5. Thermal-Mechanical Processes

Thermal-Mechanical process are discussed in four sections in this chapter. Sections 5.1 and 5.2 present thermal mechanical data and deformation and section 5.3 discusses THM model validation. Section 5.4 discusses acoustic emission/microseismic monitoring.

5.1 Thermal-Mechanical Data from the Drift Scale Test, 9/1/2000 – 3/31/2001

This short report discusses the results of strain gage data taken from the concrete liner and unconstrained concrete coupons in the Heated Drift, as part of the Drift Scale Test. The presentation of these data includes updating with recent measurements taken from the Drift Scale Test through 3/31/2001. The discussion here was presented at the 12th Thermal Test Workshop held in Las Vegas, NV, on June 7-8, 2001.

The discussions during this Thermal Test Workshop differed from previous workshops in that the primary themes were related to how the DST data can be used for performance confirmation and performance assessment. The mechanical data discussed during this workshop were the recent Plate Loading Test data, the MPBX displacement data, and acoustic emissions data. These data are used for design and performance assessment purposes in the following manner.

Design Issues

- Rock mass mechanical properties (elastic modulus, thermal conductivity) important to the design of a facility
- Development of new fractures (acoustic emissions, changes in MPBX data) that may indicate structural integrity issues

Performance Assessment (Coupled THM)

- Evidence of fracture deformation, either in the formation of new fractures, or in changes to existing fractures (shear slippage, aperture changes)
- Resulting changes in permeability which may affect water/vapor influx to the drift during cooling

5.1.1 Plate Loading Test performed Oct. 2000

The Plate Loading Tests (PLT) was conducted as part of the Drift Scale Test (DST). The purpose of the PLT was to obtain rock mass elastic modulus measurements under ambient and hot conditions for the middle nonlithophysal tuff. Two earlier tests were conducted in 1998, after which design changes were made to ensure a stiffer loading frame for improved measurements.

The PLT Niche is located about 5 m from the Heated Drift (HD) bulkhead and is driven approximately 5 m toward the north, perpendicular to the axis of the HD. The niche is a roughly 2.5 m diameter alcove with a nominally flat floor. The niche was mined using drill and blast techniques during the construction phase of the DST during early FY98. The PLT is designed to mechanically load the rock in a horizontal orientation using large square-shaped flatjacks that press against both ribs of the PLT Niche. Design of the PLT reaction frame was predicated on materials having compressive strengths in excess of 55.2 MPa (8000 psi: maximum jack pressure design) and having a minimum Modulus of Elasticity (E) of 30 GPa (4.3512 x 10^6 psi). In addition, the excavated rock surfaces of the PLT niche were required to be prepared in accordance with ASTM D4394-84. The primary design change from the 1998 tests was the use of aluminum rather than stainless steel plates for the load bearing plates. Aluminum allowed for easier installation of the plates, resulting in very little need for pre-test shims to eliminate unwanted gaps in the plates. This stiffer frame design produced negligible displacement of the plates during pressurization, thus directing all the displacing force from the flatjacks into the surrounding rock mass. The PLT setup is shown below in Figure 105.

