ANALYSES OF AIR PERMEABILITY TESTING IN BOREHOLES AT THE YUCCA MOUNTAIN SITE BY USGS

Prepared for:

Chief Yucca Mountain Project Branch

Submitted by:

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SUMMARY

I have reviewed the documents provided by Contracting Officer Representative (COR), attended a one day meeting where presentations were made by USGS and ARI, representing NYE county, Nevada, and have had meetings individually with Gary LeCain (USGS), David Cox (ARI), and Keith Kersch (SAIC). I have also reviewed some technical papers and other material, a list of which is provided in the References Section.

In my opinion the USGS testing methodology, utilizing four pneumatic packers for injecting air into a selected zone, the instrumentation for measuring pressure, temperature, relative humidity, and capability of sampling the three different zones is viable and adequate. Duration of testing, according to G. LeCain who stated that: "tests were run long enough until steady state was established, i.e., no detectable variation in the measured injection pressure" should have been sufficient. However, D. Cox, utilizing the data obtained by USGS has shown me mathematically that the wellbore storage is very large, hence, it masks the early time data, and as a result longer injection times were necessary to reach a fully developed spherical flow. I do agree that the wellbore storage is still very large even though it has already been reduced appreciably by installing a bottom-hole shut off valve which was suggested by ARI. In my meeting with Mr. LeCain we discussed possible design changes where wellbore storage can be reduced by an additional 70 to 80 percent.

The methodology used for drilling the boreholes should not have caused large resistance due to a physical Skin created as a result of wellbore damage. The geological characteristics of the formations being tested are such that even negative Skin factor is possible if some of the natural fractures were intersected at an ideal angle. While most of ARI's criticism, presented in their letters and reports to NYE county authorities, are justified, the examples cited to indicate that Skin Factor could be large, hence perhaps a much larger formation rock-mass permeability than those calculated by USGS are not justified. There is no physical reason for the Skin Factor to be very large. Having studied the data, and discussions with Messrs Cox and Kersch, it is believed the Skin Factor could be in a range of 10 to 100.

The densely fractured nature of the formations that were tested, and the randomness of the fractures present as to size, orientation, density, and orientation points to the fact that one must assume spherical flow to determine the bulk permeability specially when the equations apply to a homogeneous porous media. It should be understood that the calculated permeability applies only to the portion of the formation which is contacted by the injected air during the 10 to 15 minutes of testing. Considering spherical flow and fracture porosity the depth of penetration is limited to a short distance away from the wellbore. To assume that the calculated bulk permeability applies to the media beyond the depth of penetration would be a gross misinterpretation.

A major concern voiced both by Messrs Cox and Kersch was that the original data measured in millivolts were not kept and that the interpreted pressure data in Pascals did not have sufficient significant figures to use for derivative analyses. However, in my meeting with Mr. LeCain, he assured me that the original millivolt data were kept and pressure data to the needed significant figures can be obtained. Before using data make sure significant figures are meaningful.

It is recommended that wellbore storage be reduced as much as possible. The use of derivatives to analyze test data is recommended specially if the significant figures needed to calculate pressure differences are greater than the precision of the pressure transducer. The details of the tests should be planned in advance, on line analyses of data performed, times necessary to reach steady state be calculated and hence tests run long enough to fully develop spherical flow to enable the calculation of permeability and Skin Factor using the methodology suggested by D. Cox. Detailed recommendations are given in Section III.

I- INTRODUCTION

Results of air injection tests to determine bulk permeability in the unsaturated zone, in Yucca Mountain, Nye County, Nevada, Borehole UZ-16 was published by G. LeCain of USGS (ref. 1.1). Advanced Resources International, Inc. (ARI) were employed by Nye County to study and comment on Mr. LeCain's work. ARI completed their work and reported their results to Nye County (ref. 1.4). ARI's report harshly criticized the USGS work. A review meeting was held between ARI, USGS personnel, DOE people, and Mr. Keith Kersch of SAIC on February 8, 1995 regarding the UZ-16 well tests and interpretation methodology (ref. 1.6). The results of the meeting were reported in a letter report by ARI to Nye County. Letters were exchanged between Nye County, Department of Energy, and Yucca Mountain Project Office responding to ARI's report (refs. 1.5, 1.6).

