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THIRD PARTY REVIEW

OF PROCEDURES AND INTERPRETATION

OF AIR INJECTION PERMEABILITY TESTS

DRAFT

Prepared For:

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1.0 INTRODUCTION

Golder Associates Inc. (Golder) is pleased to submit this letter report summarizing the third party review of the procedures and methods of interpretation of air injection tests at the Yucca Mountain Project (YMP) being conducted by the US Geological Survey (USGS). The work for this study was completed during the period of May 8 and May 26, 1995. The USGS requested Golder Associates to conduct an independent review of the documents by the USGS and Advanced Resources International (ARI) related to air injection tests in the YMP, and review contrasting interpretations and recommendations developed on behalf of Nye County, Nevada by ARI.

This report summarizes our review of documents consisting of field logbooks, a publication by Le Cain and Walker (1994), and a couple of letter reports by ARI (1994 and 1995). It, also, presents an interpretation of three air injection tests using our software FLOWDIM. The main objective of this study is:

(1) Review the available information and develop an opinion as to the adequacy of the USGS testing and interpretation procedures for determining rock-mass permeability, with emphasis on duration of testing, the probable geometry of the induced flow field, and the treatment of bore hole storage and skin effects

Based on the review of the available information, and our interpretation of these tests, Golder is of the opinion that, contrary to that stated by ARI, the some of the existing data sets from the air injection tests at the YMP are amenable to interpretation.

2.0 FIELD TESTING PROCEDURE

Field pneumatic permeability tests are being conducted by the USGS to determine the in situ air permeability of the unsaturated fractured and unfractured volcanic rocks (tuff). Permeability determination is of paramount importance for the prediction of potential fluid and solute movement through the stratigraphic units. These measurements of permeability are obtained with the help of a straddle packer assembly which consists of an upper and lower guard zones and an injection interval. An injection test is conducted by imposing a constant flow rate into the active interval. Pressure and temperature are measured in all the three intervals. For interpretation purposes, the length of the "active" interval is determined based on the magnitude of the pressure response within the guard intervals. It is customarily to assume that the length of the active interval coincides with the distance between the two central packers or with that of the intervals showing maximum pressure changes. The particular size of the active interval and resulting geometry of the flow field are a point of concern.

Review of the field book for bore hole UZ-16 indicated carefully collected and well documented data. The only suggestion to improve record keeping during field operation is to prepare a selfinked stamp that outlines the data typically collected. Labels for periodic monitoring of the system performance, and emergency backup, should include: pressure, relative humidity and temperature at the active and guard intervals, flow rate, pressure of the air source, and temperature of the working area as a function of time. Such a procedure would enhance uniformity during data collection and facilitate QA/QC of the field data.

The field testing procedure should include at least one recovery data set for each location. Permeability estimates from recovery data are know to be more reliable than those during injection, because the effects of variable rates are avoided. Care should be taken to insure that the recovery tests are continued until full recovery is attained.

The ARI report recommends to identify the intervals that have the greatest permeability. We disagree with this recommendation because the purpose of the USGS investigation should be to determine the spatial variability of the permeability and areas where large contrast of permeability occur. Contrast in permeability may reveal stratigraphic controls for potential development of perched water tables or preferential flow paths. The lengths of the bore holes should be scanned as thoroughly as possible. It may be necessary to initially test using larger packer separations and then refine the measurements where warranted by the previous investigations.

As suggested by the ARI report, problems with bore hole storage could be minimized by using down-hole valve and flow meter to minimize the storage along the injection line. The researchers at the University of Arizona have successfully reduced the bore hole storage within the injection interval by placing a PVC space-minimizer. The bore hole storage dominated period was significantly reduced after placement of the minimizer. However, ARI's recommendation to replace the line for a smaller diameter tubing may not be appropriate due to the relatively large injection rates required during the testing. Additional frictional losses due to higher flow velocities within the smaller injection line may result.