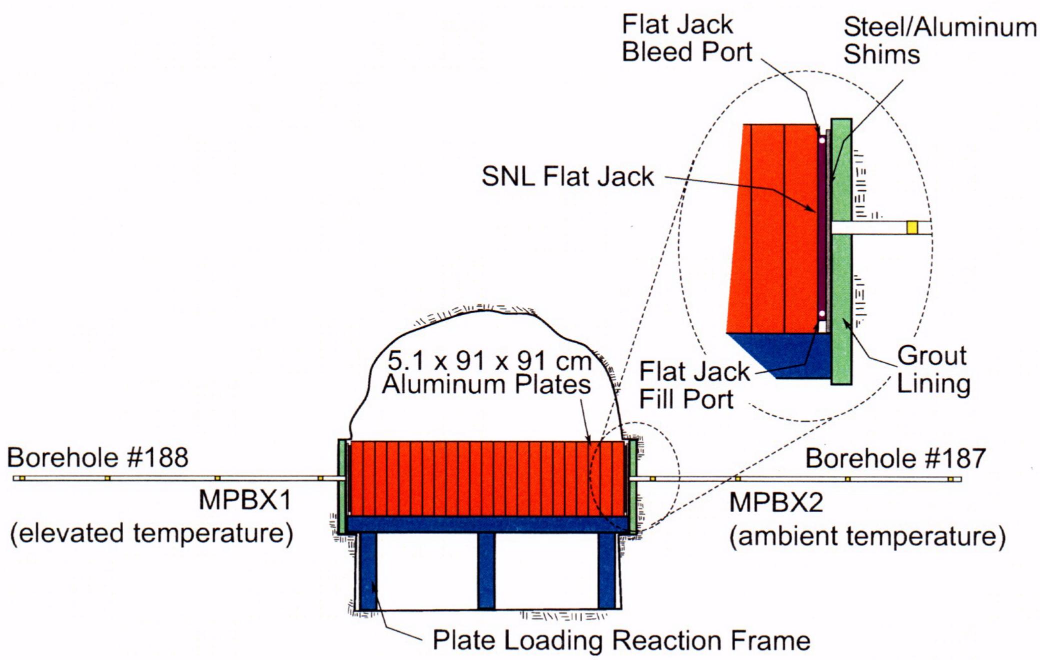

Figure 105. Plate Loading Test Setup

The displacement measured at the deep anchor, ambient side in response to the pressurized flatjacks is shown in Figure 106. The pressure was increased in a stepwise fashion, with intervening periods where the pressure was reduced. This cycling of the pressure in the flatjacks can be seen in the hysteretic behavior of the rock, which relaxes at a different modulus than when it is compressed. The rock was eventually pressurized to a maximum bearing pressure ~32 MPa (4600 psi), resulting from a maximum flatjack pressure of about 6000 psi. The temperatures in the hot and ambient sides of the test were T_{hot} = 58°C, $T_{ambient}$ = 36°C.

The resulting values of rock mass modulus from the October 2000 test, as well as from the 1998 tests, are shown in Table 3. The recent test measured higher rock mass elastic modulus values than did the 1998 tests. Some of this difference is due to the improved testing technique. There is expected to be one more plate loading test in the fall of 2001 before the heat to the DST is shut off in January 2002.

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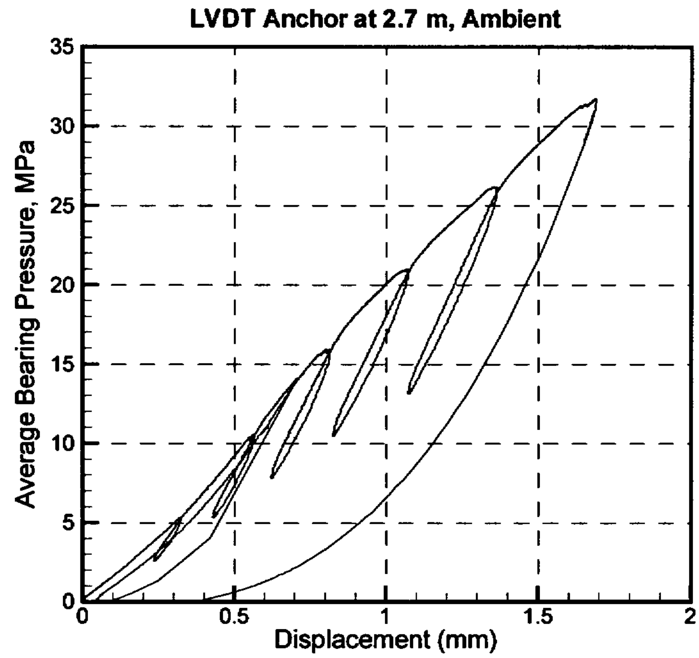

Figure 106. Measured Displacement of the Deep Anchor, Ambient Side During the PLT

Table 3. Calculated Elastic Moduli from the Plate Loading Tests

Plate Loading Test Date	Maximum Bearing Pressure (MPa)	Ambient side of PLT Niche (GPa)	Heated side of PLT Niche (GPa)
5/28/1998	6.4	**Deep – 11.7** Middle – 12.3 Shallow – 14.6	Deep – 30.1 * **Middle – 26.6** Shallow – 33.8
6/9/1998	11.9	**Deep – 11.4** Middle – 12.9 Shallow – 16.2	Deep – 29.7 * **Middle – 30.2** Shallow – 37.6
10/17/2000	31.75	**Deep – 17.3** Middle – 19.6 Shallow – 24.2	Deep – N/A **Middle – 43.0** Shallow – 53.2

* - The hot side, deep anchor results are questionable due to problems with that LVDT.
The results in **bold print** are the recommended modulus values from each test.

