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# **Effects of Long-Term Exposure of Tuffs to High-Level Nuclear Waste-Repository Conditions**

## **Preliminary Report**

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EFFECTS OF LONG-TERM EXPOSURE OF TUFFS TO HIGH-LEVEL NUCLEAR  
WASTE-REPOSITORY CONDITIONS  
Preliminary Report

by

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ABSTRACT

Tests have been performed to explore the effects of extended exposure of tuffs from the southwestern portion of the Nevada Test Site to temperatures and pressures similar to those that will be encountered in a high-level nuclear waste repository. Tuff samples ranging from highly welded, nonzeolitized to unwelded, highly zeolitized varieties were subjected to temperatures of 80, 120, and 180°C; confining pressures of 9.7 and 19.7 MPa; and water-pore pressures of 0.5 to 19.7 MPa for durations of 2 to 6 months. The following basic properties were measured before and after exposure and compared: tensile strength, uniaxial compressive strength, grain density, porosity, mineralogy, permeability, thermal expansion, and thermal conductivity.

Depending on rock type and exposure conditions, significant changes in ambient tensile strength, compressive strength, grain density, and porosity were measured. Mineralogic examination, permeability, and thermal property measurements remain to be completed.

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I. INTRODUCTION

As part of the Nevada Nuclear Waste Storage Investigations (NNWSI) Program, the Los Alamos and Sandia National Laboratories are evaluating the potential of silicic pyroclastic rocks of the Nevada Test Site (NTS) as nuclear waste repository media. The program consists of interacting laboratory, field, and computer modeling studies designed to establish the necessary design criteria to assure a safe repository. In particular, thermal and mechanical properties of the rock mass used for the repository are critical data inputs in assessing repository performance.

Several factors can affect the thermomechanical behavior of rocks. Among these are temperature, stress field, and time. The mechanisms involved are complex and beyond the scope of this report, but we note that both physical and chemical processes can result in temporary or permanent changes in the rocks. Although laboratory measurements are commonly made under a variety of temperature and stress conditions, the effect of time is seldom measured because the relatively long time scales required for such tests immobilize equipment that could otherwise be used for many shorter tests.

This project was designed to test a large number of samples at one time by an extended exposure to the hot, wet, high-stress conditions expected near a waste repository. The individual tests are designed to cover a range of temperature and pressure conditions simulating varying distances from the waste canister and different repository depths. Because the properties of tuffs vary substantially with lithology, a range of "types" covering varying degrees of welding and postdeposition mineralization were chosen.

The experiments reported here avoid the need for tying up high-temperature, high-pressure testing equipment by performing most measurements at ambient conditions. The samples were exposed to repository conditions in a sealed environment and later removed for testing. This allows a wide range of tests on a significant number of samples. By comparing the results of these tests with similar data for control samples, changes caused by the exposure can be detected.

These experiments are intended to be exploratory in nature. They were designed to detect irreversible changes in the physical and mineralogic character of the samples that may indicate potentially troublesome temperature or pressure conditions. Any adverse effects noted should be investigated further by appropriately designed experiments. Because for the most part data collection is at ambient conditions, the data presented here should not be regarded as engineering data.

## II. SAMPLES AND SAMPLE PREPARATION

Samples for this study were selected from cores taken from two test holes at the Yucca Mountain Site at the Nevada Test Site. These holes are UE25a#1 and USW-G1. General petrology and mineralogy of the rock units found in these cores have been reported elsewhere.<sup>1,2</sup> Four units were selected for the tests shown in Table I. These selections were made to provide a contrast in degree

TABLE I  
KEY TO TEST CONDITIONS

| Test # | Temperature | Confining Pressure<br>(MPa) | Pore Pressure<br>(MPa) | Duration<br>(Months) |
|--------|-------------|-----------------------------|------------------------|----------------------|
| 1      | 80°C        | 19.7                        | 5.0                    | 6                    |
| 2      | 80°C        | 9.7                         | 0.5                    | 6                    |
| 3      | 120°C       | 19.7                        | 19.7                   | 5-1/2                |
| 4      | 120°C       | 9.7                         | 0.5                    | 5-1/2                |
| 5      | 120°C       | 19.7                        | 19.7                   | 2-1/2                |
| 6      | 120°C       | 9.7                         | 9.7                    | 2-1/2                |
| 7      | 180°C       | 9.7                         | 9.7                    | 3-1/2                |
| 8      | 180°C       | 9.7                         | 9.7                    | 3-1/2                |
| 9      | 120°C       | 19.7                        | 19.7                   | 2                    |
| 10     | 120°C       | 9.7                         | 9.7                    | 2                    |

Basic mechanical comparisons (compressive strength, tensile strength, density, and porosity) were performed for all tests. Mineralogic and petrologic examinations will also be done for all tests. Permeability data will be collected for tests 3 and 6 and thermal properties for tests 1, 4, and 5.

of welding and zeolite content. In addition, the Bullfrog and Tram units selected are under consideration as target horizons for field investigations.

The samples exposed to high-temperature, high-pressure conditions were 2.54-cm-diam by 6.5-cm-long cylinders. Control samples came from the same piece of core as the test sample, in most cases cut side by side. Procedures for handling, preparing, and storing the samples are in Appendix A. A complete list of core samples tested is in Table I.

### III. EXPOSURE CONDITIONS

Test conditions were chosen to simulate different burial depths, water table levels, and distances from the waste canisters. The three temperatures (80, 120, and 180°C) reflect current targets for average formation temperatures. Confining pressures of 9.7 and 19.7 MPa simulate burial at 1500 and 3000 ft respectively, and differential pore-water pressures of 0.5 and 9.7 MPa correspond to above- and below-water-table conditions.

Exposure times ranged from 2 to 6 months. A table of these variables, along with the tests conducted and samples tested under each set of conditions, is given in Appendix B. A schematic of the pressure and temperature systems and a drawing of the pressure vessels are also in that appendix.

Temperatures and pressures were monitored continuously and recorded as part of the quality assurance program. These data are available upon request.

#### IV. TEST PROCEDURES

The characteristics studied were mineralogy, tensile strength, compressive strength, density, porosity, permeability, thermal conductivity, and thermal expansion. Table I lists the tests run and exposure conditions. Procedures for each test are given in Appendix C through F. The procedures for tests on control samples were the same as those for exposed samples.

#### V. TEST RESULTS

Results of mechanical properties tests are listed in Table II (before exposure) and Table III (after exposure). A key to the temperature, pressure, and duration of the tests is given in Table I and key numbers appear in Table III. For correlation of results, note that all samples of Calico Hills and Topopah Springs tuffs come from drill hole #UE25a-1 and all samples of Bullfrog and Tram tuffs come from drill hole #USW-G1. Individual samples are numbered by depth as indicated in column one of Tables II and III. Comparisons of data from Tables II and III and summary histograms given below can be used to judge the effect of the exposure conditions on the ambient mechanical properties of each rock. Before doing this in detail, however, some general comments about the significance of apparent changes are in order.

Because of the exploratory nature of these tests, the long duration of each test, and the large number of permutations of rock type and test conditions, extensive statistical testing was not possible. Therefore, there is a question as to whether or not any apparent changes are statistically significant or merely chance. To get some idea of the significance of the results, a two-sided *t* test was performed on all the data for which it was applicable. This tests the null hypothesis that the means of a property measurement before and after exposure are equal. For instance, a probability of 0.1 (probabilities are listed in Table III) means that if the true difference in means were zero, a deviation in either direction as large as that measured, or larger, would occur by chance only about 10 times in 100. We judge that probabilities of about 0.1 or less indicate a significant difference.

