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EARTH SCIENCES DIVISION, COLLECTED ABSTRACTS—1978

D. K. Taasevigen
A. L. Henry
S. K. Madsen

March 30, 1979

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CONTENTS

Introduction	1
Professional Roster	1
Abstracts	2
Topical Index	56

EARTH SCIENCES DIVISION COLLECTED ABSTRACTS—1978

INTRODUCTION

This report is a compilation of abstracts of papers, internal reports, and talks presented during 1978 at national and international meetings by members of the Earth Sciences Division of the Lawrence Livermore Laboratory. The arrangement is alphabetical (by author). For any given report, a bibliographic reference appears under the name of

each coauthor, but the abstract itself is given only under the name of the first author (indicated in capital letters) or the first Earth Sciences Division author.

A topical index at the end provides useful cross references, while indicating major areas of research interest in the Earth Sciences Division.

PROFESSIONAL ROSTER

Division Leadership

R. N. Schack
L. L. Schwartz

Project Leadership:

Reservoir Stimulation
Oil Shale
Radionuclide Migration/
Waste Isolation
Seismic Monitoring
Nuclear Test
Special Assignment

M. E. Hanson
A. E. Lewis

L. D. Ramspott
P. H. Moulthrop
J. Toman
H. C. Rodean

Geology

D. O. Emerson

W. Beiriger
C. Bell
R. Carlson
D. Carpenter
M. Chan
J. Cohen
D. Cornett
N. Crow
H. Ganow
D. Helm
N. Howard

D. Isherwood
K. Knauss
D. Leach
G. Ledbetter
H. McKague
W. Mead
D. Miller
J. Morse
T. Naymik
L. Owen
K. Puchlik

B. Qualheim
E. Raber
T. Steinborn
R. Stone
H. Tewes
J. Tewhey
K. Tonnessen
D. Towse
J. Wagoner
D. Wilder
T. Wolery

Oil Shale

A. J. Rothman

F. Ackerman
R. Braun
J. Carley
B. Laswell
R. Mallon
J. Raley
W. Sandholtz
N. Sherman
C. Sisemore
L. Tripp

Geophysics

A. G. Duba

A. Abey
J. Akella
G. Anderson
B. Bonner
C. Boro
N. Burkhard
N. Burr
D. Chung
M. Costantino
L. Dengler
M. Denny
W. Durham
F. Followill
W. Hannon
J. Hanson
H. Heard
J. Hearst
P. Kasamoyer
A. Kusubov

D. Larson
E. Lilley
W. Lin
J. Mills
K. Nakanishi
H. Patton
A. Piwinski
N. Pruvost
P. Rodgers
R. Rohrer
E. Schaffer
J. Scheimer
M. Sharp
H. Smith
D. Springer
D. Trimmer
H. Washington
H. Weed

Computations

P. S. Brown

J. Bryan
D. Burton
T. Butkovich
L. Dreiling
H. Glenn
M. Heusinkveld
A. Jorgensen
R. Knox
M. Lohmann
D. Maiden
D. Montan
L. Moreno
J. Nash

A. Oliver
C. Olsen
M. Pickens
J. Rambo
R. Schaffer
J. Schutz
R. Swift
R. Terhune
L. Thigpen
L. Thorson
O. Walton
V. Wheeler
E. Woodward

ABSTRACTS

Ackerman, F. J., W. A. SANDHOLTZ, A. J. Rothman, W. C. Miller, E. Cope, and J. Ronchetto, *The Lawrence Livermore Laboratory Oil Shale Retorts*, Lawrence Livermore Laboratory, Rept. UCRL-52551 (1978).

Two retorts and their supporting systems have been developed at LLL to simulate some aspects of modified *in situ* retorting of oil shale. This report first describes the retorts, their gas flow and product collection systems, and their instrumentation and process control. Thereafter, it deals with the preparation and characterization of raw shale rubble for retort experiments. The report continues with a discussion of the single dedicated minicomputer that serves both retorts. The retort computer system is multifunctional, providing data acquisition and storage, process monitoring and control, and data reduction and display. Finally, limited ex-

perimental results are presented that demonstrate some capabilities of the retort systems and the retort computer system.

ACKERMAN, F. J. and N. Sherman, *MOVIES: A Computer Code to Generate Contour Plots of Retort Temperature Data*, Lawrence Livermore Laboratory, Rept. UCID-17849 (1978).

Oil shale retorting experiments at LLL are being performed in two retorts: a small 125-kg (1 ft X 5 ft) retort and a large 6-tonne (3 ft X 20 ft) retort. Temperature data from the retorting experiments is studied in several ways. Detailed measurements of temperature propagation through both retort beds are made by an array of 13 thermocouples on each of two horizontal planes across the bed. The

MOVIES code permits visual examination of this data in a time sequence. The code produces a series of three-dimensional contour plots of the temperature data with one or more frames for each time the array data is recorded. Options in the code allow us to rotate the image at any time step in order to gain a clearer view of the temperature surface. This document describes some of the features of the code and provides directions for its use.

Ackerman, F. J., J. H. RALEY, and W. A. Sandholtz, "Results from Simulated, Modified *In-Situ* Retorting in Pilot Retorts," 11th Oil Shale Symp., Golden, Colorado, April 12-14, 1978.

Ackerman, F. J., W. A. SANDHOLTZ, and J. H. Raley, "Simulated Modified *In-Situ* Oil Shale Retorting, Pilot Experiments and Results," to be presented at the American Institute of Chemical Engineers Meeting, April 1-5, 1979, Houston, Texas.

ADAMSON, M. A., *Environmental Impact Assessment: Enhanced Oil Recovery by Combination Thermal Drive, Paris Valley, California*, Lawrence Livermore Laboratory, Rept. UCID-17863 (1978).

The U.S. Department of Energy has contracted with Husky Oil Co. to share the cost of a field experiment of the *in situ* combustion oil recovery process. This contract is one of 21 awarded to oil producers by DOE to demonstrate various techniques of enhanced oil recovery (EOR). The goal of the EOR program is to develop a process or processes that may be employed in various environments with predictable results, a requisite condition for wide-scale industrial use.

The purpose of this assessment is to describe activities proposed by Husky Oil and to evaluate any resulting environmental disruption. The experiment will take place in the Paris Valley oil field, upper Salinas Valley, California, an area that is mainly agricultural. The nearest industrial developments are at the San Ardo oil field, 10 miles south, and at King City, 10 miles north. Key issues involve air pollution, for which some mitigating measures have been taken, and surface waste-water disposal.

ADAMSON, M. A., *Environmental Impact Assessment: Enhanced Oil Recovery by Steam Injection, Cat Canyon, California*, Lawrence Livermore Laboratory, Rept. UCID-17885 (1978).

The U.S. Department of Energy has contracted with Getty Oil Co. to share the cost of a field experiment of the steam injection oil recovery process. This contract is one of 21 awarded to oil producers by DOE to demonstrate various techniques of enhanced oil recovery (EOR). The goal of the EOR program is to develop a process or processes that can be employed in various environments with predictable results, a requisite condition for wide-scale industrial use.

The purpose of this assessment is to describe activities proposed by Getty Oil and to evaluate any resulting environmental disruption. The experiment will take place in the Cat Canyon oil field, upper Santa Maria Valley, California, an area that is mainly agricultural. The nearest industrial development is at the city of Santa Maria, about ten miles north. Key issues involve air pollution, for which mitigating measures have been taken, and erosion.

ADAMSON, M. A. *Environmental Report: Enhanced-Gas-Recovery Project, Gallia County, Ohio*, Lawrence Livermore Laboratory, Rept. UCID-17945 (1978).

The U.S. Department of Energy has contracted with Mitchell Energy Corporation to share the cost of an experiment to develop and demonstrate an unconventional exploration technique designed to locate and stimulate natural-fracture reservoirs in the gas-bearing Ohio Devonian shale. The purpose of this assessment is to describe activities proposed by Mitchell Energy Corporation and to evaluate any resulting environmental disruption. The experiment will take place in central Gallia County, Ohio, a rural area devoted to forestry, agriculture, and extractive activities (such as strip mining and gas production). Key issues are the impact of the removal of local stream water for well drilling and stimulation, and potential erosion hazards due to slope and soil characteristics here. However, if appropriate mitigation measures are taken, these potential problems will be insignificant.

AKELLA, J. "Reexamination of the Quartz=Coesite Transition at 1273 and 1073 K," *Trans. Am. Geophys. Union* 59, 402 (1978).

The quartz=coesite transition was investigated at 1273 and 1073 K in a piston-cylinder solid-media apparatus. Experiments were conducted using a standard talc-ulsimag-glass (TAG) and a low-friction salt cell, and the data are compared. With the TAG cell at 1273 and 1073 K, the quartz=coesite transition curve is located at 3.28 ± 0.02 and 3.03 ± 0.02 GPa, respectively. However, with the salt cell, the transition pressures are lower. At 1273 K the measured transition curve is located at 3.10 ± 0.02 GPa, and at 1073 K it is at 2.92 ± 0.02 GPa. The equation for the quartz=coesite transition curve calculated from salt cell data is $P = 21.2 + 0.010 T$, where P is in kilobars and T is in degrees centigrade. The equation obtained for this curve using a salt cell is remarkably close to that reported by Kitahara and Kennedy [*J. Geophys. Res.* 69, 5395 (1964)].

AKELLA, J. "Partitioning of Cr, Ti, and Al Between Olivine, Spinel, and Liquid Under Controlled f_{O_2} Conditions," Eleventh Gen. Mtg. Int. Mineralogical Assoc., Novosibirsk, U.S.S.R., Sept. 1978. (Lawrence Livermore Laboratory, Rept. UCRL-80888, Preprint, 1978.)

The distribution of chromium amongst coexisting olivines, spinels, and silicate liquids has been investigated as a function of oxygen fugacity, temperature, and cooling rate between 1300° (and 1175°C and redox states near the Fe-FeO buffer. The bulk composition in this study was a pyroxene, $En_{68.5}Fs_{16.5}Wo_{15}$, to which 10 mole % $CaTiAl_2O_6$ and 2 mole % $CuCrAlSiO_6$ had been added.

The measured D_{Cr} (weight ratio of Cr_2O_3 in olivine to that in the liquid) values tend to increase with decreasing f_{O_2} and decrease with decreasing temperature. However, the data possess no statistically significant structure in terms of these variables. The value of 0.85 ± 0.15 for D_{Cr} reported by other workers is consistent with our data.

The failure of D_{Cr} to strongly correlate with a varying redox state leads us also to conclude that the valence state of Cr is not a primary factor

responsible for high Cr_2O_3 contents in lunar rocks and minerals, and that these high Cr_2O_3 contents are a reflection of originally high Cr_2O_3 concentrations in the source region of these materials.

The relative insensitivity of D_{Cr} to f_{O_2} results from the fact that under reducing conditions, Cr^{2+} is the dominant chromium species in the silicate liquid; consequently, large changes in f_{O_2} are needed to significantly affect the concentration of Cr^{2+} in the system.

Controlled cooling rate experiments suggest the Cr_2O_3 does not reequilibrate during cooling, at least between olivines and liquids. Consequently, D_{Cr} and measured Cr_2O_3 contents of olivines can be used to compute the Cr_2O_3 content of the liquid from which the olivines formed. From the present study, it is surmised that pressure may not significantly alter the trends of distribution of Cr_2O_3 between the coexisting phases. High chrome diopsides and garnets, found in the ultramafic nodules from some kimberlites, could have equilibrated in a source region which is locally rich in Cr_2O_3 in the upper mantle.

AKELLA, J., *Reinvestigation of Quartz=Coesite Transition in Piston Cylinder Apparatus Using Talc-Alsimag-Glass (TAG) and NaCl High-Pressure Cells*, Lawrence Livermore Laboratory, Rept. UCRL-81511, Preprint (1978).

The values of friction in solid-media, high-pressure, piston-cylinder apparatus were determined by reversing the quartz=coesite transition at 1273 and 1073 K in compression and decompression experiments. Talc-alsimag-glass and low friction salt cells were used for this study, and the friction values thus arrived at are compared.

With the salt cell, the double value of friction measured was 0.03 and 0.12 GPa at 1273 and 1073 K. The friction values at 1273 and 1073 K with the talc-alsimag-glass cell are 0.25 GPa and 0.29 GPa, respectively. The relatively high friction value obtained with the salt cell at 1073 K is in conflict with the observation of Mirwald *et al.* It is possible that salt may not really be a weak pressure medium at low temperatures.

ANDERSON, G. D. and D. B. Larson, "Laboratory Experiments on Hydraulic Fracture Growth near an Interface," *Proc. Nineteenth U.S.*

Sympos. Rock Mechanics, Y. S. Kim, Ed., Mackay School of Mines, University of Nevada, Reno, 1978, p. 333. (Lawrence Livermore Laboratory, Rept. UCRL-80355, Preprint, 1978.)

Experiments were performed to study the growth of hydraulically driven cracks in the vicinity of an interface between two materials. The materials used in the study were Nugget sandstone from Utah (3-6% porosity), Indiana limestone (12-15% porosity), and polymethylmethacrylate (PMMA). The fracturing fluid was oil that was injected into the test specimen through high pressure tubing which was epoxied into the specimen.

The experiments indicate that the relative values of mechanical properties (i.e., tensile strength) on either side of the interface play a role in determining whether or not a hydraulically driven crack will cross that interface. An important role is also played by the nature of the interface itself. It appears that the strength of a bonded surface compared to that of the material on the opposite side of the interface from the crack is an important parameter in bonded materials and suggests that the coefficients of friction of the surfaces are important in crack penetration in the case of unbonded surfaces.

Anderson, G. D., M. E. HANSON, R. J. Shaffer, D. N. Montan, W. Lin, B. Haimson, and M. P. Cleary, *LLL Gas Stimulation Program, Quarterly Progress Report, October through December 1977*, Lawrence Livermore Laboratory, Rept. UCRL-50036-77-4 (1978).

Anderson, G. D., M. E. HANSON, R. J. Shaffer, J. R. Hearst, B. Haimson, and M. P. Cleary, *LLL Gas Stimulation Program, Quarterly Progress Report, April through June 1978*, Lawrence Livermore Laboratory, Rept. UCRL-50036-78-2 (1978).

Anderson, G. D., M. E. HANSON, R. J. Shaffer, D. O. Emerson, R. P. Swift, K. O'Bunion, M. P. Cleary, B. Haimson, C. F. Knautson, and C. R. Boardman, *LLL Gas Stimulation Program, Quar-*

terly Progress Report, July through October 1978, Lawrence Livermore Laboratory, Rept. UCRL-50036-78-3 (1978).

Anderson, G. D. and D. B. LARSON, *Plane Shock-Wave Studies of Porous Geologic Media*, Lawrence Livermore Laboratory, Rept. UCRL-80898, Preprint (1978).

ANDERSON, G. D. and D. B. Larson, "Shock Wave Compression of Limestone and Tuff," *Trans. Am. Geophys. Union* **59**, 374 (1978).

Plane shock wave experiments were performed on dry Indiana limestone ($\rho_0 = 2.28 \text{ Mg/m}^3$, 16% porosity) and on dry ($\rho_0 = 1.46 \text{ Mg/m}^3$, 40% porosity) and water-saturated ($\rho_0 = 1.84 \text{ Mg/m}^3$) Mt. Helen Nevada tuff. The shock waves were produced by impact from a projectile accelerated by a 4-in.-diam gas gun. The experiments were designed so that shock loading and subsequent unloading by rarefaction waves occurred under conditions of uniaxial strain. The rock specimens were instrumented with electromagnetic Lagrangian particle-velocity gages. Data analysis yielded stress-density Hugoniot states behind the incident shock and unloading paths through the rarefaction. Multiple wave structure and dispersion were observed in both dry materials. The dispersive precursors observed have fronts that travel at longitudinal sound speed and are believed to be associated with the onset of matrix failure. The dispersive second wave is associated with pore collapse. Both materials show hysteresis, with the limestone undergoing 50% pore collapse at 4 GPa and the tuff undergoing complete compaction at 3 GPa. An enhancement in compaction under shock compression over that achieved under hydrostatic compression is observed in dry Mt. Helen tuff but not in the dry limestone. Why this phenomenon is not observed in both is not presently clear, but it may be due to different pore structures in the two materials or polymorphism in the limestone. The shock loading data for water-saturated Mt. Helen tuff show no evidence of phase changes observed hydrostatically. It is suggested that a metastable phase may be formed under these dynamic conditions.

Anderson, G. D., M. E. HANSON, and R. J. Shaffer, "Theoretical and Experimental Research on Hydraulic Fracturing," *ASME Energy Tech. Conf.*, 78-Pet-49 (1978). (Lawrence Livermore Laboratory, Rept. UCRL-80558, Preprint, 1978.)

Anderson, G. D., M. E. HANSON, R. J. Shaffer, D. O. Emerson, H. C. Heard, and B. D. Haimson, "Theoretical and Experimental Research on Hydraulic Fracturing," *Proc. Second Eastern Gas Shales Sympos.* (METC-SP-78/6), Vol. II, p. 124 (1978). (Lawrence Livermore Laboratory, Rept. UCRL-80969, Preprint, 1978.)

AUSTIN, M. G. and J. F. Schatz, "Seismic Wave Propagation Modeled on a Digital Computer: Effect of Variation in Rock Properties," 1978 Spring Meeting, Am. Geophys. Union, Miami, Florida, March 1978.

Results from computer simulation of seismic waves generated by an underground nuclear explosive source give synthetic body wave seismograms over a time of one to two seconds. Careful choice of the zone sizes, code noise cutoff criteria, and artificial viscosity formulation for the one-dimensional finite-difference wave-propagation computer code reduces numerical noise and non-physical wave reflections to a level where they have minimum effect on the calculated seismic signals. Calculations varying the porosity, strength, and water content of the rock surrounding the explosion show the effect that changes in these properties have on the spectra of the calculated seismic signals.

Beiriger, W. J., L. L. SCHWARTZ, D. O. Emerson, and J. D. Tewhey, "The Importance of Geosciences in Developing *In Situ* Technologies for Energy Resource Recovery," poster session presented at the Annual Meeting of the American Association for the Advancement of Science, February 12-17, 1978, Washington D.C.

Beiriger, W. J., J. E. HARRAR, J. W. Fischer, W. J. Steele, S. A. Digiallonardo, and D. D. McCoy, *Incipient Processes in the Corrosion of Mild Steel in 90°C Hypersaline Geothermal Brine*, Lawrence Livermore Laboratory, Rept. UCRL-81606, Preprint (1978).

Mild steel (AISI 1009 and 1018) specimens were exposed for ~20 h to Salton Sea, hypersaline, geothermal brine at ~90°C. The incipient growth of the precipitated scale and iron-corrosion products was analyzed by scanning and transmission electron microscopy, x-ray fluorescence, x-ray diffraction, electron diffraction, and electron microprobe techniques. In brine at its natural pH of 5.7, several distinct phases appear on the steel surfaces, the most important being iron-rich amorphous silica. The silica deposit grows in irregular patches, and corrosion of the substrate occurs between the patches. Subsequent acidification of the brine for short periods does not disturb the protective layers of silica, but it greatly increases the rate of corrosion of surface areas not covered by silica. Oxidation of mild steel in acidified brine is quite different. Rather than iron compounds, deposits of both metallic lead and $PbCO_3$, the latter in unusual crystalline needles, and an unidentified copper compound dominate the surface coverage at low pH. Lead and copper species may be involved in a direct reaction with the iron or may contribute to galvanic corrosion by forming cathodic sites on the steel surface.

Bonner, B. P. and C. GOETZE "Attenuation Measurements for Polycrystalline Salt Mixtures at High Temperature," *Trans. Am. Geophys. Union* 59, 376 (1978).

Young's modulus and attenuation have been studied during subsolidus grain boundary relaxation in hot-pressed samples of NaCl, KCl, and two-component mixtures of NaCl, KCl, and NaF to better understand upper mantle attenuation. Well-formed attenuation peaks ($Q = 20$ to 12) were observed in all cases. For single-component aggregates of NaCl and KCl, with densities within 0.3% of theoretical, peak attenuation occurred approximately at 630°C (0.75 and 0.81 T_m) for frequencies of 10^4 to 10^5 Hz. In NaCl-NaF and NaCl-KCl, a somewhat broader attenuation peak occurred at lower temperature. Activation energies for grain boundary relaxation in both NaCl and KCl fell near 45-50 kcal/mole, approximating those for bulk diffusion. Attenuation was found to be independent of strain over the range 10^{-9} to 10^{-6} . Observations agree with the dispersion relation between modulus and attenuation predicted by the Boltzmann superposition principle.

Bonner, B. P. and A. J. PIWINSKII "The Effect of Diagenetic and Hydrothermal Alteration on Sound Propagation in Sedimentary Rocks from the Dunes Borehole, Imperial Valley, California," *Trans. Am. Geophys. Union* 59, 1201 (1978).

Bonner, B., A. Duba, H. C. HEARD, D. Trimmer, and W. Lin, "Permeability of Generic Repository Rocks at Simulated *In Situ* Conditions," Symp. Underground Disposal Radioactive Wastes, International Atomic Energy Agency, Otaniemi, Finland, July 1979.

Braun, R. L. and J. F. CARLEY, *Further Studies of Ignition of In-Situ Oil-Shale Retorts with Hot Inert Gas*, Lawrence Livermore Laboratory, Rept. UCRL-82086, Preprint (1978).

Braun, R. L. and J. F. CARLEY, "Ignition of *In-Situ* Oil-Shale Retorts with Hot Inert Gas," presented at the 1978 Spring Meeting of the Combustion Institute, April 17-18, 1978, University of Colorado, Boulder, Colorado.

BRAUN, R. L., *LLL Retort Model (Modified In Situ Retorts)*, Lawrence Livermore Laboratory, Rept. UCRL-81914, Preprint (1978).

The objective of the LLL retort model is the computer simulation of the important chemical and physical processes involved in the retorting of a rubblized bed of oil shale. The model will be described, and the results of model calculations will be compared with experimental retort data. Model calculations for typical *in situ* retorting conditions will illustrate the effects of variations in input-gas properties, bed porosity, grade, and carbonate content.

Braun, R. L. and R. C. Y. CHIN, *Numerical Solutions of Chemically Reacting Flows in Porous Media*, Lawrence Livermore Laboratory Rept. UCRL-81003, Preprint (1978).

We discuss the computational aspects of a porous flow past a reacting solid undergoing pyrolysis. We present governing equations and

develop an accurate numerical method for their solution. The algorithm accurately calculates the rapidly varying component and uses a fixed step size commensurate with the smoothly varying component of the solution. The resulting nonlinear equation is solved with Newton's method; the linear system is solved using a discrete analog of the invariant-imbedding method for second-order, linear, two-point boundary-value problems. We also develop a criterion for truncating the computational domain to minimize the calculational effort, and we present some typical calculations showing that the scheme is accurate and efficient.

Braun, R. L. and R. G. MALLON, "Oil Degradation and Gas Evolution During the Retorting of Large Blocks of Oil Shale," 11th Oil Shale Symposium, Colorado School of Mines, Golden, Colorado, April 12-14, 1978.

BRAUN, R. L., *Results of the Computer Simulation of In Situ Oil Shale Retorting*, Lawrence Livermore Laboratory, Rept. UCRL-81619, Preprint (1978).

