, as described in **Attachment B**, they were used to calculate specific test responses for various cases. These were then examined to determine whether any general principles or insights could be discovered.

PREPARATION OF TYPE CURVES

Using the same methodology, the dimensionless pressure response was computed for varying skin factors and wellbore storage constants. The calculated responses have numerous similarities and differences. In all cases, the pressure reaches a stabilized level, but the response for a skin factor of zero (Figure 2) has a distinctly different shape than that for positive skin factors (Figures 3-5). The stabilized pressure level reached also depends on the skin factor, with an increase that is proportional to the skin factor (P_D approaches $S+0.15670$ for $h/r_w = 25$). The derivative curves for positive skin factor all have similar shapes, with characteristic "humps," after which the derivative follows the zero skin response.

The effect of varying the length of the test interval was also examined. If the test interval were twice as long, a slightly longer stabilized slope was observed prior to declining according to ideal spherical flow, but otherwise the results were very similar. This would also apply if the test interval were the same length, and the horizontal permeability were four times the vertical permeability (also known as directional, or anisotropic permeability). The same methodology can also be used to compute type curves for other test intervals.

THE GENERAL TYPE CURVES

Based on the results with various skin factors and storage constants, general type curves were developed. Separate type curves were needed for the zero skin and positive skin cases because of the different shapes. The positive skin results were normalized by dividing both the dimensionless pressure and dimensionless time by the stabilized pressure level reached, to simplify application.

The general type curve for skin equal to zero is presented in **Figure 6**. For zero skin, any "hump" that develops is gentle and has limited height. The shape of the zero skin pressure response is very distinctive, and is substantially different from that of the positive skin cases.

The general type curve for positive skins is presented in **Figure 7**. This curve indicates the shape of the pressure response will be very similar for any positive skin and storage constant, which implies any analysis based solely on the stable pressure will be unable to distinguish between different skin factors. The derivative curve, however, is more definitive. The