Another possibility to deal with the high compressibility of the fluid, is to interpret the tests using the pseudo-pressure and other dimensionless-time transformations commonly used in the gas and oil literature. When a variable bore hole storage coefficient is present during the test, deviations from the 45° degree (bore hole storage dominated) line are typically observed (Sabet, 1991). Most of the tests analyzed by ARI (Dec, 1994), Figures 3, 4, 5, 8, 10 to 13, show such deviations.

The report by ARI concludes that none of the 250 tests conducted by the USGS are suitable for analysis. Short test duration, two-phase flow effects, and lack of understanding of the physics of gas flow through rock masses are blamed for such fate. Although we agree that some of the tests analyzed by both the USGS and ARI are too short, some others are still amenable to successful interpretation as will be shown in the following section of this report.

3.0 TEST INTERPRETATION

There are currently two schools of thought with respect of the method of interpreting tests on fractured formations (aquifers or oil and/or gas reservoirs). The traditional approach assumes that the flow geometry is known and the tests are interpreted to give the permeability variation around the bore hole. Alternatively, the permeability of the fracture network is assumed uniform, and the tests are interpreted to give the spatial geometry of the flow system (variation of the fracture volume as a function of distance from the bore hole). The latter approach has been implemented in the numerical model FLOWDIM. This code is based mainly in the theory by Gringarten et al., (1979) and Bourdet at al., (1983). The concept of variable flow geometry was initially described by Barker (1988) and later generalized by Chang and Yortsos (1990). This methods allow for analysis of radial, linear and spherical flow as limiting cases, fractional dimensions for more general cases are also possible.

Both of these solution approaches have limitations. In reality, both spatial dimension and fracture permeability vary within a fractured rock. The major difference results however, no during flow calculations but when solute transport is considered. Fluid flow velocity under these two alternative interpretations is quite different. In some cases, both techniques may produced equally good match to the field data. One should see these alternative approaches as equally valid competing models, whose particular application will be controlled by the knowledge of the local geology and the corresponding conceptual model, keeping in mind the ultimate application of the data.

The test interpretation performed by ARI resulted in permeability values and skin parameters which are generally much larger than those estimated by the USGS. For instance, air permeability for the test in the Tiva Canyon member at a depth between 60' to 73' (Figure 2, from ARI 1994) is 210 Darcies with a skin factor of 135, whereas the USGS permeability estimate is 2.1 Darcies. In order to study such a large discrepancy, we re-interpreted the same test using the FLOWDIM code. Figure 1(a) shows the field data and the corresponding type curves for the radial flow case. Notice that the match between the derivative data is relatively poor for 'late" times within the test, just as that shown in Figure 2 from ARI (1994). However, the estimated permeability and skin factor are different to those reported by ARI (see Table 1). Our estimates are 21 Darcies and 8.1 for permeability and skin respectively. It must be noted that we used the same porosity, average fluid compressibility, air viscosity, temperature and gas deviation factor as reported by ARI (page 4 in their 1994 report). When the ARI estimated values for dimensionless compressibility and skin are substituted to compute the type curve parameter C_de^{2s}, one obtains a value of 10^{120}! This value is far beyond the typical maximum value (10^{30}) reported in the oil and gas literature (see for example Bourdet et al., 1983). Our best match in Figure 1(a) is obtained with a C_de^{2s} of 10^{10}. It is interesting to notice that all C_de^{2s} values computed from ARI's 1994 report are between 10^{60} and 10^{200} with the majority over 10^{100}.

Figure 1(b) shows the type-curve analysis for the same test (60' - 73'; Tiva Canyon) using p^2 as the dependent variable. The overall match is not significantly better than that obtained with the p-based approach. It seems that for the pressure disturbance imposed during this test either linearization approach is equally valid. As pointed out earlier, although the "pressure" versus time curve seems to match closely the type curve, the pressure derivative clearly shows the discrepancy and the lack of match between the data and the radial flow model. A type-curve match for the same data and the spherical flow model is presented in Figure 2. The match for both the pressure and pressure derivative are superior with this model. One must admit, however, that a slightly longer test would have provided the necessary evidence to categorically reject the radial model. In fact, this is the case for the test with a higher flow rate in the same location (Figure 3). In this instance, the radial flow model can be categorically discarded because enough data was collected beyond the point where pressure stabilization for such model is expected (notice the flattening of the type curve at p_D'=0.5 in Figure 3a). Indeed, Figure 3(b) shows a very good match between the data and the spherical flow model. Estimated permeability values and skin factors for all these tests are reported in Table 1. Notice that the reported skin values for the spherical flow model are much smaller than those from the radial flow model, and much more smaller than those reported by ARI.

