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Field experiments are necessary to determine the thermomechanical response of rock masses. Such experiments are of little value unless field measurements can be made which are sufficient to define adequately the pristine conditions in the rock mass and the changes brought about by these experiments.

Field measurements can be divided into two general types, regardless of whether they are used in endeavors to define the pristine conditions of a geologic site or to monitor the effects at a site of underground experiments. First, there are those techniques of field measurement which involve the detection of a signal propagated through a portion of the rock mass, such as seismic or electromagnetic waves. Second, there are those techniques which involve measurements made at specific points in the rock mass, usually in boreholes, such as measurements of pore fluid pressures or rock temperatures. The first types of measurement are essentially similar to those used in exploration geophysics. Some of them have been developed highly over considerable periods of time and at great expense for the identification of specific characteristics of the subsurface. The second type of measurement, too, has been developed for specific applications. However, outside of the scope of these specific applications there is a dearth of technology and instrumentation for making the measurements to obtain the necessary information.

In principle, many of the properties of subsurface media which determine behavior of a rock mass can be found using experimental laboratory data combined with chemical and physical analysis. However, the behavior of a large rock mass depends not only on the properties of its constituents but upon the

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geological structure of the rock and the thermodynamic conditions which prevail within it. Because the geologic structure and pristine thermodynamic conditions are important in determinining the behavior of a large rock mass, the primary goal of field measurements must be to locate and characterise geologic structures and measure the thermodynamic conditions in the subsurface. The secondary, but no less important goal, of field measurements is to obtain actual data concerning the response of the rock mass to thermomechanical experiments so as to develop and validate models capable of accounting for and predicting this response.

Measurements of the first type, that is, those using signal propagation and detection, can be used in endeavors to meet both the primary and the secondary goals identified above. However, the signal arising from many geologic structures of significance and from major changes in thermodynamic conditions is frequently small, so that the resolution of techniques using signal propagation often falls short of that required. When used to measure pristine conditions, which are essentially static, various forms of stacking can be used to enhance the ratio of the signal to the noise. However, techniques using signal propagation are subject often to conflicting and seemingly irreconcilable requirements. For example, high frequency seismic waves are needed to detect small structures, such as partially closed joints with small apertures in their void spaces, but attenuation limits the distances over which high frequency signals remain detectable. Furthermore, the relationships between the propagation and reflection of seismic signals and the principal factors of concern, such as the apertures of joints or the state of stress in the rock, are neither strong nor unique relationships. It can be argued, correctly, that the same limitations do not necessarily apply to other signal propagation techniques such as electromagnetic wave propagation or electrical resistivity. Nevertheless, it seems a general truism that experiments using signal propagation do not possess the degreees of resolution and specificity and capability to measure the quantities of direct concern that are required. Their principal attributes are that they are non-destructive and can be used to make measurements through large volumes of rock.

Measurements of the second type, that is those made at specific points in the rock mass, can be used also in endeavors to meet the primary and secondary goals identified above. Where the techniques have been developed for measuring the quantities of direct concern, such as temperature or pore fluid pressure, these measurements do provide a high degree of resolution and specificity. However, techniques for measuring many quantities of direct concern, such as the complete state of strain or stress, the apertures of joints or their hydraulic transmissivity are not yet developed to yield results of sufficient accuracy. Furthermore, many of these quantities may not be uniform and homogeneous through the rock mass, so that the important question concerning the relationship between a measured value obtained at one point to values of the same property at other points throughout the rock mass cannot be answered in the absence of other information.

As usual, it is unlikely that an issue as complex as the response of a rock mass to thermomechanical experiments can be answered simply. A multitude of partial answers will have to be assembled within the constraints of a thorough knowledge of the chemical and physical processes involved.

In order to be able to identify those features of a rock mass which cause it to behave differently in situ than would be expected from predictions based on the properties of laboratory specimens of the rock, it is necessary to know three sets of information. First, what is the range of properties for laboratory specimens of all components of the rock mass for values of stress, temperature, and pore fluid chemistry and pressure to which the rock mass is subjected? Second, what are the ranges of stress, temperature, and pore fluid chemistry and pressure which prevail in the rock mass in situ? The differences between the response of the rock mass to thermomechanical experiments as predicted from these two sets of data and its response as measured in the field must then result from features of the in situ rock mass. Therefore, the third set of data must comprise adequate and comprehensive measurements of the response of the rock mass to the thermomechanical experiments. It is the collection of the last of these three sets of information which is of principal concern at this workshop. However, before turning specifically to this question it seems advisable to review the adequacy or otherwise of the first two sets of data.

First, most laboratory tests on specimens of rock are performed for the purpose of studying stress, strain, pore pressure and failure phenomena, to obtain a fundamental understanding of the mechanisms involved. Accordingly, it has been necessary to select samples of different kinds of rock from which test specimens with homogeneous and uniform properties can be prepared to ensure that tests on these specimens are reproduceable and comparable. Important as this work has been to advancing the science of rock mechanics it has tended to obscure the inherent variability in properties within a rock mass. Furthermore, of all rock properties, thermomechanical properties at temperatures and pressures likely to be encountered in a nuclear waste repository have received least attention. Accordingly, it seems appropriate to conclude that the information on rock properties available in the literature is of great fundamental scientific value, but limited practical use in assessing the values of thermomechanical properties relevant to a waste repository in a rock mass. A first step which seems to be necessary, therefore, is to compile data on the range of thermomechanical properties of laboratory specimens of rock representing the entire rock mass. Such specimens can be obtained from very careful diamond core drilling of holes in the rock mass, which should not pose a problem as many holes are required to instrument the rock mass for a field experiment.