Figure 4: Response Functions

Skin = 10; Cd = 0, 1, 10, 100, 1000

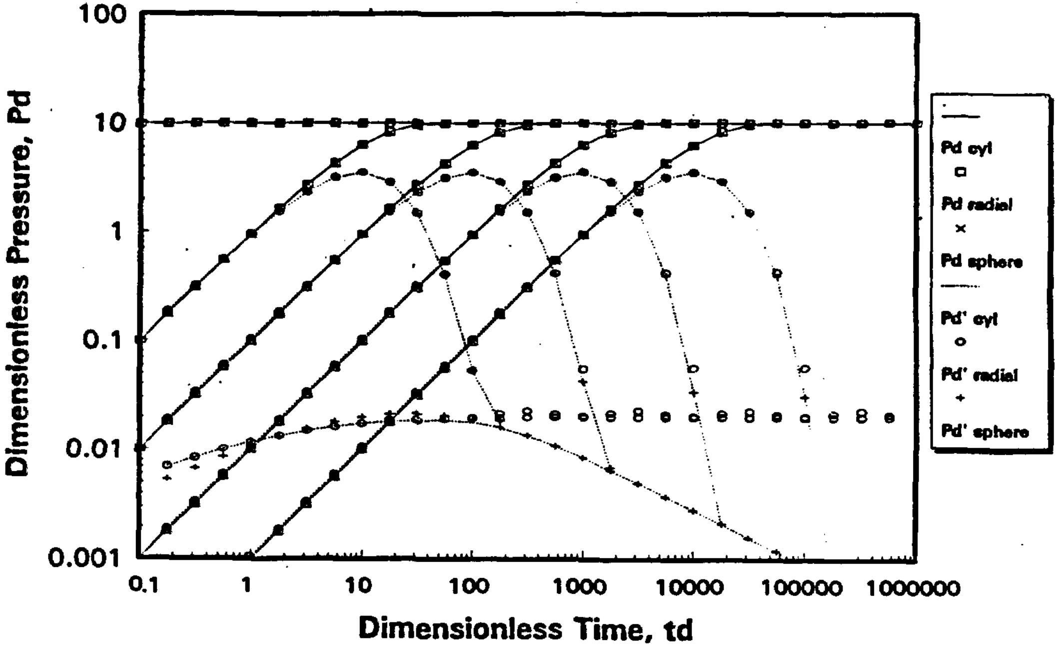


Figure 5: Response Functions

Skin = 100; Cd = 0, 1, 10, 100, 1000

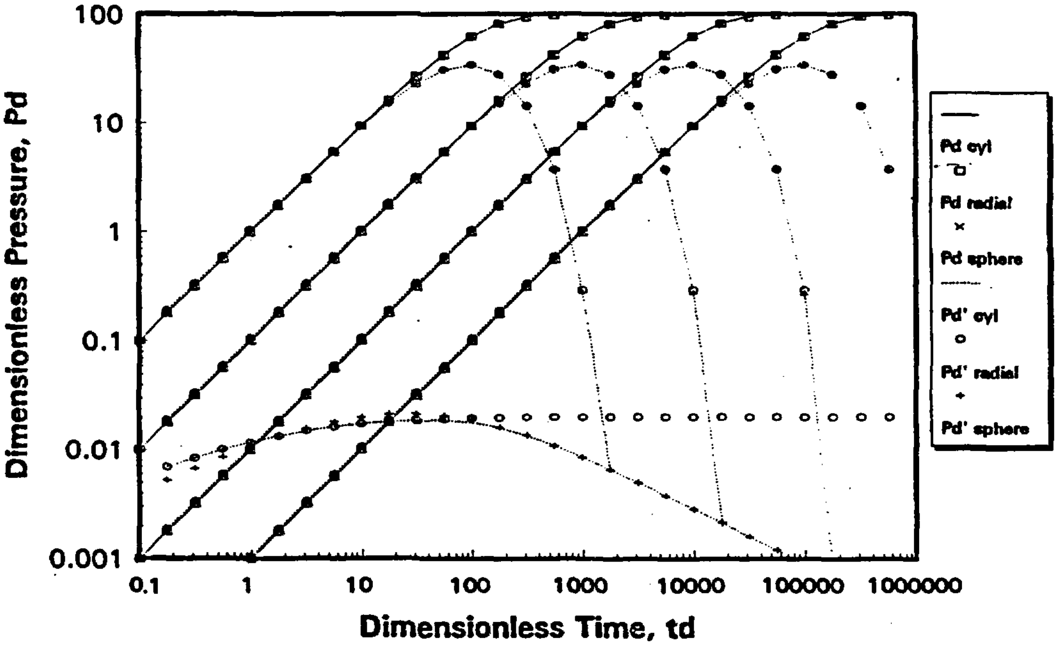


Figure 7: Type Curve for Skin > 0

Finite Cylinder, h/rw = 25

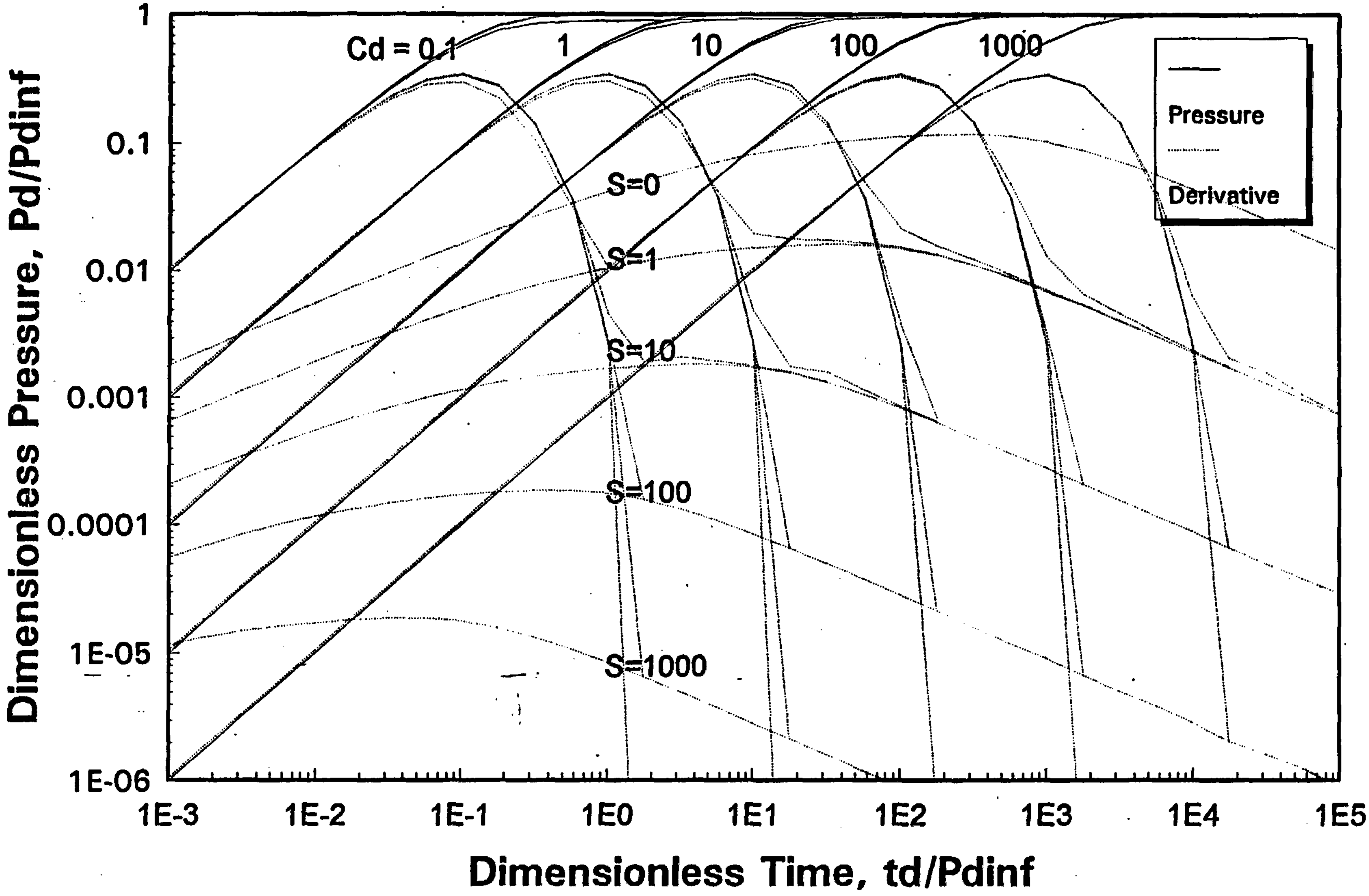


Figure 9: Computed Well Test Results

k=39600 md, S=90, Cs=1.2, q=13 Mcfd

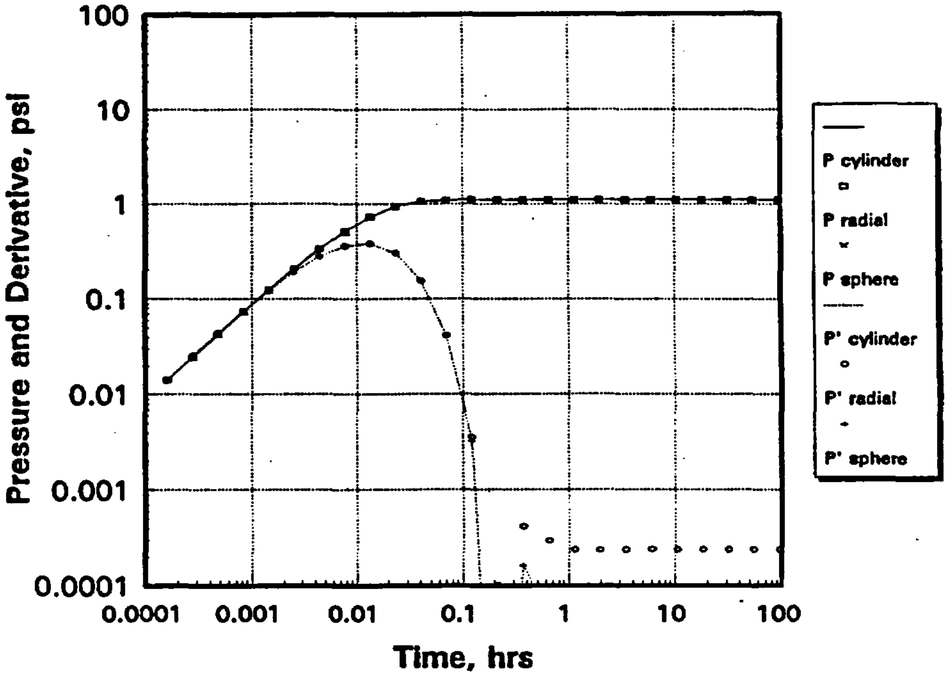
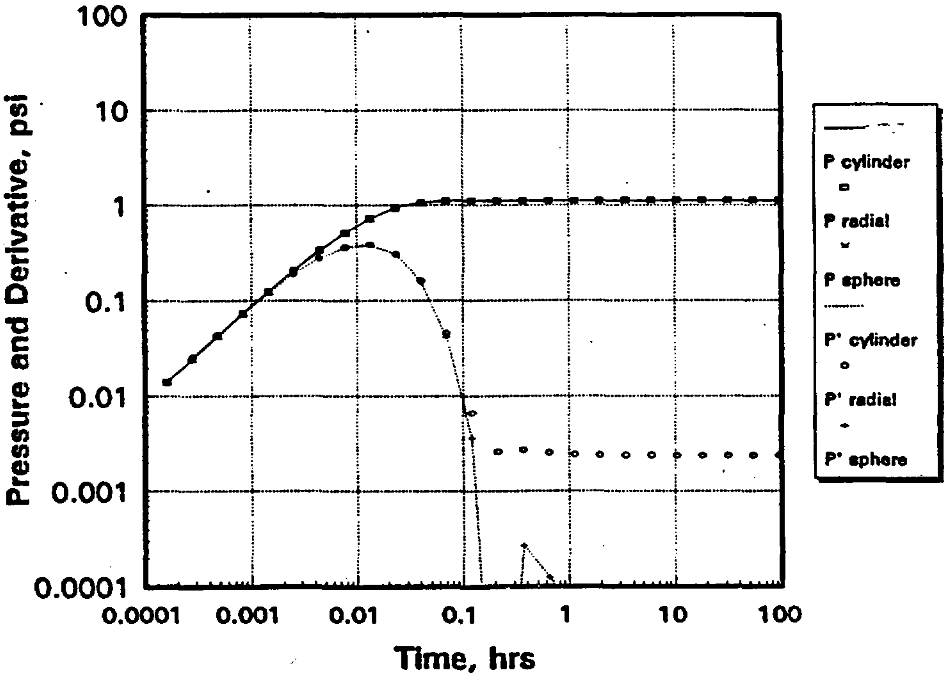


Figure 10: Computed Well Test Results

k=3960 md, S=8.9, Cs=1.2, q=13 Mcfd



The other UZ-16 tests suffered from similar defects: the tests were too short to observe the derivative break-over to the spherical flow response, or had other problems (multi-phase flow, variable rates, etc.). A key observation is the length of the steep derivative periods observed indicate high skin factors, so any analysis assuming zero skin would be incorrect.