One must make a clear distinction between skin due to well face damage and that due to other factors (such as partial penetration, and change of flow geometry away from the bore hole), pseudo-skin. Based on radial flow, any heterogeneity may be manifested as a pseudo-skin when interpreted thr ›ugh the type curve approach. Under this circumstances, pseudo-skin is nothing but a fudge factor.

One other test (UZ-16-075) between depths 177.1 and 181.1 m was analyzed with FLOWDIM. Figure 4(a) shows the radial flow type curve match, whereas Figure 4(b) shows the spherical flow type curve. From figure 4(a), one can discard radial flow as an option for interpreting this test. Once the derivative decreases sharply beyond 0.5, the radial flow model is not a candidate anymore. Figure 4(b) shows a nice fit to both the pressure and the derivative data. The skin factor for these models are 32.3 and -0.35 for the radial and the spherical model, respectively. These latter values clearly illustrate the concept of pseudo-skin in the case when the wrong model is selected.

4.0 DISCUSSION AND RECOMMENDATIONS

The letter report by ARI (1994) emphasizes the need to reduce the skin effect. They report skin factors ranging from 19 to 370 with most of them over 135. For the tests analyzed with FLOWDIM, we did not need to resource to such large skin factors to obtain very reasonable match with the type curves. Apparently, both PanSystem and FLOWDIM use the same underlying theory for the interpretation of the tests, however, the reported results are significantly different. The reason for this large discrepancy is not evident.

Based on the analysis of a limited subset of tests, it appears that the statement that "none of the 250 tests run by the USGS in bore hole UZ-16 are suitable for analysis" is not appropriate. As presented on this report, some tests result in reasonable match with the type curves and skin parameter values within the 'standard' range.

In terms of test interpretation, we agree with the position of ARI that a more exhaustive interpretation should be conducted in the existing data set. However, it must kept in mind that there may be competing conceptual models that may match the pressure and its derivative equally well. Additional hydrogeological information is required to discriminate amongst these competing solutions. Based on the early time behavior of the pressure and its derivative it seems desirable to pursue transformation of the dimensionless variables as those used in the gas industry to improve the interpretation of some of the available test data.

Finally, it is recommended that the data to be interpret as they are being collected in the field. As a minimum, a log-log plot of both pressure response and derivative should be prepared. Duration of a test can then be decided on the 'spot' so expensive testing repeats may be avoided.

5.0 REFERENCES

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Barker, J. A. (1988). A Generalised Radial Flow Model for Hydraulic Tests in Fractured Rock. Water Resources Research, Vol. 24, No. 10, pp. 1796-1804.

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Chang, J. and Yorstos, Y. C. (1990). Pressure Transient Analysis of Fractal Reservoir. SPE Formation Evaluation, March, pp. 31-38.

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LeCain, G. D. and Walker, J. N. (1994). Results of Air-Permeability Testing in a Vertical Bore hole at Yucca Mountain, Nevada. Published by *Radioactive Waste Management*, pp. 2782-2788.