TABLE II  
MECHANICAL PROPERTIES OF SAMPLES BEFORE TEMPERATURE AND PRESSURE EXPOSURE

| Sample Type<br>and Depth<br>(ft) | Tensile Strength<br>(MPa) | # <sup>b</sup> | Compressive Strength<br>(MPa) | # <sup>b</sup> | Grain Density | Bulk Density | Porosity<br>(%) |
|----------------------------------|---------------------------|----------------|-------------------------------|----------------|---------------|--------------|-----------------|
| Topopah Springs<br>680.0 - 680.5 | 19.1 ± 5.5                | 5              | -                             |                | 2.55          | 2.29         | 10.0            |
| 681.1 - 681.6                    | 18.8 ± 3.0                | 5              | -                             |                | 2.52          | 2.26         | 10.0            |
| 696.7 - 697.0                    | -                         |                | 152.2 ± 37.8                  | 2              | 2.52          | 2.22         | 12.0            |
| 708.2 - 708.9                    | 20.5 ± 3.7                | 5              | 194.4 ± 25.4                  | 2              | 2.52          | 2.29         | 9.0             |
| 730.3 - 730.9                    | 25.9 ± 2.4                | 5              | -                             |                | 2.50          | 2.26         | 10.0            |
| 1089.7 - 1090.3                  | 17.7 ± 5.2                | 5              | 137.7 ± 42.8                  | 2              | 2.54          | 2.26         | 11.0            |
| 1091.2 - 1091.6                  | 7.6 ± 0.1                 | 3              | 143.5 ± 6.4                   | 2              | 2.53          | 1.90         | 25.0            |
| 1100.6 - 1101.6                  | 23.7 ± 3.3                | 3              | 242.2 ± 90.0                  | 3              | 2.46          | 2.16         | 12.0            |
| 1101.6 - 1102.1                  | -                         |                | 160.9 ± 48.1                  | 2              | 2.56          | 2.29         | 11.0            |
| 1105.8 - 1106.8                  | 11.4 ± 2.8                | 4              | -                             |                | 2.56          | 2.33         | 9.0             |
| 1247.9 - 1248.1                  | -                         |                | 180.3 ± 28.6                  | 2              | -             | -            | -               |
| 1285.1 - 1268.0<br>(Vitrophyre)  | 8.6 ± 1.8                 | 4              | 52.4 ± 2.2                    | 2              | 2.34          | 2.29         | 1.7             |
| Calico Hills<br>1394.6 - 1395.2  | 5.3 ± 0.8                 | 5              | -                             |                | 2.20          | 1.57         | 29.0            |
| 1423.4 - 1424.2                  | -                         |                | 91.2 ± 3.8                    | 2              | 2.03          | 1.58         | 22.0            |
| 1446.0 - 1446.8                  | 5.9 ± 0.9                 | 5              | -                             |                | 2.18          | 1.61         | 26.0            |
| 1460.8 - 1461.6                  | -                         |                | 57.8 ± 5.6                    | 2              | 2.21          | 1.56         | 29.0            |
| 1478.1 - 1478.7                  | 5.6 ± 1.0                 | 5              | -                             |                | 2.16          | 1.59         | 25.0            |
| 1513.3 - 1513.9                  | -                         |                | 50.5 ± 10.6                   | 2              | 2.19          | 1.60         | 27.0            |
| 1566.2 - 1566.7                  | -                         |                | 34.3 ± 20.6                   | 2              | 2.23          | 1.65         | 26.0            |
| 1611.7 - 1612.7                  | 5.8 ± 0.8                 | 5              | 123.6 ± 53.2                  | 2              | 2.09          | 1.68         | 20.0            |
| 1640.9 - 1642.1                  | 6.2 ± 1.1                 | 5              | -                             |                | 2.17          | 1.61         | 26.0            |
| 1657.9 - 1659.0                  | -                         |                | 52.0 ± 0.4                    | 2              | -             | -            | -               |
| 1667.3 - 1668.4                  | 5.4 ± 0.4                 | 5              | 52.2 ± 2.4                    | 2              | 2.04          | 1.56         | 26.0            |
| 1680.1 - 1680.9                  | 5.1 ± 1.0                 | 5              | 60.2 ± 14.1                   | 2              | 2.31          | 1.60         | 30.0            |
| Bullfrog<br>2380.6 - 2381.2      | 2.2 ± 0.2                 | 10             | 30.0 ± 3.6                    | 4              | 2.62          | 1.91         | 26.9            |
| 2387.7 - 2388.3                  | 2.4 ± 0.2                 | 5              | 44.3 ± 0.1                    | 2              | 2.62          | 1.94         | 26.1            |
| Tram<br>2772.7 - 2773.3          | 3.7 ± 0.4                 | 5              | 40.3 ± 8.9                    | 2              | 2.53          | 1.85         | 28.3            |
| 2944.6 - 2945.0                  | 12.2 ± 3.0                | 4              | 86.5 ± 18.2                   | 2              | 2.61          | 2.19         | 16.1            |
| 2958.0 - 2958.4                  | 9.5 ± 1.2                 | 5              | 87.4 ± 12.2                   | 2              | 2.61          | 2.15         | 17.7            |

<sup>a</sup>Key to tunc units.

1. Topopah Springs - Ue25a#1 core. Densely welded, no zeolitization.
2. Calico Hills - Ue25a#1 core. Unwelded, highly zeolitized.
3. Bullfrog - USW-G1 core. Moderately welded, some zeolite.
4. Tram - USW-G1 core. Moderately welded, some zeolite.

<sup>b</sup>Number of measurements.