5.1.2 MPBX displacement data

For design purposes, the middle nonlithophysal tuff has exhibited behavior that is approximately elastic. Figure 107 compares pre-test predictions of displacement for MPBX-3 with the actual data. The pre-test elastic model using intact rock properties gives reasonably good estimates of rock mass displacement behavior. Note that the displacements for the four anchors increases gradually with time, in a manner similar to the predictions (with the notable exception of behavior with Anchor 4 around 1060 days, which is discussed later).

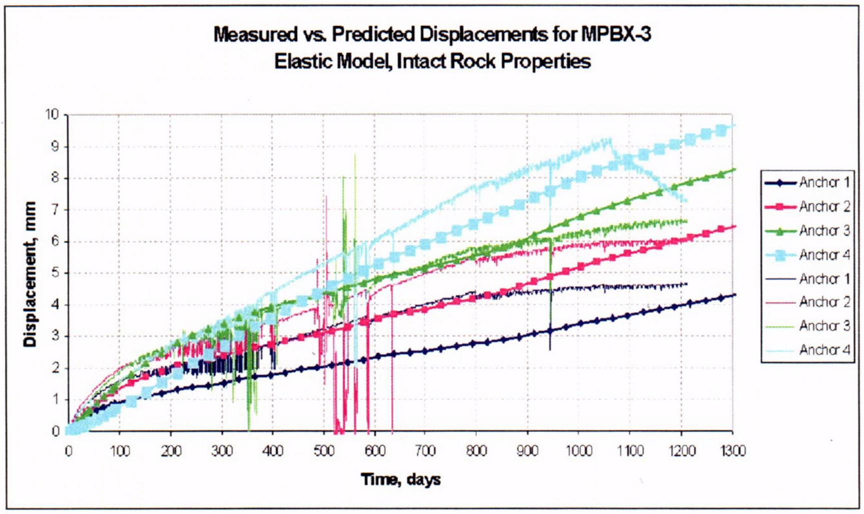

Figure 107. Measured vs. Predicted Displacements for MPBX-3

To date, the MPBX data have shown that the rock expands in a manner consistent with thermoelastic behavior, with a steadily increasing displacement between the anchors and the collar. This increase in displacement is produced by the heated rock expanding into the drift, while the cooler rock further away remains relatively unchanged. As the thermal pulse expands away from the drift, these displacements continue to increase. As the thermal test team analyzes the MPBX data, they search for "events" that may indicate fracture changes. Such changes may later be linked to structural issues for the designers, or to changes in the bulk permeability of the rock which would have consequences for the coupled thermo-hydrologic processes. One such significant event occurs for MPBX-3, in borehole 147. The displacements and temperatures for MPBX-3 are plotted in Figure 108. Anchor 4 of MPBX 3 (15 m from the collar) has a sudden change to its displacement curve beginning on day 1064 (11/1/2000), beginning a steady descent, but the other 3 anchors below it do not display any similar behavior. Because the other three anchors do not exhibit this change, there is no reason to conclude that this is an indication of rock failure near the collar. Additionally, there is nothing in the temperature data at the same time indicating a sudden change in the conditions in this borehole, although the temperature at Anchor 4 (TC-8) does begin moisture-induced oscillations about 100 days before this event. The current hypothesis regarding this event at Anchor 4 is that a major fracture between Anchors 3 and 4 is now sufficiently within the thermal pulse that it is closing. This hypothesis will be investigated further.