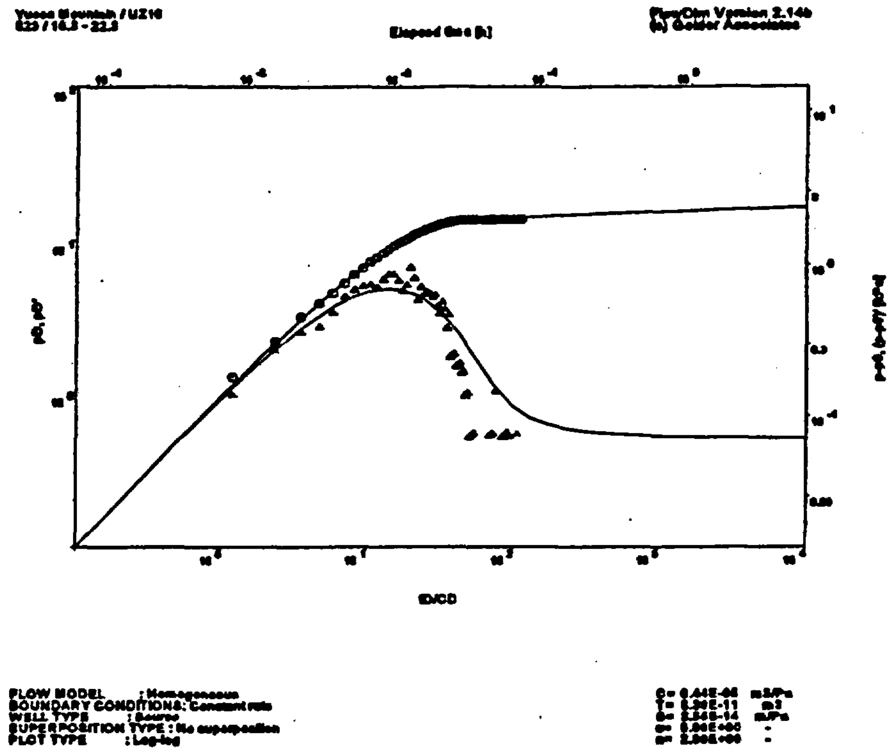
Sabet, M. A. (1991). Well Test Analysis. Contributions in Petroleum Geology & Engineering, Vol 8, by Gulf Publishing Company, Houston, Texas, pp. 260.

Table 1. Estimated Formation Parameters

Depth (feet)	Q (slpm)	Linearization Method	Flow Model	C (m^3/Pa)	T (m^3)	C_De^{2S}	k (m2)	S
60 - 73	250	p	Radial	$6.44x10^{-5}$	$8.21x10^{-11}$	10^{10}	$2.1x10^{-11}$	8.1
60 - 73	250	p^2	Radial	$3.60x10^{-7}$	$6.32x10^{-10}$	10^{10}	$1.6x10^{-10}$	10.7
60 - 73	250	p	Spherical	$6.74x10^{-5}$	$2.98x10^{-12}$	10^{6}	-	4.2
60 - 73	500	p	Radial	$6.24x10^{-5}$	$8.22x10^{-11}$	10^{15}	$2.1x10^{-11}$	13.9
60 - 73	500	p	Spherical	$6.73x10^{-5}$	$2.09x10^{-12}$	10^{6}	-	4.2
581.1 -594.2	150	p	Radial	$6.00x10^{-6}$	$4.38x10^{-12}$	10^{30}	$1.1x10^{-12}$	32.3
581.1 -594.2	150	p	Spherical	$6.36x10^{-3}$	$8.51x10^{-14}$	10^{4}	-	-0.35

FIGURE 1

(A)


FLOW MODEL
BOUNDARY CONDITIONS
WELL TYPE
SUPERPOSITION TYPE
PLOT TYPE

(B)

