Title
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Geologic disposal of nuclear wastes within excavations made at depth in suitable media has long been [1], and continues to be[2], favored as the currently most practicable means of isolating them from the biosphere over the long term. Although a significant body of experience exists concerning underground excavation, it does not include the effects of heat generation on the excavations and the geologic media. Experiments to assess some of these effects have been done for salt in Project Salt Vault[3] but it is now agreed that other media be examined[2]. Access to tunnels driven into the granite country rock 340 meters below surface adjacent to a defunct iron ore mine at Stripa, Sweden, provided a unique opportunity for doing experiments in granite without delay and at minimal cost, at a depth where conditions of stress, jointing, groundwater and other factors associated with depth similar to those likely to be encountered at the site of an actual waste repository exist.

The disposal of high level nuclear waste deep underground will result in the geologic media in the vicinity of such a repository undergoing a thermal pulse. This pulse will induce thermomechanical displacements and stresses in the rock. In general, these displacements will be directed away

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from the source of the heat while the temperature is increasing then tending to return as the temperature decreases. Likewise, the thermomechanical stresses will result in the addition to the virgin state of stress in the rock of compressive stresses within the heated zone and the addition of deviatorial stresses, including tension, outside of it.

Transport by groundwater is the most probable mechanism by which components of the wastes may find their way back to surface. The intrinsic permeability of many granites is so low that the only hydraulic conduits of concern arise from joints and fractures in masses of such rock. Clearly, the thermomechanical perturbations may have significant effects on the hydraulic transmissivity of such features. Accordingly, it is necessary that the effects of these perturbations be understood if the utility of a geologic formation as a site for a potential waste repository is to be evaluted properly. Furthermore, the design of a repository and predictions concerning its performance in the long term cannot be done without such an understanding[4].

Recognising that the value of field experiments depends upon the extent to which they provide a degree of understanding of the phenomena involved which is sufficiently great to enable these results to be transferred to other sites where repositories may be built in fact, the program involves the collection of sufficient field and laboratory data to ensure that their analyses will provide either a high degree of understanding of the behavior of the rock mass or an identification and definition of those crucial issues requiring further research.

Three different thermomechanical experiments are underway at Stripa[5]. The first is designed to study the short-term, near-field effects around an electrical heater simulating a full-size canister of reprocessed high level waste. The second is a similar experiment designed to study also the long-term, near-field effects. The third is a time-scaled experiment designed to simulate the interaction between adjacent canisters over a period equivalent to about two decades, using the quadratic relationship between time and distance in linear thermoelasticity[6].

Based on the theory of linear thermoelasticity and properties of the granite measured in conventional small scale laboratory tests, the results of all three experiments, namely, the expected temperature, displacement and stress fields as functions of time, have been predicted in advance of the collection of field data. The field data are being collected in such a way as to allow comparisons between theoretical predictions and underground measurements to be made continuously during the experiment. To date the comparisons have shown that the use of simple linear heat conduction provides an adequate prediction of the temperature fields around three experiments, Figures 1 and 2. According to the theory of linear thermoelasticity displacements should be related to temperature fields by a simple factor $\alpha[(1+\nu)/(1-\nu)]$, where α = the linear coefficient of thermal expansion of the rock, and ν = Poisson's ratio for the rock. All the measured displacements differ significantly from predicted values in two different ways, Figure 3. First, initial displacements, of the order 100 μm per meter, are highly non-linear, reflecting possibly the effects of joints in the rock. Second greater displacements than these appear to be linear but to have a magnitude only about half that expected from values derived from simple laboratory measurements. Likewise the stresses appear to have values different from that given by the temperature field and a factor $\alpha E/(1-\nu)$, where E = the Youngs' Modulus of the rock and the other symbols are as defined above, Figure 6[7,8].

The disparities between measurement and predictions using simple theory and laboratory data should not be regarded as evidence of a lack of predictive capability but, rather, as a means for identifying and understanding the important difference in behavior between a rock mass and laboratory specimens of rock.

