3.

P.S. Please tell Buckley about my arrival time next week. Raj

June 9, 1986

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My Dear Nataraj:

Thank you for asking Itasca to utilize my services on the FEA review.

I am enclosing a draft of my input for the US National committee on Rock Mechanics report on "Coupled Processes". Please give me your comments when I am in Washington next week (June 18, 10 AM). We will be discussing this report in Tuscaloosa.

With best wishes to you and family.

Sincerely
V. Rajaram

from the desk of DR. V. RAJARAM

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RAJ RAJARAM, Ph.D., P.E.
CONSULTING ENGINEER

Thermomechanical Coupling in Rock

The mechanical behavior of rock has been studied in the laboratory and in the field for over two decades (Jaeger and Cook, 1969). Interest in thermal, mechanical and coupled thermomechanical behavior of rock has intensified over the past decade with the exploitation of oil and gas in tight formations, the commercialization of geothermal energy, and the commitment to the geologic disposal of high-level radioactive waste (Noorishad, et al, 1971; Baca, et al, 1980). Fully coupled tests to determine the thermomechanical behavior of rock are yet to be conducted by the DOE as an integral part of the site characterization plan at the Hanford site, Washington, Yucca Mountain site, Nevada, and Deaf Smith site, Texas. However, attempts to understand thermal and mechanical behavior separately and couple the effects through numerical modeling have been underway at these sites (Cramer, et al, 1983). Thermal properties (e.g., conductivity and specific heat), mechanical properties (e.g., Young's Modulus, Poisson's ratio, and strength), and thermomechanical properties (e.g., coefficient of linear thermal expansion) have been determined in the laboratory and in situ (Tammemagi and Chieslar, 1985; Schmidt, et al, 1980).

Coupled processes in geomechanics were summarized by Cook (1985). The processes controlling the deformation of fractures in rock were succinctly described. Fluid conductivity of fractures (joints, faults, and fractures) is dependent on the stress normal to the fracture plane and the pore fluid pressure within it. Under some conditions, shear displacement between the two surfaces may result in major changes in the geometry of the void, and hence the hydraulic conductivity. The effective normal stress across fractures is expected to change as a result of the redistribution of stresses around excavations, thermally induced stresses, and pore pressures (Cook, 1985).

Four major processes control the rate of transport of fluids through rock. In a geologic repository, the heating of the rock by the high-level radioactive waste creates thermal stresses. The thermal expansion of water (coefficient of volumetric expansion is 0.0006/°C) contained in fractures will change the pore pressure and result in a large stress change across a fracture (Cook, 1985). Mechanical stresses are induced when openings are made in rock, and the coupled effect of these mechanical and thermal stresses is to increase the overall permeability of the rock mass. This is due to the fact that although stress increase will tend to decrease the permeability in the volume of heated rock, the compensatory decrease in stress outside the heated volume will increase permeability.
The cubic relationship demonstrated by Iwai (1976) and Gangi (1978) states that the hydraulic conductivity of fractures increases as the cube of the mean void aperture. The increased permeability leads to fluid flow in the geologic system. Geochemical reactions among water, rock and radionuclides determine the rate of transport of the radionuclides from one point to the other.

Two major approaches are available to study the thermomechanical coupling in rock. Testing in the laboratory (Reda, 1985) on cores, large scale testing in a simulated environment (Cramer, et al, 1983), and in situ testing at the depth of interest can be undertaken to determine thermomechanical behavior of rock. Another approach is to mathematically simulate rock behavior using simplified assumptions, and systematic uncoupling of the various interrelated physical phenomenon (Heuze, et al, 1985; Elsworth and Goodman, 1985; Chan, et al, 1985). The role of analytical modeling is in understanding the key processes, determining the sensitivity of key parameters, designing in situ tests, analyzing test data, and making prediction of long term thermomechanical behavior of the rock mass (Nataraj, 1983). The role of testing is to validate models, to provide input parameters for analyses, and to enhance confidence in making predictions of rock mass behavior.

In low permeability tuff located in the unsaturated zone, the diffusion of water vapor resulting from temperature-induced vapor pressure gradients is a credible mechanism for radionuclide transport. Reda (1985) conducted gas-phase permeability experiments on a sample of densely welded tuff and found that permeability was highly dependent on pore pressure, undergoing an order-of-magnitude increase as pore pressure was systematically reduced from 13.1 to 0.1MPa. The Knudsen diffusion coefficient for water vapor, at 296k, was calculated to be 3.2×10^{-7} m^2/s. Large scale field tests are being conducted at the G-tunnel in Nevada Test Site, and the Near Surface Test Facility (NSTF) in Hanford, Washington. Fully coupled tests for understanding thermomechanical compling are being planned by the U. S. Department of Energy.