TABLE III  
MECHANICAL PROPERTIES OF SAMPLES AFTER TEMPERATURE AND PRESSURE EXPOSURE

| Sample Type<br>and Depth<br>(ft)             | Test<br>No. | Tensile Strength<br>(MPa) | #/P <sup>a</sup> | Compressive Strength<br>(MPa) | #/P <sup>a</sup> | Grain Density | Bulk Density | Porosity<br>(%) |
|--|-------------|---------------------------|------------------|-------------------------------|------------------|---------------|--------------|-----------------|
| Topopah Springs<br>680.0 - 680.5             | 6           | 19.9 ± 3.8                | 5/0.8            | -                             | -                | 2.54          | 2.29         | 9.8             |
| 681.1 - 681.6                                | 2           | 19.1 ± 4.7                | 3/0.8            | -                             | -                | 2.54          | 2.22         | 12.6            |
| 696.7 - 697.0                                | 4           | -                         | -                | 161.5 ± 26.4                  | 2/0.8            | -             | -            | -               |
| 708.2 - 708.9                                | 3           | 13.5 ± 1.4                | 5/0.005          | -                             | -                | 2.50          | 2.30         | 7.9             |
| 708.2 - 708.9                                | 6           | -                         | -                | 218.0                         | 1                | -             | -            | -               |
| 730.3 - 730.9                                | 4           | 21.9 ± 4.1                | 5/0.08           | -                             | -                | 2.54          | 2.31         | 9.2             |
| 1089.7 - 1090.3                              | 3           | -                         | -                | 232.4 ± 9.1                   | 2/0.1            | -             | -            | -               |
| 1089.7 - 1090.3                              | 5           | 13.1 ± 2.6                | 5/0.12           | -                             | -                | 2.57          | 2.27         | 11.9            |
| 1091.2 - 1091.6                              | 7           | -                         | -                | 132.3                         | 1                | -             | -            | -               |
| 1100.6 - 1101.6                              | 1           | -                         | -                | 237.2 ± 46.1                  | 2/0.7            | -             | -            | -               |
| 1100.6 - 1101.6                              | 7           | 12.9 ± 0.4                | 3/0.005          | -                             | -                | 2.57          | 2.38         | 7.5             |
| 1101.6 - 1102.1                              | 5           | -                         | -                | 138.2 ± 48.3                  | 2/0.3            | -             | -            | -               |
| 1105.8 - 1106.8                              | 1           | 15.6 ± 2.9                | 4/0.09           | -                             | -                | 2.59          | 2.32         | 10.2            |
| 1247.9 - 1248.1                              | 2           | -                         | -                | 135.9 ± 6.6                   | 2/0.18           | -             | -            | -               |
| 1285.1 - 1285.6<br>(Vitrophyre)              | 8           | -                         | -                | 54.9 ± 9.3                    | 2/0.7            | -             | -            | -               |
| 1285.6 - 1286.0 <sup>b</sup><br>(Vitrophyre) | 8           | 6.6 ± 0.9                 | 5/0.06           | -                             | -                | 2.34          | 2.31         | 1.4             |
| Calico Hills<br>1394.6 - 1395.2              | 2           | Lost data                 | -                | -                             | -                | 2.25          | 1.55         | 31.0            |
| 1423.4 - 1424.2                              | 2           | -                         | -                | Lost data                     | -                | -             | -            | -               |
| 1446.0 - 1446.8                              | 1           | 6.1 ± 0.5                 | 5/0.7            | -                             | -                | 2.28          | 1.66         | 27.2            |
| 1460.8 - 1461.6                              | 1           | -                         | -                | 52.0                          | 1                | -             | -            | -               |
| 1478.1 - 1478.7                              | 4           | 6.5 ± 0.1                 | 4/0.1            | -                             | -                | 2.28          | 1.68         | 26.5            |
| 1513.3 - 1513.9                              | 4           | -                         | -                | 38.5 ± 12.9                   | 2/0.44           | -             | -            | -               |
| 1566.2 - 1566.7                              | 3           | -                         | -                | 42.1                          | 1                | -             | -            | -               |
| 1611.7 - 1612.7                              | 3           | 6.5 ± 1.2                 | 5/0.7            | -                             | -                | 2.26          | 1.73         | 23.5            |
| 1611.7 - 1612.7                              | 6           | -                         | -                | 76.2                          | 1                | -             | -            | -               |
| 1640.9 - 1642.1                              | 6           | 6.1 ± 1.4                 | 5/0.8            | -                             | -                | 2.31          | 1.60         | 31.0            |
| 1657.9 - 1659.0                              | 5           | -                         | -                | 55.5 ± 6.2                    | 2/0.5            | -             | -            | -               |
| 1667.3 - 1668.4                              | 5           | 6.6 ± 0.6                 | 5/0.004          | -                             | -                | 2.25          | 1.62         | 27.9            |
| 1667.3 - 1668.4                              | 7           | 5.9 ± 1.3                 | 5/0.5            | -                             | -                | 2.27          | 1.62         | 28.6            |
| 1680.1 - 1680.9                              | 7           | -                         | -                | 52.7                          | 2/0.6            | -             | -            | -               |
| Bullfrog<br>2380.6 - 2381.2                  | 8           | 2.4 ± 0.2                 | 4/0.11           | 32.9 ± 6.6                    | 2/0.5            | 2.62          | 1.93         | 26.4            |
| 2380.6 - 2381.2 <sup>b</sup>                 | 8           | 2.5 ± 0.1                 | 5/0.002          | 39.2 ± 1.3                    | 2/0.03           | 2.62          | 1.93         | 26.4            |
| 2387.7 - 2388.3                              | 9           | 2.3 ± 0.2                 | 5/0.6            | 42.3 ± 0.9                    | 2/0.09           | 2.62          | 1.93         | 26.3            |
| 2387.7 - 2388.3                              | 10          | 2.2 ± 0.2                 | 5/0.14           | 36.8 ± 1.5                    | 2/0.03           | 2.62          | 1.92         | 26.8            |

<sup>a</sup># = number of measurements. P = probability from t test (see text).

<sup>b</sup>J-13 well water was used in these tests. All other tests used distilled water.

TABLE III (cont)

| Sample Type<br>and Depth<br>(ft) | Test<br>No. | Tensile Strength<br>(MPa) | #/P <sup>a</sup> | Compressive Strength<br>(MPa) | #/P <sup>a</sup> | Grain Density | Bulk Density | Porosity<br>(%) |
|----------------------------------|-------------|---------------------------|------------------|-------------------------------|------------------|---------------|--------------|-----------------|
| Tram<br>2772.7 - 2773.3          | 9           | 3.9 ± 0.9                 | 5/0.7            | 36.8 ± 2.4                    | 2/0.7            | 2.58          | 1.92         | 25.9            |
| 2772.7 - 2773.3                  | 10          | 2.6 ± 0.7                 | 4/0.03           | 30.3 ± 4.1                    | 2/0.33           | 2.59          | 1.90         | 26.7            |
| 2944.6 - 2945.0 <sup>b</sup>     | 8           | 12.0 ± 2.3                | 5/0.8            | 90.3 ± 8.4                    | 2/0.8            | 2.61          | 2.22         | 14.8            |
| 2958.0 - 2958.4                  | 8           | 12.9 ± 2.4                | 5/0.03           | 87.6 ± 4.7                    | 2/0.8            | 2.61          | 2.18         | 16.6            |

<sup>a</sup># = number of measurements. P = probability from t test (see text).

<sup>b</sup>J-13 well water was used in these tests. All other tests used distilled water

One of the assumptions of the t test is that the measurements are normally distributed about the means. The validity of this assumption can be judged from examples shown in Figs. 1 and 2 for tensile strength. Note that although the distributions are approximately normal, some skewness is apparent. The bimodal distribution in Fig. 2 reflects an apparently true difference in tensile strength of Topopah Springs tuffs at depths ~700 ft and ~1100 ft. The tuffs at these depths are known to be mineralogically and structurally different so a reflection of this in tensile strength (and probably other physical properties) is not surprising.

#### A. Results at 80°C

Tensile strength, compressive strength, porosity, and grain density for exposures of 80°C are summarized in Figs. 3 to 5.

1. Topopah Springs. There is an insignificant change in tensile strength at 9.7 MPa confining pressure after 6-months' exposure for the rock from 681-ft depth. However, for rock from 1106-ft depth exposed at 19.7 MPa confining pressure, there is a significant increase of 37% in tensile strength.

A decrease in compressive strength of 25% at 9.7 MPa confining pressure for rock from the 1248-ft depth is marginally significant. The apparent decrease at 19.7-MPa confining pressure for rock from the 1100-ft depth is statistically insignificant.

There is little or no change in grain density but a consistent increase in porosity.

2. Calico Hills. There are essentially no changes in tensile or compressive strength of Calico Hills tuffs at these exposure conditions. Both porosity and grain density appear to increase slightly.

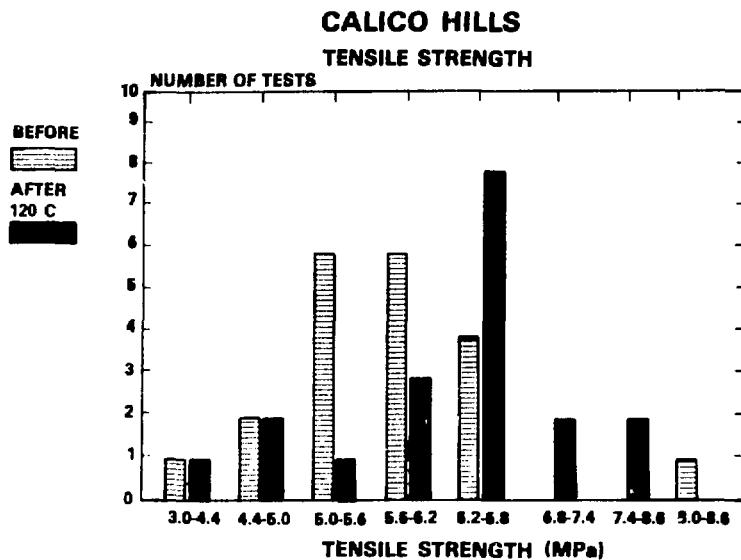


Fig. 1.  
Histogram of tensile strengths of Calico Hills tuffs before and after extended exposure to 120°C.