The power levels of the two full scale heaters are 3.6 kW and 5 kW corresponding to those projected for reprocessed fuel 5 years and 3.5 years after discharge from the reactor[9]. These power levels, together with the peripheral heaters used in the second stage of the 5 kW heater experiment to simulate the effects of increasing the temperature of the rock containing a waste canister, have produced thermal stresses on the walls of the boreholes containing these heaters below, at and above those sufficient to cause decrepitation of these holes[10]. This has enabled the conditions causing decrepitation to be defined, Figure 5.

The core from every instrumentation hole at Stripa was logged during drilling and the core kept. A laboratory test program to obtain the thermo-mechanical properties of specimens of core taken from the same hole in which the measurements of displacements and stress have been made is underway. These tests will be done over a range of hydrostatic and deviatorial stresses and temperature covering and exceeding those to which this rock has been subjected in the field. They will include specimens of intact and jointed rock. These values will then be used to refine the predictive models, incorporating such nonlinear properties as may be revealed by these laboratory tests.

Finally, starting in June 1979, power to the heaters has been turned off. Continuous measurements are being made during the cool down period, as they were during the heat up period. It is expected that a substantial amount of additional information, especially concerning nonlinear phenomena, will be obtained by observing hysteresis over a full thermal cycle.

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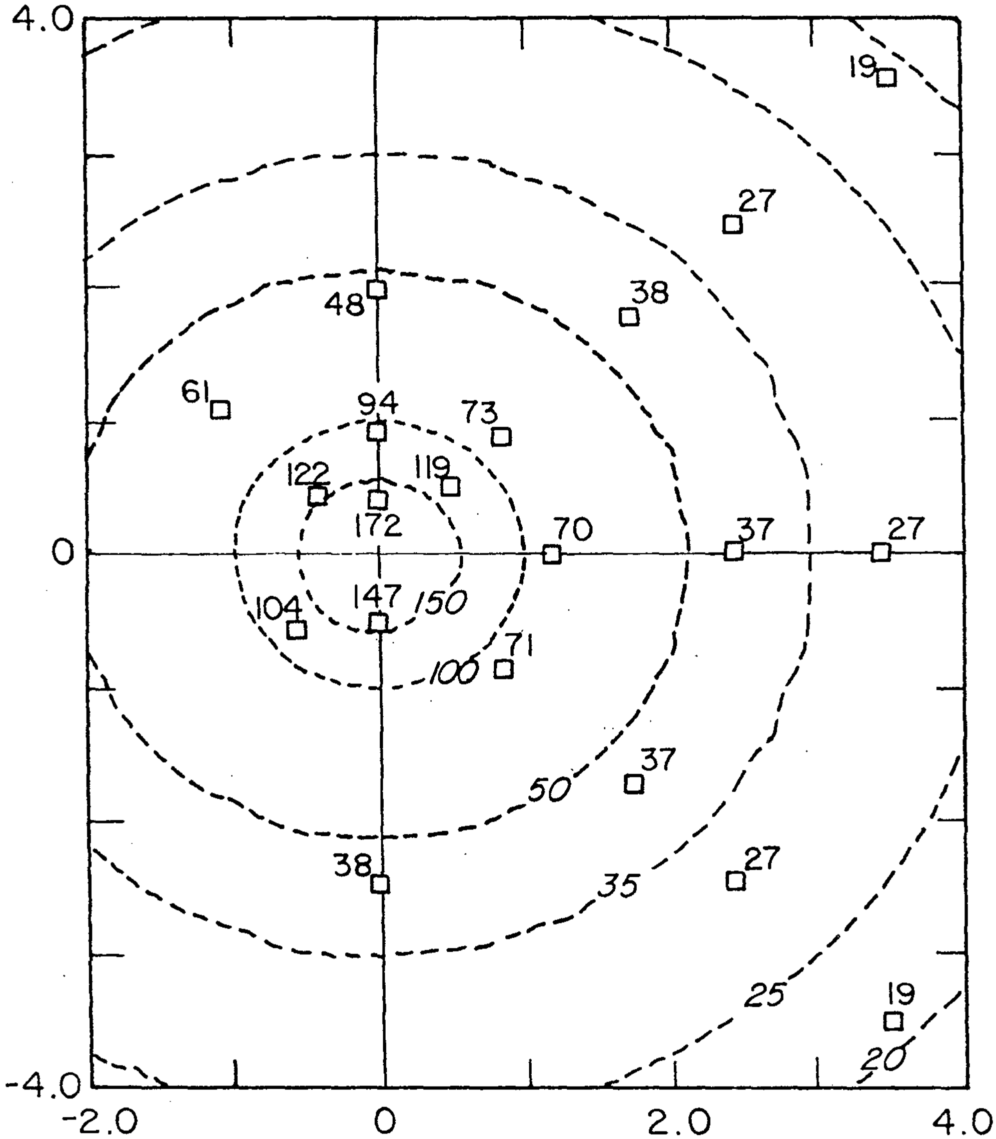