A mathematical model has been developed for simulating the processes involved in the *in situ* retorting of rubblized beds of oil shale. The model is a transient, one-dimensional treatment of a packed bed reactor. It is based on the thermodynamics and kinetics of the numerous chemical reactions and physical processes that are most important for both hot-inert-gas retorting and combustion retorting.

The predicted retorting results for conditions of interest to commercial *in situ* retorting are discussed in detail. The initial shale properties, such as grade, carbonate content, particle size distribution and packing fraction, are shown to have an important bearing on the maximum retort temperature, the rate of retorting and the oil yield. The input-gas properties, such as composition, flow rate, and temperature, are likewise shown to strongly influence the retorting results. The latter properties, particularly the input-gas composition, can readily be changed during the course of the retorting operations and thereby offer a sensitive means of retort control.

Braun, R. L. and A. E. LEWIS, "Retorting and Combustion Processes in Surface Retorts," 12th

Oil Shale Symposium, Golden, Colorado, April 18-20, 1978. (Lawrence Livermore Laboratory, Rept. UCRL-82085, Preprint, 1978.)

Braun, R. L. and H. Y. SOHN, *Simultaneous Fluid-Solid Reactions in Porous Solids: Part I. Reactions between One Solid and Two Fluid Reactants*. (Lawrence Livermore Laboratory, Rept. UCRL-81066, Preprint, 1978.)

A general model describing simultaneous independent reactions between one solid reactant and two fluid reactants is presented. Such reaction systems are attracting much attention in the areas of oil shale retorting, direct reduction of metal oxides with reformed natural gas, coal gasification, etc.

The model has been formulated in general terms so as to allow the incorporation of specific details of an actual system. The law of additive reaction times previously proposed for single fluid-solid reactions has been applied to the reaction system under consideration, and it has yielded useful approximate solutions for various aspects of the simultaneous reactions, which otherwise must be obtained by numerical methods. Furthermore, the approximate solution provides simple descriptions and criteria for various asymptotic regimes in terms of chemical kinetics and diffusion.

BROWN, P. S. and M. L. Lohmann, *Computational Studies of a Voitenko Compressor*, Lawrence Livermore Laboratory, Rept. UCRL-82010, Preprint (1978). (Submitted to Nuclear Blast and Shock Simulation Symposium, San Diego, California, November 28-30, 1978.)

Two successful shock tube experiments were recently performed at the Lawrence Livermore Laboratory. The experiments simulated the high-enthalpy flow conditions that might arise in the nuclear blast encounter of a tunnel-based missile. The experiments, using a modified Voitenko high-explosive generator, produced megabar pressure conditions at the inlet of the 2 cm-diameter air-filled shock tubes.

Computer calculations have been done to model the 10^5 -fold-increase in air pressure in the Voitenko generator. These calculations are

necessary to describe the source for the experiments and to permit better interpretation of the experimental data. A detailed understanding of the phenomenology of the compressor is also essential for optimization of future experiments, especially those involving scaling up to larger size shock tubes.

An arbitrary Lagrange-Eulerian computer code was selected to calculate the late-time high-explosive-driven motion of a steel plate into the bell-shaped compressor section. We found that ordinary Lagrangian and Eulerian codes had difficulty in properly treating the steel-air interfaces, whereas an arbitrary Lagrange-Eulerian code was capable of modeling the complex flow of air past the steel interfaces in the compressor region. Using an improved equation of state for air, excellent agreement has been obtained in the source timing for the shock tube experiments, and we now have a much more detailed understanding of the Voitenko generator operation.

BRYAN, J. B., D. E. Burton, M. E. Cunningham, and L. A. Lettis, Jr., "A Two Dimensional Computer Simulation of Hypervelocity Impact Cratering: Some Preliminary Results for Meteor Crater, Arizona," *Proc. Lunar Planet. Sci. Conf. 9th* (Pergamon Press, New York, 1976), pp. 3931-3964.

A computational approach used for subsurface explosion cratering has been extended to hypervelocity impact cratering. Meteor (Barringer) Crater, Arizona, was selected for our first computer simulation because it was the most thoroughly studied. It is also an excellent example of a simple, bowl-shaped crater and is one of the youngest terrestrial impact craters. Shoemaker estimates that the impact occurred about 20,000 to 30,000 years ago [Roddy (1977)]. Initial conditions for this calculation included a meteorite impact velocity of 15 km/s, meteorite mass of 1.57×10^8 kg, with a corresponding kinetic energy of 1.88×10^{16} J (4.5 megatons). A two-dimensional Eulerian finite difference code called SOIL was used for this simulation of a cylindrical iron projectile impacting at normal incidence into a limestone target. For this initial calculation a Tillotson equation-of-state description for iron and limestone was used with no shear strength. A color movie based on this calculation was produced using computer-generated graphics.

Results obtained for this preliminary calculation of the formation of Meteor Crater, Arizona, are in good agreement with Meteor Crater measurements.

Bryan, J. B., M. E. HEUSINKVELD, and J. M. Thomsen, *Calculations for Miss Jade Underground Nuclear Test*, Lawrence Livermore Laboratory, Rept. UCRL-52579 (1978).

BRYAN, J. B. and D. E. Burton, "Meteorite Impact Cratering Modeled on a Digital Computer: Some Preliminary Results for Barringer Crater," submitted to 1978 Spring Meeting, Am. Geophys. Union, April 17-21, 1978, Miami Beach, Florida.

Results from a computer simulation of impact cratering appear to be in good agreement with measured crater dimensions of Barringer Crater (Meteor Crater, Arizona). Initial conditions included a meteorite mass and impact velocity of 1.67×10^8 kg and 1.5×10^4 m/s yielding a kinetic energy of 1.88×10^{16} J (4.5 megatons). The meteorite projectile was treated as an iron cylinder having equal length and diameter of 30 m impacting at normal incidence to the limestone target interface. In this preliminary calculation the iron and limestone were described using a Tillotson equation of state with no shear strength. The dynamic phase including impact and shock wave propagation was modeled to a time of 0.500 s using the two-dimensional Eulerian SOIL code by Johnson and is similar to an earlier effort by Bjork. A final crater configuration was calculated using a ballistic trajectory treatment in a constant gravitational field (8.80 m/s^2) with a slope stability adjustment, a technique used successfully in previous subsurface explosion cratering calculations. A color movie based on this calculation has been produced using computer-generated graphics. A similar calculation using lunar gravity (1.62 m/s^2) produced a final crater having radius and volume increased by about 50 and 200 percent, respectively.

BRYAN, J. B., "Meteorite Impact Cratering on a Digital Computer: A Simulation of the Formation of Meteor (Barringer) Crater, Arizona," submitted to Meteoritical Society Sudbury '78 Meeting, Laurentian University, Sudbury, Ontario, Canada (1978).

A computational approach used successfully for subsurface explosion cratering has been extended to hypervelocity impact cratering. In this two-dimensional simulation the Canyon Diablo meteorite was assumed to impact at normal incidence with a velocity of 15 km/s, a mass of 1.67×10^8 kg, and a corresponding kinetic energy of 1.88×10^{16} J (4.5 megatons). The meteorite was treated as an iron cylinder having length and diameter of 30 m. The layered earth materials were approximated as a single limestone material.

The initial or dynamic phase of the calculation extending to a time of 0.5 s was performed using an Eulerian finite-difference computer code called SOIL. During this phase a portion of the vaporized meteorite penetrated to a maximum depth of about 270 m. At a time of 0.1 s about 36 and 58% of the total energy were coupled into the limestone as kinetic and internal energy, respectively. After the velocity field was established in the mound region, the final or ballistic phase of the simulation was performed to compute the trajectories of the ejecta material in a gravitational field. The final crater profile was calculated from this ejecta distribution using a slope stability adjustment. Results for this simulation of impact cratering were in good agreement with actual crater dimensions of Meteor (Barringer) Crater, Arizona. A computer generated color movie based on this calculation has been produced.

Bryan, J. B. and W. R. WOODRUFF, *Single-Charge Craters Excavated during Subsurface High-Explosive Experiments at Big Black Test Site, Mississippi*, Lawrence Livermore Laboratory Rept. UCRL-52591 (1978).

Lawrence Livermore Laboratory performed single-charge and row-charge subsurface cratering experiments to learn how close spacing enhances single-crater dimensions. Our first experimental phase established cratering curves for 60-lb charges of the chemical explosive. For the second phase, to be described in a subsequent report, we designed and executed the row-cratering experiments. This data report contains excavated dimensions and auxiliary data for the single-charge cratering experiments. The dimensions for the row-charge experiments will be in the other report. Significant

changes in the soil's water content appeared to cause a variability in the excavated dimensions. This variability clouded the interpretation and application of the cratering curves obtained.

Bryan, J. B., T. R. BUTKOVICH, and D. E. Burton, *Modeling Permeability Enhancement from Explosive Fracture*, submitted to 1978 Spring Meeting, Am. Geophys. Union, March 1978.

Burton, D. E., J. B. BRYAN, M. E. Cunningham, and L. A. Lettis, Jr., "A Two-Dimensional Computer Simulation of Hypervelocity Impact Cratering: Some Preliminary Results for Meteor Crater, Arizona," *Proc. Lunar Plant. Sci. Conf. 9th* (Pergamon Press, New York, 1978), pp. 3931-3964.

Burton, D. E. and J. B. BRYAN, "Meteorite Impact Cratering Modeled on a Digital Computer: Some Preliminary Results for Barringer Crater," submitted to 1978 Spring Meeting, Am. Geophys. Union, April 17-21, 1978, Miami Beach, Florida.

Burton, D. E., T. R. BUTKOVICH, and J. B. Bryan, *Modeling Permeability Enhancement from Explosive Fracture*, submitted to 1978 Spring Meeting, Am. Geophys. Union, March 1978.

Burton, D. E., R. W. TERHUNE, H. D. Glenn, H. L. McKague, and J. T. Rambo, *Calculational Study of the Baneberry Event*, American Physical Soc. Mtg., June 11-13, 1979.

Burton, D. E., R. W. TERHUNE, H. D. Glenn, H. L. McKague, and J. T. Rambo, *Numerical Simulation of the Baneberry Event*, Lawrence Livermore Laboratory, Rept. UCRL-81807, Preprint (1978).

BUTKOVICH, T. R., D. E. Burton, and J. B. Bryan, *Modeling Permeability Enhancement from Explosive Fracture*, submitted to 1978 Spring Meeting, Am. Geophys. Union, March 1978.

Explosives are normally used to break rock working against a free face to take advantage of the

low tensile strength of rock. We are attempting to develop a new technology of using explosives far from a free face to fracture ore bodies and to introduce and/or enhance permeability for *in situ* recovery processes. Our ultimate objective is to use computer models to predict permeability enhancement for such applications. Because our models calculate fracture and not permeability, we must relate experimental measurements of fracture intensity and permeability enhancement to calculable fracture parameters. Calculations have shown that observed fracture intensity around explosion centers can be correlated to the total failure-induced distortional strain, and this parameter has been adopted as a damage indicator. From measurements around a multiple-charge experiment in a coal seam, the intrinsic permeability determined from results of slug tests in wells near the explosion centers is shown to correlate qualitatively with the calculated residual tensile fracture porosity. Planned modifications to the failure model, which include dilatancy from shear failure, are being made. A computerized color movie of the results of the multiple charge coal calculation with the two-dimensional TENSOR code has been produced.

BUTKOVICH, T. R., "Predicting Underground Explosive Fracture and Permeability Enhancement," in *Energy and Technology Review*, Lawrence Livermore Laboratory, Rept. UCRL-52000-78-4 (April 1978).

We are using our stress-wave propagation codes to calculate explosive fracture and to predict permeability enhancement. These codes were originally designed to calculate how the attenuating high-intensity stress wave propagating from the explosion center displaces and alters the physical and mechanical properties of the surrounding rock. Only recently has there been any incentive to calculate the residual porosity and permeability induced by the explosion.

Since underground coal gasification involves pumping large volumes of gas through the coal, it depends strongly on some means for enhancing the permeability of the coal. We have been investigating the possibility of doing this with explosions. In addition to full-scale experiments in the field, we have

modified our codes and introduced two new code-calculable fracture parameters. One is the shear-failure-associated distortional strain, which correlates well with observations of intensity and extent of fracture in our experiments. The other is the residual tensile-failure-associated void volume, which correlates well with permeability measurements.

CARLEY, J. F. and R. L. Braun, "Ignition of In-Situ Oil-Shale Retorts with Hot Inert Gas," presented at the 1978 Spring Meeting of the Combustion Institute, University of Colorado, Boulder, April 17-18, 1978.

An ideal beginning for controlled-combustion retorting of oil-shale rubble would have these properties: (1) it would quickly establish the retorting and combustion fronts evenly across the bed, (2) it would be simple and safe to execute whatever the size of the retort, (3) it would minimize waste of the resource, (4) it would add little to the cost of oil recovery and (5) it would keep temperatures below the softening range of spent shale, about 1000°C. Preheating of the top layers of the rubble bed with hot inert gas, then switching over to combustion gas, has been investigated by simulation, using the LLL computer model of *in situ* retorting. Factors investigated were: temperature and flow rate of preheating gas, Fischer assay of raw shale, depth from the top surface of the rubble at which switchover is made, switchover temperature at that level, and switchover programming. We found that a depth of penetration of the preheated zone of two to four meters is required to set up an initial spatial separation between the combustion and retorting fronts and thereby to avoid temperatures in excess of 1000°C. The subsequent behavior of the main retorting process quickly settles into a pseudo-steady state no matter what the choice of preheating factors, but those choices do affect strongly the extreme temperatures reached during the first few days after switchover. Plots will show the expected movements of the temperature profile and the profile of residual char down the retort after the start of preheating.

CARLEY, J. F., "Sample Size Required for Analysis of Oil Shale of Widely Varying Grade and Particle Size," presented at the EPA Oil Shale

Sampling Analysis and Quality Assurance Symposium, Denver, March 26-28, 1979. (Lawrence Livermore Laboratory, Rept. UCRL-82078, Preprint, 1978.)

Almost all the interesting properties of oil shale vary with its kerogen content, which usually shows a wide range of variation in any lot of mine-run shale, sometimes even in a single large block. Even when approved procedures of sampling and subdivision are followed, misleading analytical results may be obtained if the sample size is inadequate for the range of properties in the lot and the particle sizes involved.

A statistical rationale is developed in this paper that leads to an equation and graphical procedure for finding the minimum representative size of a sample of oil shale. This is applied to several types of analyses commonly done on oil shale. We then look into the case of a retorting experiment in which the oil yield exceeded the Fischer assay.

CARLEY, J. F. and R. L. Braun, *Further Studies of Ignition of In Situ Oil-Shale Retorts with Hot Inert Gas*, Lawrence Livermore Laboratory Rept. UCRL-82086, Preprint (1978).

Preheating with hot, inert gas appears to be a promising method to prepare for the ignition of a modified-*in situ* oil-shale retort. In an earlier paper [Carley, J. F. and Braun, R. L., "Ignition of *In Situ* Oil-Shale Retorts with Hot Inert Gas," *In Situ* 2 (4), (1978)], the authors explored, by computer simulation, the effects of preheating time, preheating-gas temperature, and depth of penetration of selected gas temperatures on time to changeover from preheating to air/steam retorting, on the peak temperatures reached after changeover and on the "bank" of char generated in the topmost (preheat-) portion of the rubble. The present effort is focusing on important factors held constant (at realistic levels) in the previous study: grade of shale, void fraction of rubble, and particle sizes. Using the results of recent experiments with the spontaneous ignition of preheated oil-shale char, it is now possible to specify more confidently that the changeover temperature should be nearer 400 than 500°C. In addition, because the LLL model of modified-*in situ* retorting is continually being improved, we have

rerun some of the original cases to assess the effects of model changes.

Carlson, R. C., J. R. HEARST, and J. W. Schmoker, *Effects of Terrain on Borehole Gravity Data*, Lawrence Livermore Laboratory, Rept. UCRL-80994, Preprint (1978).

Chan, M. A., J. D. TEWHEY, P. W. Kasameyer, and L. B. Owen, "Development of Injection Criteria for Geothermal Resources," *Geotherm. Resources Council, Trans.* 2, 649 (July 1978) (Lawrence Livermore Laboratory, Rept. UCRL-81007, Preprint, 1978).

CHUNG, D. H., *Parametric Studies of the Earth's Upper Mantle*, Lawrence Livermore Laboratory, Rept. UCRL-81713, Preprint (1978).

Seismic body-wave and surface-wave data indicate the existence of a substantial low-velocity, low-Q zone in the upper mantle beneath western North America. Conditions in this zone are distinctively different from those that are typical of the upper mantle in shield regions. The present study, using Walsh's model for partially melted rock, suggests a common mechanism for low-velocity and low-Q zones. This parametric study also indicates that the pronounced low-velocity, low-Q zone and anomalous travel-time delays of both P and S waves in the Basin and Range Province are consistent with the combined effects of high temperature, chemical composition, phase changes, and partial melting. The observed low P_n velocity in this region is consistent with high temperature, chemical composition, and the presence of a partially molten layer within the upper mantle, but the observed teleseismic delay times result principally from the thickness of the low-velocity zone. The teleseismic delay-time variations are therefore related to the seismic Q distribution in the asthenosphere. Conditions a few kilometers beneath the Moho boundary influence the P_n velocity; however, the observed correlation among the teleseismic signal amplitudes, travel-time delays, and the upper mantle Q indicates that the P_n velocity is a better indicator of upper mantle Q than suggested by the P_n path alone. This knowledge of the upper mantle seems to account for the

anomalous effects of the Basin and Range Province on observations of teleseismic events. This will provide a practical technique for comparing seismic observations made in unstable tectonic regions with observations made in shield areas. Alternatively, a correction for the higher attenuation in the upper mantle beneath the Basin and Range province can be made to estimate the difference that would result in teleseismic signals if a seismic source were in a shield area rather than an unstable tectonic range.

CHUNG, D. H., M. E. Hummel, and H. C. Ro-dean, "Attenuation in the Upper Mantle of the Basin and Range Province," *Trans. Am. Geophys. Union* 59, 319 (1978).

The apparent attenuation (Q^{-1}) of the low velocity zone in the Basin and Range upper mantle has been seismologically determined to be in the neighborhood of 0.04 to 0.06. The attenuation $1/Q_B$ of a model Basin and Range upper mantle consisting of a peridotitic rock composition has been simulated with the application of Walsh's partial melting theory. The inputs to this study are rock equations of state for high pressure and high temperature, geophysical data for stable and unstable regions of the earth, and theoretical and experimental relations for seismic attenuation. A frequency-dependent attenuation $1/Q_B$ of a model Basin and Range upper mantle was studied. It was found that values of $1/Q_B$ at 1 Hz, for example, are about 0.03 to 0.05 with the melt concentration of about 5 to 15%. The result seems to be in concert with the recent seismological data, and further this result enables us to estimate the melt concentration and "effective viscosity" of the low velocity zone. The Walsh theory as used here is seen to be rather sensitive to the melt geometry present in the rock composition. To illustrate this sensitivity, we have performed a computer experiment varying the shape and size (thus aspect ratio) of the melt concentration. We assumed aspect ratios of 0.05, 0.005 and 0.0005.

COHEN, J., *Determination of Acceptable Risk Criteria for Nuclear Waste Management*, Lawrence Livermore Laboratory, Rept. UCRL-52404 (1978).

The Laboratory and its subcontractors have provided technical support to the U.S. Nuclear Regulatory Commission in its Waste Management Program. Part of this support has been to develop acceptable risk criteria (ARC) for waste management operations. The initial phase of the work performed during FY 1977 consisted of performing a "scoping" study to define issues, determine an optimal methodology for their resolution, and compile a data base for ARC development. The issues, spanning technical, psychological, and ethical dimensions, were categorized in seven major areas: (1) unplanned or accidental events, (2) present vs future risks, (3) institutional controls and retrievability, (4) dose-response mechanism and uncertainty, (5) spatial distribution of exposed populations, (6) different types of nuclear wastes, and (7) public perception. The optimum methodology for developing ARC was determined to be multi-attribute decision analysis encompassing numerous specific techniques for choosing, from among several alternatives, the optimal course of action when the alternatives are constrained to meet specified attributes. The data base developed during the study comprises existing regulations and guidelines, maximum permissible dose, natural geologic hazards, non-radioactive hazardous waste practices, bioethical perspectives, and data from an opinion survey.

COHEN, J. J., *Review of Issues Relevant to Acceptable Risk Criteria for Nuclear Waste Management*, Lawrence Livermore Laboratory, Rept. UCRL-80793, Preprint (1978).

Development of acceptable risk criteria for nuclear waste management requires the translation of publicly determined goals and objectives into definitive issues which in turn, require resolution. Since these issues are largely of a subjective nature, they cannot be resolved by technological methods. Development of acceptable risk criteria might best be accomplished by application of a systematic methodology for the optimal implementation of subjective values. Multi-attribute decision analysis is well suited for this purpose.

COHEN, J. J., *An Evaluation of the Effect of Natural Background Radiation on Cancer Incidence*, Lawrence Livermore Laboratory, Rept. UCRL-80678, Preprint (1978).

Previous studies on the relationship between levels of natural background radiation and cancer incidence indicate no significant correlation. This observation is shown to be consistent with certain predicted effect levels of ionizing radiation on malignancy production (BEIR, ICRP). Other theoretical predictions on the effects of ionizing radiation indicate induction rates to be as high as 8×10^{-3} cancers/person-rem. Assuming this factor were correct, then roughly one-half of the cancer incidence in the U.S. could be attributed to exposure to natural background radiation. By statistically testing various hypothetically assigned cancer induction rates against observed data, it is possible to develop a probabilistic perspective on the cause-effect relationship. Tests have been performed using normalized (by age, death rate, etc.) cancer incidence by state against levels of background radiation. This evaluation allows for the determination of the probability of observing the actual data given that the hypotheses were correct. Graphic relationships between hypothetically assigned radiation induced cancer rates vs. the probability of observing the actual incidence are developed and presented. It is shown that if the cancer induction rate were in excess of $\sim 10^{-3}$ cancers/person-rem, it would be highly improbable that there would, in fact, be a lack of correlation between the rates of natural background radiation and cancer incidence.

COHEN, J. J., J. W. Lathrop, S. R. Watson, and V. N. Campbell, *Radiological Performance Objectives Derived from Public Values for Nuclear Waste Management*, Lawrence Livermore Laboratory, Rept. UCRL-52574, NUREG/CR-0540 (1978).

This paper describes the application of decision analysis concepts to the development of criteria for nuclear waste management.

COHEN, J., *Suggested Nuclear Waste Management Radiological Performance Objectives*, Lawrence Livermore Laboratory, Rept. UCID-17880 (1978).

Development of criteria for the safe disposal of nuclear wastes in geologic media requires the establishment of definitive objectives against which the adequacy of various waste management

methods may be judged. This report suggests certain guidelines that might serve as first approximations pending promulgation of official criteria. These include the following:

- The allowable radiation dose to individuals should be related to the predicted probability of receiving the dose such that as the dose increases, the events leading to that dose should become less probable. A quantitative relationship is developed and discussed.