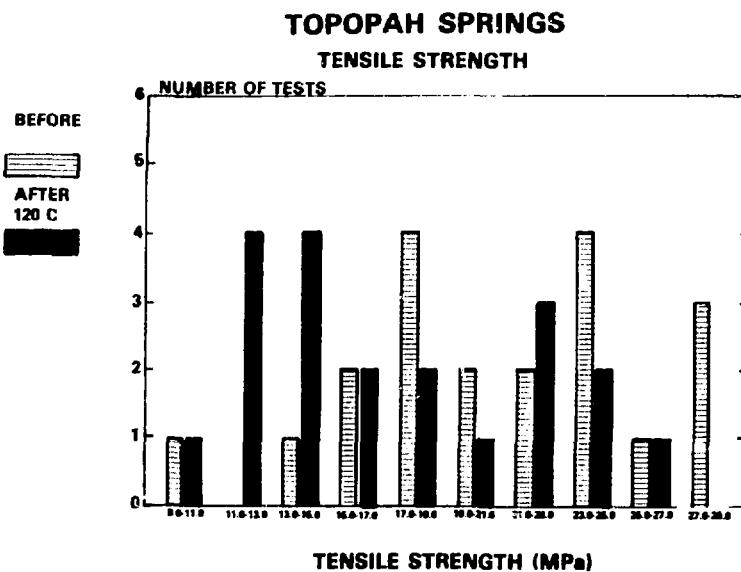


Fig. 2.  
Histogram of tensile strengths of Topopah Springs tuffs before and after extended exposure to 120°C.

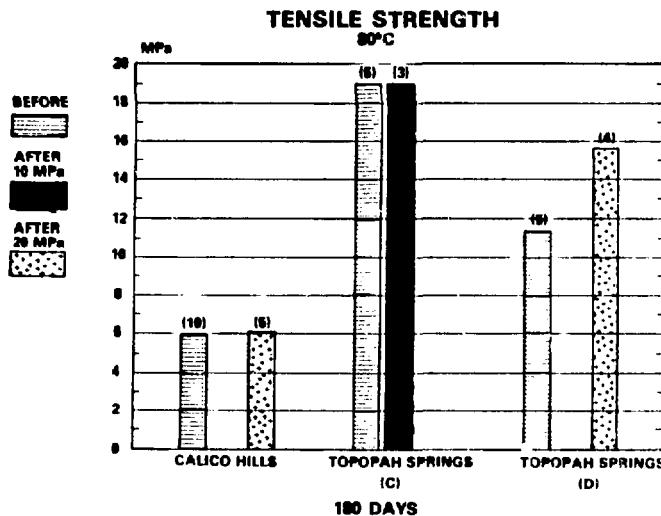


Fig. 3.

Tensile strengths of Calico Hills and Topopah Springs tuffs before and after 180-day exposure to 80°C and confining pressures of approximately 10 and 20 MPa. Numbers in parentheses refer to the number of tests at each condition - (C) refers to a depth of  $\sqrt{681}$  ft and (D) to a depth of  $\sqrt{1106}$  ft in drill hole UE25a-1.

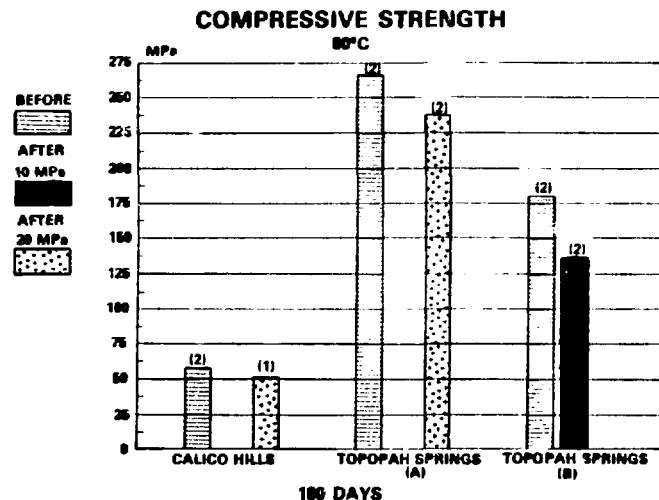


Fig. 4.

Compressive strengths of Calico Hills and Topopah Springs tuffs before and after 180-day exposure to 80°C and confining pressures of approximately 10 and 20 MPa. (A) refers to a depth of  $\sqrt{1100}$  ft and (B) to a depth of  $\sqrt{1248}$  ft in drill hole UE25a-1. Other notations are the same as in Fig. 3.

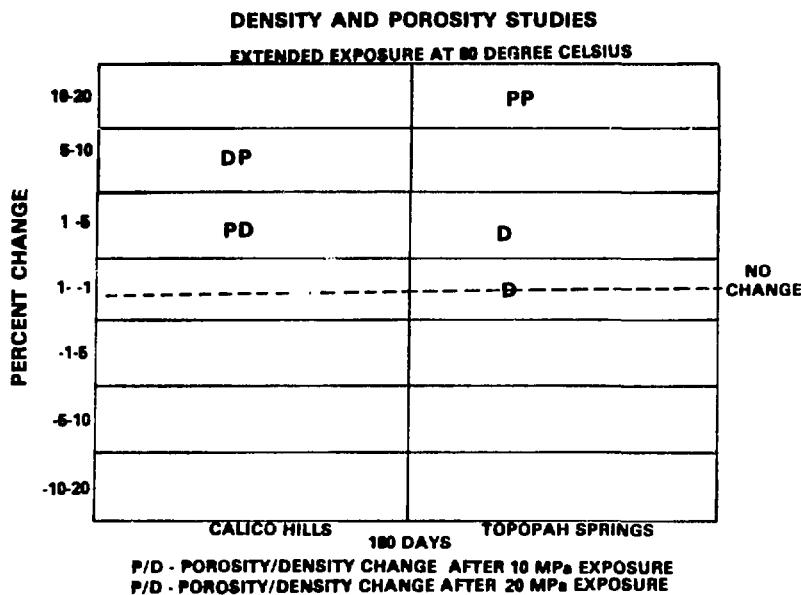


Fig. 5.  
 Grain density changes (D) and porosity changes (P) of Calico Hills and Topopah Springs tuffs after 180-day exposure to 80°C and confining pressures of approximately 10 and 20 MPa.

#### B. Results at 120°C

Tensile strength, compressive strength, porosity, and grain density changes for exposures at 120°C are summarized in Figs. 6 to 8.

1. Topopah Springs. There is a significant decrease of 15% in tensile strength for rock from 730-ft depth at 9.7-MPa confining pressure. An apparent increase at these conditions for rock at 680-ft depth is not significant. At 19.7-MPa confining pressure, rock from 708-ft depth shows a significant decrease of 34% and there is a marginally significant decrease of 26% for rock from the 1090-ft depth.

None of the slight changes in compressive strength at 9.7-MPa confining pressure are considered significant. At 19.7-MPa confining pressure there is an apparently significant increase in compressive strength of 69% for rock from the 1090-ft depth. This is contradicted by a marginally significant decrease of 14% for rock from the 1101-ft depth. Inconsistencies such as this are to be expected for a small number of tests in a rock that is highly inhomogeneous.

This inconsistency is even more apparent in porosity measurements, especially at 19.7 MPa. For the rock from 708-ft depth, porosity decreases 12%

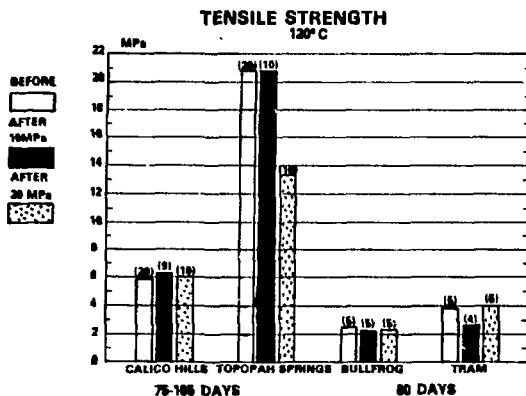


Fig. 6.  
Tensile strengths of Calico Hills, Topopah Springs, Bullfrog, and Tram tuffs before and after exposure to 120°C. Other notations are the same as in Fig. 3.