On May 1, 1995, I met with Dr. Dudley of USGS, who explained the situation and provided me with the documents and data (refs. 1.1-1.6). My task was to study the documents and prepare for a meeting to be held on May 8, 1995. I was told that two other reviewers, like myself, have also been selected to do the same.
A meeting organized by Dr. Dudley (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 discussion were generated and a number of issues were clarified. A copy of material presented by ARI, marked draft, was handed out (ref. 2.2). A technical paper (ref.2.3) was provided by Mr.Kersch.

Following the meeting Mr. Keith Kersch of SAIC called me and we had at least three technical discussions on the telephone (May 9 - May 15) and a meeting in Denver on May 17, 1995. I received a copy of material presented by Mr. LeCain at the meeting and a new (readable) diskette containing the interpreted data for UZ16023, Uz16024, and Uz16025 (the same data that had been used by ARI) and two higher pressure tests that were run for longer time periods, namely, UZ16075 and UZ16076 (ref. 2.1). On May 17 I received a FAX from Mr. Cox showing a type curve for a Finite Cylinder Injection source and the response functions for various Skin (S) and Dimensionless Storage (Cd) (ref.2.4).

I requested to meet with Mr. LeCain and we met for over two hours on May 23, 1995. I asked a number of question regarding the equipment used, its capabilities, limitation, accuracy and reliability and the procedure and methodology employed in carrying

out the tests and analyzing the data.
I requested to meet with Mr. Cox and we met for over two hours on May 24, 1995. I asked him a number of questions regarding the methods of analyses employed, Skin, Storage Factor, and the new type curves being suggested. He showed me their PanSystem 2 software capable of utilizing various flow equations and analyses techniques to analyze well test data.

I have reviewed several texts, technical papers, and mongraph series to refresh myself (refs. 3.1 - 3.6).
What follows in Sections II (DISCUSSION) and III (SUGGESTIONS AND RECOMMENDATIONS) are based on all of the material that I have reviewed, the joint meeting held on May 8, 1995 and meetings held individually with Messrs Kersch, LeCain and Cox.

II- DISCUSSION

Section I, Introduction, contains the sequence of events as they happened and reference to the reports, data, and articles that were reviewed. In this section a detailed account of my opinion which was summarized in the Summary section is given.

II.1 Adequacy of Testing Equipment and Methodology

Use of four pneumatic packer system and the instrumentation used to measure pressure, temperature, relative humidity, and the capability of sampling in the injection zone, the upper guard zone, and the lower guard zone as described in reference 1.1 and later described in more detail during my meeting with Mr. LeCain of USGS shows that an up-to-date technique is being used to determine bulk permeability. The precision of the instruments are greater than the reliability of the data. The fact that individual zones can be sampled provides the capability to carry out slug tests, using tracers, to possibly determine vertical permeability. In my opinion determination of vertical permeability is more important than the bulk permeability because of its use in the computer models which will be used in the future to simulate fluid flow around the repository. The equipment should be modified to reduce wellbore storage. This is discussed in detail in Section II.4.

As described by Mr. LeCain, in our meeting on May 23, 1995, the packer system is lowered to the bottom of the wellbore, then the formations of Calico Hills, Topapah Springs, and Tiva Canyon are tested in intervals of 4 meters, systematically from bottom up. While this technique may be more practical it is not the best approach. In Section III (Suggestions and Recommendations) suggestions are made on how to improve the methodology. It was understood that the boreholes are logged by a service company and 15 different logs are obtained for each borehole. These logs should be utilized to calculate formation rock properties. A technique was discussed, in our meeting, where I showed how one may be able to utilize the data obtained from the logs and core testing to determine fracture porosity. This is assuming that data obtained have adequate accuracy and precision. Understanding the geology and rock properties, tests should be planned in advance to target specific formations. Thicker sections should be tested, within the limitation of the flow equipment, to have a better representation of spherical flow.