- Selection of a waste management method should be made in accordance with the principles of ALARA.

- Doses to future generations should be considered to be equally as serious as doses to present populations.

- When the hazard potential of an underground nuclear waste repository becomes less than that of typical hazardous ore formations (i.e., 0.2% uranium ore), further concern is unwarranted.

COHEN, J. J. and W. C. King, *Determination of a Radioactive Waste Classification System*, Lawrence Livermore Laboratory, Rept. UCRL-52535 (1978).

Several classification systems for radioactive wastes are reviewed, and a system is developed that provides guidance on disposition of the waste. The system has three classes: high-level waste (HLW), which requires complete isolation from the biosphere for extended time periods; low-level waste (LLW), which requires containment for shorter periods; and innocuous waste (essentially non-radioactive), which may be disposed of by conventional means. The LLW/innocuous waste interface was not defined in this study. Reasonably conservative analytical scenarios were used to calculate that HLW/LLW interface level which would ensure compliance with the radiological exposure guidelines of 0.5 rem/y maximum exposure for a few isolated individuals and 0.005 rem/y for large population groups. The recommended HLW/LLW interface level for ^{239}Pu or mixed transuranic waste is $1.0 \mu\text{Ci}/\text{cm}^3$ of waste.

Levels for other radionuclides are based upon a risk equivalent to this level. A cost-benefit analysis in accordance with as low as reasonably achievable (ALARA) and National Environmental Protection Act (NEPA) guidance indicates that further reduc-

tion of this HLW/LLW interface level would entail marginal costs greater than \$10⁸ per man-rem of dose avoided. The environmental effects considered were limited to those involving human exposure to radioactivity.

COHEN, J. J. and T. L. Steinborn, "The Rock-Melt Approach to Nuclear Waste Disposal in Geological Media," presented at Materials Research Society Meeting, Boston, Massachusetts, December 1978.

The effect of temperature rise due to decay heat has been a source of serious concern in conventionally proposed methods for disposal of nuclear waste in geologic media. Detrimental effects of increased temperatures can be manifested directly by degradation of the waste form itself, or indirectly by alteration of the surrounding geologic and hydrologic environment so as to enhance access of ground water to the waste.

An unconventional method for geologic disposal of nuclear waste has been proposed which could utilize this decay heat for beneficial purposes. This is the rock-melt concept, which calls for the direct addition of high level waste either in solution or slurry form into a deep mined cavity in silicate rock. Following the period of waste addition, the cavity is allowed to boil dry. Subsequently, the decay heat melts the waste and the surrounding rock. The molten rock dissolves the waste and the molten mixture grows, reaching its maximum radius in times typically estimated at tens to hundreds of years. When the rate of conductive heat loss from the system exceeds that of heat input from radioactive decay, the system begins to cool and solidify. Total resolidification could require several centuries. During that period, fission products will have essentially decayed away, leaving the actinide components. The ultimate result would be the encapsulation of this radioactive material in a relatively insoluble rock matrix deep underground. At 1000 years after initial emplacement, the relative toxicity of the resolidified rock mixture would be less than 1% that of natural pitchblende. This is due to the fact that the total heat output of the accumulated nuclear waste can melt large volumes of the surrounding rock.

Cortez, J. L. M., M. E. HEUSINKVELD, and J. M. Thomsen, *Scaling of Shallowly Buried Nuclear Explosions*, Lawrence Livermore Laboratory, Rept. UCRL-52439 (1978).

COSTANTINO, M. S., "Statistical Variation in Stress-Volumetric Strain Behavior of Westerly Granite," *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.* **15**, 105 (1978).

A lower bound was determined for the experimental uncertainty, caused by "natural rock variability," in measurements of stress-volume strain. Ten similar, hydrostatic and triaxial compression experiments were performed on Westerly granite. The uncertainty owing to rock variability was estimated by determining the mean and standard deviations of the volume strains at several stresses. Under hydrostatic compression, mean volume strain is given by $\bar{\epsilon}_H = 202P^{0.618}$, where P is the pressure in MPa. One standard deviation (S) and the standard deviation of the mean (S_m) for $P = 50$ MPa were 21% (7%) and for $P = 100$ MPa were 15% (5%). After rejection of three of the experiments that showed large deviations from the mean, I found $S(S_m)$ to be 9% (3%) and 5% (2%) for the same pressures, respectively. The dilatant volume-strain data (over 1000 $\epsilon_v - \tau$ pairs) for triaxial compression up to 80% of fracture stress could be fitted within $\pm 20\%$ using the relation $\epsilon_v = \epsilon_H - [a_0 + a_1\tau + b_0\exp(b_1\tau)]$, where τ is the shear stress. The fracture curve was reproducible within 2% in τ and 3% in mean stress $\bar{\sigma}$. The hydrostatic bulk modulus was reproducible within about 4%. These results suggest that a lower bound for experimental deviation in measurements of physical properties of rocks is about 20% in absolute volume strain. Therefore, modeling and theoretical efforts aimed at better describing limited data are not justified at this time.

CROW, N. B. and G. Ledbetter, *An Environmental Geology Workshop for the Geysers-Calistoga Known Geothermal Resources Area*, Lawrence Livermore Laboratory, Rept. UCRL-52418 (1978).

At the request of the U.S. Department of Energy, Lawrence Livermore Laboratory (LLL) is

studying ways in which the environmental quality of The Geysers-Calistoga known geothermal resources area may be protected from any significant harmful consequences of future geothermal development. The LLL study includes the effects of development on air and water quality, geology, and ecosystem, socioeconomics, and noise. The Geothermal Resource Impact Projection Study (GRIPS) has grants to undertake similar work. On 28 and 29 November 1977, LLL and GRIPS jointly sponsored a workshop at Sonoma State College at which knowledgeable earth scientists presented their views on the potential geological hazards of geothermal development. The workshop produced recommendations for studies in geological mapping, slope stability, subsidence, seismicity, and groundwater hydrology. These recommendations will be evaluated along with other considerations and in conjunction with other subjects of the LLL study. The results of the study will be contained in a preplanning report of final recommendations to the Department of Energy.

CROW, N. B. and P. W. Kasameyer, "Monitoring Natural Subsidence and Seismicity in the Imperial Valley as a Basis for Evaluating Potential Impacts of Geothermal Production," *Geotherm. Resources Counc. Trans.* **2**, 125 (1978).

Monitoring programs designed to obtain baseline data about natural subsidence and seismicity in the Imperial Valley are described. The data obtained have not yet been studied in detail, but preliminary analysis indicates that substantial levels of natural subsidence and seismicity are occurring in the region of the Imperial Valley. Studies to characterize subsidence and to attempt to relate it to the geologic structure of the region are underway. Work done by the U.S. Geological Survey, based on data from a seismographic network augmented as part of our program, has shown that earthquake swarms are characteristic in the Imperial Valley and that the pattern of recent swarms can be correlated with regional tectonic activity. Use of such patterns will make it easier to distinguish between natural and any induced activity which might result from geothermal power production. This work was carried out as part of the Imperial Valley Environmental Project.

Crow, N. B. and P. W. KASAMEYER, "Baseline Measurements of Geologic Events Can Remove Potential Roadblocks to Geothermal Development," 144th National Meeting of the American Association for the Advancement of Science, Washington, D.C., February 12-17, 1978.

DENGLER, L. A., "Microcracks and Matrix Deformation in Stressed Gas-Bearing Sandstones," in *Scanning Electron Microscopy/1978*, Vol. 1, O. Jouhari (Ed.), (SEM, Inc., Hoffman Estates, Illinois, 1978), pp. 603-609.

The microstructure of laboratory and nuclear explosively deformed low-permeability sandstones is studied by SEM examination of ion-thinned polished thick sections. Samples prepared in this manner can be oriented relative to coordinate axes, enabling semi-quantitative descriptions of pore structure and matrix deformation. The undeformed rock contains an intricate intergranular network of authigenic chlorite and kaolinite causing the average pore size to be 2-3 μm . Chlorite platelets are typically oriented in random directions.

Uniaxial-strain testing causes elongation and bending of chlorite platelets. Preferential orientation of platelets perpendicular to the direction of applied stress is associated with increased strains. Grain fracturing rarely extends further than a grain diameter.

The effect of uniaxial-stress testing depends on the confining pressure of the test. Fracturing occurs primarily at grain boundaries within the immediate fault zone in samples tested at less than 50 MPa confining pressure. Away from the fault, matrix and pore structure are essentially unaltered. At higher confining pressures, grain fracturing is common and occurs further from the fault, although rarely extending beyond a grain diameter. Compaction and preferential alignment of chlorites is common. At 600-MPa confining pressure, the pore size associated with chlorite-filled areas is less than a micron.

Nuclear-explosive-deformed samples contain long macroscopic fractures oriented perpendicular to the shock-front direction. In the vicinity of these fractures, chlorite deformation is similar to that observed in the laboratory-tested samples. Away from these areas, the microstructure is unaltered.

Dengler, L. A., E. S. SPRUNT, and D. Sloan, "Effects of Metamorphism on Quartz Cathodoluminescence," *Geol.* 6, 305 (1978).

A relationship between cathodoluminescence color and metamorphism is shown by two sequences of naturally deformed quartzites. The metamorphic grade of quartzites from the Bergell Alps varies from low greenschist to high amphibolite. The metamorphic grade of quartzites from the Johnson Spring Formation of Inyo County, California is not precisely known, but the state of deformation varies from slight alteration to complete recrystallization. Luminescence of detrital grains in undeformed quartzite is heterogeneous, varying from dull red to blue. Secondary quartz overgrowths and veins luminesce a rusty red color. Greenschist facies samples also luminesce rusty red. Recrystallized and amphibolite facies samples luminesce blue violet. Of the quartzites examined those from granite contacts in the Bergell Alps had the bluest quartz cathodoluminescence. Metamorphism appears to homogenize luminescence, with the color being related to metamorphic grade—low temperature causing red luminescence and high temperature, blue.

DREILING, L. A. and R. A. Bell, *The Chemical Composition and Temperature of Vega*, Lawrence Livermore Laboratory, Rept. UCRL-81952, Preprint (1978).

Several flux-constant, line-blanketed model stellar atmospheres have been computed for the bright star Vega. The stellar effective temperature has been found to be 9650 K by comparisons of observed and computed absolute fluxes at 5556 Å, of relative absolute fluxes between 3300 and 10800 Å, and of Balmer line profiles. The Ti II and Fe II curves of growth give abundances of $\log N(\text{Ti}) = 4.8 \pm 0.3$ and $\log N(\text{Fe}) = 7.2 \pm 0.3$ on the scale $\log N(\text{H}) = 12.0$. These abundances are slightly less than normalized meteoritic values and solar values deduced from ionized lines.

DUBA, A. G., A. J. Piwinski, M. Santor, and H. C. Weed, "The Electrical Conductivity of Sandstone, Limestone, and Granite," *Geophys. J. R. Astr. Soc.* 53, 583 (1978).

The electrical conductivity of cylindrical cores of Westerly granite, Indiana limestone and Nugget, St. Peter, and Kayenta sandstones was measured at about 25°C *in vacuo*, in air, and after saturation in distilled water, tap water, and 0.1 M NaCl solution. The three-electrode technique with a guard ring and the two-electrode technique without a guard ring were used. Core aspect ratio over the range of 2.00 to 0.25, as well as frequency over the range of 50 Hz to 10 kHz, influences the conductivity of all rocks, especially those measured *in vacuo*. Measurements from water-saturated samples using a guard ring are not appreciably different from those obtained without a guard ring. The conductivity of rocks saturated in 0.1 M NaCl solution changes least with a change in aspect ratio; for these rocks a linear relationship, known as Archie's Law, exists between log porosity and log conductivity. No simple correlation was found between those factors in rocks saturated with tap or distilled water. Thus, it appears Archie's Law is of questionable value for correlating laboratory data from rocks saturated with low-conductivity fluids.

DUBA, A. G., D. T. Davis, E. F. Laine, and R. J. Lytle, *Geotomography and Coal Gasification*, Lawrence Livermore Laboratory, Rept. UCRL-81923, Preprint (1978).

Laboratory data indicate that the electrical conductivity of coal increases about eleven orders of magnitude when the coal is heated from 300° to 900°C during gasification. From these observations, a field system using underground radio waves transmitted between boreholes has been tested and proven effective in detecting the burn front during *in situ* gasification of coal in Wyoming.

DUBA, A. G., "Some Problems with the Electrical Conductivity of Basalt," presented at Fourth Workshop Electromagnetic Induction Earth and Moon, Murnau, West Germany, September 1978.

Laboratory measurements of the electrical conductivity of basalt under controlled oxygen fugacity indicate several difficulties which may afflict these measurements and render the data uninterpretable. Samples of the fine-grained Picture Gorge basalt

from the Columbia Plateau were heated up to melting at various rates. Below about 900°C, the conductivity decreased with time; above this temperature and below the solidus, conductivity increased with time. At temperatures slightly above the solidus, conductivity increased even more rapidly with time and approached values obtained upon complete fusion of the basalt. These results indicate that it is not necessary to melt basalt in order to achieve high conductivity. Further, reactions and processes which occur in the solid state will either increase or decrease the conductivity of basalt samples in the laboratory. The direction of conductivity change will depend at least on the previous history of the basalt, the temperature at which the measurements are made, and the oxygen fugacity. These results emphasize the difficulty of designing laboratory measurements which are meaningful in terms of conditions at depth in the earth.

DUBA, A. G. and R. NETHERTON, *An Apparatus for Simultaneously Measuring Electrical Conductivity and Oxygen Fugacity*, Lawrence Livermore Laboratory, Rept. UCRL-52394 (1978).

Electrical conductivity studies of silicates are useful in determining temperature vs depth in the earth. Realistic laboratory measurements of conduction mechanisms require that exact determinations of oxygen fugacity (f_{O_2}) be made in the experimental environment. An apparatus is described that monitors system f_{O_2} with a calcia-doped zirconia-oxygen cell while measuring electrical conductivity of iron-bearing silicates at high temperature (>1000 K). The f_{O_2} calculated thermodynamically from CO/CO_2 mixing ratios agreed well with measurements made with the zirconia cell at 1473 K, except for $f_{O_2} > 10^{-4}$ Pa, where, on a $\log_{10}$ scale, mixing-ratio errors were as large as ± 0.2 . These errors are attributed to oxygen contamination in the CO_2 and to mobile carbon deposits that formed in the apparatus.

DUBA, A. G., T. J. SHANKLAND, and U. NITSAN, *Optical Absorption and Radiative Heat Transport in Olivine at High Temperature*, Los Alamos Scientific Laboratory, Report LA-UR-1042 (1978). (Lawrence Livermore Laboratory, Rept. UCRL-81047, Preprint, 1978.)

The optical absorption spectra of natural single crystal and polycrystalline olivine ($\text{Mg}_{1.8}\text{Fe}_{0.2}\text{SiO}_4$) have been measured in the wavelength range 300 to 8000 nm at temperatures ranging from 300 to 1700 K and under oxygen fugacity well within the sample stability field. The absorption significantly increases with increasing temperature due to a regular broadening of both crystal field and multi-phonon lattice vibrational absorption bands; these are the principal absorption bands in the spectral region involved in radiative heat transfer. In the "window" region between these bands, the absorption coefficient increases from near zero at 300 K to about 10^{-5} cm^{-1} at 1700 K. Under mantle conditions, the radiative thermal conductivity (K_R) calculated from the olivine single crystal spectra increases from near zero at 300 K to about $5 \times 10^{-3} \text{ cal/cm} \cdot \text{sec} \cdot \text{K}$ ($2 \text{ W/in} \cdot \text{K}$) at 1700 K. Any strong temperature dependence of K_R is largely offset by the marked decrease in the photon mean free path with increasing temperature. Our determination of K_R is 10–20% lower than previous estimates based on absorption measurements under different experimental conditions. In polycrystalline (dunite) samples the transmission decreased substantially with temperature cycling due to scattering at intergranular interfaces created by differential thermal expansion.

Duba, A. G., R. J. LYTLE, and J. L. Willows, *Alternative Methods for Determining the Electrical Conductivity of Core Samples*, Lawrence Livermore Laboratory, Rept. UCRL-81695, Preprint (1978).

Electrode configurations are described that can be used in measuring the electrical conductivity of a core sample and that do not require access to the core end faces. The use of these configurations eliminates the need for machining the core ends for placement of end electrodes. This is because the conductivity in the cases described is relatively insensitive to the length of the sample. We validated the measurement technique by comparing mathematical models with actual measurements that were made perpendicular and parallel to the core axis of granite samples.

Duba, A. G., J. S. HUEBNER, and L. B. Wiggins, *Electrical Conductivity of Pyroxene and the Lunar*

Temperature Profile—A Petrologic Approach, Lawrence Livermore Laboratory, Rept. UCRL-81891, Preprint (1978).

Three natural orthopyroxene single crystals, measured in the laboratory over the temperature range 850–1200°C, are more than one-half order of magnitude more electrically conducting than previously measured crystals. Small concentrations (1–2%) of Al_2O_3 and Cr_2O_3 present in these crystals may be responsible for their relatively high conductivity. The new conductivity values for pyroxene are responsible for the relatively large bulk conductivity calculated for (polymineritic) lunar mantle assemblages. The results permit a somewhat cooler lunar temperature profile than previously proposed. Such lower profiles, several hundred degrees Celsius below the solidus, are quite consistent with seismic data for the lunar mantle.

Duba, A. G., J. S. HUEBNER, L. B. Wiggins, and H. E. Smith, "Electrical Conductivity of Orthopyroxene: Measurements and Implications," *Proc. Lunar Planet. Sci. Conf. 9th* (Pergamon Press, New York, 1978).

Two crystals (MF #1 and MF #2) were analyzed by optical and electron microscopy, X-ray diffraction, and electron microprobe techniques. Each is chemically homogeneous, yet the crystals have distinct chemical compositions. Rectangular plates were cut perpendicular ($\pm 3^\circ$) to the principal crystallographic axes and mounted in a high-temperature, volume conductivity cell. Because iron potentially could diffuse from the pyroxene into the platinum electrodes at high temperature, representative conductivity couples were analyzed by microprobe after measurement. As found previously, the pyroxenes did not change composition as long as they did not partially melt. Conductivity measurements reported here pertain to samples that had not been heated to their solidus. Mineralogic studies show conclusively that the orthopyroxene retained its structural state during the measurements. Oxygen fugacity (f_{O_2}) was controlled by a flow of $\text{CO} + \text{CO}_2$ gas past the sample; the f_{O_2} actually specified by each mixture was periodically monitored with an electrochemical cell.

Measurement precision (1 S. D.) and absolute uncertainty in log conductivity (in Siemens) are estimated to be 0.05 and ± 0.10 , respectively, for any given pyroxene plate. Except as noted, the entire measurement process could be repeated, and it yields values that agree to within 0.10.

Measurements of different [010] plates of crystal MF#1 resulted in significantly different conductivity-temperature relationships. We can find no explanation for, or reason to reject, these results. Somewhat surprisingly, there is no strong dependence of conductivity on fO_2 , as was found previously for olivine, at any temperature investigated.

We do not attribute the conduction to the presence of ferric iron. The two pyroxene crystals were investigated over a wide range of fO_2 (from that of iron-wüstite to above the fayalite-magnetite-silica assemblage) and contain appreciable iron (10.6% and 8.5% by weight as FeO), conditions which could produce a significant variation in the atomic fraction of Fe^{3+} . We propose that the greater conductivity of crystal MF#1 relative to MF#3 is associated with the relatively large minor element content of MF#1, 1.9% Al_2O_3 and 0.5% Cr_2O_3 by weight. The presence of the trivalent cations in octahedral sites, which are normally occupied by divalent cations, may facilitate mobilization of valence electrons normally localized about oxygen atoms, leading to increased electrical conductivity. We further suggest that minor elements may similarly affect volume (lattice) diffusion rates in pyroxene, especially where the diffusion mechanism involves the movement of electrons through the lattice. In minerals such as pyroxene, diffusion of cations through the lattice may be more sensitive to changes in minor or trace element chemistry than to fO_2 .

If orthopyroxene is a major constituent of the lunar interior, our results necessitate revision of the selenotherm based on volume conductivity by decreasing the temperatures of the profile. The presence of grain boundary conduction would not greatly change the results. Knowledge of minor element partitioning between silicate melt (magma) and crystals (source region of lunar interior) suggests that pyroxene of the lunar mantle will have appreciable contents of chromium and aluminum, much like crystal MF#1. This pyroxene has a significantly greater conductivity than the silicates upon which previous selenotherms were based. A

lunar thermal profile calculated from the volume conductivity of MF#1 lies well below the peridotite solidus and well below previous selenotherms calculated from measurements on silicates at low fO_2 values. Such temperature profiles do not contradict models of a cooling planet that last erupted partial melts 3 AE ago.

Duba, A. G. and T. J. SHANKLAND, "Electrical Conduction in Upper Mantle Rocks and Minerals," *Trans. Am. Geophys. Union* 59, 269 (1978).

One intention of laboratory electrical conductivity measurements in rocks and minerals is to interpret surface field conductivity data in order to obtain temperature, oxygen partial pressure (PO_2), and amount of partial melting. Present conductivity values for individual mantle minerals such as olivine and pyroxene are reproducible and partly understood in terms of the controlling variables temperature, pressure, PO_2 , Fe content, and Mg/Si stoichiometry. However, field electromagnetic measurements mostly provide conductivities higher than those of olivine or pyroxene at expected upper mantle temperatures. Laboratory measurements of rock conductivities at high temperatures are hard to reproduce because of the difficulty of simultaneously confining rocks to prevent cracking and also maintaining a controlled PO_2 ; rock conductivities tend to be higher than in the minerals olivine and pyroxene at a given temperature. This discrepancy could be due to hydrous phases, high-conductivity grain boundaries, or to defects caused by changes in Mg/Si stoichiometry of olivine and pyroxene in equilibrium together.

Duba, A. G. and H. C. HEARD, *Capabilities for Measuring Physicochemical Properties at High Pressure*, Lawrence Livermore Laboratory, Rept. UCRL-52420 (1978).

Duba, A. G., H. C. HEARD, D. Trimmer, W. Lin, and B. Bonner, "Permeability of Generic Repository Rocks at Simulated *In Situ* Conditions," prepared for Sympos. Underground Disposal Radioactive Wastes, International Atomic Energy Agency, Otaniemi, Finland, July 1979.

DURHAM, W. B., C. Froidevaux, and O. Jaoul, "Creep Behavior of Forsterite at Low Stress," *Trans. Am. Geophys. Union* 59, 375 (1978).