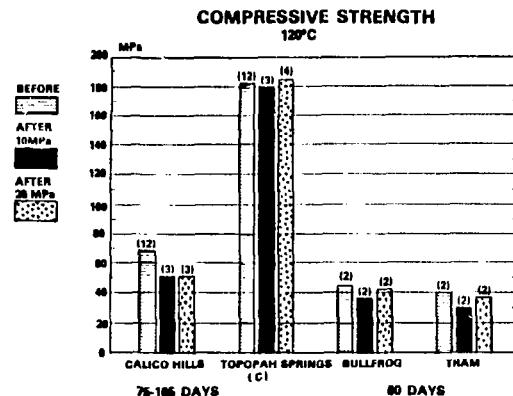
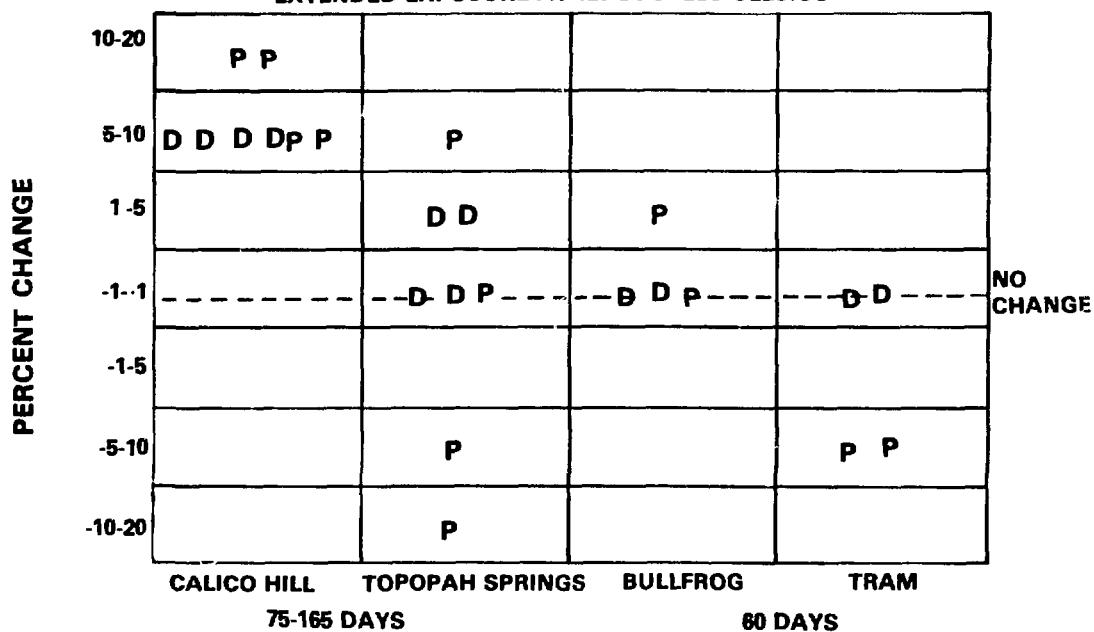


Fig. 7.  
Compressive strengths of Calico Hills, Topopah Springs, Bullfrog, and Tram tuffs before and after exposure to 120°C. Other notations are the same as in Fig. 4.

**DENSITY AND POROSITY STUDIES**  
EXTENDED EXPOSURE AT 120 DEGREES CELSIUS



P/D- POROSITY/DENSITY CHANGE AFTER 10 MPa EXPOSURE

P/D- POROSITY/DENSITY CHANGE AFTER 20 MPa EXPOSURE

Fig. 8.

Grain density and porosity changes of Calico Hills, Topopah Springs, Bullfrog, and Tram tuffs before and after exposure to 120°C. Notations are the same as in Fig. 5

whereas for rock from 1090 ft it increases 8%. Grain densities either remain the same or increase slightly.

2. Calico Hills. There is a marginally significant increase of 16% in tensile strength at 9.7-MPa confining pressure; changes at 19.7 MPa are insignificant.

Compressive strength consistently decreases up to 25% at both 9.7- and 19.7-MPa confining pressure, but these changes are only marginally significant.

The most consistent changes occur in grain density and porosity, both of which increase from 5 to 19% at both confining pressures.

3. Bullfrog. The Bullfrog tuffs exhibit the lowest tensile strengths of all the units tested. There is a further marginally significant decrease of 8% at 9.7-MPa confining pressure. A slight decrease at 19.7-MPa confining pressure is statistically insignificant.

Compressive strength decreases 17% at 9.7-MPa confining pressure and 5% at 19.7 MPa. Both changes are judged to be statistically significant.

Grain densities are unchanged. Porosities are unchanged or slightly increased.

4. Tram. Results for Tram tuffs are almost identical to those of the Bullfrog. Tensile strength decreases 30% at 9.7-MPa confining pressure. This change is judged to be statistically significant. The slight change at 19.7-MPa confining pressure is insignificant.

Compressive strength decreases up to 25% in a manner similar to that for Bullfrog tuffs; however, the tests cannot be judged to be statistically significant in this case.

Grain densities remain unchanged. Porosities decrease up to 9% at both 9.7- and 19.7-MPa confining pressures.

#### C. Results at 180°C

Tensile strength, compressive strength, porosity, and grain density changes for exposures at 180°C are summarized in Figs. 9 to 11.

1. Topopah Springs. Tensile strength is reduced 46% after exposure at 9.7-MPa confining pressure for 3-1/2 months. This reduction is judged to be statistically significant.

Compressive strength is reduced 8% in a single test at 9.7-MPa confining pressure.

Porosity decreased 38% and grain density increased slightly.

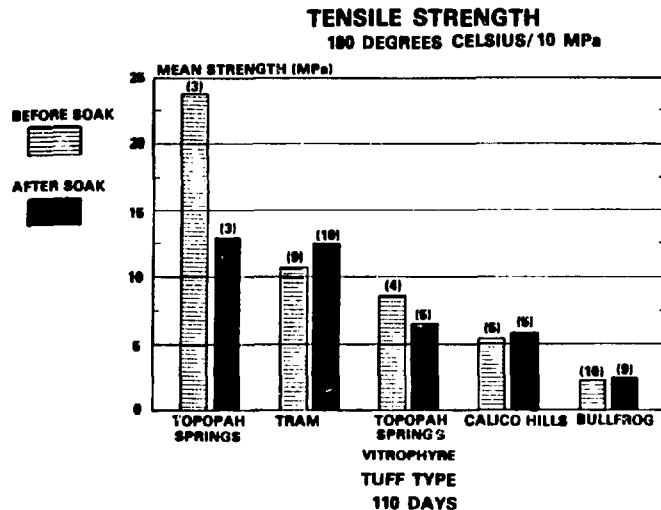


Fig. 9.  
Tensile strengths of Calico Hills, Topopah Springs, Bullfrog, and Tram tuffs before and after exposure to 180°C. Notations are the same as in Fig. 3.