Second, although it is relatively easy to measure temperatures, and pore fluid chemistry and pressure through boreholes in the rock mass and these properties are relatively homogeneous, the measurement of the complete state of stress has so far proved to be illusive. In principle, stress in a rock mass can be measured directly by the substitution of an hydraulic pressure for a component of normal stress or, indirectly, by measuring the strain relief following trepanning a borehole and inferring the stresses from a stress-strain relationship for the rock. Only under special circumstances can direct substitution of hydraulic pressure for components of normal stress yield the complete state of stress, and even then it involves some assumptions. In theory, a sufficient number of strain relief measurements can be used to infer the complete state of strain or stress in the rock but the inferences are only as valid as the knowledge of the stress-strain relationships for rock under the appropriate conditions. This is especially so because the measurements are made in a hole which itself disturbs very significantly the state of stress and strain which is being measured. It is fair to conclude that little certainty can be attached to determinations of the complete state of strain or stress even at one point in a rock mass with the technology available today. Even if this difficulty were resolved, the state of stress in a rock mass may not be homogeneous, so that the significance of measurements made at one point for other parts of the rock mass is not clear. One of the most important advances that needs to be made is the development of technology, instruments and methods for making in situ measurements of the complete state of strain or stress in a rock mass.

As has been noted, to study the response of a rock mass to thermomechanical experiments an appropriate number of measurements of several kinds must be made. It is important to decide what quantities need to be measured. Current data handling equipment has capabilities far in excess of current capabilities for making measurements in the rock mass.

It is obvious that one of the most important and fundamental sets of measurements which needs to be made in any thermomechanical experiment is that of the power going into the rock and the temperature field generated by it in the rock, as a function of time. Fortunately, such measurements can be made with comparative ease, although they do involve placing suitable temperature transducers in boreholes located at appropriate distances from the heat source. There do not appear to be any methods using signal propagation which will yield measurements of the temperature field in the rock of comparable accuracy.

A fundamental property of materials is that they tend to undergo changes in volume in response to changes in temperature. Accordingly, the changes in temperature brought about in the rock mass by heating it should give rise to deformations in the rock. Measurements in a rock mass are of necessity made in boreholes which disturb the state of strain and stress because of the hole. The magnitude of this disturbance depends upon the stress-strain relationship for the rock, which may not be understood very well. The perturbation introduced by the borehole can be reduced by measuring displacements along its axis over distances of an order of magnitude greater than its diameter or more. Instruments for such measurements are known as extensometers. Mechanical extensometers are used commonly for this purpose. Although electronic distance measuring devices are used extensively in surveying, electronic and interferometric extensometers have not been used in underground experiments to any significant degree.

To be able to interpret measurements of deformation it is necessary to measure the resistance to deformation induced in the rock mass. The difficulties of making meaningful stress measurements have been alluded to already. The changes induced by thermomechanical stresses may be sufficiently large to be detected by signal propagation measurements but detection is not measurement. If there is one key measurement essential to understanding of experiments on the thermomechanical response of rock masses it is the measurement of the state of strain or stress in the rock.

In conclusion, it is appropriate to summarise those field measurements which must be taken to enable the response of a rock mass to thermomechanical experiments to be determined. Not only is it necessary to identify the critical measurements but also the ranges over, and accuracy with which they are likely to be needed.

Measurements as a function of time are needed of:

i) rock temperatures including the initial values;

ii) rock movements;

iii) the state of strain or stress in the rock, including the initial values, and

iv) fluid pressures in the rock, including initial values.

The duration of field experiments to study the thermomechanical response of rock masses is likely to range from less than a year to a few decades, and the linear dimensions of the rock mass influenced significantly by them may range from as little as a meter to several hundred meters.

Data collection and the provision of a time base present no new technical problems other than those posed by the underground environment.

The maximum temperatures may reach several hundred degrees centigrade but average maximum temperatures are much more likely to be less than 100°C. From this it follows that away from the source changes in temperature of a few degrees centigrade are of interest and that the accuracy of temperature measurement should, therefore, be better than 1°C. However, if temperature measurements are to be used to detect small perturbations to conductive heat flow in the rock, such as may arise from the movement of water through joints, it would be necessary to resolve temperatures to an accuracy of 0.1°C.

The unconstrained coefficient of linear thermal expansion of most rocks is generally somewhat less than 10^{-5}/°C. Average temperature changes of 100°C will therefore, result in thermal strains in the rock mass caused by thermal expansion of the order 10^{-3}. There is some difficulty in measuring the displacements associated with such strains over a gauge length of about one meter to an accuracy of even 100μm with mechanical extensometers. However, the hydraulic transmissivity of joints with an aperture of 1μm is significant and that of joints with an aperture of 10μm is important. Accordingly, the accuracy with which displacement measurements must be made should resolve displacements of 10μm, at least.

The magnitude of the vertical component of the initial state of stress in the rock mass is close to that given by the weight of the overlying rock, namely, 25 MPa/km of depth. The Young's modulus of most rocks in which a nuclear waste respository may be excavated lies in the range 10 GPa to 100 GPa. Thermally induced strains of interest may be as low as 10^{-5}, so that measurements of the state of strain or stress should be able to measure strains of the order of 10^{-5} or stresses of the order of 1 MPa.

Finally, an important word of caution is necessary concerning displacement or strain measurements made on, relative to, or at, the surface of underground excavations. These excavations perturb the state of initial strain or stress and the thermally induced changes in strain or stress much as do boreholes. However, the perturbations of excavations such as drives is much more serious than is that of boreholes for two reasons. First, because of their large size the extent of the perturbation is farther reaching. Second, the scale on which it takes place affects the rock mass and, therefore, includes many of the uncertainties concerning its response, the measurement of which is the major purpose of field experiments.

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