II.2 Testing Period

Questions were raised whether tests were run long enough or not? When Mr. LeCain described his testing procedure he stated that tests are run at a predetermined rate of 250, 500, or 750 slpm injection rate until steady state is reached, meaning that the changes in pressure are within the accuracy of the pressure transducer. This means that longer time will not result in any further changes in pressure. If this is the case then testing period is sufficient. However, Mr. Cox showed me that because of the large wellbore storage, the time necessary to develop fully spherical flow or steady state is much larger. I do agree with his findings. Longer tests have been run which show very minor change in the measured pressure. However, both Mr. Cox and Mr. Kersch argue that the significant figures shown in the pressure measurement are not sufficient to observe whether there are changes in the pressure measurements or not. They were concerned that original data measured in millivolts were not recorded, therefore one could not go back and obtain pressure data with more significant figures. However, I was assured by Mr. LeCain that the original raw data are intact and can be retrieved. If significant figures needed in the pressure measurements to carry out the differential analysis are not within the precision of the transducer, then more than likely the result of the analysis, even though mathematically correct, but will have very little physical meaning if any. Once the wellbore storage is substantially (70 to 80%) reduced, then the testing time should not be an issue.

II.3 Skin Factor

Any time wellbore is damaged due to drilling there will be physical skin present at the wellbore. Its resistance to flow will be a direct function of its permeability and an inverse function of its thickness. In drilling oil or gas wells drilling muds are used which create a more significant skin than if air was used. The methodology used for drilling UZ-16 indicates there should be minimal damage, hence a small positive skin. Since the formations drilled through contain densely naturally fractured zones, it is possible to have some sections which may have a negative skin factor if the fractures were intersected in an ideal manner. In the petroleum industry tight formations containing oil or gas are hydraulically fractured to create a lower resistance at the wellbore in other words a negative skin factor. Having studied the data, and discussions with Messrs Cox and Kersch, it is believed the Skin Factor could be in a range of 10 to 100.

The Skin Factor can be determined using the new differential analysis technique being suggested by Mr. Cox. The wellbore storage must be reduced to utilize short term test data. Longer term data utilizing meaningful significant figures of the pressure measurements can also lead to the determination of Skin Factor.

II.4 Wellbore Storage

Study of the data and discussions in the various meetings held leads me to believe that the wellbore storage is significantly high and it is masking pressure variation at the transient stage. The wellbore storage can be reduced ba a factor 70 to 80% by making slight design modifications. A few different ideas for wellbore storage reduction were discussed in my meeting with Mr. LeCain on May 23, 1995.

II.5 General Comments

Determination of bulk air-permeability in the unsaturated zone of relatively shallow boreholes with densely fractured formations of Yucca Mountain by injecting air into a selected zone using a four pneumatic packer system is unique. This is different from routine petroleum well testing where gas or oil flows from a drainage radius more than thousands of times larger than the wellbore radius. The geologic characteristics and rock properties should be thoroughly understood. The mathematical equations applied to analyze the results should be completely understood with respect to the assumptions that were made to reduce the general diffusivity equation. A fact that we all know but often forget is that the mathematics should attempt to represent the physics of the natural phenomena and nature will not know that it has to follow a particular mathematical formula. Therefore, the physics should be understood before equations are used blindly.

The densely fractured nature of the formations that were tested, and the randomness of the fractures present as to size, orientation, density, and orientation points to the fact that one must assume spherical flow to determine the bulk permeability specially when this complex fractured formation is assumed to be a homogeneous and isotropic porous media. It should be understood that the calculated permeability applies only to the portion of the formation which is contacted by the injected air during the 10 to 15 minutes of testing. Considering spherical flow and fracture porosity the depth of penetration is limited to a short distance away from the wellbore. To assume that the calculated bulk permeability applies to the media beyond the depth of penetration would be a gross misinterpretation.

III- RECOMMENDATIONS

The recommendations suggested in this section are set up in order of priority. The highest priority is the reduction of wellbore storage by a significant percentage.

III.1 Reduction of Wellbore Storage

The present system uses a 2" pipe to house the pressure transducers, the thermistor, the thermocouple psychrometer, the electrical cable, the nylon tubing for gas injection and inflation of the packers, and the steel cable to support the weight of the packers and tubing bundle. If the size of the pipe is increased from 2" to 5", the reduction in the wellbore storage in a 6" wellbore will be (21/32)% or approximately 70%. The size of the housing pipe should be determined within the bounds of practical limits of lowering and raising the packer system.

III.2 Error and Sensitivity Analyses

An error analysis should be performed to calculate the effect of possible errors in the variables used to determine permeability. A range for the maximum error and minimum error should be calculated. When reporting the calculated results make sure that the significant figures do not exceed the accuracy of the results.