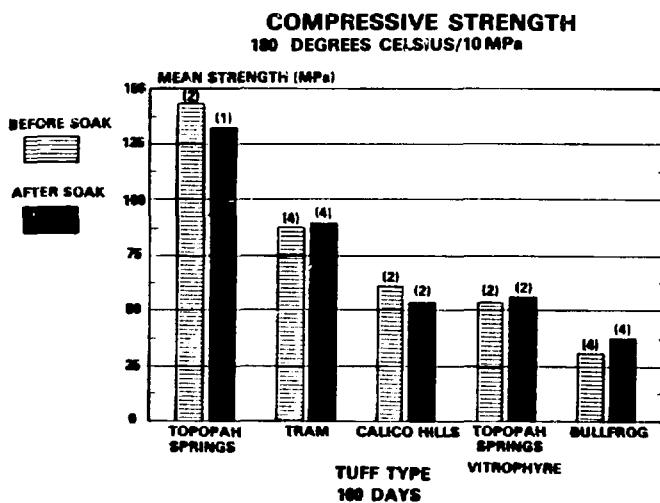


Fig. 10.  
Compressive strengths of Calico Hills, Topopah Springs, Bullfrog, and Tram tuffs before and after exposure to 180°C. Notations are the same as in Fig. 4.

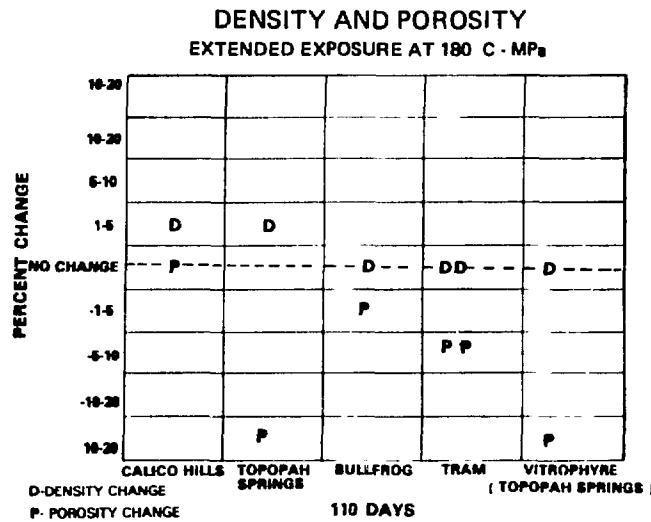


Fig. 11.

Grain density and porosity changes of Calico Hills, Topopah Springs, Bullfrog, and Tram tuffs before and after exposure to 180°C. Notations are the same as in Fig. 5.

2. Topopah Springs Vitrophyre. Tensile strength decreased 23% after exposure of the glassy vitrophyre sample at 9.7-MPa confining pressure. The change was judged to be statistically significant.

Compressive strength changed slightly with no statistical significance.

The small initial (crack?) porosity decreased 22% with no change in grain density.

3. Calico Hills. Tensile strength apparently increased slightly, but this was not statistically significant. Similarly, compressive strength appeared to be reduced after exposure, but this change was also judged not to be statistically significant.

Porosity was unchanged and grain density increased slightly.

4. Bullfrog. Tensile strength increased up to 14% after exposure at 9.7-MPa confining pressure. Although this increase is small, it was judged to be statistically significant.

Compressive strength apparently increased up to 31% after exposure at 9.7-MPa confining pressure. This change was judged to be statistically significant.

Grain density remained unchanged but porosity decreased slightly.

5. Tram. Tensile strength increased up to 36% after exposure at 9.7-MPa confining pressure. This change was judged to be statistically significant.

Compressive strength appeared to increase slightly; however, these changes were not statistically significant.

Grain density remained unchanged, but porosity decreased up to 8% after exposure.

## VI. CONCLUSIONS

Exposure of NTS tuffs to temperatures, confining pressures, and water pore pressures similar to those expected near a high-level nuclear waste repository resulted in statistically significant changes in ambient tensile strength, compressive strength, grain density, and porosity. These changes occurred over time periods of 2 to 6 months. The changes are not entirely consistent, reflecting the inherent inhomogeneity of these complex rocks. Causes of the changes are presently unknown. However, planned permeability measurements and detailed mineralogic examination of test samples should help identify mechanisms of property change.

## VII. OTHER MEASUREMENTS

Mineralogic examination of samples before and after exposure to test conditions, permeability measurements, and thermal properties measurements are currently being performed. Results will be given in the final report.

## REFERENCES

1. P. I. Carroll, F. A. Caporuscio, and D. L. Bish, "Further Description of the Petrology of the Topopah Spring Member of the Paintbrush Tuff in Drill Holes UE25A-1 and USW-G1, and of the Lithic-Rich Tuff in USW-G1, Yucca Mountain, Nevada," Los Alamos National Laboratory report LA-9000-MS (November 1981).
2. D. L. Bish, F. A. Caporuscio, J. F. Copp, B. M. Crowe, J. D. Purson, J. R. Smyth, and R. G. Warren, "Preliminary Stratigraphic and Petrologic Characterization of Core Samples from USW-G1, Yucca Mountain, Nevada," Los Alamos National Laboratory report LA-8840-MS (November 1981).

## APPENDIX A

### HANDLING, STORAGE, AND SHIPPING PROCEDURE FOR THE NEVADA NUCLEAR WASTE STORAGE INVESTIGATIONS PROJECT

#### I. PURPOSE

The purpose of this procedure is to provide measures for handling, storage, and shipping of geologic materials used on the NNWSI Project.

#### II. SCOPE

This procedure applies to all geologic materials used on the NNWSI Project and controls the material from the time of shipment to Los Alamos National Laboratory, through the testing phase, and during storage.

#### III. GENERAL

Geologic materials including hydrologic samples will be identified, handled, stored, and shipped according to this procedure.

#### IV. SELECTION AND IDENTIFICATION

Sample material shall be selected by designated qualified personnel. Samples requiring special handling (for example, wax wrap or inert atmosphere container) will be tagged and documented in field notebooks. Each sample selected will be identified on tape, or a label applied to the sample or container, and will bear the following information:

- (1) Sample identification number,
- (2) Location where taken (that is, drill hole),
- (3) Downhole arrow or orientation information where appropriate.

In addition, a log book entry will contain the following information:

- (1) Sample identification number,
- (2) Footage (from-to) if taken from a drill hole,
- (3) Number of pieces,
- (4) Any special sample characteristics.

Samples lacking any of the above identification requirements upon receipt at Los Alamos National Laboratory will be segregated and not used in laboratory investigations until they can be positively identified.

The assigned identification number will be placed on the container of each sample cut, ground, or otherwise taken from the parent sample to assure

traceability. The identification number will also follow any natural ground-water samples separated or taken from the main lot. Documentation of samples taken from a parent sample will be by logging in laboratory notebooks.

## V. HANDLING

When handling geologic material samples, care will be taken to not disrupt the continuity and structure of the sample except where investigations require crushed or ground samples.

If the sample is contained in special atmospheric containers, the container will be opened only under suitable atmospheric conditions as determined by a qualified chemist or geologist. The core may be wrapped in aluminum foil or other suitable material and dipped in liquified beeswax at the discretion of the chemist or geologist.

If the sample core is broken to fit a shipping container, the end of hammer breakage will be painted and will be documented in the field notebook. If the sample is to be used in certain chemistry investigations where paint is undesirable, another method of indicating the ends of hammer breakage may be used. This method will be noted in the field notebook.

Upon receipt of the sample at Los Alamos, a qualified chemist or geologist will inspect and verify the condition of the sample. This verification shall be documented in a log entry notebook.

In case of rupture of the container, the Los Alamos National Laboratory will document in the entry log notebook the condition of the sample. The sample will be held for disposition decision by the Technical Program Officer (TPO) or his designate. A Nonconformance Report (NCR) will be initiated if appropriate.

Accidental droppage of any sample core will be documented in the laboratory notebooks and held for disposition decision by the TPO or his designate. An NCR will be initiated if appropriate.

## VI. STORAGE

Upon receipt of a geologic material sample at Los Alamos National Laboratory, measures will be established and implemented to assure proper storage at Los Alamos National Laboratory.

A sample entry log or laboratory notebook will be used to document incoming samples and will include as a minimum:

- (1) Sample identification number,
- (2) Drill hole or area location sample was taken,
- (3) Footage (from-to) if taken from a drill hole,
- (4) Number of core pieces,
- (5) If more than one piece, length of largest piece,
- (6) Storage location.