The creep properties of single crystals of synthetic forsterite, Mg_2SiO_4 (For_{100}), were studied in a series of uniaxial compression tests at 1-atm confining pressure of $H_2 + Ar$. Applied stress, $\sigma_1 - \sigma_3$, ranged from 1.5 to 37.8 MPa (1 MPa = 10 bars) and temperature from 1480° to 1750°C. The orientations of applied stress used were (1) midway between [100] and [001], referred to as [101]_c; and (2) equidistant from all three axes, or [111]_c. Steady state creep was achieved for both orientations at $\sigma_1 - \sigma_3 \geq 3$ MPa. When the data are fit to a flow law of the form $\dot{\epsilon} = A(\sigma_1 - \sigma_3)^n e^{-Q/RT}$, the results are

[111]_c orientation (23 runs):

$$n = 2.8, \text{ s.d.} = 0.2$$

$$Q = 6.83 \times 10^5 \text{ J/mol, s.d.} = 0.29 \times 10^5 \text{ J/mol}$$

$$(163 \text{ kcal/mol, s.d.} = 7 \text{ kcal/mol})$$

$$\log A = -5.5 \text{ SI units (s.d.} = 0.6 \text{ SI units)}$$

[101]_c orientation (7 runs):

$$n = 2.6 \text{ (s.d.} = 0.5)$$

$$\log A = -6.3 \text{ SI units (for } n = 2.8, Q = 163 \text{ kcal/mol)}$$

Qualitatively, the relationship between $A[101]_c$ and $A[111]_c$ is similar to that for natural olivine single crystals of composition For_2 . The value of n is approximately 0.5 lower for For_{100} , and the value of Q is roughly 1.5×10^5 J/mol (35 kcal/mol) higher.

Transient behavior could not be detected within measurement uncertainty following a step up in stress from 0 to >10 MPa and following a step down from >10 MPa to 3 MPa. However, there was a pronounced incubation time required following a step up from 0 to ≤ 7.8 MPa; typically the amount of strain imparted in even the highest temperature samples was immeasurable (<0.2%) after one hour.

DURHAM, W. B., "Mechanism of Plastic Flow in Olivine," invited lecture, University of California, Davis, February 1978.

A total of 41 selectively oriented single crystals of olivine (For_{92}) were deformed under uniaxial stress of 100 to 1800 bars in the temperature range 1150° to 1600°C. Under uniform stress no strain inhomogeneities were observed. For all orientations both strain rate and dislocation structure stabilized

after 1–2% strain and remained stable to the highest strains achieved (40%). For all orientations, creep could be represented by a power law of the form $\dot{\epsilon} = A\sigma^{3.6}$, where A varied with orientation by a factor of 50. Shape change and crystallographic rotation data for some orientations could only be accounted for by a substantial dislocation climb contribution to the strain rate. All specimens were decorated to show the dislocation structure.

Durham, W. B., R. P. SWIFT, J. F. Schatz, J. R. Hearst, and A. S. Kusubov, "Effect of Simultaneous and Sequential Detonation on Explosive-Induced Fracture," *Proc. Nineteenth U.S. Sympos. Rock Mech.*, Y. S. Kim, Ed. (Muckay School of Mines, University of Nevada, Reno, 1978), p. 235.

Durham, W. B., R. P. SWIFT, and J. F. Schatz, "Explosive-Induced Fracture Effects from Sequential and Simultaneous Detonations," *Trans. Am. Geophys. Union* 59, 379 (1978).

Emerson, D. O., M. E. HANSON, G. D. Anderson, R. J. Shaffer, R. P. Swift, K. O'Banion, M. P. Cleary, B. Haimson, C. F. Knutson, and C. R. Boardman, *LLL Gas Stimulation Program, Quarterly Progress Report, July through September 1978*, Lawrence Livermore Laboratory, Rept. UCRL-50036-78-3 (1978).

Emerson, D. O., M. E. HANSON, G. D. Anderson, R. J. Shaffer, and H. C. Heard, "Theoretical and Experimental Research on Hydraulic Fracturing," *Proc. 4th Annual DOE Symp. on Enhanced Oil and Gas Recovery and Improved Drilling Methods*, August 29–31, Tulsa, Oklahoma. (Lawrence Livermore Laboratory, Rept. UCRL-80969, Preprint, 1978.)

Emerson, D. O., M. E. HANSON, H. C. Heard, B. C. Haimson, G. D. Anderson, and R. J. Shaffer, "Some Theoretical and Experimental Considerations of the Hydraulic Fracturing Process and Supporting Research," *Proc. Second Eastern Gas Shales Symp.*, METC-SP-78/6, Vol II (1978).

Emerson, J. D., L. L. SCHWARTZ, J. D. Tewhey, and W. J. Beiriger, "The Importance of Geosciences in Developing *In Situ* Technologies for Energy Resource Recovery," poster session presented at the Annual Meeting of the American Association for the Advancement of Science, February 12-17, 1978, Washington, D.C.

GANOW, H. C., R. C. Greenlaw, and R. T. Langland, "Geotechnical Instrumentation Applied to *In Situ* Coal Gasification Induced Subsidence," Lawrence Livermore Laboratory, Livermore, Rept. UCRL-81267, Preprint (1975).

A comprehensive geotechnical instrumentation program has been conducted in conjunction with the second Lawrence Livermore Laboratory (LLL) *in situ* coal gasification experiment. Instrumentation systems selected for use include multiple position borehole extensometers, borehole deflectometers, piezometers, electrical shear strips, and surface bench marks. The instruments have been arrayed about the experimental site based on the writers' experience and intuition, the results of a preliminary finite-element-method (FEM) model calculation, and detailed knowledge of the site geology. The resulting data will be used to assess the potential environmental impact of subsidence caused by *in situ* coal gasification and to provide a factual data base for comparison with FEM computer code results. The philosophy of instrument application and their installation are discussed in the context of the expected surface and subsurface deformations, and the site geology. Preliminary data from the extensometers and shear strips, and piezometers document progressively higher roof collapse and its associated effect on subsurface fluid pressures, respectively. Although bubbler tests on gas-sample tubes suggest that roof collapse has occurred to 60 ft. (18.3 m) above the top of the Felix No. 2 Coal, surface subsidence has been minimal. It is likely that the Felix No. 1 Coal participated in the gasification process to a limited extent.

Ganow, H. C., S. W. MEAD, and F. T. Wang, *Control Aspects of Underground Coal Gasification: LLL Investigations of Ground-Water and Subsidence Effects*, Lawrence Livermore Laboratory, Rept. UCRL-81887, Preprint (1978).

Ganow, H. C., S. W. MEAD, and F. T. Wang, *Ground-Water and Subsidence Investigations of the LLL In Situ Coal Gasification Experiments*, Lawrence Livermore Laboratory, Rept. UCRL-81271, Preprint (1978).

Ganow, H. C., S. W. MEAD, and F. T. Wang, *Environmental Investigations of In Situ Coal Gasification Experiments*, Lawrence Livermore Laboratory, Rept. UCRL-81395, Preprint (1978).

Ganow, H. C., S. W. MEAD, J. H. Campbell, R. T. Langland, R. C. Greenlaw, F. T. Wang, and R. V. Homsy, *LLL Environmental Studies of In Situ Coal Gasification, Annual Report Fiscal Year 1977*, Lawrence Livermore Laboratory, Rept. UCRL-500032-78 (1978).

GLENN, H. D., H. R. Kratz, D. D. Keough, and R. P. Swift, "Mach 130 Air Shock Attenuation Studies," Lawrence Livermore Laboratory, Rept. UCRL-82012, Preprint (1978).

Voitenko compressors were used to generate ~ 4.5 cm/ μ sec air shocks in a steel and a grout outlet pipe. Diaphragm burst times and time-of-arrival data of shock-front luminosity along the 2-cm-i.d. exit pipes are provided by fiber-optic ports. Pressure profiles were obtained for this high enthalpy shock propagation for the first time and at many locations in both experiments. The Voitenko-grout experiment represents the first laboratory attempt to study shock propagation with this type of compressible wall material.

The primary purpose of these two experiments was to examine the effect of wall material on high-energy shock propagation. In the interval between 10- and 250-cm from the diaphragm the velocity and peak pressure of the shock front attenuated from ~ 4.5 to 0.5 cm/ μ s and ~ 21 to ~ 0.2 kb, respectively. Over this distance the shock propagation gave nearly identical results for both experiments within the range of experimental accuracy. This rapid attenuation of the shock front velocity and pressure is attributed to ablation and entrainment of wall material. An interesting feature that was observed, confirmed by multiple measurement techniques, was rapid oscillations of the pressure profiles. The results indicate that the shock

propagation is independent of wall composition to the extent of materials considered over the 250-cm distance of the outlet pipes.

Glenn, H. D., R. W. TERHUNE, D. E. Burton, H. L. McKague, and J. T. Rambo, *Calculational Study of the Baneberry Event*, American Physical Soc. Mtg., June 11-13, 1979.

Glenn, H. D., R. W. TERHUNE, D. E. Burton, H. L. McKague, and J. T. Rambo, *Numerical Simulation of the Baneberry Event*, Lawrence Livermore Laboratory, Rept. UCRL-81807, Preprint (1978).

Glenn, H. D. and R. W. TERHUNE, *Estimate of Residual Shear Strength Around Explosion Cavities in Earth Media*, Lawrence Livermore Laboratory, Rept. UCRL-80393, Preprint (1978).

HANSON, J. M., "Thermoelastic Effects in Fracture Flow," for the American Geophysical Union Pacific Northwest Meeting, Tacoma, Washington, September 28-29, 1978.

The fluid conductance of fractures is very sensitive to changes in fracture width. Commercial exploitation of geoheat in significant amounts reduces the temperature of large volumes of rock resulting in a substantial volume strain due to thermal contraction. The resulting displacement of the fracture walls will influence the subsurface flow pattern of the thermal fluid and may be of great importance for the time development of a forced recovery system. Many current numerical models of the interaction of thermal and hydrologic phenomena in geothermal systems apply Goodier's whole space solution to estimate thermal strain in fractured media. This approach ignores the boundary condition on stress at the fracture walls and may result in a significant error in fracture width. We have estimated the magnitude of this error using an analytic method applied to an idealized fracture flow model and have found that, for the conditions expected in a forced geoheat recovery system under a fracture flow, the error in fracture width can be on the order of 30%. Furthermore, the idealized model indicates that the error in fracture width is, to first

order, independent of the fracture flow rate and depends primarily on the value of Poisson's ratio of the rock mass bounding the fracture.

HANSON, J. M. and P. W. Kasameyer, "Predicting Production Temperature Using Tracer Methods," in *Trans. Geothermal Resources Council Annual Meeting*, July 25-27, 1978, Hilo, Hawaii.

Estimates of the thermal history of reinjected fluid are necessary to insure that power production and plant equipment performance can be maintained for the design lifetime of the heat recovery system. Uncertainty in the knowledge of the flow geometry may lead to significant error in the projected production temperature. Using a simple reservoir model, it can be shown that the length of time required for an injected fluid element to heat to a given temperature is independent of the streamline path taken by the fluid element. This rather general statement suggests that a knowledge of the distribution of fluid residence time between injection and production wells is sufficient to estimate the production temperature history for reservoirs for which the model is applicable. The distribution of fluid residence time can be obtained using tracer standard methods. A general expression for the production temperature is obtained based on this observation and the assumption that the porosity thickness product, ϕh , is known or can be estimated.

HANSON, M. E., G. D. Anderson, and R. J. Shaffer, "Theoretical and Experimental Research on Hydraulic Fracturing," prepared for the ASME Petroleum Division's 1978 Energy Technology Conference, November 5-8, 1978, Houston, Texas. (Lawrence Livermore Laboratory, Rept. UCRL-80558, Preprint, 1978.)

We are conducting a joint theoretical/experimental research program on hydraulic fracturing. Newly developed two-dimensional numerical models (which include complete descriptions of the elastic continuum and porous flow fields) have been applied to analyze the effects of pore pressure on the

fracturing process. By means of small-scale experiments, we are acquiring a better understanding of the effects of the *in situ* stress field, the porosity and permeability of the solid, and the presence of interfaces or layering in the solid.

Experimentally, we have been studying the growth of cracks near an interface in several materials, including polymethylmethacrylate (PMMA), Nugget sandstone, and Indiana limestone. Results have shown that the mechanical properties of the interface relative to the properties of the materials on either side are important. A crack will not cross a well-bonded interface between two pieces of PMMA, even in the presence of a 2000-psi normal load. Cracks will cross a well-bonded interface from PMMA to limestone, but not vice versa. Similarly, cracks will propagate across a bonded interface from Nugget sandstone to limestone, but not the other way. Pressure-driven cracks will cross an unbonded interface between limestone blocks at normal loads as low as 3.45 MPa (500 psi). The fluid pressure at which a crack initiates in limestone also determines whether a crack crosses an unbonded interface under a given load.

HANSON, M. E. and R. J. Shaffer "Some Results from Continuum Mechanics Analyses of the Hydraulic Fracturing Process," 1979 Symposium on Low-Permeability Gas Reservoirs, May 20-22, 1979, Denver, Colorado. (Lawrence Livermore Laboratory, Rept. UCRL-81707, Preprint, 1978.)

Hydraulic fracturing models have been developed to analyze the hydraulic fracturing process. These models have been applied to fracturing near interfaces, pore pressure effects, and distortion of the earth's surface above the hydraulically created fractures. For a well bonded interface, the calculations indicate that the stress intensity factor of the leading crack tip decreases as the crack approaches a higher modulus material. As the tip crosses the interface into the higher modulus material, the stress intensity factor is seen to increase abruptly to a value much higher than it was in the lower modulus material. When the situation is reversed we note that the intensity factor increases as the tip approaches the interface and then abruptly decreases when the tip crosses the interface. Another analysis has shown that increases in pore

pressure due to leakage of fluids from the fracture into the surrounding media cause the stress intensity factor to drop. Decrease in the stress intensity factor can be interpreted as a reduction in the tendency to break.

In other calculations we analyze layer effects on surface tilt due to a vertical hydrofracture and find that the geometry of a layer, typified by a Poisson's ratio different than its surroundings, causes large tilt variations. The same is true for a layer typified by a Young's modulus different than its surroundings if Poisson's ratio is relatively large. For a given layer geometry, changes in the elastic constants of the layer relative to its surroundings produce significant effects on surface tilt.

HANSON, M. E., G. D. Anderson, R. J. Shaffer, D. O. Emerson, H. C. Heard, and B. Haimson, "Theoretical and Experimental Research on Hydraulic Fracturing," *Proc. 4th Annual DOE Symp. on Enhanced Oil and Gas Recovery and Improved Drilling Methods*, August 29-31, 1978, Tulsa, Oklahoma. (Lawrence Livermore Laboratory, Rept. UCRL-80969, Preprint, 1978.)

We are conducting a joint theoretical/experimental research program on hydraulic fracturing.

Newly developed two-dimensional numerical models (which include complete descriptions of the elastic continuum and porous flow fields) have been applied to analyze the effects of pore pressure on the Mode I stress intensification factor. These analyses indicate that as the fluid migrates from the fracture into the surrounding medium, the stress concentration factor decreases. Other results indicate that for a fracture symmetrically located across an interface between two materials, the stress concentration factor is larger in the material with the higher Young's modulus.

We have made predictions of surface tilt above a vertical hydrofracture and a horizontal layer, assuming various elastic parameters in the layer and the surrounding medium and different layer widths and positions relative to the hydrofracture. Two general layer configurations are studied. In the first, one layer is above the hydrofracture; in the second, the layer contains the hydrofracture. We found that the layer geometry and the elastic constants affect both the surface tilt and the local strain field.

Experimentally, we have been studying the growth of cracks near an interface in several materials, including polymethylmethacrylate (PMMA), Nugget sandstone, and Indiana limestone. Results have shown that the mechanical properties of the interface relative to the properties of the materials on either side are important. A crack will not cross a well-bonded interface between two pieces of PMMA, even in the presence of a 2000-psi normal load. Cracks will cross a well-bonded interface from PMMA to limestone, but not vice versa. Similarly, cracks will propagate across a bonded interface from Nugget sandstone to limestone, but not the other way. Pressure-driven cracks will cross an unbonded interface between limestone blocks at normal loads as low as 500 psi. The fluid pressure at which a crack initiates in limestone also determines whether a crack crosses an unbonded interface under a given load.

HANSON, M. E., G. D. Anderson, R. J. Shaffer, D. O. Emerson, H. C. Heard, and B. Haimson, "Some Theoretical and Experimental Considerations of the Hydraulic Fracturing Process and Supporting Research," *Proc. Second Eastern Gas Shales Symp.* METC-SP-78/6, Vol. II (1978).

A joint theoretical-experimental program is being pursued to analyze the hydraulic fracturing process to improve the design and analysis of this stimulation technique. Theoretical analyses with newly developed two-dimensional numerical models, which include complete descriptions of the elastic continuum and porous flow fields, have been applied to analyze the effects of pore pressure on the Mode I stress concentration factor. These analyses indicate that, as the fluid migrates from the fracture into the surrounding medium, the stress concentration factor decreases. Other results indicate that, for a fracture symmetrically located across an interface between two materials, the stress concentration factor is larger in the material with the higher Young's modulus due to the presence of the other material. In addition, predictions of surface tilt above a vertical hydrofracture and a horizontal layer are made for several cases. These cases correspond to (1) varying the elastic parameters in the layer and the surrounding medium and (2) differing layer width and position relative to the hydrofracture. Two general layer configurations are studied: one in

which the layer is above the hydrofracture and another in which the layer contains the hydrofracture. We found that both the layer geometry and the elastic constants affected surface tilt and the local strain field.

Experimentally we have been studying the growth of cracks near an interface in several materials including polymethylmethacrylate (PMMA), Nugget sandstone, and Indiana limestone. Results have shown that the mechanical properties of the interface relative to the properties of the materials on either side are important.

Mechanical properties measurements of the Devonian shale have been completed with shale cores from Columbia gas well No. 20403. These measurements include tensile strength, failure envelope under pressure, loading moduli, loading path (up to the failure envelope), pressure volume behavior, and dynamic elastic moduli as a function of pressure. The results indicate that, in general, there is no discernible trend in tensile strength with either depth or between rock units for the same orientation. Furthermore, the tensile strength parallel to bedding seems to be about two times that measured normal to bedding. Dynamic measurements indicate that the rock samples show significant anisotropy in both compressional and shear wave velocities. For compressional waves, the anisotropy decreases with increasing pressure.

HANSON, M. E. and R. J. Shaffer. "Some Continuum Considerations of the Hydraulic Fracturing Process," prepared for presentation at the 19th U.S. Symposium on Rock Mechanics, May 1-3, 1978, Lake Tahoe, Nevada. (Lawrence Livermore Laboratory, Rept. UCRL-80360, Preprint, 1978.)

The hydraulic fracturing process has been the subject of analysis with newly developed two-dimensional theoretical numerical models. These models include descriptions of both the elastic continuum and porous flow fields which are coupled to permit study of the effects of pore pressure changes on the fracturing process.

Three hydraulic fracturing problem areas have been the subjects of analysis with these models. The first has to do with the observable surface deformation due to horizontal layering near a vertical hydrofracture. For layering which is defined by changes in the Poisson's ratio across the layer with

constant Young's modulus in the medium, the positions of the maximum slope and deflections on the surface did not change much from the homogeneous case. On the other hand, changes in Young's modulus across the layers resulted in some change in the position of the maximum slopes and deflections.

The second problem area analyzed has to do with the effects of changes in the pore pressure and thus the stress field around the fracture due to migration of the fracturing fluid into the material surrounding the fracture. The pore pressure effects are evidenced by a reduction in the compressive lobes adjacent to the fracture faces and a widening of the dilatational lobes surrounding the fracture tips as the pore pressure increases. The results also indicate that the stress intensity factors decrease as the pore pressure around the fracture increases. The third problem area involves the effects of layering on the stress field around the fracture. Here the elastic parameters can have a significant effect on the stress field around the fracture.

HANSON, M. E., G. D. Anderson, and R. J. Shaffer, *Some Theoretical and Experimental Considerations of the Hydraulic Fracturing Process*, Lawrence Livermore Laboratory, Rept. UCRL-80558, Preprint (1978).

A joint theoretical-experimental program is being pursued to analyze the hydraulic fracturing process to improve the design and analysis of this stimulation technique. Theoretical analysis is being performed with newly developed two-dimensional numerical models which include descriptions of both the elastic continuum and porous flow fields which are coupled to permit study of the effects of the pore pressure changes on the fracturing process. The experimental program is being pursued with controlled small scale experiments. Presently results are being developed to understand the effects of the *in situ* stress field, the mechanical properties of the solid, the porosity and permeability of the solid and the presence of interfaces or layering in the solid.

Experimentally we have been studying the growth of cracks near an interface in several materials including polymethylmethacrylate (PMMA), Nugget sandstone, and Indiana limestone. Results have shown that the mechanical properties of the interface relative to the properties

of the materials on either side are important. It was found that a crack will not cross a well bonded interface between two pieces of PMMA even in the presence of a 2000 psi normal load. On the other hand, cracks will cross a well bonded interface from PMMA to limestone, but not vice versa. Similarly, we note that cracks will propagate across a bonded interface from Nugget sandstone to limestone, but not the other way. Pressure driven cracks will cross an unbonded interface between limestone blocks at normal loads as low as 500 psi. Fluid pressures at which a crack initiates in limestone also determines whether a crack crosses an unbonded interface under a given load.

Theoretical analyses have been pursued to analyze the observable surface deformation due to horizontal layering near a vertical hydraulic fracture. Here the analysis indicates that with layers simply defined by changes in Poisson's ratio but with constant Young's modulus the free surface locations of the maximum surface slopes and deflections did not change significantly from the homogeneous case. However, variations in Young's modulus across the layers resulted in some change in the positions of the maximum surface slopes and deflections. It was also found that the elastic parameters as well as the flow parameters can have a significant effect on the stress field around the fracture and on the stress intensity factors of the fracture tips. Pore pressure increases and thus changes in the stress field due to migration of the fracturing fluid into the surrounding medium are evidenced by a reduction in the compressive lobes adjacent to the fracture faces and a widening of the dilatational lobes near the fracture tip. Additionally, the stress intensity factors decrease as the pore pressure around the fracture increases.

HANSON, M. E., R. J. Shaffer, G. D. Anderson, D. M. Montan, W. Lin, B. Haimson, and M. P. Cleary, *LLL Gas Stimulation Program, Quarterly Progress Report, October through December 1978*, Lawrence Livermore Laboratory, Rept. UCRL-50036-77-4 (1978).

This report summarizes the research and accomplishment of the LLL Gas Stimulation program during the first quarter of fiscal year 1978. Work

has continued on the trace models for stimulating, respectively, the local and distant effects of the hydraulic fracturing process. This work has been limited primarily to the expansion of the mesh sizes near the boundaries to allow the numerical boundary effects to be reduced in the calculations. Additionally, a dynamic model is being modified to analyze fracture propagation across interfaces. A literature search concerning the use of singular integral equations for three-dimensional hydraulic fracturing calculations was completed. In one segment of the experimental program, new equipment, to allow the smooth application of borehole pressure, has been checked out. We have completed another segment of the experimental program, to determine if the magnitude of the vertical stress affects the fracture geometry and orientation. The sensitivity of fracture orientation to differences in the two minimum stresses has also been experimentally determined. Measurements of the material properties of the Devonian shale cores from the Columbia Gas Well No. 20403 have been essentially completed with the acoustic measurements under various confining stresses compiled this quarter. Calculations of the attenuation of pulses for various pulse lengths were made to determine the well spacings and testing times at which pulse testing would be a viable technique for determining pertinent reservoir parameters.