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Figure 1. A plan of the horizontal plane through the middle of the 5 kW full-scale heater showing the predicted isotherms (dashed lines) and actual temperatures (squares with numbers) measured along different directions at 190 days after the start of heating. Note the relatively good correlation between measurement and prediction and the high degree of axial symmetry (Scales for the X- and Y-axes are shown in meters.)

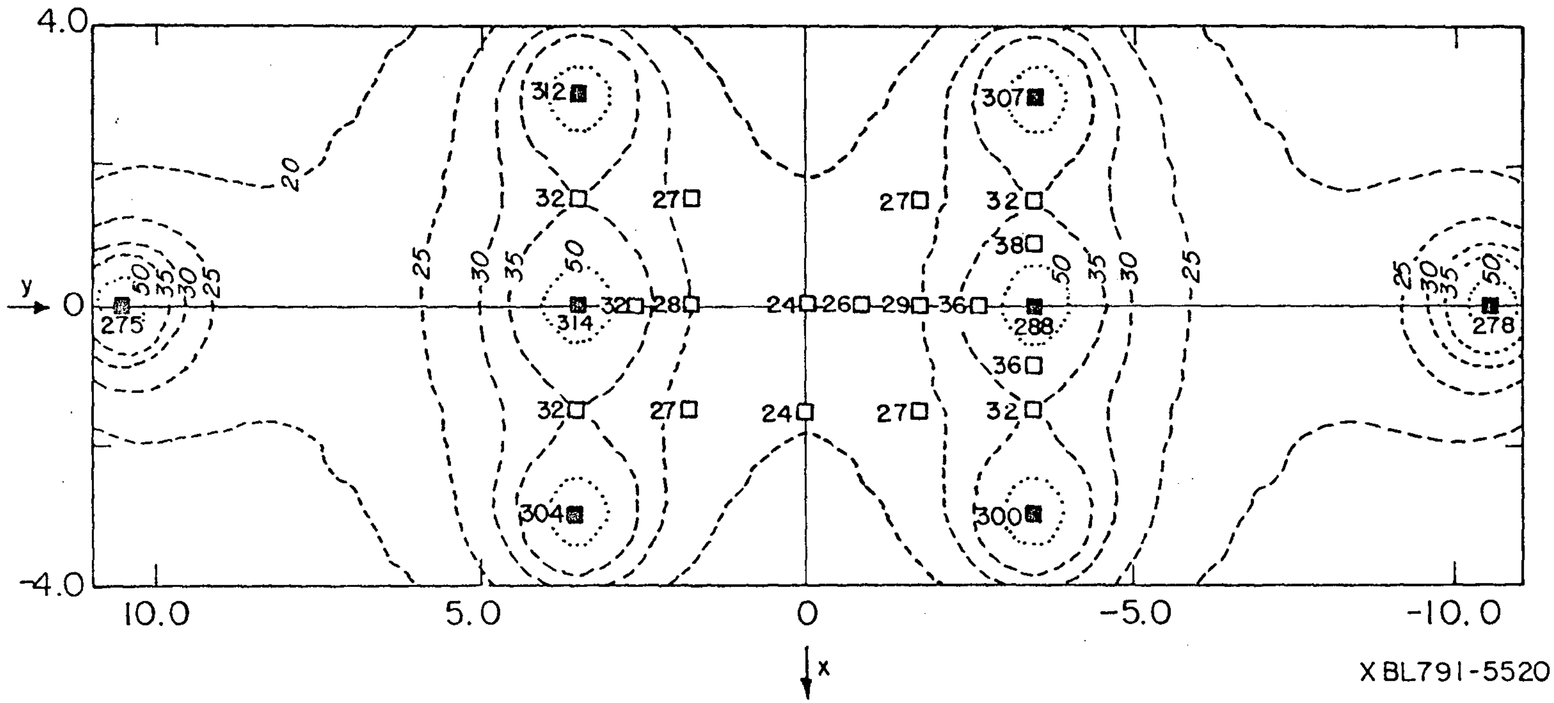

Figure 2. A plan of the horizontal plane through the middle of the array of 8 time-scaled heaters showing the predicted isotherms (dashed lines) and measured temperatures (squares with numbers) at 190 days after the start of the experiment. Actual distances between the heaters (black squares) are given in meters along the X- and Y-axes. The spacing between these heaters corresponds to 7 meters and 22 meters for full-scale heaters and the temperatures to those at 1,938 days (5.3 years) because of the time scaling.

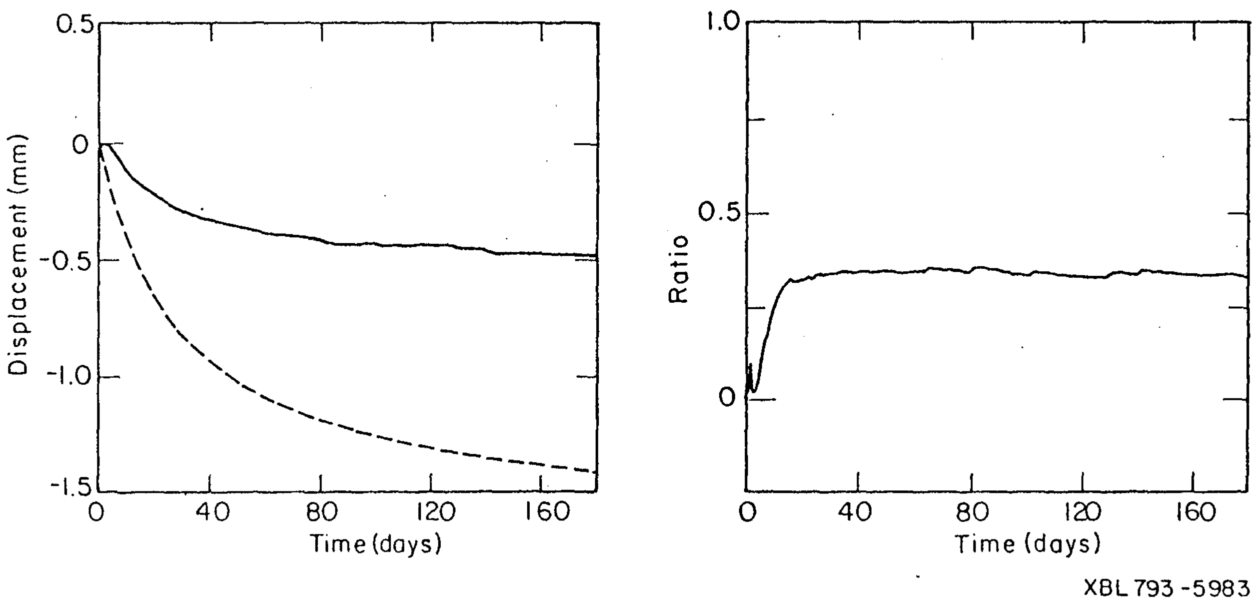

Figure 3. An example showing the predicted (dashed lines) and measured (solid lines) displacements between anchor points situated 3 meters above and below the mid-plane of the 5 kW heater and at a radial distance of 2 meters as a function of time (left), together with a plot of the ratio between the measured and predicted values as a function of time (right). Note the initial non-linearity of the displacements and their subsequent linear, but lower than predicted, behavior revealed by the right hand plot.