Observed deviations from the elastic pattern previously described might signify "events" that could indicate the creation of a fracture, or sudden slippage along an existing fracture. A sudden decrease or increase in displacement in the MPBX data is a potential marker for such an event. Thus, the MPBX data can be used to determine if scaling observed in the Heated Drift thus far is significant. During a recent cleaning and reinstallation of the DST bulkhead windows (April 23, 2001), loose rock was observed at several locations above the welded wire fabric attached to the roof of the Heated Drift. Cables from two instrumented boreholes located 2.7m and 11.9m from the bulkhead along the longitudinal axis of the Heated Drift were observed to have pulled loose from the welded wire fabric. These cables were originally fastened to the wire fabric during installation and remained fastened during prior video imaging in October 2000. This suggests that much of the scaling had occurred since then. This scaling is described in greater detail elsewhere in this progress report. However, one event in the MPBX data that has possible ties to scaling is shown in the data from MPBX-7 (21 m from the bulkhead - see Figure 109). Note that Anchor 1 of MPBX-7 (1m from the collar) begins a abrupt drop in displacement of about 2 mm beginning about day 985 (August 14, 2000). One possible explanation of this drop is a slight loosening of the rock around Anchor 1. However, there is not enough evidence to state this for certain. Anchors 3 and 4 do not show a similar sudden change at this time (Note: Anchor 2 failed earlier in the test). This would indicate that the collar was unaffected by any possible rock movement suggesting the volume of rock affected by fracturing is relatively small. Indeed, the other four MPBXs (MPBX-4, MPBX-5, MPBX-8, and MPBX-9) in the roof at these two stations (13.7 m and 21.0 m from the bulkhead) do not display this behavior. Based on this, it can be concluded that the scaling observed to date is probably due to free surface effects. Therefore this appears to involve only a relatively small volume of rock and not to involve large-scale failure of rock in the roof.

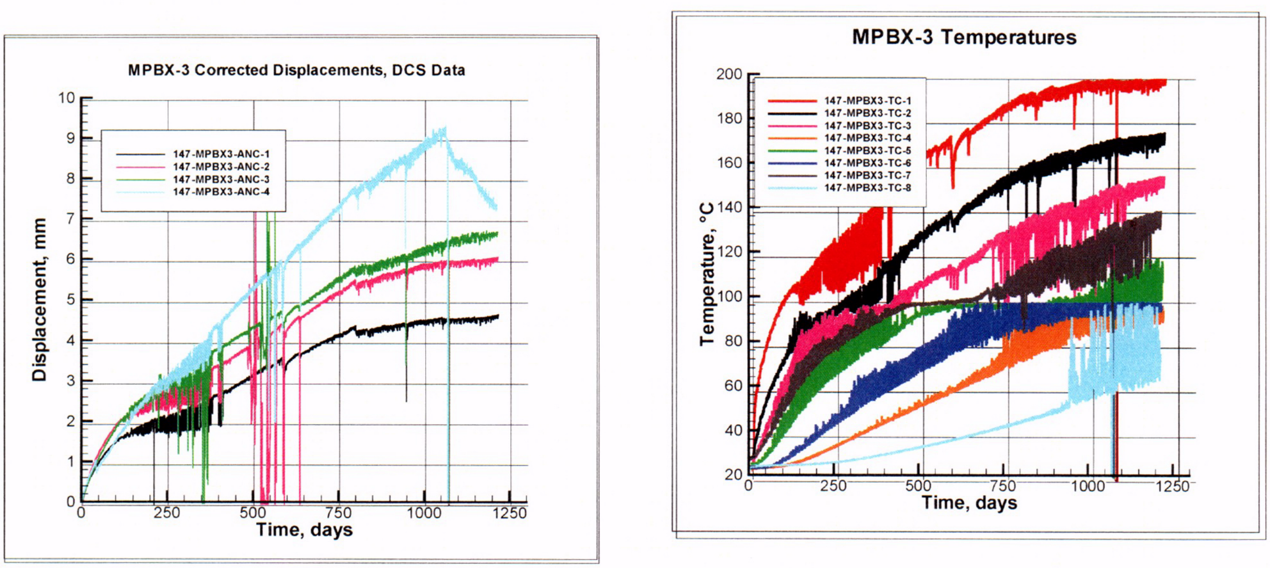

Figure 108. Displacements and Temperatures for MPBX-3 (Borehole 147)