HANSON, M. E., G. D. Anderson, R. J. Shaffer, D. M. Montan, B. Haimson, and M. P. Cleary, *LLL Gas Stimulation Program, Quarterly Progress Report, January through March 1978*, Lawrence Livermore Laboratory, Rept. UCRL-50036-78-1 (1978).

This report summarizes the research and accomplishments of the LLL Gas Stimulation Program during the second quarter of fiscal year 1978. We have continued to develop and apply our hydraulic fracturing models, and some calculations of the local and distant effects of the hydraulic fracturing process have been performed. Analyses of the surface deformation effects in a layered medium above a hydraulic fracture have been completed. Some of these results are included here, and a report outlining our detailed findings is in preparation.

We are conducting a theoretical and laboratory analysis of the effects of layering and interfaces on

the hydraulic fracturing process. Early results indicate that the stress concentration factors at the tips of a pressurized fracture across an interface are significantly affected by the differences in the mechanical moduli on either side of the interface. Additionally, the frictional characteristics of the interfaces strongly affect propagation across the interface.

Theoretical dislocation models are being advanced for application to problems related to crack propagation across an interface. Experiments are being pursued to determine the effects of principal stress magnitudes on the orientation of a hydraulic fracture in porous basalt.

We have analyzed pressure test data taken by Mobile Research and Development Corporation and DOE at a Piceance Creek MHF-stimulated well (unit Well F31-13G) that shows fairly good flow rates. Our analysis indicates relatively short fracture wing lengths in the production reservoir rock and damage by the fracturing fluid on the fracture faces.

HANSON, M. E., G. D. Anderson, R. J. Shaffer, J. R. Hearst, B. Haimson, and M. P. Cleary, *LLL Gas Stimulation Program, Quarterly Progress Report, April through June 1978*, Lawrence Livermore Laboratory, Rept. UCRL-50036-78-2 (1978).

This report summarizes the research and accomplishments of the LLL Gas Stimulation program during the third quarter of fiscal year 1978. We have used two-dimensional models to analyze the behavior of hydraulically pressurized fractures near well-bonded interfaces that are located between two materials with different mechanical moduli. The results of these calculations indicate that when a fracture in a lower modulus material approaches an interface of a higher modulus material, the Mode I stress-intensity factor at the tip decreases as the crack tip nears the interface. In addition, when the crack tip penetrates the interface, the Mode I stress-intensity factor at that tip is significantly increased. When a pressurized crack in a higher modulus material approaches an interface with a lower modulus material on the other side, just the reverse is true. This report also summarizes research on some of the basic concepts of fracturing, including the fundamental problems of the hydraulic fracturing process and crack growth

across unbonded interfaces under a normal load. These experiments indicate that different mechanisms may control propagation across sandstone-standstone and limestone-limestone interfaces.

HANSON, M. E., G. D. Anderson, R. J. Shaffer, D. O. Emerson, R. P. Swift, K. O'Banion, M. P. Cleary, B. Haimson, C. F. Knutson, and C. R. Boardman, *LLL Gas Stimulation Program, Quarterly Progress Report, July through September 1978*, Lawrence Livermore Laboratory, Rept. UCRL-50036-78-3 (1978).

This report summarizes the research and accomplishments of the LLL Gas Stimulation Program during the fourth quarter of fiscal year 1978. We have applied two-dimensional theoretical models to the changes in the elastic stress field due to the presence of lenses in a surrounding medium. Here the lenses had different elastic moduli than the surrounding medium, and the imposed load was assumed to be due to the overburden. In these calculations we note that the growth of a vertical fracture toward a lens with elastic moduli larger than the surrounding medium would be impeded. Other two-dimensional calculations indicate some effects of material parameter changes across an interface on fracture mechanics. These calculations confirm results prescribed before that when a fracture in a lower modulus material approaches a well bonded interface with a higher modulus material, the stress intensity factor decreases. Our experimental results show that water saturation can have a significant effect on hydraulic fracture propagation. For instance, a hydraulic fracture across a normally loaded interface from an unsaturated limestone block into a saturated block but not conversely for the same hydraulic pressure and normal load. We have also completed some preliminary experiments to determine how rock behaves when subjected to loads at rates higher than hydraulic fracturing but lower than explosives. In this case our preliminary results indicate more than the two fracture wings which are common to normal hydraulic fracturing. A survey of several operators and logging companies operating in the western tight gas sands has indicated that log measurements are not able to indicate pertinent reservoir parameters with sufficient accuracy to be of use in exploiting these reservoirs.

HEARD, H. C. and A. Duba, *Capabilities for Measuring Physicochemical Properties at High Pressure*, Lawrence Livermore Laboratory, Rept. UCRL-52420 (1978).

In this report we describe a group of high-pressure systems that measure physicochemical properties of various media up to 2000°C and 30 GPa. With these systems it is possible to determine complete stress-strain behavior, ultrasonic velocities, permeability, phase studies, fracture-flow behavior, and optical and electrical properties. We describe the apparatus in terms of published results, photographs, and schematic diagrams.

HEARD, H. C., D. Trimmer, W. Lin, B. Bonner, and A. Duba, "Permeability of Generic Repository Rocks at Simulated *In Situ* Conditions," Symp. Underground Disposal Radioactive Wastes, International Atomic Energy Agency, Otaniemi, Finland, July 1979.

The safe terminal storage of solidified high-level radioactive wastes in a mined repository in the earth's crust requires that the time constant for fluid movement from the repository to the biosphere be long compared to the decay of the waste. Further, adequate diagnostic monitoring of the repository is necessary to provide assurance that all changes are in accordance with predictions.

We report here new measurements of the permeability of large rock samples of igneous and metamorphic rocks over a range of confining pressure, pore (water) pressures, and deviatoric stress. Seven rocks are being evaluated: three granites, a granodiorite, a gabbro, a gneissic granite, and an argillite. The range of pressure, pore pressure, and stress were chosen to span the range of probable conditions which might exist in an acceptable repository at depths to 2000 m. For all measurements, pore pressures were maintained at 0.5 of the confining (lithostatic) pressure. Deviatoric stress ranged up to 0.5 of the failure stress at that pressure. Test samples were cylinders up to 15 cm in diameter by 28 cm long. Two types of sample geometries were used: (1) material selected to be as representative as possible of the sound country rock without any large-scale fractures or faults, and (2) rock samples identical to (1) *except*

that they contain an induced through-going fracture. Simultaneously we also determine the compressional wave velocity and electrical conductivity. A major purpose here is to establish a quantitative relationship among pressure, stress, strain, permeability, velocity, and conductivity through each rock at likely repository conditions.

Haupt, H. C., M. E. HANSON, G. D. Anderson, R. J. Shaffer, and D. O. Emerson, "Theoretical and Experimental Research on Hydraulic Fracturing," *Proc. 4th Annual DOE Symp. on Enhanced Oil and Gas Recovery and Improved Drilling Methods*, August 29-31, Tulsa, Oklahoma, (Lawrence Livermore Laboratory Rept. UCRL-80969, Preprint, 1978.)

Haupt, H. C., M. E. HANSON, B. Haimson, G. D. Anderson, R. J. Shaffer, and D. O. Emerson, "Some Theoretical and Experimental Considerations of the Hydraulic Fracturing Process and Supporting Research," *Proc. Second Eastern Gas Shales Symp. METC-SP-78/6*, Vol II (1978).

HEARST, J. R., *Recent Well Logging Research at Lawrence Livermore Laboratory*, Lawrence Livermore Laboratory, Rept. UCRL-80855, Preprint (1978).

Much of the Eastern United States is underlain by gas-bearing Devonian shales. Gas production is enhanced by explosive and, recently, hydraulic fracturing. We are attempting to use acoustic methods to locate sections of natural fracture, not intersecting the hole, which will be the best places for stimulation in a well. When we use long sweeps on the acoustic log, and examine the coda of the signal, it appears that sections of hole in which the coda ends earlier than in surrounding sections are those that naturally yield gas, and are most amenable to stimulation. A dryhole logging system is being constructed for this work.

There is evidence that kerogen, associated with gas, is present when the gamma-ray log gives a high reading. We have shown that this high reading is caused by the presence of uranium, which is concentrated in the kerogen.

Some time ago we used Monte Carlo calculations to study the effect of bulk density on neutron

log readings, and we calculated that the effect is significant. We have since constructed a hydrogen content test facility to simulate partially saturated media with several bulk densities for the same water content. We have made measurements in simulations of very large holes with a standard sonde, with and without special shielding, and in air- and water-filled 12-in.-square holes. In the large holes and the water-filled small holes, measurements and calculations both show the count rate decreasing with increasing density. In small air-filled holes the count rate increases with increasing density, and calculations agree with this. Additional calculations indicate that the use of Al_2O_3 in part of the facility does not significantly affect the result.

A machine to drill sidewall cores approximately 1 m into the walls of Nevada Test Site emplacement holes has been built and successfully tested. The cores appear to contain undisturbed material. We hope to adapt this device to include shear modulus and perhaps shear stress measurements at high shear stress.

It appears that borehole gravimetry can be useful in examining the effects of exploitation of a geothermal area. The amount of solid precipitated during reinjection, and the settling caused by extraction are amenable to study. A high-temperature housing for a gravimeter has also been studied.

HEARST, J. R., *BIFUR II, a Program for Calculating Borehole Gravity Caused by Two-Dimensional Structure*, Lawrence Livermore Laboratory, Rept. UCID-17852 (1978).

A revised computer program, BIFUR II, has been written to compute the gravitational effect of structures describable in two dimensions by straight line segments. The primary application is to borehole gravimetry, but the program can also be used for surface gravity problems. Input is much simpler than that required by the previous program by the same author, and application is not limited to structures bounded by vertical sides.

HEARST, J. R., J. W. Schmoker, and R. C. Carlson, *Effects of Terrain on Borehole Gravity Data*, Lawrence Livermore Laboratory, Rept. UCRL-80994, Preprint (1978).

The effect of terrain upon gravity measurements in a borehole, and upon formation density derived from borehole gravity data, is studied as a function of depth in the well, terrain elevation, and radial distance to the terrain. The vertical attraction of gravity in a borehole, g_T , due to a terrain element is small at the surface, reaches an absolute maximum at a depth that depends on the radial distance to the terrain element, and decreases again at greater depths. The effect of terrain upon formation density ρ_T is proportional to the vertical derivative of g_T , and is maximum at the surface, passes through zero at the depth where $|g_T|$ is greatest, and reaches a second extremum of opposite sign to the first and of much lower magnitude further down the borehole. The accuracy criteria presented for borehole gravity terrain corrections show that elevation requirements are most stringent for the case of nearby terrain and near-surface gravity stations. The measurement of the free-air gradient of gravity, commonly made slightly above the ground surface, is extremely sensitive to topographic irregularities within about 1000 ft (300 m) of the measurement point. ρ_T due to terrain 13.6–103.6 mi (21.9–166.7 km) from the well (Hammer's zone M through Hayford-Bowie's zone O) is nearly constant with depth. At these distances, the terrain correction will be equivalent to a DC shift of about $\pm 0.016 \text{ g/cm}^3$ per 1000 ft ($0.053 \text{ g/cm}^3/1000 \text{ m}$) of average elevation above or below the correction datum. The effect upon ρ_T of all topography beyond 103.6 mi (166.7 km) is not likely to exceed 0.01 g/cm^3 .

HEARST, J. R., "Laboratory Studies of an Improved Carbon/Oxygen Log," *The Log Analyst* 17 (November–December 1978).

A new method of taking carbon/oxygen logs has been tested in the laboratory. The method uses a 15-cm-diameter by 15-cm-long NaI detector. At low carbon/oxygen atomic ratios (below 0.1), this detector provides about four times the resolution of previously reported logs, permitting carbon to be measured within 1 at.%,

HEARST, J. R., *Calibration of a Neutron Log in Partially Saturated Media*, Lawrence Livermore Laboratory, Rept. UCRL-81657, Preprint (1978).

An epithermal neutron logging sonde has been calibrated in a facility containing nine samples. Each sample represents a different combination of bulk density and water content. The facility simulates very large (approx 2-m-diam) dry holes and 30-cm-diam dry and water-filled holes. The neutron log data are affected not only by water content, but also by bulk density and the gap between the sonde and the wall of a dry borehole. For large holes and the wet 30-cm hole, the count rate generally decreases with increasing bulk density. For the dry 30-cm hole, however, the count rate increases with increasing density. Algorithms for fitting count rate to water content, density, and gap have been developed for a shielded and unshielded logging sonde. By using this algorithm, we have been able for the first time to log for water content in dry holes in partially saturated media and obtain good agreement with sample data.

HEARST, J. R., P. W. Kasameyer, and L. B. Owen, *Potential Uses for a High-Temperature Borehole Gravimeter*, Lawrence Livermore Laboratory, Rept. UCRL-52421 (1978).

It is possible to design a canister to cool a borehole gravimeter for use in geothermal and high-temperature (up to 350°C) gas wells. Repeat surveys with such a gravimeter could (1) help estimate the extent of reservoir plugging in geothermal injection wells after one year of operation and (2) detect compaction of a geothermal aquifer if the change in thickness of the aquifer exceeds 1 m. The instrument could be used together with conventional logging tools to evaluate radial dependence of density around a well, or to estimate gas-filled porosity around wells drilled with mud. A high-temperature borehole gravimeter could also be used to evaluate structure and stratigraphy around geothermal and high-temperature gas wells.

Hearst, J. R., R. P. SWIFT, W. B. Durham, J. F. Schatz, and A. S. Kusubov, "Effect of Simultaneous and Sequential Detonation on Explosive-Induced Fracture," *Proc. Nineteenth U.S. Sympos. Rock Mech.*, Y. S. Kim, Ed. (Mackay School of Mines, University of Nevada, Reno, 1978), p. 235.

Hearst, J. R., M. E. HANSON, G. D. Anderson, R. J. Shaffer, B. Haimson, and M. P. Cleary, *LLL Gas Stimulation Program, Quarterly Progress Report, April through June 1978*, Lawrence Livermore Laboratory, Rept. UCRL-50036-78-2 (1978).

Henry, A. L., W. A. QUITQUIT and G. P. Ledbetter, *Earth Sciences Division, Collected Abstracts—1977*, Lawrence Livermore Laboratory, Rept. UCRL-52514 (1978).

HEUSINKVELD, M. E., J. B. Bryan, and J. M. Thomsen, *Calculations for Miss Jade Underground Nuclear Test*, Lawrence Livermore Laboratory, Rept. UCRL-52579 (1978).

Computer calculations have been made on the effects of an underground cavity explosion in the MISS JADE geometry. MISS JADE is a planned event in which a 1-MT surface nuclear explosion above an MX trench will be simulated by a contained underground explosion. A tunnel will lead away from the hemispherical cavity, and a covered trench will extend outward under this tunnel.

The calculations included the hydrodynamics of the air in the cavity and tunnel in response to the explosion. It was found that, because of the gas confinement, the pressure remained higher and the shock moved faster than in an unconfined surface explosion geometry. Comparisons were made between calculations for a cavity of 25-m radius and a cavity of 19.8-m radius.

Also calculated was the response of the trench to the air pressure history in the tunnel floor above. It was found that, at a distance of 30 m from the center of the cavity, the effects of the pressure acting in the ground surface were overbalanced by the effects of the gas pressure inside the trench from gas flow from regions nearer the explosion, and that the trench tended to expand. Separate calculations were made for tuff and for grout backfill above the trench, and for tunnel and free-air-burst pressure histories on the surface above the trench.

HEUSINKVELD, M. E., J. M. Thomsen, and J. L. M. Cortez, *Scaling of Shallowly Buried Nuclear Explosions*, Lawrence Livermore Laboratory, Rept. UCRL-52439 (1978).

Scaling studies made by computer calculations compared a 20-ton underground explosion with a 1-kt reference explosion. The 20-ton explosion was from a nuclear device emplaced 27 cm beneath the surface of a tuff medium, while the 1-kt reference device was emplaced 1 m deep. The early calculations were made on a two-dimensional Lagrangian finite difference code, and these results were linked to the two-dimensional Eulerian RAD9 code. Calculations were carried out to 500 μ s for 1-kt explosion and to 136 μ s for the 20-ton explosion. The scaled results from the two calculations were very similar, the differences being ascribed primarily to the nonscaling of the dimensions of the two nuclear devices. Our studies of the results from the computer calculations used equation-of-state data from two sources: the LLL tabulated data and the values from the Tillotson equation. Results from the two calculations were quite similar, although there were minor differences.

HOWARD, N. W., B. Grothaus, and H. L. McKague, "Subsurface Correlation of Tertiary-Quaternary Desert Alluvial Deposits, Northern Yucca Flat, Nevada," Quaternary Faulting Symposium, Geological Society of America, San Jose, California, April 11, 1979.

The chaotic nature of desert alluvial deposits makes subsurface correlation difficult, if not impossible. The large number of boreholes in Yucca Flat, Nevada Test Site (NTS), provide an unusual opportunity for stratigraphic correlation within alluvial basin fill. The late Tertiary and Quaternary colluvium and alluvium deposits consist of detritus from Tertiary tuffs and Paleozoic and Precambrian clastics and carbonates. Subsurface alluvium in Yucca Flat can be divided into a younger mixed alluvium, where the volume of Paleozoic detritus is equal to or greater than the volume of tuff detritus, and an underlying alluvium in which tuff detritus predominates. Traditional methods of lithologic correlation as well as methods utilizing borehole geophysical tools have given favorable results. In the tuffaceous alluvium minor ash falls and carbonate rich debris flows are utilized for correlation. Downhole geophysical tools measure physical properties that are not evident in samples, but are correlatable between holes. Included are measurements of bulk density, magnetic susceptibility, and

electrical resistivity, as well as downhole photography. Downhole samples and cores permit correlations based on measured CO_2 content and grain density. Correlations of thinner units are possible over several hundred feet or more; major units can be correlated several miles or more. Identification and correlation within the alluvial basin fill has resulted in a preliminary understanding of the Quaternary geological history of Yucca Flat.

Howard, N. W., H. L. MCKAGUE, and B. Grothaus, "Recognition of Faults in Tertiary-Quaternary Alluvium in Northern Yucca Flat, Nevada," Quaternary Faulting Symposium, Geological Society of America, San Jose, California, April 10, 1979.

Hummel, M. E., D. H. CHUNG, and H. C. Roedean, "Attenuation in the Upper Mantle of the Basin and Range Province," *Trans. Am. Geophys. Union* 59, 319 (1978).

ISHERWOOD, D., "A Critical Review of Retardation Factors Used to Predict Radionuclide Migration," prepared for American Chemical Society, Spring 1979 Meeting, Honolulu, April 1-6, 1979.

Sorption (ion exchange) is considered the primary geochemical control on radionuclide migration from a nuclear waste repository. In computer models used to simulate radionuclide migration, sorption is represented by the retardation factor—that is, the velocity of the groundwater relative to that of the radionuclide. Retardation factors can be calculated from ion exchange distribution coefficients (K_d), provided we assume equilibrium conditions, rock homogeneity, and interstitial groundwater flow rather than fracture flow. Unfortunately, these conditions are often absent in nature, and there is little assurance that the K_d measured in the laboratory represents the *in situ* sorption properties of the rock. A literature survey shows that most K_d measurements are done in an oxidizing environment using simple solutions. This is in sharp contrast to deep groundwaters which are reducing and contain numerous complexing agents. Since retardation factors take into account only ion exchange, other factors which effect retardation,

such as polymerization, precipitation, irreversible reactions and kinetic barriers, are ignored. As a first step to understanding the complexities of retardation, a chemical equilibrium code was used to test the relative importance of oxidation potential, acidity, and the groundwater composition on the formation of stable aqueous species. The results from this initial study suggest that species likely to be present in groundwater are quite different from those used in K_d experiments and that retardation factors currently in use to predict radionuclide migration must be viewed with caution.

ISHERWOOD, D., "Geochemistry and Radionuclide Migration," Waste Management 78 Symposium, Tucson, Arizona, March 6-8, 1978.

Effective isolation of nuclear waste in a deep geologic depository can be described in terms of interacting multiple barriers. Of these, the least understood is the *geochemical barrier*, identified as a series of waste/water/rock interactions involving sorption (ion exchange), ion filtration, hydrolysis, precipitation, complexing, and the leach resistance of the waste form. In this report we describe these various interactions, pointing out that only sorption can be expressed in quantitative terms based on experimental evidence. Theoretically, we can calculate the solubility of most radionuclides from thermodynamic data, but we know very little about their actual solubilities in natural waters. A few radionuclide complexes have been identified, but nothing is known of their reaction rates. Future research needs are obvious. For the present, geochemistry related to the study of deep geologic disposal of high level waste is limited by an information base which relies heavily on theory.

Isherwood, D. J., A. M. KAUFMAN, and B. Ross, "Calculated Radionuclide Migration from a Geologic High Level Waste Repository," in *Proc. ASTM Conf.*, July 10-14, 1978, Johnson, Vermont (in press).

Transport by groundwater is the most likely means of escape for radioactive waste contained in a geologic repository. The rock formations through which the groundwater flows are characterized by

inhomogeneities on all distance scales. Large-scale inhomogeneities cause pulses of dissolved pollutants to spread both in the direction of motion and transverse to it. This phenomenon is known as macroscopic dispersion. Similarly, inhomogeneities in the chemical properties of the rock will cause this spreading to be greater for species whose movement through the rock is retarded by waste/rock chemical interactions.

Previous risk analyses of nuclear waste disposal which have ignored macroscopic dispersion found that predicted radiation doses to individuals are very sensitive to the waste dissolution time. When macroscopic dispersion is incorporated into the analysis, the sensitivity of risk to dissolution time is greatly reduced.

Isherwood, D., P. A. HECKMAN, D. F. Towse, T. Harvey, and T. Holdsworth, *High Level Waste Repository Site Suitability Study—Status Report*, Lawrence Livermore Laboratory, Rept. UCRL-52633 (1978).

KASAMEYER, P. W., J. F. Schatz, and J. A. Cheney, *A Method of Using In Situ Porosity Measurements to Place an Upper Bound on Geothermal Reservoir Compaction*, Lawrence Livermore Laboratory, Rept. UCRL-80984, Preprint (1978). (Prepared for U. C. Berkeley Well Testing Symposium, October 1978.)

Placing an upper bound on reservoir compaction requires placing a lower bound on the reservoir effective compaction modulus. Porosity-depth data can be used to find that lower-bound modulus in a young sedimentary basin. Well-log and sample porosity data from a geothermal field in the Imperial Valley, California, give a lower-bound modulus of 7.7×10^3 psi. This modulus is used with pressure drops calculated for a reservoir to determine an upper bound on reservoir compaction. The effects of partial reinjection and aquifer leakage on upper-bound subsidence estimated from the compaction are illustrated for a hypothetical reservoir and well array.

KASAMEYER, P. W. and N. B. Crow, "Baseline Measurements of Geologic Events Can Remove Potential Roadblocks to Geothermal Develop-

ment," 144th National Meeting of American Assoc. for the Advancement of Science, Washington, D.C., February 12-17, 1978.