A variation of 1 degree centigrade in the temperature will cause a variation of 339 pascal in pressure assuming ideal gas equations and a constant wellbore storage volume. The effect of wellbore storage volume on the rate at which pressure changes when injecting at different rates becomes obvious if errors in the pressure measurement, flow measurement, temperature measurement, and assumption of ideal gas equation are taken into consideration.

Sensitivity analysis should be performed to determine the relative magnitude of changes in the calculated parameter against the changes in the various variables. This will result in determining the most and least sensitive variables and the degree of accuracy required in measurements.

The results obtained should be compared to those available from other sources or those calculated using other methods. If there is large difference one should examine the results closely. The following is an example of calculating bulk permeability knowing fracture characteristics.

A very simplistic approach, assuming the fractures to be capillary tubes leads to the development of an equation which relates permeability to the capillary tube diameter. A permeability of 1 darcy (10E-12m2) is equivalent to a capillary tube having a diameter of 0.0006 centimeters (ref. 3.3 equation 1-19). Fracture mapping and other fracture analyses techniques may provide fracture sizes which could be used for comparison purposes. For example, for a wellbore height of 1 meter and radius of 6 inches assuming it contains 20 fractures. Also assume that an average fracture has an opening of 0.001 cm. by 24 cm. If the matrix permeability is assumed to be 0.1 millidarcy (10E-16m2), the bulk permeability is calculated, using Equation (1-21, ref. 3.3) to be approximately 0.2 darcy (2X10E-13m2). Actual fracture numbers and sizes, matrix permeability, and other actual dimensions could be used to calculate the bulk permeability. The results could be used as a check within an order of magnitude.

III.3 Preplanning and Data Analyses

Planning the well tests prior to their executions extremely important. Well logs available should be used to determine porosity of the matrix and when possible porosity of the fracture system. Methods outlined on page 139 of reference 3.3 could be used to estimate fracture porosity if the fracture porosity is greater than the measurement errors. Permeability using equations relating porosity to permeability can be calculated for ball park comparison. One should be thoroughly familiar with the entire formation in the wellbore prior to testing. The injection interval should be set as high as possible within the physical limitation of the packer system and the injection equipment. The well should be tested with the wide injection interval from bottom to the top, recognizing the delineation between the distinct formations. Data analyses should be performed simultaneously. Calculated permeabilities should be compared to those obtained by other methods. If longer test times or other changes in the testing methodology are needed it will be realized if the obtained results are much different than those expected.

III.4 Use of PanSystem or other Software

It might prove useful to use software such as the PanSystem (software currently used by ARI) or other comparable software to analyze the data. This will provide a fast mean of using various alternative data analysis and decision making while the testing equipment is in place and changes are relatively inexpensive compared to retesting at a later time.

III.5 Use of Tracer Injection

While meeting with Mr. LeCain, he mentioned that some slug tests had been performed by injecting tracer/s in the injection zone and monitoring the response in the upper and lower guard zones. These type of tests are encouraged. If properly performed, through prior planning, these tests could prove to be valuable in determining vertical permeabilities. The results of these type of tests could be combined with those from multiple well testing to determine formation heterogeneity.

III.6 Collection of Recovery Data

It was understood that since the installation of the downhole shut off valve, fall off data can be recorded after the flow is shut off. These data will provide an alternative mean to calculate permeability and skin factor.

IV- REFERENCES

1. Documents Provided by USGS

1.1 LeCain, G.D. and Walker, J.N., 1994, "Results of Air Permeability Testing in a Vertical Borehole at Yucca Mountain, Nevada," Published in Radioactive Waste Management, p.2782-88.

1.2 LeCain, G.D. and Walker, J.N., 1994, "Air Permeability Data from UZ-16 Borehole and a 395-page Technical Data QA package for that Borehole.

1.3 Reduced pressure, temperature, and mass-flow data in engineering units on six 3-1/2" diskettes.

1.4 AN ANALYSIS OF AIR PERMEABILITY TESTING IN BOREHOLE UZ-16, YUCCA MOUNTAIN, NEVADA, a report prepared by Advanced Resources International, Inc. for The Nye County Nuclear Waste Repository Project Office, December 1994.

1.5 Letter from Larry R. Hays, Technical Project Officer to Russ Patterson, Team Leader Hydrology and Climate, Yucca Mountain Site Characterization Office, U.S. Department of Energy, February 28, 1995.