The FEFFLAP (finite-element fracture and flow analysis program) has been developed at Lawrence Livermore National Laboratory, and verified with laboratory experiments (Heuze, et al, 1985). Coupling of boundary element and finite element procedures provide optimization in solution efficiency in analyzing the hydromechanical behavior of rock masses (Elsworth and Goodman, 1985). A three-dimensitional finite element model, MOTIF (model of transport in fractured/porous media), has been developed by the Atomic Energy of Canada, Ltd. to simulate coupled processes of groundwater flow, heat transport, brine transport, and one-species radionuclide transport in geologic media (Chan, et al, 1985). Contractors for the Nuclear Regulatory Commission (NRC) and the Department of Energy (DOE) are developing codes to understand thermomechanical behavior of rock and predict the long term (10,000 years) performance of geologic repositories in basalt, tuff, salt, and crystalline rocks.

References

1. Jaeger, J. C., and Cook, N. G. W. (1969), Fundamentals of Rock Mechanics, Methuen & Co., Ltd., London.
2. Baca, R. G., Case, J. B., and Patricio, J. G. (1980), Coupled Geomechanical/Hydrological Modeling: An Overview of BWIP - Studies," Proceedings, Workshop on Thermomechanical Hydrochemical Modeling for a Hardrock Waste Repository, LBL-11204, Berkeley, CA, pp. 70-80.
3. Chan, T., Guvanesan, V., and Keith Reid, J. A., (1985), Numerical Modeling of Coupled Thermo-Hydro-Mechanical Processes in Nuclear Fuel Waste Disposal, International Symposium on Coupled Processes Affecting the Performance of a Nuclear Waste Repository, Lawrence Berkeley Laboratory, September 18-20, p. 235.
4. Elsworth, D., and Goodman, R. E., (1985), Hydromechanical Modeling of Fractured Rock Masses Using Coupled Numerical Schemes, International Symposium on Coupled Processes Affecting the Performance of a Nuclear Waste Repository, Lawrence Berkeley Laboratory, September 18-20, p. 235.
5. Henze, F. E., Shaffer, R. J., and Ingraffea, A. R. (1985), A coupled model for fluid-driven fractures, International Symposium on Coupled Processes Affecting the Performance of a Nuclear Waste Repository, Lawrence Berkeley Laboratory, September 18-20, p. 235.
6. Schmidt, B., Daly, W. F., Bradley, S. W., Squire, P. R., and Hulstrom, L. C., (1980), Thermal and mechanical properties of Hanford basalts: Compilation and analyses, RHO-BWI-C-90,

Rockwell Hanford Operations, Richland, WA 99352.

7. Tammemagi, H. Y. and Chieslar, H. Y., (1985), Interim Rock Mass Properties and Conditions for Analysis of a Repository in Crystalline Rock, BMI/OCRD-18, Battelle Memorial Institute, Columbus, OH, 84 p.

8. Cramer, M. L., Cunningham, J. P., and Kim, K. (1983), Rock Mass Deformation Properties from a large-scale block test, Bull. Assoc. Eng. Geol. V. 21, No. 1, pp. 47-54.

9. Nataraj, M. (1983), Coupled Thermal Effects: Thermal-Hydrological-Mechanical-Chemical Interaction, NRC Briefing, August 25.

10. Noorishad, J., Witherspoon, P. A., and Brekke, T. L., (1971), A Method for Coupled Stress and Flow Analysis of Fractured Rock Masses, Publ. No. 71-6, Univ. of California, Berkeley, March.

11. Reda, D. C. (1985), Slip-flow experiments in welded tuff; the Knudsen diffusion problem, International Symposium on Coupled Processes Affecting the Performance of a Nuclear Waste Repository, Lawrence Berkeley Laboratory, September 18-20, p. 235.

12. Cook, N. G. W. (1985), Coupled Processes in Geomechanics, International Symposium on Coupled Processes Affecting the Performance of a Nuclear Waste Repository, Lawrence Berkeley Laboratory, September 18-20, p. 235.

13. Gangi, A. F. (1978), Variation of whole and fractured rock permeability with confining pressure, Int'l Jour. of Rock Mech. Min. Sci. 15, pp. 249-257.

14. Iwai, K. (1976), Fundamental studies of fluid flow through a single fracture, Ph.D. Thesis, Univ. of Cal., Berkeley.

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Dr. V. Rajaram

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Via telephone to V. Rajaram from Tanions

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