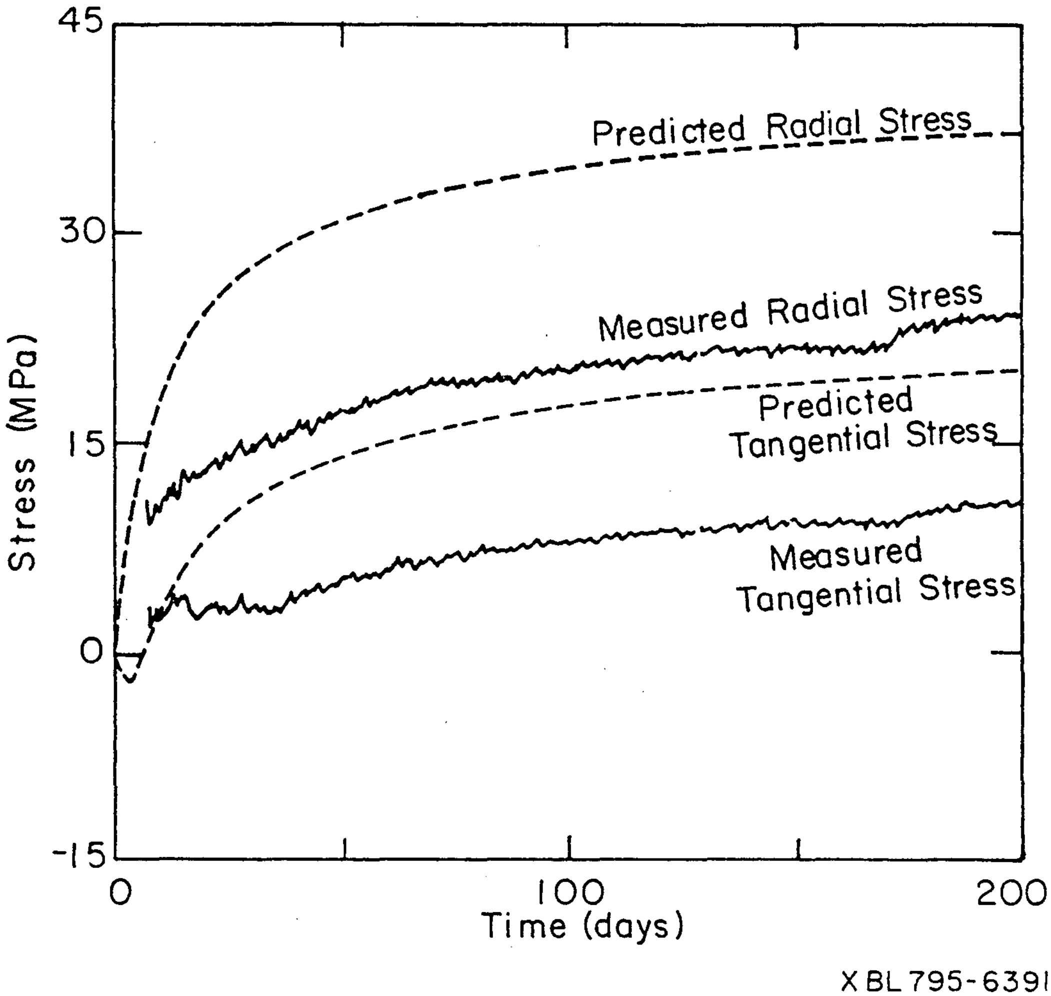

Figure 4. An example of the predicted changes (dashed lines) and measured changes (solid lines) in stress as a function of time, inferred from a vibrating wire borehole strain gauge located 0.85 meters above the mid-plane and 1.5 meters radially from the 5 kW full-scale heater.