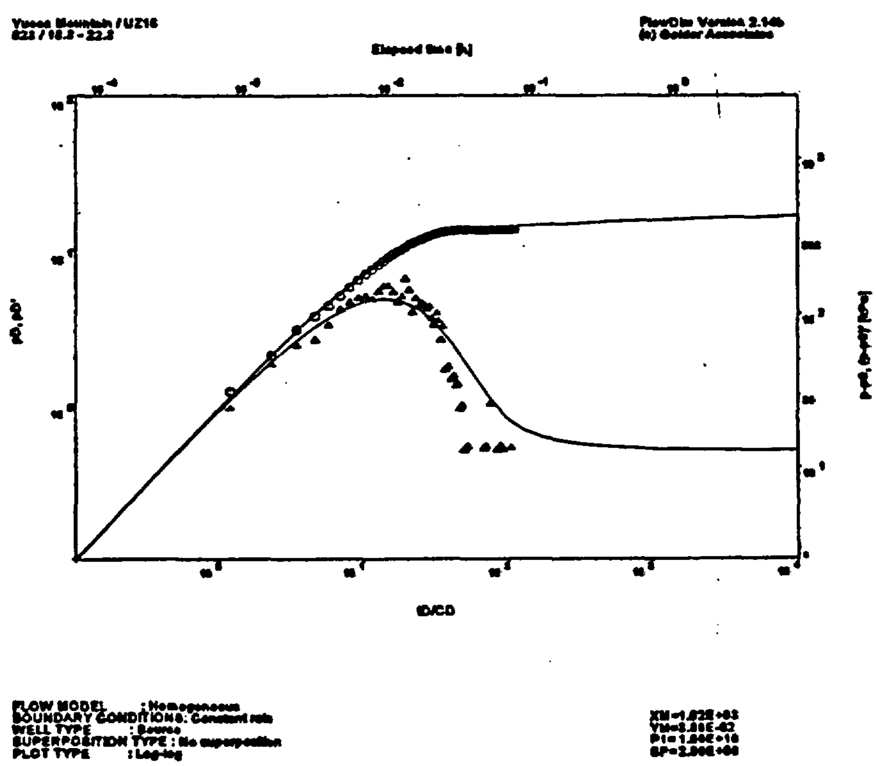

FLOW MODEL
BOUNDARY CONDITIONS
WELL TYPE
SUPERPOSITION TYPE
PLOT TYPE

FIGURE 2

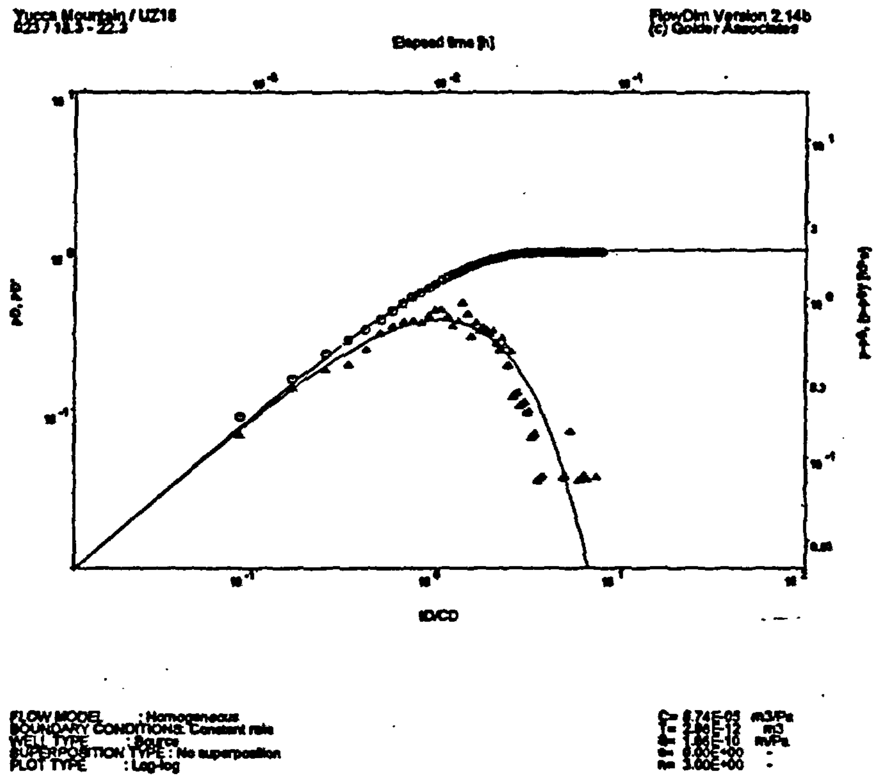
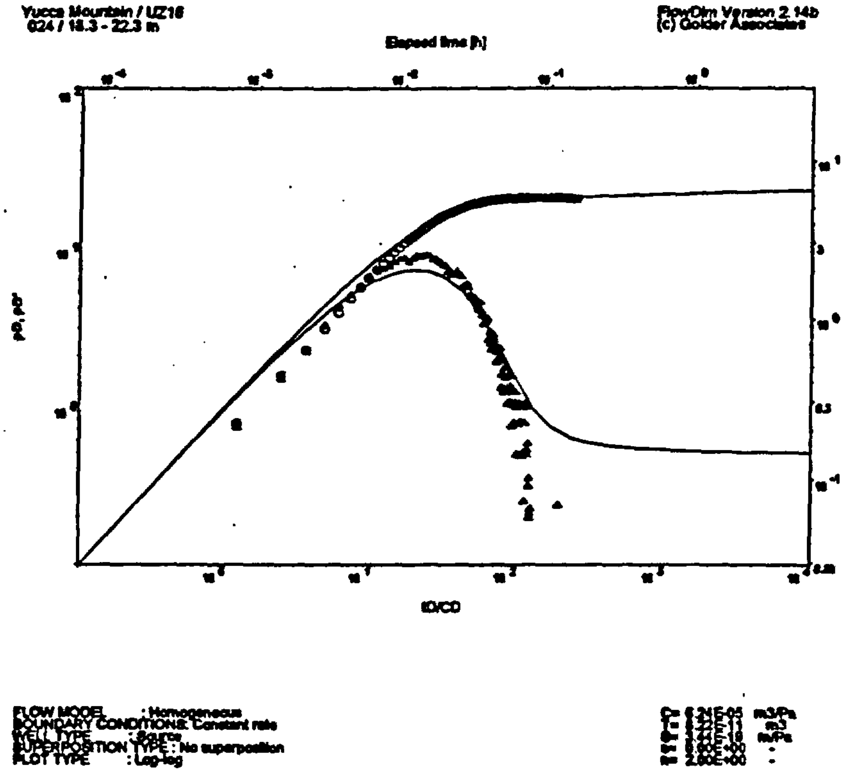