1.6 Letter from Russel L. Patterson, Team Leader for Hydrology to Larry R. Hays, Technical Project Officer for Yucca Mountain Site Characterization Project, March 21, 1995, which includes a letter from David Cox, Vice President of Advanced Resources International, to Nick Stellavato, Nye County Nuclear Waste Repository Project Center, Review Meeting Regarding UZ-16 Well Tests, February 24, 1995.

2. Documents Provided at the Meeting or Received at a Later Date

2.1 A copy of material presented by Gary LeCain at the meeting held in USGS offices in Lakewood on May 8, 1995 plus a 3-1/2" diskette containing air-k tests from UZ-16: UZ16023-25, UZ16075-76.

2.2 A copy of material presented by David Cox regarding New Type Curves, presented at the meeting held in USGS offices in Lakewood on May 8, 1995.

2.3 J. Garcia-Rivera, and R. Raghavan, "Analysis of Short-Time Pressure Data Dominated by Wellbore Storage and Skin," p.106-114, distributed at the meeting by Keith Kersch of SAIC.

2.4 FAX received from David Cox, May 17, 1995, "Additional Type Curve for UZ-16 Well Tests," a plot of dimensionless pressure, vs. Dimensionless time (td/Cd) for a Finite Cylinder Response Functions for various Skin and Cd.

2.5 R.C. Earlougher, Jr., and Keith M. Kersch, "Analysis of Short-Time Transient Test Data By Type-Curve Matching," Journal of Petroleum Technology July 1974, p793-800.

2.6 A hand out by Gary LeCain: USW NRG-6, list of Logs run on Boreholes at the Yucca Mountain Site, May 23, 1995.

3. Other References

3.1 Applied Petroleum Reservoir Engineering, B.C. Craft and F.H. Hawkins, Prentice-Hall INC., 1973

3.2 Practical Petroleum Reservoir Engineering Methods, H. C. Slider, Petroleum Publishing Company, Tulsa, Oklahoma, 1976.

3.3 Naturally Fractured Reservoirs, Dr. Roberto Augilera, Petroleum Publishing Company, Tulsa, Oklahoma, 1980.

3.4 Well Testing, John Lee, SPE Textbook Series Vol.1, New York 1982.

3.5 Advances In Well Test Analysis, Robert C. Earlougher, Jr., Society of Petroleum Engineers Mongraph Volume 5, New York, 1977.

3.6 Pressure Buildup And Flow Tests In Wells, C.S. Maithews and D.G. Russell, Society of Petroleum Engineers Mongraph Volume 1, New York, 1967.

Attachment F

CONSULTANT'S REPORT

To: L.R. Hayes, Chief, Yucca Mountain Project Branch

Through: W.W. Dudley, Jr., COR, Yucca Mountain Air Permeability Testing Program External Review

From: S. A. Marinello, Ph.D., Consultant

Date: May 30, 1995

Subject: Analysis of Air Permeability Testing Program for the Yucca Mountain Project, including review of USGS and ARI documentation, consultations and informational meeting discussions.

I have reviewed the materials and documentation provided and have participated in the informational discussions taking place at the USGS facilities in the Federal Center on May 8, 1995. I have also discussed some relevant issues of concern with Dave Cox of Advanced Resources International following said meeting. There would seem to have been some fairly strong feelings developed with regard to the subject at hand which may be based mostly on differing technical backgrounds and experiences. They should not be allowed to cloud interpretation of the data.

I would like to consider this a Provisional Report with the intent to follow-up on some of Dave Cox's latest type curve generation and test analyses. I would expect to accomplish such a review within the next ten days, if at all possible. It should not entail more than two to four hours time, if that is acceptable.

In general, I must state that my interpretations basically parallel those of Mr. Cox as they were developed and presented at the May 8th meeting. This might be expected because of our similar petroleum engineering based well test analysis backgrounds. However, this does not prejudice my review of the testing and analysis procedures that have been presented.

I actually began by evaluating the material in reverse, such that the first document reviewed was the response of Gary LeCain to ARI's December 1994 report titled, "An Analysis of Air Permeability Testing in Borehole UZ-16, Yucca Mountain, Nevada". Following that review, I turned to the item that had elicited such a response. After review of that report and the test data provided I came to a number of interim conclusions.