Samples will be protected during storage from weather elements to prevent deterioration.

Thin-section slides will be stored in slide containers in a designated shelf storage location to prevent damage to the slides. A thin-section slide log will be kept as a record of all slides examined.

Storage of samples during testing will remain consistent with atmospheric requirements for that particular experiment.

Sample material used at the Laboratory will be held for disposition decision by a qualified chemist or geologist upon completion of experiments or tests. Disposition will be logged in the geologist's notebook.

An archive sample of the parent material may be taken at the discretion of the chemist or geologist before experiments or tests.

The identification requirements of Section IV of this procedure will be applied to all archive samples.

The geologist performing the work will decide the size or amount of sample to be taken for archive.

Record of archive sample storage location will be made in laboratory notebooks. All archive samples will be kept together on a designated shelf location.

## VII. SHIPPING

Shipments from the NTS will be properly crated to assure minimal breakage during transit. Sample cores being hand carried will be crated at the discretion of the chemist or geologist. In both cases, identification markings as delineated in Sec. IV of this procedure will appear on all samples.

Shipments to and from the Los Alamos National Laboratory will be handled in the same manner as shipments from the NTS. Samples not having identification requirements as delineated in Sec. IV of this procedure will not be accepted by the receiving group. Transfers of samples will be recorded in laboratory notebooks.

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## APPENDIX B

### SAMPLE PREPARATION AND EXPOSURE CONDITIONS

Samples were selected in pairs and marked with core depth in feet (or other identification) and either "A" or "B." "A" samples were exposed to the appropriate soak conditions and then tested according to Table I. "B" samples were tested without soaking. Where possible, "A" and "B" samples were cut side by side; otherwise they were taken from the same core as close together as possible. The assignments of specific samples to specific tests are shown in Table II.

Samples were cut to 2.5 cm diam by 6.4 cm long (nominal) under deionized water and stored in sealed containers with excess water until needed. Samples to be soaked were placed in annealed copper jackets and sealed into externally heated pressure vessels (see Fig. B-1), after sealing the vessel by evacuating with a mechanical pump for 30 to 60 minutes at room temperature and introducing deionized water.

The equipment used to supply the exposure conditions consists of:

- (1) Pressure vessels (Fig. B-1),
- (2) Ovens 1 through 4 corresponding to temperatures 1 through 4 (see Tables I and B-I),
- (3) Two confining pressure manifolds supplying nitrogen gas pressures,
- (4) Two pore-pressure manifolds supplying water pressures, and
- (5) Control/Data Acquisition system to perform continuous leak checks and record temperature and pressure conditions. Temperatures were measured by two thermocouples in each oven. Primary measurement of pressures was by Heise gauges on each pressure manifold. Leak tests and secondary pressure records are by electrical transducers on each test station.

A schematic diagram of the pressure manifold arrangement is shown in Fig. B-2.

| Pressure <sup>a</sup>  | $P_c = 9.7 \text{ MPa}$<br>$P_p = 0.5 \text{ MPa}$<br>(or = $P_c$ ) | $P_c = 19.7 \text{ MPa}$<br>$P_p = 9.7 \text{ MPa}$<br>(or = $P_c$ ) |
|--|---|--|
| <u>Temperature</u>   |   |  |
| $80^\circ\text{C} \pm 10^\circ\text{C}$                                    | Basic parameters <sup>b</sup><br>thermal parameters <sup>c</sup>    | Basic parameters   |
| $120^\circ\text{C} \pm 10^\circ\text{C}$                                   | Basic parameters +<br>permeability                                  | Basic parameters +<br>thermal parameters                             |
| $120^\circ\text{C} \pm 10^\circ\text{C}$<br>(short duration <sup>d</sup> ) | Basic parameters +<br>thermal parameters                            | Basic parameters +<br>permeability                                   |
| $180^\circ\text{C} \pm 10^\circ\text{C}$                                   | -   | Basic parameters   |

<sup>a</sup> $P_c$  = confining pressure;  $P_p$  = pore pressure.

<sup>b</sup>Basic parameters to be measured on all specimens both before and after 6-month soak: tensile strength (Brazil), compressive strength, mineralogy/petrology, density, porosity.

<sup>c</sup>Thermal parameters include thermal conductivity and thermal expansion.

<sup>d</sup>These short exposures are currently planned for 1 to 2 months. Tests on additional tuff units may be run sequentially.

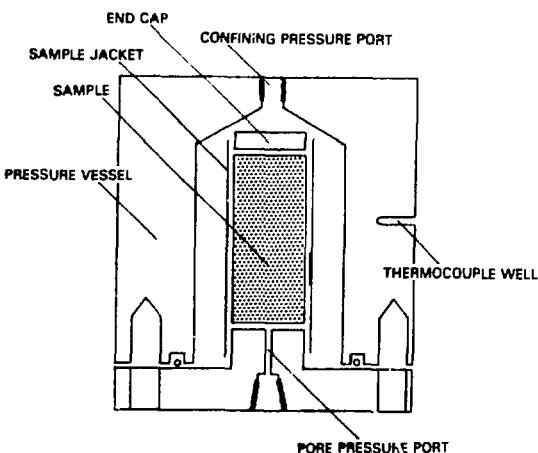


Fig. B-1.  
Schematic of individual pressure vessel for temperature and pressure exposure of tuff samples.

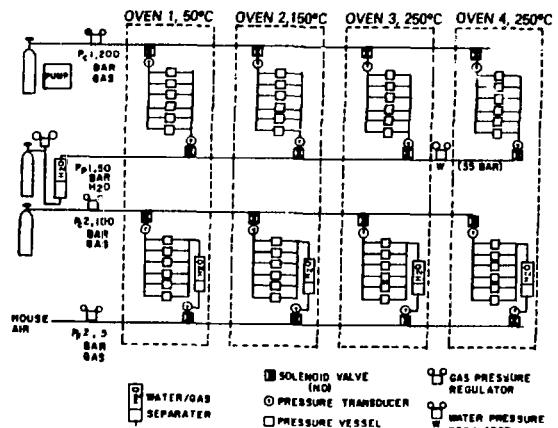


Fig. B-2.  
Plumbing diagram for confining and pore-pressure system.

## APPENDIX C

### BRAZIL INDIRECT STRENGTH TESTS

These tests measure the tensile strength of samples by applying a compressive diametral load to a disk-shaped sample. The procedure followed is that described in Bieniawski and Hawkes<sup>1</sup>. Samples are 2.54 cm diam by 1.25 cm thick prepared by slicing the cylindrical test specimens described above. An Instron testing machine supplied the load required at a constant displacement rate of 0.001 cm/s. The load cell was calibrated against dead weights.

Tensile strength was calculated from the equation

$$T = 0.636 P/Dt , \quad (C-1)$$

where P is the ultimate load in Newtons, D is the sample diameter in mm, and t is the sample thickness in mm.

For each test cylinder (2.54 cm diam by 6.4 cm long) five Brazil test samples were prepared. The results reported are average values for these five specimens.

#### REFERENCE

1. Z. T. Bieniawski and I. Hawkes, Int. J. Rock Mech. and Mining Sci. 15, 101-103 (1978).

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## APPENDIX D

### COMPRESSIVE STRENGTH TESTS

These tests measure the uniaxial compressive strength of small cylindrical samples. The procedure followed is that described in Bieniawski and Berneale<sup>1</sup>. Test samples were recored from the original 2.54- by 6.4-cm cylinders to smaller cylinders nominally 1.2 by 3.2 cm. Two samples were cut from each original. The ends were prepared by surface grinding to be parallel  $\pm 0.01$  mm TIR. A servo controlled testing machine operating in displacement control applied load to the samples through a swivel platen. The latter was built according to specifications in Bieniawski and Berneale. The ultimate

strength values reported are averages of the two samples from each original unless otherwise stated.