Yucca Mountain / UZ16
FlowDim Version 2.14b
(c) Golder Associates
Elapsed time [h]
tD/CD
FLOW MODEL : Homogeneous
BOUNDARY CONDITIONS: Constant rate
WELL TYPE : Source
SUPERPOSITION TYPE : No superposition
PLOT TYPE : Log-log

FIGURE 3

(A)


Yucca Mountain / UZ16
024 / 18.3 - 22.3 m
FlowDim Version 2.14b
(c) Golder Associates
Elapsed time [h]
tD/CD
FLOW MODEL : Homogeneous
BOUNDARY CONDITIONS: Constant rate
WELL TYPE : Source
SUPERPOSITION TYPE : No superposition
PLOT TYPE : Log-log

(B)

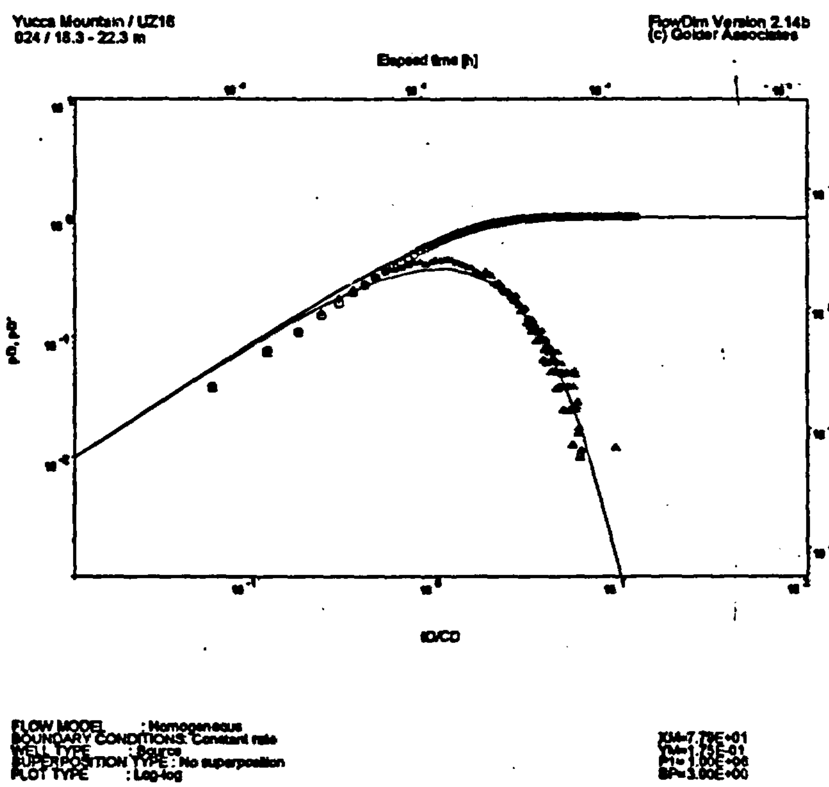
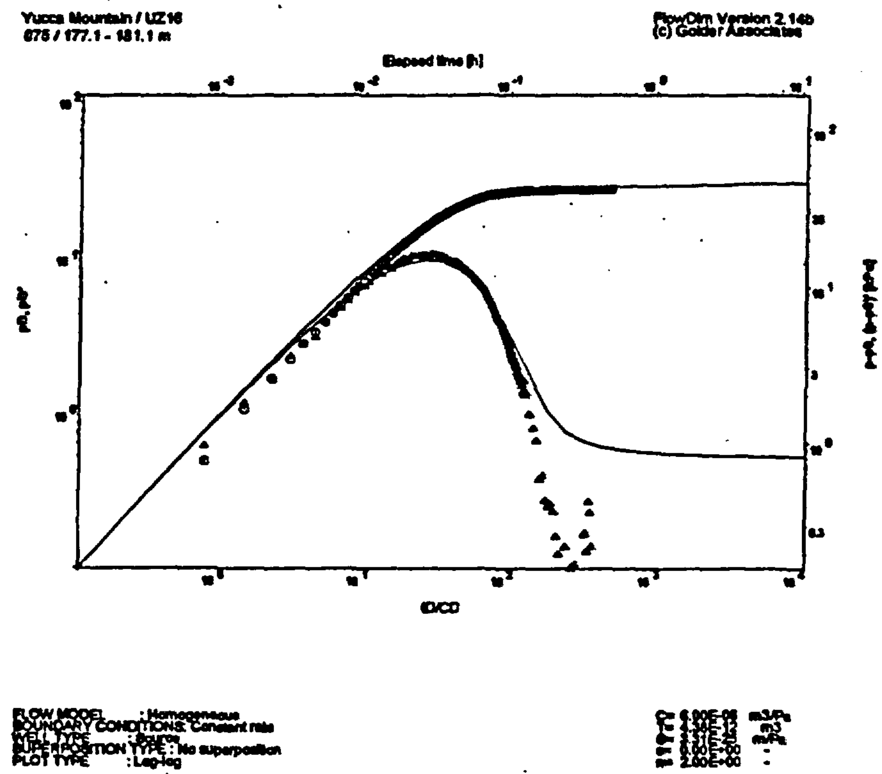
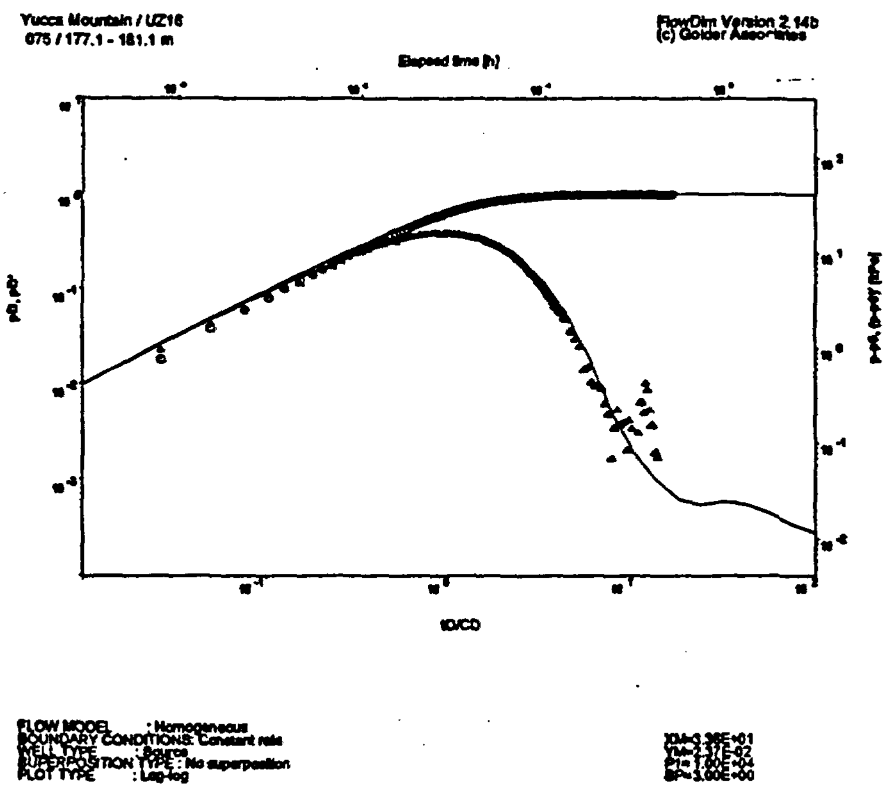