Large-scale production of electricity from geothermal fluids in southern California may possibly cause adverse environmental effects such as water pollution, earthquakes, or subsidence. The LLL Imperial Valley Environmental Project, in cooperation with several organizations, is making baseline measurements of water chemistry, seismology, and surface elevation before production starts. Natural geologic events have been observed which might have been considered environmental effects of production had full production been in progress. Documentation of the variability of natural geologic activity is reducing the risk that public reaction to a natural event will stop production. One event was an earthquake swarm. Fewer than 40 earthquakes per month were detected near the Niland field in 5 months. Over 300 earthquakes occurred in the sixth month. Assuming the events had a stationary Poisson distribution, the change in seismicity is highly improbable. Because the natural seismicity rate is variable it is not a practical discriminant between natural and production-related events. The depth-of-focus or source-mechanism may be a better discriminant.

KASAMEYER, P. W., "Natural Fluid-Flow Patterns in the Salton Sea Geothermal Field," *Geotherm. Resources Council Trans.* 2, 359 (1978).

The direction and magnitude of the horizontal flow at the Salton Sea Geothermal Field (SSGF) is discussed in this paper. Evidence has been published indicating that the natural flow in the field is from the southeast to the northwest. We suggest that a model of large-scale convection about an intrusion explains many aspects of the natural temperature distribution. In this model the direction of natural flow is exactly opposite to that predicted from regional hydrology. This model is by no means unique, nor is the proof of the direction of flow definitive. The model is discussed in order to indicate our uncertainty in the direction of preproduction flow. This model can be tested with numerical simulators such as those of Riney *et al* and Cathles.

The results of those simulations could suggest additional measurements or analysis which would determine the true direction of flow.

Kasameyer, P. W. and L. YOUNKER, *A Revised Estimate of Recoverable Thermal Energy in the Salton Sea Geothermal Resource Area*, Lawrence Livermore Laboratory, Rept. UCRL-52450 (1978).

We have made a revised estimate of the recoverable thermal energy in the Salton Sea Known Geothermal Resource Area (KGRA) using the strong correlation between the temperature distribution and the magnetic anomaly. Our estimates of the power-generating potential range from 1300 MW-20 years (for indicated resources) to 8700 MW-20 years (for hypothetical resources). These figures are compatible with previously published estimates. Comparison of various estimation procedures reveals major differences in techniques used to assess reservoir volume. However, authors agree generally on parameters used to convert reservoir volume to recoverable energy. Our conservative estimates justify continued research and development to solve the technical problems that stand in the way of commercialization of the Salton Sea resource.

Kasameyer, P., D. DAVIS, and J. Lytle, "Instrumentation for Evaluation of *In-Situ* Recovery Projects," American Association of Petroleum Geologists Bulletin 62/6, p. 1082, June 1978.

In-situ recovery techniques, such as coal gasification and oil-shale retorting, are currently under investigation at Lawrence Livermore Laboratory and elsewhere. Information about the size and location of the "burn" as a function of time adds greatly to the understanding of these processes. One way to obtain such information is through the use of thermocouples implanted at many points throughout the expected burn region. Unfortunately, thermocouples sample only small volumes and fail at the high temperatures encountered in such processes. We have developed a technique of high-frequency electromagnetic mapping (HFEM) which

has been successful in following the progress of a burnfront during an underground coal-conversion experiment.

During an experiment at Hoe Creek, Wyoming, the HFEM technique successfully detected and followed the vertical position and extent of the burnfront between each of several pairs of wells during the 72-day burn. Seven wells located at the expected perimeter of the burn region were available for transmitting and receiving antennas. The transmissivity of the coal to radio-frequency waves was determined as a function of depth by lowering the two antennas in unison. Regions occupied by the burnfront were more opaque to the electromagnetic waves.

Kasameyer, P. W. and J. M. HANSON, "Predicting Production Temperature Using Tracer Methods," in *Trans. Geothermal Resources Council Annual Meeting, July 25-27, 1978*, Hilo, Hawaii.

Kasameyer, P. W., J. D. TEWHEY, M. A. Chan, and L. B. Owen, "Development of Injection Criteria for Geothermal Resources," *Geothermal Resources Council, Trans. 2*, 649 (July 1978). (Lawrence Livermore Laboratory, Rept. UCRL-81007; Preprint, 1978.)

Kasameyer, P. W., J. R. HEARST, and L. B. Owen, *Potential Uses for a High-Temperature Borehole Gravimeter*, Lawrence Livermore Laboratory, Rept. UCRL-52421 (1978).

Kasameyer, P. W. and N. B. CROW, "Monitoring Natural Subsidence and Seismicity in the Imperial Valley as a Basis for Evaluating Potential Impacts of Geothermal Production," *Geotherm. Resources Council. Trans. 2*, 125 (1978).

KNOX, R. J., *VuGraph: A Code for Generating Presentation Viewgraphs*, Lawrence Livermore Laboratory, Rept. UCRL-52560 (1978).

The VuGRAPH code offers possibly the fastest method of generating professional quality viewgraph transparencies. The viewgraphs are con-

structed on a four-color plotter controlled by a HP-9825A desk-top minicomputer. The program uses a unique line enhancement scheme to produce bold characters optimally suited for projection in most auditoriums. Twenty-four "single-key" commands simplify operation for users. This feature and the fast-response typewriter keyboard have proved attractive to both technical and clerical personnel. This document, which includes 16 illustrations, explains the program methods and serves as a user's manual. Several examples of computer/user responses relative to the program are presented.

KUSUBOV, A. S., *Seismic Experiments at Yucca Lake, Test Execution Report, the Rayleigh Wave Experimental Program*, Lawrence Livermore Laboratory, Rept. UCRL-52446 (1978).

Experiments are described that recorded the characteristics of seismic signals from single and multiple explosions conducted at the Nevada Test Site in Yucca Flat, Nevada. Most of the data were obtained from small-scale underground explosions (total yields ranged from a fraction of a pound to 100 lb of explosives) that were designed to permit characterization of seismic signals as a function of explosive-source configuration. Other data were from explosions conducted in the area by others: two underground nuclear detonations with yields of 4 and 40 kt, respectively, and several surface explosions whose yields ranged from 700 lb to 100 tons. The project included a comprehensive study of the Yucca lake bed, close-range recording of seismic signals from explosions, and excavation of cavities generated by small-scale high-explosive charges.

KUSUBOV, A. S., J. F. Schutz, and T. J. Ahrens, "Shock Wave Generated Fractures Under Confining Pressure," *Bull. Am. Phys. Soc.* **23**, 70 (1978).

To study permeability enhancement at overburden stresses, explosive wire experiments were carried out in clear plastic (PMMA) under pressures up to 0.35 GPa. Preliminary results show that the crack envelope radius at a confining pressure of 0.2 GPa has been reduced by a factor of two as compared to experiments performed under similar conditions with no external pressure applied to the samples.

KUSUBOV, A. S., "Quasi-Isentropic Compressibility of Hydrogen," Compressed Hydrogen Meeting, Paris, September 1978.

New experimental techniques and calculational methods are proposed to study the isentropic compressibility and the metallic phase transition of hydrogen.

Quasi-isentropic compression up to about 4 Mbar will be achieved by shocking a mixture of liquid hydrogen with beads of a relatively incompressible material, such as tungsten. The result will be a multiple-step compression with a much lower compressional temperature than for single-step compression along the Hugoniot. The metallic phase transition will be detected by recording the change in the sound velocity behind the shock front.

An alternate technique, permitting observation of the metallic phase transition up to about 9 Mbar, will involve measuring the electrical conductivity, shock velocity, and opacity of a liquid hydrogen sample compressed by a cylindrical implosion system designed to generate a ramp-like compressional wave, resulting in quasi-isentropic compressibility at the center of the system.

KUSUBOV, A. S., R. N. Schock, and T. J. Ahrens, "Rock Fracture Under Confining Pressure," *Trans. Am. Geophys. Union* **59**, 1191 (1978).

A laboratory study of high explosive-generated fractures in limestone and gas-bearing sandstone has been conducted to simulate the effect of overburden pressure on crack formation. The experiments consisted of detonating up to 160 mg of high explosive in samples of Sego sandstone and Indiana limestone under confining pressure up to 0.048 GPa. Post-shot analysis in sandstone samples revealed that up to 0.028-GPa confining pressure, a well-defined cavity and a compaction zone were formed; at 0.048 GPa, a cavity and a compaction zone were practically nonexistent. For Indiana limestone, fractures were suppressed at confining pressures above 0.024 GPa. The results obtained demonstrate that overburden pressure plays a more significant role than previously thought in energy-coupling and *in situ* rubblelization of geologic materials.

Kusubov, A. S., R. P. SWIFT, J. F. Schatz, W. B. Durham, and J. R. Hearst, "Effect of Simultaneous and Sequential Detonation on Explosive-Induced Fracture," *Proc. Nineteenth U.S. Sympos. Rock Mech.*, Y. S. Kim, Ed. (Mackay School of Mines, University of Nevada, Reno, 1978), p. 235.

LARSON, D. B., "The Effects of Variations in Source and Medium Parameters upon Far Field Spectra," *Trans. Am. Geophys. Union* **59**, 325 (1978).

The effects of variations in source and medium properties upon far field frequency spectra for elastic waves are examined theoretically. The objectives are to determine (a) the relative effects of the various parameters, (b) the significance of these parameters in a comparison of explosive energy coupling in tamped and decoupled explosions, and (c) the best approach in the use and interpretation of available experimental data. The theoretical approach makes use of the Fourier transform of the elastic displacement produced by a pressure pulse acting on a spherical surface inside an elastic medium. The comparisons of the effects of the various parameters are made using dimensionless velocity potentials and frequencies. These results are employed in examining the differences in explosive energy coupling in the Salmon (tamped) and Sterling (decoupled) nuclear experiments in salt and then as a guide for the analysis of laboratory and field data to be used in determining the perturbations that various material properties have upon the source spectra for far field motion.

LARSON, D. B., *Shock Wave Studies of Blair Dolomite*, Lawrence Livermore Laboratory, Rept. UCRL-80819, Preprint (1978).

Two types of shock wave experiments have been conducted on samples of Blair dolomite. The first employed a light-gas gun to obtain a state of uniaxial strain, while the second used a spherical high-explosive charge to produce radial divergent flow. Comparisons of data taken from these two types of experiments (i.e., at strain rates, $\dot{\epsilon}$, of $10^6/s$ and $10^4/s$, respectively, with quasistatic data ($\dot{\epsilon} \approx 10^{-4}/s$) show that Blair dolomite is strongly time

dependent in its behavior. Other data presented for Blair dolomite show evidence of time-independent behavior over the entire interval of stress between 0.24 and 5.33 GPa. This latter observation differs from that of another group who observed time-independent flow below 2.5 GPa.

LARSON, D. B. and G. D. Anderson, *Plane Shock-Wave Studies of Porous Geologic Media*, Lawrence Livermore Laboratory, Rept. UCRL-80898, Preprint (1978).

Plane shock-wave experiments have been conducted on two highly porous rocks, Mt. Helen tuff and Indiana limestone, in both dry and water-saturated states. A light-gas gun was used to load the sample in uniaxial strain and the subsequent wave motion was monitored with particle-velocity gages. All four materials studied show evidence of time-dependent behavior. The time dependent behavior in the highly porous dry rocks is associated with the closing of pores, and the strong time dependence observed in these materials would seem to preclude the use of quasistatic data in constitutive models that are used to describe dynamic processes. In the water saturated rocks, the time dependence is associated with the water, which shows no indication of transformation to the higher pressure ice phases in the time frame of these shock-wave experiments. This suggests the possibility of a metastable form of water existing under dynamic conditions.

Larson, D. B. and G. D. ANDERSON, "Shock Wave Compression of Limestone and Tuff," *Trans. Am. Geophys. Union* **59**, 374 (1978).

Larson, D. B., and G. D. ANDERSON, "Laboratory Experiments on Hydraulic Fracture Growth near an Interface," *Proc. Nineteenth U.S. Sympos. Rock Mech.*, Y. S. Kim, Ed., (Mackay School of Mines, University of Nevada, Reno, 1978), p. 333. (Lawrence Livermore Laboratory, Rept. UCRL-80355, Preprint, 1978.)

Ledbetter, G. and N. B. CROW, *An Environmental Geology Workshop for the Geysers-Calistoga Known Geothermal Resources Area*, Lawrence

Livermore Laboratory, Rept. UCRL-52418 (1978).

Lettis, L. A., Jr., J. B. BRYAN, D. E. Burton and M. E. Cunningham, "A Two Dimensional Computer Simulation of Hypervelocity Impact Cratering: Some Preliminary Results for Meteor Crater, Arizona," *Proc. Lunar Planet. Sci. Conf. 9th* (1978). (See also Lawrence Livermore Laboratory, Rept. UCRL-80539, Preprint, 1978.)

LEWIS, A. E. and R. L. Braun, "Retorting and Combustion Processes in Surface Retorts," 12th Oil Shale Symposium, Golden, Colorado, April 18-20, 1978. (Lawrence Livermore Laboratory, Rept. UCRL-82085, Preprint, 1978.)

A mathematical model for a batch retorting process has proved useful in understanding *in situ* retorting in a bed of oil shale rubble. An improved level of understanding of the physical and chemical processes has been obtained in recent years and provides the basis for the model. This LLL model has been modified to calculate the retorting of shale moving through a retort as required for a continuous process in surface equipment. Results of calculations illustrate the advantages and disadvantages of inert gas and combustion retorts. It is concluded that temperature control and the efficient use of energy from the nonliquid products of pyrolysis are key problems in surface retorting processes. The quantity of gas produced by combustion of char with air is insufficient to retort shale without large temperature gradients. Steep temperature gradients in turn result in difficulty in controlling temperature and in loss of oil yield. We believe that application of this model can contribute to improvements in surface processing.

LEWIS, A. E., "Application of LLL Model to Surface Retort," Oil Shale Conversion Symposium, Grand Junction, Colorado, December 6-8, 1978. (Lawrence Livermore Laboratory, Rept. UCRL-81913, Preprint, 1978.)

The LLL model has been modified to calculate the retorting of shale moving through a retort. Results of preliminary calculations provide an

insight into limitations on operating conditions and gas flow rates. We believe that present understanding of the retort process as assembled in this model can contribute to improvements in surface retorting.

Lewis, A. E. and A. J. ROTHMAN, "Recent Experimental Developments in the Modified *In-Situ* Oil Shale Program at Lawrence Livermore Laboratory," American Institute of Chemical Engineers Meeting, Miami, Florida, November 12-16, 1978.

LIN, W., *A Review of Soviet Studies Related to Peaceful Underground Nuclear Explosions*, Lawrence Livermore Laboratory, Rept. UCID-17729 (1978).

We review and summarize theoretical and empirical studies of contained and crater-forming underground nuclear explosions by U.S.S.R. investigators. We compare published data on U.S., U.S.S.R., and French cavity-forming nuclear explosions with those predicted by the formula. We summarize empirical studies on American and Soviet cratering explosions, both high explosive and nuclear, and review the parameters governing an excavation explosion.

LIN, W. and C. Wang, *P-Wave Velocities in Rocks at High Pressure and Temperature and the Crustal Constitution of the Central California Coast Ranges*, Lawrence Livermore Laboratory, Rept. UCRL-81249, Preprint (1978).

Velocities of compressional waves are determined for central California rocks at pressures up to 0.7 GPa (7 kb) and temperatures up to 450°C. These data are used to interpret the seismic velocity structure of the crust in the California Coast Ranges. Besides some patches of low-density sediments on the surface, seismic data on both sides of the San Andreas fault are consistent with the following constitution: on the northeast side the upper 10 to 15 km of the crust consists predominantly of sedimentary and metasedimentary rocks of the Franciscan assemblage; the lower crust, of a

thickness of 15 to 20 km, may be composed of gabbroic or other mafic rocks. Across the fault, the entire crustal section on the southwest side is probably a granitic complex similar to that exposed on the surface. A gravity profile calculated for the proposed model compares favorably with the observed gravity anomaly.

LIN, W., *Measuring the Permeability of Eleana Argillite from Area 17, Nevada Test Site, Using the Transient Method*, Lawrence Livermore Laboratory, Rept. UCRL-52604 (1978).

We use the transient method to determine the permeability of Nevada Test Site (NTS) Eleana argillite specimens, both intact and fractured, as a function of effective pressure up to 24.0 MPa. In using the transient method, pressures in the upstream reservoir are calculated numerically as a function of time for the exact specimen characteristics and reservoir sizes used in the experiment. The permeability is determined by comparing the laboratory-observed pressure-decay curve with the calculated one. The input parameters to the calculations are permeability, porosity, and compressibility of rock, and the viscosity and compressibility of water.

Our results indicate that the intact Eleana argillite has very low permeability, ranging from about 10^{-16} to 10^{-19} cm² (10^{-8} to 10^{-11} Darcys), depending on the effective pressure and depth of sample origin. The equivalent permeability of a similar specimen containing one through-going fracture varies from about 10^{-12} cm² at effective pressure of about 1.0 MPa to 10^{-17} cm² at pressures of about 24.0 MPa.

LIN, W., "Determination of Rock Permeability Using the Transient Method," *Trans. Am. Geophys. Union* **59**, 1193 (1978).

To determine the permeability of a low permeability rock specimen, one must use the transient method in which the decay of a small pressure increment in the upstream reservoir is observed. We have developed a transient method that is suitable for any size of specimen and reservoir. Pressures in the upstream reservoir are calculated numerically as a

function of time for the exact specimen and reservoir sizes used in the experiment, with various values of permeability, porosity, and compressibility of rock, and viscosity and compressibility of fluid. We determine the permeability of the rock specimen by comparing the laboratory-observed pressure decay curve with the calculated ones.

Permeabilities of both intact and fractured Eleana shale specimens (NTS) are determined using this method as a function of effective pressures up to 24 MPa. Our results indicate that the intact Eleana shale has very low permeability, ranging from about 10^{-9} to 10^{-10} Darcys depending on the effective pressure and the depth of sample origin. The equivalent permeability of a similar shale specimen containing a single fracture oriented parallel to the fluid flow direction varies from about 10^{-5} Darcys at effective pressures of about 1.0 MPa to 10^{-8} Darcys at pressures of about 24 MPa.

Lin, W. and D. R. STEPHENS, *Relationships Among Permeability, k , Porosity, n , and Formation Factor, F* , Lawrence Livermore Laboratory, Rept. UCRL-80856, Preprint (1978).

We derive some useful relationships among permeability, porosity, and formation factor, and compare derivations with previous works, some of which are in error. The simple equation,

$$k = \frac{m^2}{k_0 F^{5/4}}$$

is shown to be in reasonable agreement with experimental data for a number of rocks.

Lin, W., M. E. HANSON, R. J. Shaffer, G. D. Anderson, D. M. Montan, B. Haimson, and M. P. Cleary, *LLL Gas Stimulation Program, Quarterly Progress Report, October through December 1978*, Lawrence Livermore Laboratory, Rept. UCRL-50036-77-4 (1978).

Lin, W., H. C. HEARD, D. Trimmer, B. Bonner, and A. Duba, "Permeability of Generic Repository Rocks at Simulated *In Situ* Conditions," prepared for Symp. Underground Disposal

Radioactive Wastes, International Atomic Energy Agency, Otaniemi, Finland, July 1979.

Lin, W., B. Bonner, A. Duba, H. C. HEARD, and D. Trimmer, "Permeability of Generic Repository Rocks at Simulated *in Situ* Conditions," Symp. Underground Disposal Radioactive Wastes, International Atomic Energy Agency, Otaniemi, Finland, July 1979.

Lohmann, M. L. and P. S. BROWN, *Computational Studies of a Voitenko Compressor*, Lawrence Livermore Laboratory, Rept. UCRL-82010, Preprint (1978), submitted to Nuclear Blast and Shock Simulation Symposium, San Diego, California, November 28-30, 1978.

MALLON, R. G., *Effect of Oil Wetting on Pressure Difference in Experimental Oil Shale Retorts*, Lawrence Livermore Laboratory, Rept. UCRL-81939, Preprint (1978).

An analytical study of pressure gradient data from laboratory oil shale retorts is described. A review of the flow-pressure equation shows it to have the same form for transitional as for laminar and turbulent flow, provided that the Reynolds number variation is small. Comparison of measured with calculated vertical pressure differences in a small retort reveals good agreement above the level where maximum temperature is reached. Below this level, values differ by at least 30% because of retained oil, which reduces the gas flow space. Methods for calculating total pressure difference across a retort, and implications for *in situ* oil shale processing are also suggested.

MALLON, R. G. and R. L. Braun, "Oil Degradation and Gas Evolution During the Retorting of Large Blocks of Oil Shale," 11th Oil Shale Symposium, Colorado School of Mines, Golden, Colorado, April 12-14, 1978.

Of concern in *in situ* oil shale technology is degradation of oil during generation in large blocks. Intraparticle oil degradation was investigated by retorting 1/4-tonne and 1-tonne blocks of oil shale

in a flowing nitrogen atmosphere. The oil yield was estimated from the residual organic carbon in the spent shale and the evolved organic carbon in the gas products. The loss in oil yield is interpreted to be due to coking of part of the immobile oil liquid and cracking of part of the flowing oil vapor. A calculational model based on these mechanisms is used to analyze the experimental data and to determine effective rate coefficients for the reactions. The model is extended to quantify the intraparticle oil degradation for a range of heating rates and a range of particle sizes of interest in *in situ* technology.

McKAGUE, H. L., B. Grothaus, and N. W. Howard, "Recognition of Faults in Tertiary-Quaternary Alluvium in Northern Yucca Flat, Nevada," Quaternary Faulting Symposium, Geological Society of America, 1978.

The presence or absence of faults near proposed underground nuclear tests at the Department of Energy's Nevada Test Site (NTS) is an important parameter in site evaluation. A statistical study of faulting indicates approximately 10 faults/mi² in the hills surrounding Yucca Flat. This high number of faults plus the occurrence of low-magnitude earthquakes around Yucca Flat indicates an area of active faulting. Traditional methods of fault recognition in Quaternary alluvium depend upon recognition of fault-related geomorphic features, such as fault scarps, photolineations, and modifications of drainage, or trenching across suspected areas. Some faults such as Yucca Fault and the Boundary Fault have a natural expression; others such as the Carpetbag Fault and the Area 3 Fault have surface expression induced by nuclear testing. A third group have no surface expression, but have been identified or inferred, by surface gravimetry, to be present in the subsurface. The presence or absence of these inferred faults has been demonstrated by using stratigraphy, downhole geophysical logs, geochemical techniques, and downhole photography. Correlations of lithology, physical or chemical properties between two or more boreholes is the most common technique. Electrical conductivity and downhole photography have been used successfully to identify faults in a single hole. Although the resolution is not as good in alluvium as in bedrock, indications are that there are fewer faults cutting the alluvium than cut the underlying volcanic and Paleozoic rocks.

McKague, H. L., R. W. TERHUNE, H. D. Glenn, D. E. Burton, and J. T. Rambo, "Calculational Study of the Baneberry Event," American Physical Soc., June 11-13, 1979.

McKague, L., N. W. HOWARD, and B. Grothaus, "Subsurface Correlation of Tertiary-Quaternary Desert Alluvial Deposits, Northern Yucca Flat, Nevada," Quaternary Faulting Symposium, Geological Society of America, 1978.

McKague, H. L., R. W. TERHUNE, H. D. Glenn, D. E. Burton, and J. T. Rambo, *Numerical Simulation of the Baneberry Event*, Lawrence Livermore Laboratory, Rept. UCRL-81807, Preprint (1978).