## REFERENCE

1. Z. T. Bieniawski and M. J. Berneale, Int. J. Rock Mech. and Mining Sci. 16, 137 (1979).

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## APPENDIX E

### PROCEDURE FOR DENSITY AND POROSITY DETERMINATIONS

#### I. PURPOSE

The purpose of these tests is to measure the bulk density and connected porosity of rock samples.

#### II. EQUIPMENT AND PROCEDURE

Equipment consists of an analytical balance (Metler model H31AR). This balance shall be calibrated in accordance with the requirements of QM1 9-1 of the Quality Assurance Manual.

Porosity and bulk density measurements will be performed as follows:

Evacuate specimen under fore-pump vacuum for at least 24 h.

Weigh in air ( $W_{DD}$ ).

Evacuate in bell jar fitted with  $H_2O$  access. Use fore-pump vacuum.

Cover with deionized  $H_2O$  and release to atmospheric pressure.

Without removing sample from water, weigh submerged. Take tare and buoyance of any supports into account ( $W_{SS}$ ).

Measure temperature of water.

Remove sample from water and gently blot the surface with paper towel.

Weigh in air ( $W_{SD}$ ).

#### III. DATA ANALYSIS

Data will be analyzed as follows:

Calculate "grain density,"

$$\rho_g = \frac{\rho_w W_{DD}}{W_{DD} - W_{SS}} \quad . \quad (E-1)$$

Calculate "bulk density" (dry)

$$\rho_b = \frac{\rho_w W_{DD}}{W_{SD} - W_{SS}} \quad . \quad (E-2)$$

Calculate "porosity"

$$\phi = \frac{W_{SD} - W_{DD}}{W_{SD} - W_{SS}} \quad . \quad (E-3)$$

$\rho_w$  is the density of water at the measured temperature.

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## APPENDIX F PERMEABILITY MEASUREMENTS

### I. INTRODUCTION

This is a procedure for the measurement of the permeability of unfractured rock by a pressure transient method. Temperature, confining pressure, and pore pressure are controlled. By this method, permeabilities in the range of  $10^{-17}$  to  $10^{-21} \text{ m}^2$  can be measured with water as the permeating fluid.

### II. APPARATUS

The sample is a cylinder of rock 25.4 mm diam by 15 to 25 mm long. This sample is placed in a cylindrical sleeve of Teflon. Pressed stainless steel fiber discs are then placed on either end of the sample. These discs have appreciably higher permeability than the rock and assure that the fluid pressure will be uniform over the ends of the sample during the tests. Steel cylinders, to which the pore pressure lines are attached, are then inserted into the ends of the flexible sleeve. Two grooves are cut into the circumference of these cylinders. The one further from the sample holds an "O" ring and the other is left open enabling the sleeve material to deform into it when confining pressure is applied.

This assembly is placed in a pressure vessel, which is then pressurized with water. If the confining pressure (pressure in the large vessel) is maintained above that of the pore pressure, the flexible sleeve forms an effective seal against the stainless steel cylinders on either end of the sample and there is no communication between the confining and pore-pressure fluids.

### III. PERMEABILITY MEASUREMENT

For water flowing in the positive x direction and following Darcy's law, the pore pressure as a function of distance x and time t will follow the partial differential equation

$$\frac{\partial^2 P}{\partial x^2} = [\mu(\beta_p + \theta\beta_w)/k] \frac{\partial P}{\partial t}, \quad (F-1)$$

with the boundary conditions

$$\frac{\partial P}{\partial x} = (\mu V_1 \beta_w / A k) \frac{\partial P}{\partial t} \quad (F-2)$$

for  $t > 0$  and  $x = 0$ , and

$$\frac{\partial P}{\partial x} = (\mu V_2 \beta_w / A k) \frac{\partial P}{\partial t} \quad (F-3)$$

for  $t > 0$  and  $x = L$ . Where  $P$  is the core pressure,  $\mu$  is the viscosity of the water,  $k$  is the permeability,  $\beta_p$  is the pore compressibility of the sample,  $\theta$  is the porosity,  $\beta_w$  is the compressibility of water,  $V_1$  and  $V_2$  are the volumes of the upper and lower pore-pressure lines respectively,  $A$  is the cross-sectional area, and  $L$  is the length of the sample.

Unfortunately there is no known analytical solution for Eq. F-1. However, Brace et al.<sup>1</sup> have suggested that

$$P_1 - P_f = \Delta P_0 [V_2 / (V_1 + V_2)] e^{-\alpha t}, \quad (F-4)$$

where

$$\alpha = (kA/\mu\beta_w L)(1/V_1 + 1/V_2) \quad (F-5)$$

is an adequate approximation. Here  $P_1$  is the pressure in the upper pore pressure volume,  $P_f$  is the final pore pressure when the pressure step across the sample has decayed to zero, and  $\Delta P_0$  is the pressure difference across the sample at time zero.

From Eq. (F-4) it follows that

$$\Delta P = \Delta P_0 e^{-\alpha t}, \quad (F-6)$$

where  $\Delta P$  is the pressure difference across the sample at time  $t$ . To check that Eqs. (F-5) and (F-6) are adequate, a numerical solution for Eqs. (F-1)-(F-3) was calculated using a finite difference method. The permeability was then calculated by applying Eqs. (F-5) and (F-6) to the numerically generated data. For the experimental apparatus used in this study, Eqs. (F-5) and (F-6) yield permeabilities in agreement with the numerical solution within 6%, provided at least 20% of the initial pressure step is allowed to decay away before data gathering begins.

The permeability is therefore obtained by introducing a pressure step of approximately 1 MPa across the sample and allowing the step to decay to about 0.6 MPa. Thirty pressure measurements are then made at regular time intervals. A least squares fit to Eq. (F-6) is then made to determine  $\alpha$  and Eq. (F-5) is used to calculate  $k$ .

#### IV. PRESSURE MEASUREMENT

Pressure measurements are made by means of pressure transducers. The confining pressure is read by a Viatran model 214, the upper pore pressure by a Precise Sensor model 70053-2, and the difference between the upper and lower pore-pressure lines by a Viatran model 220-24 differential pressure transducer.

There are three Heise bourdon tube gauges in the system that measure the confining pressure and upper and lower pore pressures. The transducers measuring the confining pressure and upper pore pressure are restandardized against these gauges whenever a discrepancy greater than 0.1 MPa exists. The differential transducer contains a shunt calibration circuit and it is calibrated using this circuit just before each pressure step is imposed across the sample.

Once a month the Heise gauges and the calibration circuit of the differential transducer are checked using Heise gauge #72633 as a primary standard.

## V. TEMPERATURE MEASUREMENT

The temperature is measured by means of a stainless steel sheathed chromelalumel thermocouple, which was calibrated against the melting points of ice and lead.

## VI. PRESSURE LINE VOLUME DETERMINATION

The volumes the upper and lower pore-pressure lines must be known to calculate permeabilities. Measurement of these volumes is accomplished by means of a metering valve inserted into the pore-pressure line. By opening and closing this valve, small well-known stem displacements and hence well-known changes in volume of the pore-pressure line can be achieved. By changing the pore-pressure volume in this way and observing the attending pressure change in the line and knowing the compressibility ( $\beta_w$ ) of the water, the volume of the line can be calculated from the relation

$$V = \Delta V / \beta_w \Delta P , \quad (F-7)$$

where  $V$  is the volume of the line,  $\Delta V$  is the change in the volume due to the stem displacement of the metering valve, and  $\Delta P$  is the corresponding change in pressure. While making these measurements, the rock sample is replaced by an impermeable stainless steel cylinder. This method has yielded volume measurements with a precision of about 1%.

## REFERENCE

1. W. F. Brace, J. B. Walsh, and W. T. Frangos, "Permeability of Granite Under High Pressure," *J. Geophys. Res.* 73, 2225-2236 (1968).