METHODS TO IMPROVE TESTING

With several simple modifications, test results can be greatly improved. Positive skin should be expected in most tests at Yucca Mountain, because of flow convergence toward the well and incomplete connection to the natural fracture system. With this in mind, the applicable type curve will generally be **Figure 7**. The most definitive results will be obtained from **Figure 7** if the derivative response reaches the limiting spherical flow form (the less steep region) before a slope of -½ is reached. For this to happen, wellbore storage should be minimized. The best way to accomplish this is to shut in the well following injection with a downhole shut-in tool. With downhole shut-ins, the wellbore storage constant should be reduced by a factor of 10 to 100 times, compared to the previous tests. In this manner, good results should be attainable with tests as short as 10 minutes to 2 hours in duration. Surface read-out (SRO) gauges will improve test quality by reducing the number of tests that are run for too short a period.

Downhole shut-ins have the added benefit of improving the accuracy of the derivative calculation. The derivative response is a critical element in accurate type curve analysis. Small rate variations during the injection portion of the test can cause substantial inaccuracies in the computed derivative. With a shut-in (falloff), the rate is decisively set a known value -- zero. The type curves should be applicable as long as an essentially stable pressure was reached during the injection portion of the test; otherwise, desuperposition or deconvolution should be used to remove the effect of the initial flow period. The equivalent time approach should not be applied, inasmuch as flow will not generally be transient, radial flow.