1. The characterization and analysis of the tests using a radial flow model by Mr. Cox was not precisely correct. The system would in all likelihood not respond in a true radial manner.
2. However, the premise that this would totally invalidate the analysis presented by Mr Cox, as presented by Mr. LeCain in his response, is equally incorrect. The characteristic shapes of

response curves is altered by the flow geometry, but there are still inherent characteristics of the responding flow system that can be inferred from plots based on a radial system. And the recognized problems and recommendations related to apparent wellbore storage are certainly not rendered incorrect nor are the use and accuracy of type curves. A set of curves for a correct system geometry would not yield infinite permeability values with Mr. LeCain's "late-time" data. (This matter was addressed in detail at the May 8th meeting.)

3. I am familiar with the PanSystem well test analysis package that Mr. Cox utilized and, although it is not perfect, it is an excellent tool from which to elucidate information during progressive analysis. The clear flag that consistently comes up in analysis is that the test length does not appear to provide time for flow to stabilize in a characteristic transient flow regime, the regime in which the pressure response will yield an accurate determination of formation properties utilizing semilog analysis. This evaluation is consistently presented in the log-log type curve analyses presented by Mr. Cox which show that the pressure derivative (radial derivative) plots of the data versus elapsed time do not reach to the horizontal flat portion of the type curve, indicating that wellbore effects are still influencing the data. This is something that required further investigation into the test procedures in order to determine the factors contributing to the situation.

4. It is clear in reviewing the test procedures that it is likely that wellbore storage is still influencing the pressure response data. This would have to be expected considering the highly compressible nature of the test fluid (air) and the relatively large volumes contained in the tubing and well space adjacent to the reservoir that were not excluded from the test response through volume minimization and isolation.

5. It was suggested in the ARI report that pressure fall-off testing be initiated to minimize saturation change and displacement effects. I concur with this recommendation.

6. Before any analysis can be deemed complete, the results obtained and analyzed must be consistent with the probable, or at least a possible, flow model. This includes geometry and geological characteristics with their potential influence on the test pressure response. It would seem clear based on a petroleum engineering fluid flow/reservoir engineering background and well test analysis experience that we are not seeing "steady state" flow in the system under analysis. In fact, the fractured nature of the formation raises one particular flag to consider, that of "skin" effects. I am not talking solely about formation damage skin in this case. In addressing the total skin effect, it must be recognized that it may be derived from damage due to plugging from drilling operations and the release of formation fines and from the incomplete or partial connection of the wellbore flow system to the fracture system in a fractured matrix formation. The latter has typically contributed to significant, and often very high, values of skin, as noted by Mr. Cox. In the case of the USGS analysis by Mr. LeCain, the flow model basic geometry, probably elliptical or near spherical, may be accurate, but consideration of the geologic characteristics of the system and their effects on flow/pressure response is incomplete and not consistent with the responding system. We also do not know the real success of the LM-300 system in reducing skin damage.

Following review and analysis of the documentation and data, I was looking forward to the meeting of May 8th. I hoped that an open discussion including all parties would be very fruitful in bridging the differences in interpretation and understanding. For the most part, I believe that was true. However, as the meeting wore on, some resistance to outside opinions became evident. Some of the relevant discussions that should impact the testing program follow.

1. Mr. LeCain made a presentation that attempted to support the premise that all flow was essentially steady state and that any wellbore storage or transient flow took place at very short times. He pointed out that a straight line semilog response was achieved at these extremely short times and that this proved that his interpretation was correct.

   I must completely and absolutely disagree with this interpretation. Whether this response was indicative of the type of pressure device and response or was a straight line artifact relating to gas compressibility, it is clearly not a stable transient response. As stated previously, the use of a specific analytical model is only appropriate when the geometry and other physical factors support that model. In this case that is an erroneous conclusion, wholly unsupported by known formation information and gas well test analysis experience. Such mistakes are not, unfortunately, uncommon in analyses by consultants, oil and gas industry engineers or students in graduate, as well as undergraduate, courses. They arise when consideration of the system being analyzed is not made and the response/shape of the data dominates the selection of the region to be analyzed.

   On the subject of whether the flow regime during these tests has been steady state or transient, I think that it is clear that it is not even in stable transient flow, must less steady state flow. It clearly can mimic some steady state characteristics due to the compressibility of the large wellbore storage volume.