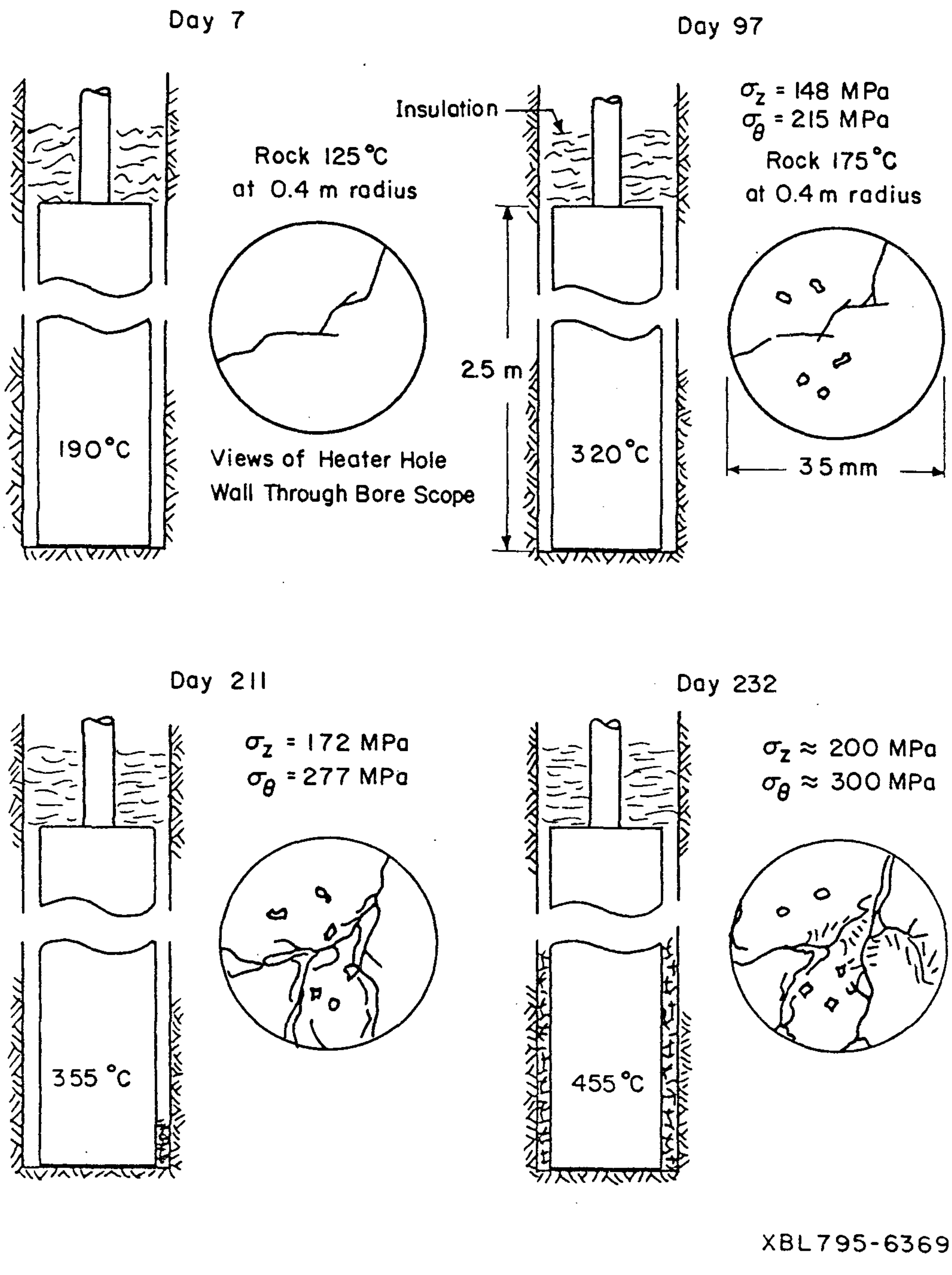

Figure 5. Axial sections through the 5 kW full-scale heater with sketches of borescope views of portions of the hole containing this heater at 7, 97, 211 and 232 days after the start of heating, illustrating the decrepitation of the borehole wall caused by thermally induced stresses, the magnitudes of which are given. Note that the gross decrepitation caused by the additional stress induced by turning on the 8 peripheral heaters on day 204 impeded the radiant heat transfer from the heater to the rock causing the temperature of the heater to increase by about 100°C.

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