Once the spherical derivative is reached, the permeability can be computed from the spherical flow, zero skin derivative response, since the same limiting derivative form is reached regardless of the skin factor or wellbore storage. Thus, accurate interpretations are possible as long as the test is run long enough, and data are accurate enough, that the limiting derivative response is clearly defined.

$$\begin{aligned}\bar{u} &= \frac{e^{-\sqrt{s}\sqrt{R^2+(z-z')^2}}}{4\pi\sqrt{R^2+(z-z')^2}} \\ &= \frac{1}{2\pi^2}\int_0^\infty \cos[\xi(z-z')]\,K_0[\eta R]\,d\xi \end{aligned} \tag{2}$$

$$\begin{aligned} \textit{where } \eta &= \sqrt{\xi^2+s} \\ R^2 &= x^2 + y^2 \\ &= r^2 + r^2 - 2rr'\cos[\theta-\theta'] \end{aligned}$$

In this instance, we wish to consider a test condition where the well is packed off above and below the test interval. In this case, it is necessary that:

$$\left(\frac{\partial P}{\partial r}\right)_{r=a} = 0 \tag{3}$$

where a is the wellbore radius. The solution v to the problem was determined by setting $v=u+w$, where u is the infinite reservoir solution above, and w is a function chosen to offset the flow at the well caused by u. The Addition Theorem for modified Bessel functions was used to select w (Carslaw and Jaeger, p. 377):

$$\begin{aligned} K_0[\eta R] &= \sum_{n=-\infty}^{\infty}\cos[n(\theta-\theta')]I_n[\eta r]K_n[\eta r'] \quad \textit{for } r<r' \\ &= \sum_{n=-\infty}^{\infty}\cos[n(\theta-\theta')]I_n[\eta r']K_n[\eta r] \quad \textit{for } r>r' \end{aligned} \tag{4}$$

Considering that the source function is needed <u>in</u> the reservoir, it was assumed that $r<r'$. The K_0 portion of w was then equal to:

$$\begin{aligned} \left(\frac{\partial K_0[\eta R]}{\partial r}\right)_{r=a} &= \sum_{n=-\infty}^{\infty}\cos[n(\theta-\theta')]\,\eta\, I_n'[\eta a]K_n[\eta r'] \\ &= -\left(\frac{\partial \bar{w}}{\partial r}\right)_{r=a} \end{aligned} \tag{5}$$

$$\textit{so } \bar{w} = -\sum_{n=-\infty}^{\infty}\cos[n(\theta-\theta')]\frac{I_n'[\eta a]}{K_n'[\eta a]}K_n[\eta r]K_n[\eta r']$$

and the source function response for an instantaneous point source in a reservoir with an

$$\frac{1}{h}\int_{-h/2}^{+h/2} \cos[\xi(z-z')]\,dz' = \left(-\frac{\sin[\xi(z-z')]}{\xi h}\right)_{-h/2}^{+h/2}$$

$$= \frac{2}{\xi h}\cos[2\xi z]\sin[\xi h], \quad so \tag{9}$$

$$\overline{v_{cyl}} = \frac{2}{\pi h}\int_0^{\infty} \sin[\xi h]\cos[2\xi z]\frac{K_0[\eta r]}{K_1[\eta]}\frac{d\xi}{\eta\xi}$$

In the special case with the source and response at the well, *z=0* and $r_D=1$, the dimensionless wellbore pressure response for a continuous, finite cylindrical source in Laplace domain was found to be:

$$\overline{F} = \frac{2}{\pi h s}\int_0^{\infty} \sin[\xi h]\frac{K_0[\eta]}{K_1[\eta]}\frac{d\xi}{\eta\xi} \tag{10}$$

Note that the pressure response is a function of the dimensionless source length *h*, and the Laplace domain variable *s*. (As is usual, the instantaneous source relation was divided by *s* to obtain the response to a continuous source.) **Equation 10** is the basic relation for the pressure response in Laplace domain for the continuous, finite cylindrical wellbore, in the absence of any bed boundaries.