2. The matter of the incorrect flow geometry, elliptical/spherical versus radial, was addressed by Dave Cox with the presentation of type curves developed for such systems. In the presentation, it was also brought out that pressure response is affected only slightly by flow geometry or completion interval. The methodology of development is sound and the results clearly show that characteristic responses can be expected for given systems exhibiting varying degrees of wellbore storage or skin. Therefore, analysis of these transient responses should provide for an accurate determination of skin and permeability. With the proper type curves, the required test duration can be established in order to ensure that semilog analysis of the transient data would provide the best possible estimates of these formation properties. This coincides with the breakaway of the derivative curve which indicates that wellbore effects have ended and that proper transient analysis of spherical flow can be accomplished.

   This was all clearly set out in Mr. Cox's draft letter to Mr. Stellavato, date May 8th, and provided for all participants at the meeting. Mr. Cox has provided a copy of the collapsed set of that data presented and I look forward to evaluating the application of these type curve sets in the analysis of past and future air permeability tests for the Yucca Mountain Project.

3. One of the most, and least, productive discussions dealt with the use and understanding of type curves for analysis. In particular, Mr. LeCain began to understand the significance of the use of the pressure derivative function as a tool increasing the accuracy of log-log type curve analysis, although he consistently questioned the accuracy of type curve usage in general. I will have to disagree with him, for the most part, on that subject. Type curves, developed and applied properly to given systems, are often as accurate as other methods for analysis. They simply collapse multiple scenarios onto individual characteristic curves through the use of dimensionless variables. Through this, the dimensional "picturing" of a given system response is possible. It should be noted that, in my opinion, prior to the development, understanding and use of the pressure derivative function plots, type curve usage was a much less accurate exercise.

   The significant point made here was that, with the properly developed type curves, test response could be analyzed in real time as the test is being run in order to ensure that test length is adequate and that the response is as might be expected. The use of real time monitoring of the tests is strongly recommended.

4. It was shown by Mr. Cox that, with modifications made to reduce wellbore storage, proper tests and analysis could be performed with flow periods of under two hours. Mr. LeCain pointed out that the USGS had already proceeded to modify their equipment to minimize such effects.

5. It was suggested by Mr. LeCain that inter-wellbore tests were the only way to really determine formation properties because there are inherent inaccuracies when the test well and monitoring well are the same. This is not necessarily true, depending on the ability to account for wellbore effects. However, it is certainly true that, for a project this significant, all methods of testing that sample across different sections and with different methods should probably be pursued. That is why pressure fall-off tests are recommended, as well as interwell tests. It should be pointed out, however, that interwell testing does not only sample the part of the formation between test (impulse) and monitoring wells, but samples the formation volume swept by the flow, be it spherical or radial, during the test time flow period. This is one of the common mis-assumptions regarding interwell tests and should be accepted as one of the reasons that response analysis is often surprising with such tests.

My conclusions and recommendations for the air permeability testing program would be as follows:

1. Although the repeatability of the test responses seems good, the interpretation is sorely lacking in terms of what is known about the formation tested and similar formations.

2. The system can best be approximated with a model of elliptical/spherical flow. Analysis of subsequent tests should be made based on that assumption.

3. Clearly there has been significant wellbore storage affecting the past test responses. With modifications as suggested by ARI and already in implementation by the USGS APTP, to reduce test system volume, these effects can be minimized.

4. Real time analysis of the testing should be done recognizing that the system will need 10 minutes to two hours to reach stable transient flow. This should be analyzed with the developed type curves to ensure necessary test duration. The use of pressure derivative functions in the log-log type curve analysis will help establish the onset of stable spherical transient flow. Steady state flow analysis methods are not applicable, in my opinion, in the span of testing I have seen.

5. The characteristic skin of the formation needs to be determined and this should be accomplished with the combination of log-log and semilog analysis of the pressure response data. This is significant for two reasons; first to determine the interconnectivity or disconnectivity of the fracture system and, second, to allow a determination of the effectiveness of the LM-300 drilling system at reducing formation damage. This can be accomplished through the use of two transient tests at different rates. Flow connectivity in the fractures should be a rate dependent effect while formation damage will not be affected by rate.

6. Interwell testing is suggested. This will not necessarily provide more accurate permeability or skin data for the formation, but it may provide an ideal of longer distance interconnectivity of fractures.