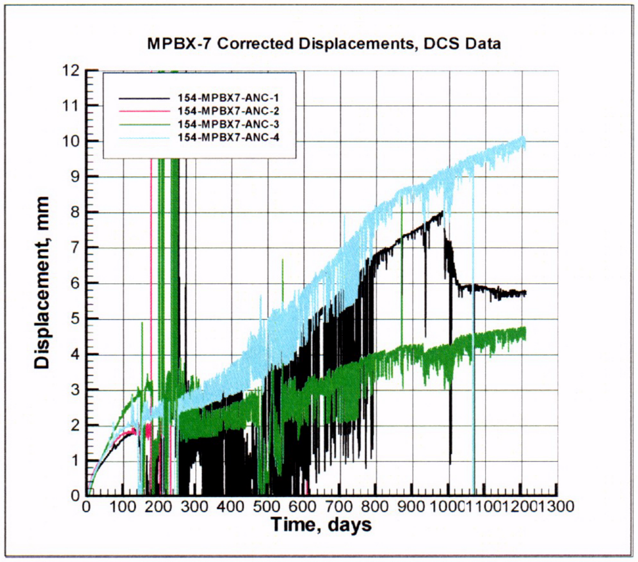

Figure 109. Measured Displacements in MPBX-7 (Borehole 154)

5.1.3 Smoothing effects of moisture-induced oscillations

The MPBX data are meant to provide a measure of rock deformation due to thermal expansion and mechanical stresses in the rock surrounding the Heated Drift. The data were expected to have a "smooth" appearance, with any discontinuities likely relating to sudden movements along fractures. However, many of the data traces exhibit "noise", which makes the data difficult to read and interpret. In general, there are two types of noise that have been identified in the MPBX data. One type is identified by either a wildly oscillating mean value with no discernable pattern, or by values that go outside the expected range of displacement values. These data values are understood to be "bad data", where the gage is experiencing either temporary or permanent incorrect readings. The second type is identified by data that has a discernable pattern (typically, the pattern would follow a curve fit to the top "edge" of the data on a displacement-vs.-time curve), and the data oscillates at values below the predominant curve. These data are being affected by temperature oscillations in the MPBX borehole caused by water recirculation within the borehole. The recirculating water, which alternately boils, rises, condenses, and falls in a cyclic fashion in the borehole, causes the Invar connecting rods to shrink/expand, and also affects the calibration constants of the LVDTs based on the temperature at the collar. It is thought that the surrounding rock mass is negligibly affected by these temperature oscillations, and thus the oscillating MPBX measurements do not represent the actual rock behavior. In order to use the MPBX data to validate thermal-mechanical models, or to use them to derive rock mass thermal-mechanical properties, the true rock mass behavior must somehow be extracted from the noisy data. It is this requirement that led to this initial attempt to smooth the MPBX data.

There are several issues which make a scientifically based algorithm for smoothing the MPBX data a complex matter: the contraction/expansion of the Invar rods, the effect of temperature on the LVDT, the need to capture true fracture deformation events, other causes of unlikely data values. Therefore, as an initial attempt to provide smooth data for use in validating thermal-mechanical models, a simplified approach using technical judgment was used. Jay Cho (M&O) developed the approach used for this TDIF; after Jay left the YMP, Steve Sobolik (SNL) took on the responsibility of completing this initial data submittal. Under Jay's approach, the acquired MPBX measurements from the LVDTs, as calculated by the Data Collection System, were corrected for the thermal expansion of the Invar connecting rods in essentially the same manner as the developed MPBX data that is regularly submitted to the TDMS. The acquired MPBX and temperature data, and the corrected MPBX data, are listed in an Excel spreadsheet, one for each MPBX. Then, several steps were taken to smooth the data. First, based on the technical judgment of the analyst, sections of data that were considered unusable were deleted from the file. Typically, these data were either the results of a problem with the gage itself: failure, erratic voltage readings, etc. Then, other sections of noisy data were identified using a 0.3-mm difference between values at six-hour intervals. If the behavior of the identified data matched the assumed behavior caused by the recirculating water, then that range of values was discarded. While discarding data, it was important to retain information that may represent other physical processes, such as a sudden permanent shift which may indicate fracture slippage or closure. An example of the results of this smoothing procedure is shown in Figure 110, comparing the before and after plots for data from MPBX-11 (Borehole 178).