MC LEOD, J., *Environmental Impact of The Coalinga Enhanced-Oil-Recovery Project*, Lawrence Livermore Laboratory, Rept. UCID-17916 (1978).

The Coalinga Polymer Demonstration Project, funded jointly by the Shell Oil Company and the U.S. Department of Energy, is designed to test polymer flooding as a method of enhancing oil recovery in existing oil fields. Polysaccharide biopolymer will be mixed with water and injected into the underground oil reservoir. Its effect will be to increase the viscosity of the water, thus reducing its ability to flow in the reservoir and causing it to enter otherwise bypassed pore spaces (where it can contact more oil). The goal of the Coalinga Project is to generate data to calibrate a reservoir model that will be used in predicting the performance of a full-scale water flood followed by a polymer flood.

The purpose of this report is to assess the impact of the Coalinga Project on the environment of the Coalinga Oil Field in Fresno County, California. Our basic conclusion is that the project will have no significant adverse impact.

MEAD, S. W., J. H. Campbell, H. C. Ganow, R. T. Langland, R. C. Greenlaw, F. T. Wang, and R. V. Homsy, *LLL Environmental Studies of In Situ Coal Gasification, Annual Report Fiscal Year 1977*, Lawrence Livermore Laboratory, Rept. UCRL-500032-78 (1978).

This is the first annual report on a continuing investigation at the Lawrence Livermore Laboratory (LLL) into the environmental ramifications of *in situ* coal gasification. The investigation is focused on changes in ground-water quality and the effects of ground movement and subsidence, which represent important environmental concerns associated with the *in situ* coal gasification process. Our methods include laboratory measurements, predictive modeling studies, and field measurements carried out in conjunction with LLL coal gasification experiments in northeastern Wyoming. These activities will serve as a basis for the identification of appropriate environmental control technologies.

Our measurements of ground-water quality near the first LLL gasification experiment indicate that the concentration of many potential contaminants decreases significantly as a result of adsorption by the surrounding coal. For example, the concentration of phenolic materials decreased by a factor of 50 in a period of 280 days. To investigate subsidence phenomena, we have conducted triaxial strength tests on geologic core samples from the gasification site and have installed an array of surface and subsurface geotechnical instruments to be used in conjunction with a second LLL gasification experiment. Such measurements will enable us to refine our finite element modeling capabilities, which have been used to predict subsidence effects at the LLL *in situ* gasification site.

MEAD, S. W., F. T. Wang, and H. C. Ganow, *Environmental Investigations of In Situ Coal Gasification Experiments*, Lawrence Livermore Laboratory, Rept. UCRL-81395, Preprint (1978).

Although *in situ* coal gasification offers important environmental advantages when compared with more conventional methods of coal utilization, there are significant environmental concerns that need to be investigated. Ground-water sampling and subsidence measurements have been carried out at the sites of two *in situ* coal gasification experiments conducted in northeastern Wyoming by the Lawrence Livermore Laboratory (LLL). Changes in ground-water quality and the possible effects of subsidence and ground movement induced by the

gasification cavity represent important environmental concerns associated with the *in situ* coal gasification process. Our ground-water quality measurements near the site of the first experiment (Hoe Creek I) show a continuing decrease, after more than a year, in the concentration of important contaminants such as phenolic materials. Laboratory measurements have provided detailed information concerning phenol adsorption by coal. Long-term effects due to ground-water flow, and the detailed behavior of other contaminants remain to be investigated. Data from subsurface geotechnical instruments installed at the second gasification experiment (Hoe Creek II), as well as measurements of ground-water levels indicate that roof collapse has connected the gasification cavity with overlying aquifers. The implications of this interconnection for the dispersal of underground contaminants are being investigated.

MEAD, S. W., F. T. Wang, and H. C. Ganow, *Ground-Water and Subsidence Investigations of the LLL In Situ Coal Gasification Experiments*, Lawrence Livermore Laboratory, Rept. UCRL-81271, Preprint (1978).

Ground-water sampling and subsidence measurements have been carried out at the sites of two *in situ* coal gasification experiments conducted in northeastern Wyoming by the Lawrence Livermore Laboratory (LLL). Changes in ground-water quality and the possible effects of subsidence and ground movement induced by the gasification cavity represent important environmental concerns associated with the *in situ* coal gasification process. Our ground-water quality measurements near the site of the first experiment (Hoe Creek I) show a continuing decrease, after more than a year, in the concentration of important contaminants such as phenolic materials. Laboratory measurements have provided detailed information concerning phenol adsorption by coal. Long-term effects due to ground-water flow, and the detailed behavior of other contaminants remain to be investigated. Data from subsurface geotechnical instruments installed at the second gasification experiment (Hoe Creek II), as well as measurements of ground-water levels indicate that roof collapse has connected the gasification cavity with overlying aquifers. The

implications of this interconnection for the dispersal of underground contaminants are being investigated.

MEAD, S. W., F. T. Wang, and H. C. Ganow, *Control Aspects of Underground Coal Gasification: LLL Investigations of Ground-Water and Subsidence Effects*, Lawrence Livermore Laboratory, Rept. UCRL-81887, Preprint (1978).

Changes in ground-water quality and the possible effects of subsidence and ground movement induced by the underground gasification cavity represent significant environmental concerns associated with the *in situ* gasification process. We have measured these effects at the sites of two *in situ* coal gasification experiments conducted in northeastern Wyoming by the Lawrence Livermore Laboratory. Our measurements of ground-water quality in the vicinity of the gasification experiments indicate that the reaction products, such as ash and some coal tars, that remain underground following gasification, are a potential source of localized ground-water contamination. However, the concentration of important contaminants, such as phenols, show a significant decrease due to adsorption by the surrounding coal. Complementary laboratory measurements are providing detailed information concerning this adsorption process.

We have also conducted laboratory and field measurements, in conjunction with modeling studies, to evaluate the effects of subsidence phenomena. Data from subsurface geotechnical instruments installed at the second gasification experiment, as well as measurements of ground-water levels, indicate that roof collapse connected the gasification cavity with overlying aquifers. The environmental implications of this interconnection are being investigated. Our results suggest that hydrogeological site-selection criteria may be of considerable environmental importance in choosing locations for commercial-scale operations.

MILLER, D. G. and A. B. Bailey, *Sphere Drag at Mach Numbers from 0.3 to 2.0 at Reynolds Numbers Approaching 10⁷*, Lawrence Livermore Laboratory, Rept. UCRL-81150 (1978).

Our analysis of 18th and 19th century cannon firings shows that knowledge of sphere drag can be

substantially extended into the region of $0.3 \leq M_w \leq 2.0$ and Re_{md} up to 107. Bashforth's chronographic measurements (1868) are of a quality comparable to modern measurements. The data of Mayevski (chronograph, 1868), Hutton (ballistic pendulum, 1787-1791), and Didion (ballistic pendulum, 1839-40) are of lesser accuracy but in agreement with Bashforth's. These cannon data are combined with modern data to provide the most extensive curves available of C_D vs Re_{md} in this region. Interesting features of these curves for $M_w \leq 1.0$ are briefly described.

Miller, W. C., W. A. SANDHOLTZ, F. J. Ackerman, A. J. Rothman, E. Cope, J. Ronchetto, *The Lawrence Livermore Laboratory Oil Shale Retorts*, Lawrence Livermore Laboratory, Rept. UCRL-52551 (1978).

Montan, D. M., M. E. HANSON, G. D. Anderson, R. J. Shaffer, B. Haimson, and M. P. Cleary, *LLL Gas Stimulation Program, Quarterly Progress Report, January through March 1978*, Lawrence Livermore Laboratory, Rept. UCRL-50036-78-1 (1978).

Montan, D. M., M. E. HANSON, R. J. Shaffer, G. D. Anderson, W. Lin, B. Haimson, and M. P. Cleary, *LLL Gas Stimulation Program, Quarterly Progress Report, October through December 1978*, Lawrence Livermore Laboratory, Rept. UCRL-50036-77-4 (1978).

MORSE, J. G. and L. D. Thorson, "Reservoir Engineering Study of a Portion of the Salton Sea Geothermal Field," *Geotherm. Resources Council Trans.* 2, 471 (July 1978).

A well testing program is being conducted in the Salton Sea Geothermal Field in the vicinity of the Geothermal Loop Experimental Facility. Six well tests have been conducted as of January 15, 1978. Equipment has been developed and modified for use in the corrosive hot-temperature brine environment. A computer program using superposition of analytic solutions is being developed to assist in analyzing the data. Initial results indicate that the reservoir has horizontal permeabilities of 100 to

500 md while vertical permeabilities across the shale layers are from 0.1 to 1.0 md.

NAYMIK, T. G., *The Application of a Digital Model for Evaluating the Bedrock Water Resources of the Maumee River Basin, Northwestern Ohio*, Lawrence Livermore Laboratory, Rept. UCRL-81548, Preprint (1978).

Increasing population and industrial development in northwestern Ohio has created the need for an evaluation of the bedrock ground-water resources of the region. A digital ground-water model was therefore designed and used as a tool for predicting water-level declines resulting from projected ground-water withdrawal. Potentiometric surfaces, keyed to historic, accelerated, and peak projected ground-water withdrawals, were predicted by decades to the year 2036. These withdrawals at the calculated rates will cause severe overdrafts at Lima, Toledo, and Findlay, Ohio, and at Ft. Wayne, Indiana, by the year 2036.

NAYMIK, T. G. and G. D. Mendez, *User's Manual for a Material Transport Code on the Octopus Computer Network*, Lawrence Livermore Laboratory, Rept. UCID-17986 (1978).

A code to simulate material transport through porous media was developed at Oak Ridge National Laboratory. This code has been modified and adapted for use at the Lawrence Livermore Laboratory. This manual, in conjunction with report ORNL-4928, explains the input, output, and execution of the code on the Octopus Computer Network.

NAYMIK, T. G., *User's Manual for a Two-Dimensional, Ground-Water Flow Code on the Octopus Computer Network*, Lawrence Livermore Laboratory, Rept. UCID-17908 (1978).

A ground-water hydrology computer code, programmed by R. L. Taylor [*Proc. Amer. Soc. Civ. Eng. J. Hydraulics Div.* 93(HY2), 25 (1967)], has been adapted to the Octopus computer system at Lawrence Livermore Laboratory. Using an example problem, this manual details the input, output, and execution options of the code.

NAYMIK, T. G., *An Application of a Method for Comparing One-Dimensional and Two-Dimensional Models of a Ground-Water Flow System*, Lawrence Livermore Laboratory, Rept. UCRL-52541 (1978).

To evaluate the inability of a one-dimensional ground-water model to interact continuously with surrounding hydraulic head gradients, simulations using one-dimensional and two-dimensional ground-water flow models were compared. This approach used two types of models:

- Flow-conserving one- and two-dimensional models.
- One-dimensional and two-dimensional models designed to yield two-dimensional solutions.

The hydraulic conductivities of controlling features were varied and model comparison was based on the travel times of marker particles. The solutions within each of the two model types compare reasonably well, but a three-dimensional solution is required to quantify the comparison.

OWEN, L. *Apparatus for Field Evaluation of Geothermal Effluent Injection*, Lawrence Livermore Laboratory, Rept. UCRL-81022, Preprint (1978).

Methods for evaluating subsurface disposal systems, based on data derived from membrane filtration tests and core flooding experiments, have been described in the literature. Utilizing these techniques, we have developed and successfully tested equipment for evaluation of injectability of any geothermal effluent including hypersaline brine from the Salton Sea Geothermal Field (SSGF).

Owen, L. B., J. D. TEWHEY, M. A. Chan, and P. W. Kasameyer, "Development of Injection Criteria for Geothermal Resources," *Geotherm. Resources Counc. Trans.* 2, 649 (July 1978). (Lawrence Livermore Laboratory, Rept. UCRL-81007, Preprint, 1978.)

Owen, L. B., J. R. HEARST, and P. W. Kasameyer, *Potential Uses for a High-Temperature Borehole*

Gravimeter, Lawrence Livermore Laboratory, Rept. UCRL-52421 (1978).

PIWINSKII, A. J. and D. L. Springer, *Propagation of Lg Waves across Eastern Europe and Asia*, Lawrence Livermore Laboratory, Rept. UCRL-52494 (1978).

We have assembled and discussed a large body of information published between 1954 and 1977 on Lg propagation across Asia and eastern Europe. The data from earthquakes located within the boundaries of the U.S.S.R. indicate that both short- and long-period Lg waves propagate efficiently across most of the Soviet Union land mass. The data from certain border regions, however, display erratic characteristics that may be due to propagation, source depth, or radiation pattern. These regions include paths across southern portions of the Black and Caspian Seas, the Caucasus Mountains, the Uzbek and Tadzhik Republics, the Sea of Okhotsk, and the northern seas (e.g., the Kara Sea). The only areas that appear to block Lg propagation completely are the central portions of the Sea of Japan and regions of the People's Republic of China.

PIWINSKII, A. J., *Experimental Investigations of the Permeability of Sandstones to Hypersaline Brine from 70° to 90°C at 10.3-MPa Confining Pressure*, invited lecture, Stanford University, May 1978.

Permeabilities of 10.2-cm-long, 2.5-cm-diam Kayenta (porosity, $20.7 \pm 1.66\%$) and St. Peter (porosity, $13.6 \pm 0.13\%$) sandstone samples to Salton Sea Geothermal Field brine containing suspended solids were determined from 70° to 90°C at 10.3-MPa confining pressure. Experiments were performed without filters, with one 10- μ m filter, and with two 10- μ m filters inserted upstream of the core sample. In all cases there was a dramatic decrease in permeability within the first hour of flow (the first few hundred pore volumes of flow through the core). Experiments which were conducted without filters or with one filter yielded permeabilities that represented both the rock and the 2- to 3-mm amorphous silica-iron layer on the top face of the core. Permeability decline may result from

the mobilization of calcite and precipitation of amorphous silica in the pore channels of the rocks.

PIWINSKII, A. J. and B. P. Bonner, "The Effect of Diagenetic and Hydrothermal Alteration on Sound Propagation in Sedimentary Rocks from the Dunes Borehole, Imperial Valley, California," *Trans. Am. Geophys. Union* **59**, 1201 (1978).

Ultrasonic pulse transmission (~800 kHz) has been employed to characterize a suite of sedimentary rocks obtained from the Dunes borehole. The mineralogy and petrology of the various deltaic sands, conglomerates, silts, and shales have been previously described by Bird and Elders, University of California at Riverside. Compressional velocity (V_p), shear velocity (V_s), and the corresponding acoustic impedances were measured for air-dried and brine-saturated (filtered Magmamax No. 1 brine, ionic strength: 3.5) 25.4-mm $\times$ 25.4-mm cylindrical cores at 25°C and 150 kPa. Relative pulse amplitudes of P were determined for the air-dried samples. V_p and V_s increase approximately by a factor of two, while the acoustic impedances increase nearly four times as the density of the sedimentary rocks increases from ~1.5 to 2.5 g/cm³ with extensive alteration. Relative pulse amplitudes increase by a factor of one hundred over the same density range for the air-dried samples. If this large apparent decrease in attenuation can be verified for seismic frequencies and amplitudes, high Q zones located by broadband seismic and logging techniques may be useful indicators of extensively altered regions in geothermal reservoirs.

Piwnskii, A. J., A. DUBA, M. Santor and H. C. Weed, "The Electrical Conductivity of Sandstone, Limestone, and Granite," *Geophys. J. R. Astr. Soc.* **53**, 583-597 (1978).

Piwnskii, A. J. and H. C. WEED, "Viscosity of Silicate Melts at 101.3 kPa (1 atm) from 1373 to 1923 K," *Trans. Am. Geophys. Union* **59**, 1219 (1978).

Piwnskii, A. J., H. C. WEED, and L. Dibley, *A High Temperature Viscometer for Use at 100 kPa*,

Lawrence Livermore Laboratory, Rept. UCRL-52477 (1978).

PUCHLIK, K. P., *Hydrogeochemical and Stream Sediment Reconnaissance Basic Data Report for Winnemucca NTMS Quadrangle, Nevada*, Lawrence Livermore Laboratory, Rept. UCRL-52469 (1978).

This report presents the results of geochemical reconnaissance sampling in the Winnemucca 1° $\times$ 2° quadrangle of the National Topographic Map Series (NTMS). We collected wet and dry sediment samples throughout the 18,770-km² arid to semi-arid area and water samples at available streams, springs, and wells. We present neutron activation analyses of uranium and trace elements and other measurements made in the field and laboratory in tabular hardcopy and microfiche format. The report includes 5 full-size overlays for use with the Winnemucca NTMS 1:250,000 quadrangle. Water sampling sites, water-sample uranium and thorium concentrations, sediment sampling sites, and sediment-sample total uranium and thorium concentrations are shown on the separate overlays. We present general geological and structural descriptions of the area, and describe the 12 known uranium occurrences.

The results indicate that the uranium geochemistry of the area is diverse. High concentrations (greater than 5 ppm) of uranium in sediments are associated mainly with rhyolitic ash falls and flows and silicic intrusives. In defining areas of interest the ratio of relatively insoluble thorium to uranium was considered. The anomalies as defined are then the sediment samples containing low Th/U and high uranium concentrations. These areas consist mainly of fluvial-lacustrine units. Most known uranium occurrences were also identified by this technique. The main Humboldt River shows an irregular increase in uranium concentration downstream which may be related to agricultural modification of the stream flow. U/Cl ratios were used to evaluate the effects of evaporative concentration. Of interest are spring and tributary waters containing high U/Cl and high uranium values. These waters mainly drain acid intrusives, silicic volcanic rocks and related sediments. One such area is the Shoshone and Cortez Mountains.

PUCHLIK, K. P., B. E. Holder, and C. F. Smith, *Raw Data Report Smoke Creek Desert Basin Orientation Study Lovelock and Susanville 1° X 2° NTMS Area, Nevada*, Lawrence Livermore Laboratory, Rept. UCID-17704 (1978).

This report presents the results of the Smoke Creek Desert Basin, Nevada, orientation study in the Lovelock and Susanville 1° X 2° quadrangles of the National Topographic Map Series (NTMS). Wet, dry, and playa sediment samples were collected throughout the 420-km² semi-arid, closed basin. Water samples were collected at the few available wells, streams, and springs. In addition to neutron activation analysis for uranium and 15 to 20 trace elements on all samples, field and laboratory measurements were made on water samples. Analytical data and field measurements are presented in tabular hardcopy and fiche format. Four full-size overlays for use with the Lovelock and Susanville NTMS 1:250,000 quadrangles are included. Water site locations, water sample uranium concentrations, sediment site locations, and sediment sample total uranium concentration are shown on the separate overlays. A general description of the area and the rock type distribution is presented.

PUCHLIK, K. P., B. E. Holder, and C. F. Smith, *Raw Data Report Winnemucca Dry Lake Basin Orientation Study Nevada*, Lawrence Livermore Laboratory, Rept. UCID-17699 (1978).

This report presents the results of the Winnemucca Dry Lake Basin, Nevada, orientation study in the Lovelock and Reno 1° X 2° quadrangles of the National Topographic Map Series (NTMS). Wet, dry, and playa sediment samples were collected throughout the 597-km² semi-arid, closed basin. Water samples were collected at the few available streams and springs. In addition to neutron activation analysis for uranium and 15 to 20 trace elements on all samples, field and laboratory measurements were made on water samples. Analytical data and field measurements are presented in tabular hardcopy and fiche format. Eight full-size overlays for use with the Lovelock and Reno NTMS 1:250,000 quadrangles are included. Water sample site locations, water sample

uranium concentration, sediment sample site locations, and sediment sample total uranium concentration are shown on the separate overlays. A general description of the area and the rock type distribution is presented.

QUITQUIT, W. A., G. P. Ledbetter and A. L. Henry, *Earth Sciences Division, Collected Abstracts—1977*, Lawrence Livermore Laboratory, Rept. UCRL-52514 (1978).

RALEY, J. H., "Evaluation of Retort Performance From Gas Data," prepared for 12th Oil Shale Symposium, Golden, Colorado, April 18-20, 1979. (Lawrence Livermore Laboratory, Rept. UCRL-82079, Preprint, 1978).

Improved methods for diagnosis and control are especially valuable for *in situ* retorts because of limited emplaced instrumentation. The possibilities for using off-gas data to monitor performance will be illustrated by results from simulated *in situ* retort operations. Alkene/alkane ratios in the gas indicate overall effective shale heating rate, existence of localized high temperatures, and particle size effects in oil yield. Other gas components reflect stream reactions, gas bypassing, and kerogen conversion. Both intra-retort and off-gas data may also be employed to monitor operation of surface retorts.

RALEY, J. H., "Use of Off-Gas Data for Retort Diagnosis and Control," Oil Shale Conversion Symposium, Grand Junction, Colorado, December 6-8, 1978. (Lawrence Livermore Laboratory, Rept. UCRL-81912, Preprint, 1978).

Data from operating 125-kg and 6000-kg oil shale retorts in a simulated, *in situ* mode illustrate the utility of off-gas measurements for retort monitoring. Alkene/alkane ratios in the off-gas reflect changes in the effective shale heating rate, fluctuations in peak temperature, or localized, intense heating. Hydrogen content indicates the extent of chemical participation of water during stream-air combustion retorting. Response time to changing retort conditions is short. Off-gas data may be particularly useful for *in situ* retorts with limited emplaced instrumentation.

RALEY, J. H., W. A. Sandholtz, and F. J. Ackerman, "Results from Simulated, Modified *In-Situ* Retorting in Pilot Retorts," 11th Oil Shale Symp., Golden, Colorado, April 12-14, 1978.

Data obtained from operating 1.5-m $\times$ 0.3-m and 6-m $\times$ 0.9-m laboratory retorts to simulate a modified *in situ* process are summarized. The effects of feed-gas composition, including addition of steam, shale particle size, and bed porosity on retorting rate, temperature maxima and profiles, off-gas composition, and oil yield are presented. Inclusion of steam is shown to increase retorting rate, reduce maximum temperature, and markedly increase hydrogen content of the off-gas. With a narrow shale particle size range, the experimental data agree well with model calculations based on the underlying physical and chemical processes. The experimental results with a broader range of particle size indicate complexities possibly due to gas flow non-uniformity and oil holdup. The use of intra-retort gas composition and temperature data to detect and interpret these complexities is demonstrated.

Raley, J. H., W. A. SANDHOLTZ, and F. J. Ackerman, "Simulated Modified *In-Situ* Oil Shale Retorting, Pilot-Experiments and Results," to be presented at the American Institute of Chemical Engineers Meeting, April 1-5, 1979, Houston, Texas.

RAMBO, J. T. and B. L. Coles, *User's Manual for the Livermore Economic Modeling System*, Lawrence Livermore Laboratory, Rept. UCRL-52526 (1978).

Analysts and programmers in the Energy and Resource Planning Group at the Lawrence Livermore Laboratory have developed an Economic Modeling System (EMS) consisting of software and a special input language for representing markets and economic processes and solving for market clearing prices and quantities. EMS is the foundation of the Livermore Energy Policy Model (EPM), which is now being used to analyze the effects of governmental policies on the energy sector of the U.S. economy through the year 2025.