Yucca Mountain / UZ16
024 / 18.3 - 22.3 m
FlowDim Version 2.14b
(c) Golder Associates
Elapsed time [h]
tD/CD
FLOW MODEL : Homogeneous
BOUNDARY CONDITIONS: Constant rate
WELL TYPE : Source
SUPERPOSITION TYPE : No superposition
PLOT TYPE : Log-log
XM=7.79E+01
YM=1.73E-01
PI=1.00E+06
SP=3.00E+00

FIGURE 4

(A)


Yucca Mountain / UZ16
875 / 177.1 - 181.1 m
FlowDim Version 2.14b
(c) Golder Associates
Elapsed time [h]
pD, pD'
tD/CD
FLOW MODEL : Homogeneous
BOUNDARY CONDITIONS: Constant rate
WELL TYPE : Source
SUPERPOSITION TYPE : No superposition
PLOT TYPE : Log-log

(B)


Yucca Mountain / UZ16
875 / 177.1 - 181.1 m
FlowDim Version 2.14b
Elapsed time [h]
pD, pD'
tD/CD
FLOW MODEL : Homogeneous
BOUNDARY CONDITIONS: Constant rate
WELL TYPE : Source
SUPERPOSITION TYPE : No superposition
PLOT TYPE : Log-log

Attachment E

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May 25, 1995

Dr. William W. Dudley, Jr.
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Dear Dr. Dudley:

Thank you for the opportunity to participate in reviewing documents regarding air-permeability tests, and analyses of the results in boreholes at the Yucca Mountain site, Nevada.

I have completed the three tasks of the statement of works as follows:

1) Review pertinent documents -- The documents listed in the Reference section of the "Written Opinion" were picked up from COR's office on May 1, 1995. Other documents were provided at the meeting on May 8, 1995, or sent later by FAX or mail. These documents have all been reviewed.

2) Attend clarification/discussion meeting -- A meeting organized by COR on May 8, 1995, in Building 53 of the Federal Center was attended. Those present at the meeting were: W. Dudley and G. LeCain (USGS), N. Stellavato and L. Bradshaw (Nye County), D. Cox (ARI), S. Marinello, A. Guzman, and B. Jafari (Reviewers), and K. Kersch (SAIC). The meeting started at 9:00 A.M. and ended 3:30 P.M. Presentations were made by G. LeCain of USGS and D. Cox of ARI. Questions were asked by the reviewers and others. This was an informative meeting. Interesting technical discussions were generated and a number of issues were clarified.

3) Prepare and submit written opinion -- A written opinion has been written and is attached to this letter. This opinion is based upon the documents and technical references that were reviewed, results of meetings held individually with G. LeCain, D.Cox, and K. Kersch, and telephone discussions with K. Kersch. The write up consists of a summary and four sections: I- Introduction, II- Discussion, III- Recommendations, and IV- References.

It was a pleasure to serve on the review panel. If there are any questions or I can provide any further assistance, please contact me be telephone or FAX at the numbers given on the letterhead.

Sincerely yours,

B. A. Jafari

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