This procedure for smoothing the MPBX data can (and likely will) be improved upon in the future. This initial attempt was done to provide smoothed data for use in comparison to the thermal-mechanical analyses in the recently submitted THM-AMR. The data files submitted for this TDIF include data through 7/31/2000 (i.e., through 971 days of heating). For the purposes of the THM-AMR, this is acceptable; at a later date, the project may decide to update all the MPBX data with a more refined smoothing technique.

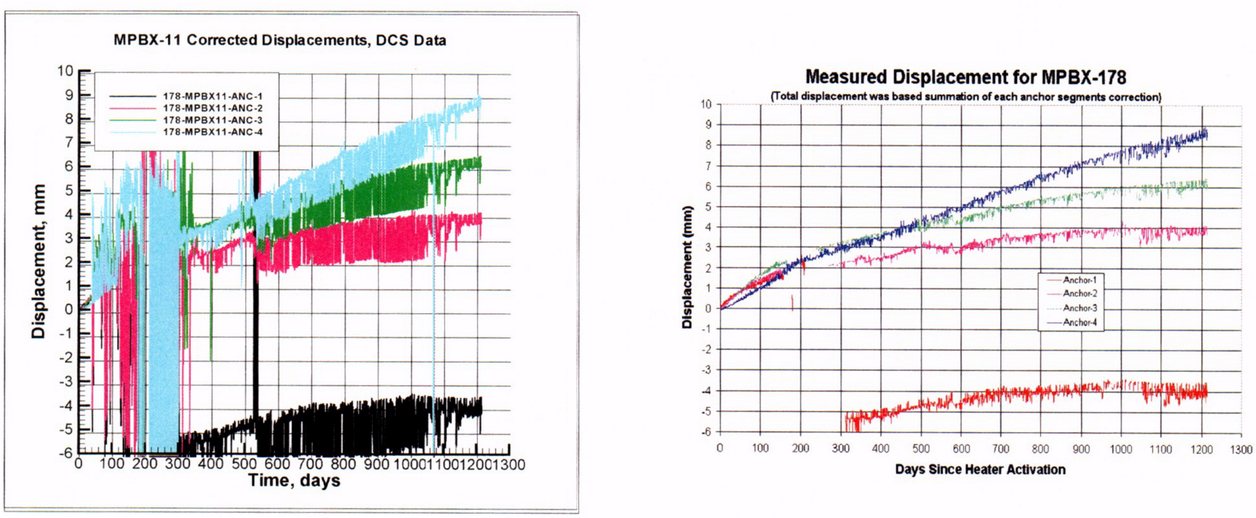

Figure 110. Pre- and Post-Smoothing Plots of Displacement Data for MPBX-11

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5.1.4 Comparison of MPBX and Acoustic Emissions Data

Acoustic emissions (AE) data obtained by Lawrence Berkeley National Laboratories are used to determine the occurrence and location of microseismic events caused by the thermal response of the host rock. An earlier comparison of the measurements of the two instrumentation systems (AE and MPBX) identified events monitored by the AE and MPBXs in an attempt to correlate temporally and spatially, and to determine if such correlations are indicative of a rock mass event recorded by both systems. Because of the types of measurements (seismic versus displacement), the frequency of recorded measurements, and locations of the measuring devices, it was unknown whether events such as fracture generation, slippage along fractures, or seismic events would be detected and recorded by both instruments. That earlier study, which examined data through 3/21/2000, found no apparent correlation between MPBX and AE events. With the recent scaling events, more recent AE data were evaluated to determine if any correlations exist between these events. The following conclusions were drawn from this latest comparison:

- There is no apparent temporal correlation between AE data and rockfall events.
- AE data indicates several significant "pops" in the drift crown at earlier times, which may or may not indicate the stress relief that caused the rockfall.
- Rock spalling itself probably does not generate enough signal to register in AE data; the signal is weak, and the high temperatures around it wash that out.

The MPBX and AE data will be looked at on a regular basis to detect any other possible events that might be related to rockfall. This evaluation will take on a greater importance after heater shutdown, when temperatures cool and stresses are relieved.