LIMITING FORM FOR EARLY TIME

The asymptotic formulae for K_0 and K_1 Bessel functions were used to estimate the response at early time (large *s*), as follows:

$$\eta = \sqrt{\xi^2+s} \approx \sqrt{s}, \textit{ for large } s, \quad so$$

$$\overline{F} \approx \frac{2}{\pi h s}\frac{K_0[\sqrt{s}]}{\sqrt{s}K_1[\sqrt{s}]}\int_0^{\infty} \sin[\xi h]\frac{d\xi}{\xi} \tag{11}$$

$$= \frac{1}{h}\frac{K_0[\sqrt{s}]}{s^{3/2}K_1[\sqrt{s}]}$$

The latter relation is the same as the response for a finite diameter well for one-dimensional, radial (cylindrical) flow (Sabet, p. 407), thereby demonstrating that flow initially is radial. (P_D is normally defined in the petroleum industry based on the formation thickness; but in this case, it was defined based on the wellbore radius. Hence, the term *1/h* is present in **Equation 11.**)

The first three terms of the series were directly computed, and Euler acceleration was applied to the remaining terms. Using this technique, the series was computed to 10-digit accuracy with 20 terms of the series.

Wellbore storage and skin effect were incorporated in the standard fashion (Sabet, 1991 and Raghavan, 1994). Let *f(t)* be the response function for a continuous cylindrical source, as would be obtained for example by inverting **Equation 10**. The interplay between the unit response function, the skin effect and wellbore storage are then determined as follows:

$$
\begin{aligned}
&q_D = \left(r_D \frac{\partial P_D}{\partial r_D} \right)_{r_d = 1}, \quad \textit{the sandface rate} \\
&P_D = \int_0^{t_D} F'[t_D - \tau_D] q[\tau_D] d\tau_D, \quad \textit{the pressure convolution integral} \\
&P_{wD} = P_D - S \left(r_D \frac{\partial P_D}{\partial r_D} \right)_{r_D = 1}, \quad \textit{the skin effect at the sandface} \\
&\left(-r_D \frac{\partial P_D}{\partial r_D} \right)_{r_D = 1} + C_D \frac{dP_{wD}}{dt_D} = 1, \quad \textit{the wellbore storage condition}
\end{aligned}
\qquad (15)
$$

Such relations as these are generally not used directly, because of the complexity of the convolution integral. In Laplace domain, these relations are considerably simpler:

$$
\begin{aligned}
&\overline{q_D} = - \left(r_D \frac{d\overline{P_D}}{dr_D} \right)_{r_D = 1}, \quad \textit{the rate condition} \\
&\overline{P_D} = s\, \overline{F}\, \overline{q}, \quad \textit{the pressure convolution integral} \\
&\overline{P_{wD}} = \overline{P_D} - S \left(r_D \frac{d\overline{P_D}}{dr_D} \right)_{r_D = 1}, \quad \textit{the skin effect at the sandface} \\
&\left(-r_D \frac{d\overline{P_D}}{dr_D} \right)_{r_D = 1} + s\, C_D \overline{P_{wD}} = \frac{1}{s}, \quad \textit{the wellbore storage condition}
\end{aligned}
\qquad (16)
$$

The Laplace domain equations were rearranged to determine the response at the well including the effects of wellbore storage and skin:

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Attachment D

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Golder Associates

June 12, 1995

Our Ref: 953-2901

US Geological Survey
P.O. Box 25046 M.S. 425
Denver Federal Center
Denver, Co. 80225

Attention: Mr. William W. Dudley

RE: DRAFT LETTER REPORT FOR THE THIRD PARTY REVIEW OF PROCEDURES AND INTERPRETATION OF AIR INJECTION PERMEABILITY TESTS.

Dear Mr. Dudley,

Golder Associates Inc. is pleased to present this draft letter report summarizing our review of the procedures for conducting air permeability tests in fractured volcanic rock, and method of analysis of such tests. The major comments by Advanced Resources International are addressed and their possible impacts on tests interpretation are discussed.

This report is currently undergoing internal review within our office. Please advise me of any changes or comments that you would like to include in the final draft. We appreciate the opportunity to work with the US Geological Survey on this project. If you have any questions or comments, please contact us.

Sincerely,

GOLDER ASSOCIATES INC.

Amado Guzman, Ph.D.
Project Manager