This manual was prepared for the EMS user who wishes to run his own calculations and for the production assistant who needs to understand the procedures for maintaining EMS. The names, locations, functions, and execute lines of each of the EMS programs are given, together with examples of the format of input and output files. EMS was designed for a CDC 7600 computer.

Rambo, J. T., W. F. ROUSSEAU, S. S. Sussman, and R. N. Castleton, *Economic Models and Algorithms Used in the Livermore Economic Modeling System*, Lawrence Livermore Laboratory, Rept. UCRL-52527 (1978).

This report presents the economic models and equation solution methods built into the Livermore Economic Modeling System (EMS). Networks, microeconomic models, solution by iteration, and simulation of government-imposed constraints are all discussed. Microeconomic models are described in great detail in nomenclature similar to that used in the data set. References to other EMS reports are included.

Rambo, J. T., W. F. ROUSSEAU, R. N. Castleton, and S. S. Sussman, *Computer Code Documentation for the Livermore Economic Modeling System*, Lawrence Livermore Laboratory, Rept. UCRL-52519 (1978).

The Livermore Economic Modeling System (EMS) is a package of computer codes for constructing, solving, and presenting results from general equilibrium economic models. To be used with other documentation on EMS and on the Livermore Energy Policy Model (EPM), this report provides additional information for the programmer who must maintain the codes or convert them to another installation. A brief overview is presented on each code. Interactions between codes are defined and key internal data and file structures are described in detail. Practical information on compiling and debugging changes is provided. Included also on microfiche is a complete program listing with extensive comments.

Rambo, J. T., R. W. TERHUNE, H. D. Glenn, D. E. Burton, and H. L. McKague, *Numerical*

Simulation of the Baneberry Event, Lawrence Livermore Laboratory, Rept. UCRL-81807, Preprint (1978).

Rambo, J. T., R. W. TERHUNE, H. D. Glenn, D. E. Burton, and H. L. McKague, *Calculational Study of the Baneberry Event*, American Physical Soc. Mtg., June 11-13, 1979.

RAMSPOTT, L. D., *Waste Isolation Projects—FY 1977*, Lawrence Livermore Laboratory, Rept. UCRL-50050-77 (1978).

RAMSPOTT, L. D., *Laboratory and Field Measurements of Granitic Rocks Under Repository Stress Conditions*, to be presented at Society for Experimental Stress Analysis Meeting, May 20-25, 1979, San Francisco, California.

The Lawrence Livermore Laboratory (LLL) is making laboratory and field measurements for input to safety analysis and design of a nuclear waste repository in granitic rock. In the laboratory, the thermal properties are measured as a combined function of temperature, confining pressure, and pore fluid, and permeability and other mechanical/electrical properties are measured as a function of confining pressure, pore fluid pressure, and deviatoric stress. In the field, LLL has carried out tests during heating of granitic rock at the Nevada Test Site (NTS). As part of these tests, rock permeability adjacent to boreholes has been measured as a function of rock temperature. The current status of LLL field programs in granitic rock at the NTS will be reviewed.

Rodean, H. C., D. H. CHUNG and M. E. Hummell, "Attenuation in the Upper Mantle of the Basin and Range Province," *Trans. Am. Geophys. Union* 59, 319 (1978).

ROHRER, R. F., *Selected Surface-Motion Measurements from High-Explosive Cratering Experiments at Big Black Test Site in Mississippi During 1976-1977*, Lawrence Livermore Laboratory, Rept. UCRL-52457 Rev. 1 (1978).

In 1976 and 1977, Lawrence Livermore Laboratory conducted a series of single- and row-charge cratering experiments for possible application in various excavation projects. This report describes a selected number of those experiments, giving the onset of first motion, peak spall velocity, onset of gas acceleration, and velocity at the end of gas acceleration for the center target of each single-charge experiment and for every target in the row-charge experiments. Graphs illustrate the unsmoothed displacement of each target as a function of time. For each single-charge experiment, peak velocities are compared to crater dimensions and the charge depth that produced the highest velocity and largest crater dimension is identified. Peak velocities from the row-charge experiments are also related to charge depth and spacing to determine an optimum depth for the single charges as well as an optimum depth and spacing for the row charges that produced the highest surface velocities.

ROTHMAN, A. J., "Experimental Work on Retorting of Oil Shale at Lawrence Livermore Laboratory," 11th Engineering Conf. on Particle Sci. and Eng., Pacific Grove, California, June 18-23, 1978.

A program aimed at eventual commercial extraction of oil from oil shale by a modified *in situ* process has been active at Lawrence Livermore Laboratory for five years. The process uses mining and high explosives to form a column of oil shale rubble, which is then retorted (pyrolyzed) in place using combustion in a continuous supply of air and diluent gas. The experimental program is directed toward understanding of oil-shale retorting. Much of the effort involves retorting of oil shale particles in above-ground pilot units outfitted with heaters at the walls for heat loss compensation. A comprehensive retort computer system is used for operation, control, and data acquisition. Supporting laboratory work includes studies of oil generation and degradation kinetics in powders and blocks, decomposition kinetics, and reactions of mineral carbonates in oil shale, and reactions of oil shale char with oxygen, steam, and carbonate. Submodels have been developed for these processes in blocks, and an overall one-dimensional retorting model has been developed from fundamental mechanisms

based on laboratory data. The model is used to interpret and predict pilot retorting data without the use of empirical constants, and does so successfully with monodisperse particles 1-2 cm in diameter. However, broad ranges of particle size including fines show different behavior, viz., higher, fluctuating peak temperatures and lower yields than predicted by the model. These effects appear to be related to nonuniform gas flow and apparent liquid "plugging" in the rubble, as evidenced by temperature patterns and gas pressure drop behavior. Further development of the model and supporting research is underway to deal with such complexities.

ROTHMAN, A. J. and A. E. Lewis, "Recent Experimental Developments in the Modified *In Situ* Oil Shale Program at Lawrence Livermore Laboratory," American Institute of Chemical Engineers Meeting, Miami, Florida, November 12-16, 1978.

The Lawrence Livermore Laboratory has been engaged in a program aimed at extraction of oil from thick oil shale deposits. The modified *in situ* process proposed involves forming oil shale rubble in columns underground by mining out a portion of the shale and breaking up the remainder using conventional high explosives. The organic material (kerogen) is then pyrolyzed to oil, gaseous components, and char by a stream of hot gas, produced by the burning of the residual char in air. The experimental program includes retorting studies in two pilot retorts up to 6 m high and laboratory studies to determine the rates and heats of the reactions of both organic materials and inorganic components, especially carbonates. Studies were also made of the degradation of the oil to coke and gaseous products, and the results interpreted by appropriate models. Finally an overall retorting model was derived from basic heat and mass transfer and chemical reactions to predict the effects of parameters such as particle size, inlet gas flow rate, and composition on yield, outlet gas composition, and temperature profile. Among the developments to be discussed are the effect of steam diluent on retorting, especially on gas composition and the effect of both large particles and fines on nonuniform gas flow and nonuniform burning.

Rothman, A. J., W. A. SANDHOLTZ, F. J. Ackerman, W. C. Miller, E. Cope, J. Ronchetto, *The Lawrence Livermore Laboratory Oil Shale Retorts*, Lawrence Livermore Laboratory, Rept. UCRL-52551 (1978).

SANDHOLTZ, W. A., J. H. Ruley, and F. J. Ackerman, "Simulated Modified *In-Situ* Oil Shale Retorting, Pilot Experiments and Results," to be presented at the American Institute of Chemical Engineers Meeting, April 1-5, 1979, Houston, Texas.

Features of *in situ* oil shale processing simulated in laboratory retorts are void fraction in the shale bed and low heat losses to the environment. Experimental results with and without heat loss control are compared. The axial temperature profile is markedly influenced by heat losses.

Reasonable agreement exists between experimental measurements and a predictive computer model of retorting rates, temperature profiles, and oil yields. Oil yields of more than 90% of Fischer assay have been realized in these experiments. Typically, yield is lower from beds of wide particle size range than from a narrow range of particle sizes. Experimental results with a broad range of shale particle sizes show process complexities owing to oil holdup and gas flow distribution. Intra-retort temperatures and gas compositions aid interpretation of these data. Steam as a feed-gas diluent is shown to increase retorting rate, oxygen efficiency, and hydrogen content of the off-gas. Even though the increased hydrogen raises the heating value of the off-gas, it is a minor effect owing to the dominant influence of the C_4^+ constituents.

SANDHOLTZ, W. A., F. J. Ackerman, A. J. Rothman, W. C. Miller, E. Cope, J. Ronchetto, *The Lawrence Livermore Laboratory Oil Shale Retorts*, Lawrence Livermore Laboratory, Rept. UCRL-52551 (1978).

Two retorts and their supporting systems have been developed at LLL to simulate some aspects of modified *in situ* retorting of oil shale. This report first describes the retorts, their gas flow and product collection systems, and their instrumentation and

process control. Thereafter, it deals with the preparation and characterization of raw shale rubble for retort experiments. The report continues with a discussion of the single dedicated minicomputer that serves both retorts. The retort computer system is multifunctional, providing data acquisition and storage, process monitoring and control, and data reduction and display. Finally, limited experimental results are presented that demonstrate some capabilities of the retort systems and the retort computer system.

Sandholtz, W. A., J. H. RALEY, and F. J. Ackerman, "Results from Simulated, Modified *In-Situ* Retorting in Pilot Retorts," 11th Oil Shale Symp., Golden, Colorado, April 12-14, 1978.

SCHATZ, J. F. and M. M. Carroll, "Volumetric Response of Wet Porous Rock Based on Spherical Model," 1978 Spring Meeting, Am. Geophys. Union, March 1978.

The spherical pore model has been previously applied, with success, to the loading and unloading response of dry porous rock. Inelastic behavior, such as hysteresis during cycling, are well predicted. This work extends the spherical model to pores containing water. It has been previously observed, in porous, waterbearing rock, that the apparent order of the first water phase transition is reduced as the rock is loaded to sufficient pressure. This is evidenced by a smooth, rather than abrupt, reduction of volume during a pressure-volume test. This behavior is usually attributed to a distribution of internal pressure among the pores caused by varying pore geometry, and resulting in the water in each pore undergoing its phase transition at different values of external pressure. The spherical pore model, however, correctly predicts the smoothing of the phase transition without using a pore geometry that varies from pore to pore. Instead, the inelastic-to-elastic transition boundary surrounding the pore moves outward during the water transition, and the pressure at the outer boundary of the rock is forced to increase smoothly with respect to its volume change. Although few pores in rock are truly spherical, this work demonstrates again that a simple model using equivalent spherical pores can be successful, if the matrix solid material is allowed to have the appropriate inelastic behavior.

Schatz, J. F. and M. G. AUSTIN, "Seismic Wave Propagation Modeled on a Digital Computer: Effect of Variation in Rock Properties," presented at the Spring Annual Meeting, American Geophysical Union, 1978.

Schatz, J. F., P. W. KASAMEYER, and J. A. Cheney, *A Method of Using In Situ Porosity Measurements to Place an Upper Bound on Geothermal Reservoir Compaction*, Lawrence Livermore Laboratory, Rept. UCRL-80984, Preprint (1978). (Prepared for U. C. Berkeley Well Testing Symposium, October 1978.)

Schatz, J. F., A. S. KUSUBOV, and T. J. Ahrens, "Shock Wave Generated Fractures Under Confining Pressures," *Bull. Am. Phys. Soc.* 23, 70 (1978).

Schatz, J. F., R. P. SWIFT, W. B. Durham, J. R. Hearst, and A. S. Kusubov, "Effect of Simultaneous and Sequential Detonation on Explosive-Induced Fracture," *Proc Nineteenth U.S. Sympos. Rock Mech.*, Y. S. Kim, Ed. (Mackay School of Mines, University of Nevada, Reno, 1978), p. 235.

Schatz, J. F., R. P. SWIFT, and W. B. Durham, "Explosive-Induced Fracture Effects from Sequential and Simultaneous Detonations," *Trans. Am. Geophys. Union* 59, 379 (1978).

SCHNORR, J. K., *Environmental Impact Assessment: Enhanced Gas Recovery by Massive Hydraulic Fracturing in Lincoln County, West Virginia*, Lawrence Livermore Laboratory, Rept. UCID-17896 (1978).

The U. S. Department of Energy, through the Morgantown Energy Technology Center, has contracted with the Columbia Gas Transmission Corp. to share the cost of a field experiment of the Massive Hydraulic Fracturing (MHF) process for natural gas recovery. The project is part of a larger program to develop reservoir stimulation techniques for natural gas within the Devonian Shale formation of the Appalachian region. The experiment will take place in Lincoln County, W. Va., and

will include the preparation of sites and the stimulation of three wells by the MHF process. The size and duration of the program are such that no significant environmental degradation is expected.

Schock, R. N., A. S. KUSUBOV, and T. J. Ahrens, "Rock Fracture Under Confining Pressure," *Trans. Am. Geophys. Union* 59, 1191 (1978).

SCHWARTZ, L. L., D. O. Emerson, J. D. Tewhey, and W. J. Beiriger, "The Importance of Geosciences in Developing *In Situ* Technologies for Energy Resource Recovery," poster session presented at the Annual Meeting of the American Association for the Advancement of Science, February 12-17, 1978, Washington, D.C.

Technologies for energy resource recovery through modifying or processing the resource *in situ* are receiving renewed emphasis as a result of improved economics for recovery of low-grade, deeper, or more difficult-to-recover resources. In addition, there are perceived environmental advantages of *in situ* processing over some conventional methods. Because the major processing activities (fracturing, fluid flow, heating or chemical modification) take place in the formation at depth, the geosciences play an important role in developing these technologies and assessing their environmental impacts. Some of the geoscience topics of major concern are 1) the mechanical response of formation rocks to explosive or hydraulic fracturing; 2) geochemistry relevant to chemical processing and environmental effects; 3) geochemical considerations for underground and surface stability; and 4) geological and hydrological criteria and assessment for site suitability. Ongoing studies dealing with these are presented for *in situ* technologies in coal gasification, oil shale, and gas stimulation.

Shaffer, R. J. and M. E. HANSON, "Some Results from Continuum Mechanics Analyses of the Hydraulic Fracturing Process," 1979 Symposium on Low-Permeability Gas Reservoirs, May 20-22, 1979, Denver, Colorado (Lawrence Livermore Laboratory, Rept. UCRL-81707, Preprint, 1978).

Shaffer, R. J., D. O. Emerson, H. C. Heard, B. C. Haimson, M. E. HANSON and G. D. Anderson, "Some Theoretical and Experimental Considerations of the Hydraulic Fracturing Process and Supporting Research," *Proc. Second Eastern Gas Shales Symp. METC-SP-78/6*, Vol II (1978).

Shaffer, R. J., M. E. HANSON, G. D. Anderson, D. M. Montan, B. Haimson, and M. P. Cleary, *LLL Gas Stimulation Program, Quarterly Progress Report, January through March 1978*, Lawrence Livermore Laboratory, Rept. UCRL-50036-78-1 (1978).

Shaffer, R. J., M. E. HANSON, G. D. Anderson, D. O. Emerson, H. C. Heard, and B. D. Haimson, "Theoretical and Experimental Research on Hydraulic Fracturing," *Proc. 4th Annual DOE Symp. on Enhanced Oil and Gas Recovery and Improved Drilling Methods*, August 29-31, Tulsa, Oklahoma. (Lawrence Livermore Laboratory, Rept. UCRL-80969, Preprint, 1978.)

Shaffer, J. R., M. E. HANSON, G. D. Anderson, R. J. Shaffer, J. R. Hearst, B. Haimson, and M. P. Cleary, *LLL Gas Stimulation Program, Quarterly Progress Report, April through June 1978*, Lawrence Livermore Laboratory, Rept. UCRL-50036-78-2 (1978).

Shaffer, R. J. and M. E. HANSON, "Some Continuum Considerations of the Hydraulic Fracturing Process," prepared for presentation at the 19th U. S. Symposium on Rock Mechanics, May 1-3, 1978, Lake Tahoe, Nevada. (Lawrence Livermore Laboratory, Rept. UCRL-80360, Preprint, 1978.)

Shaffer, R. J. M. E. HANSON, and G. D. Anderson, "Theoretical and Experimental Research on Hydraulic Fracturing," prepared for the ASME Petroleum Division's 1978 Energy Technology Conference, November 5-8, 1978, Houston, Texas. (Lawrence Livermore Laboratory, Rept. UCRL-80558, Preprint, 1978.)

Shaffer, R. J., M. E. HANSON, G. D. Anderson, D. M. Montan, W. Lin, B. Haimson, and M. P.

Cleary, LLL Gas Stimulation Program, Quarterly Progress Report, October through December 1978, Lawrence Livermore Laboratory, Rept. UCRL-50036-77-4 (1978).

Shaffer, R. J., M. E. HANSON, G. D. Anderson, D. O. Emerson, R. P. Swift, K. O'Banion, M. P. Cleary, B. Haimson, C. F. Knutson, and C. R. Boardman, LLL Gas Stimulation Program, Quarterly Progress Report, July through September 1978, (Lawrence Livermore Laboratory, Rept. UCRL-50036-78-3, 1978.)

Sherman, N. and F. J. ACKERMAN, MOVIES: A Computer Code to Generate Contour Plots of Retort Temperature Data, Lawrence Livermore Laboratory, Rept. UCID-17849 (1978).

Smith, H. E., J. S. H'IEBNER, A. Duba, and L. B. Wiggins, "Electrical Conductivity of Orthopyroxene: Measurements and Implications," *Proc. Lunar Planet. Sci. Conf. 9th* (Pergamon Press, New York, 1978).

Springer, D. L. and A. J. PIWINSKII, *Propagation of L_R Waves across Eastern Europe and Asia*, Lawrence Livermore Laboratory, Rept. UCRL-52494 (1978).

Steinborn, T. L. and J. J. COHEN, "The Rock-Melt Approach to Nuclear Waste Disposal in Geological Media," presented at Materials Research Society Meeting, Boston, Massachusetts, December 1978.

Steinborn, T. L., T. R. DONICH, A. M. Kaufman, G. D. Sauter, and D. F. Towse, *Additional Media Studies for Site Suitability Criteria (Nuclear Waste Disposal)*, Lawrence Livermore Laboratory, Rept. UCID-17887 (1978).

SWIFT, R. P., J. F. Schutz, W. B. Durham, J. R. Hearst, and A. S. Kusubov, "Effect of Simultaneous and Sequential Detonation on Explosive-Induced Fracture," *Proc. Nineteenth U.S. Sympos. Rock Mech.*, Y. S. Kim, Ed.

(Mackay School of Mines, University of Nevada, Reno, 1978), p. 235.

Tests were conducted in samples of polystyrene to study the effects of detonation delay on explosively induced fracturing. Two explosive charges in separate emplacement holes were fired at several choices of delay. The effect of free surfaces was minimized to make the experiments a study of blast-induced fracturing in a confined mode, i.e., deeply buried. All fractures formed on radial planes with respect to the emplacement holes. Simultaneous firing connected emplacement holes and produced fractures strongly oriented in the plane of the holes. Delayed firings in the second hole tended to suppress fracturing in the general direction of the first shot hole but to enhance fracturing away from the first hole. The effect was most dramatic in the "medium" delay firings; i.e., where the delay time was comparable to the dilatational wave transit time between holes. Using total surface area of cracks as a measure of damage, it was found that no choice of delay, including zero delay, could enhance the per-hole damage above that produced by an isolated shot. For medium delays, in fact, the total damage was measurably reduced.

SWIFT, R. P., W. B. Durham, and J. F. Schatz, "Explosive-Induced Fracture Effects from Sequential and Simultaneous Detonations," *Trans. Am. Geophys. Union* **59**, 379 (1978).

Experiments to study the effect of simultaneous and sequential detonations of explosive charges on the fracture pattern induced around two emplacement holes were conducted with cylindrical polystyrene blocks using 38 mg PETN detonator charges. Emplacement hole center-to-center spacings were varied, with charges detonated simultaneously, at short sequential delays on the order of wave transit time between charge spacing, and at delay orders of magnitude greater than wave transit time. Observations show that fractures are initiated by the circumferential tension developed from the divergent stress wave. For simultaneous and short sequential delay detonations regions of inhibited fracture and enhanced fracture are evident. Inhibited damage is a result of the stress wave interacting in a way that the tension necessary to

initiate or sustain fracture is prevented. Enhanced fracture occurs along the plane joining the emplacement holes and in extension of outgoing fractures that are nearly parallel to this plane. Simultaneous detonation is more effective than sequential detonation in connecting the emplacement holes. Fracture caused by the first shot in long delayed detonations are randomly oriented and do not necessarily "see" the other hole. These fractures mask the presence of the first hole from the second hole when it is shot and consequently, fractures caused by the second shot do not necessarily connect the holes. The results are indicative that permeability around and between emplacement holes will be directional and strongly dependent on hole spacing and firing sequence.

Swift, R. P., M. E. HANSON, G. D. Anderson, R. J. Shaffer, D. O. Emerson, K. O'Banion, M. P. Cleury, B. Haimson, C. F. Knutson, and C. R. Boardman, *LLL Gas Stimulation Program, Quarterly Progress Report, July through September 1978*, Lawrence Livermore Laboratory, Rept. UCRL-50036-78-3 (1978).

TERHUNE, R. W., *Analysis of Depth of Burial Criteria for Containment*, Lawrence Livermore Laboratory, Rept. UCRL-52395 (1978).

The testing of nuclear weapons requires that the devices be buried at a sufficient depth to assure containment of the radioactive gases. Testing experience over the last twenty years has led to historic depth of burial criteria. This paper examines the explosion phenomenology behind these historic rules, and proposes a model which appears to explain them. The model identifies two key material properties important to containment. These are the sound speed to the surface and the shear strength of the media. The model is applied to approximately 400 past detonations. The results are encouraging but not conclusive; however, specific events have been pinpointed for further study for specific reasons. An explanation as to why low-yield events are a greater containment hazard than large yield events is also given.

TERHUNE, R. W. and H. D. Glenn, *Estimate of Residual Shear Strength Around Explosion Cavities*

in Earth Media, Lawrence Livermore Laboratory, Rept. UCRL-80393, Preprint (1978).

A method to determine the residual shear strength of the fractured rock surrounding an explosion has been developed using measured or inferred cavity radii. The residual shear strength of the fractured rock, after passage of the initial shock wave, controls the subsequent dynamic motion of the rock and the residual stresses which can reduce the permeability.

Numerical computer codes that model the explosion phenomenology are utilized to develop the functional relationship between the normalized cavity displacement and the normalized shear strength of the rock. In this sense the computer models serve the role of a replica model to which dimensional analysis is applied to interpret the field experience. The effects of gravity and overburden pressure are separated from the effects of the material properties, and scaling laws for each are given. The analysis is applied to approximately 500 nuclear detonations at the Nevada Test Site for a variety of rock types. Good agreement was obtained between the predicted shear strengths and those from numerous laboratory measurements on core samples.

TERHUNE, R. W., H. D. Glenn, D. E. Burton, H. L. McKague, and J. T. Rambo, *Numerical Simulation of the Baneberry Event*, Lawrence Livermore Laboratory, Rept. UCRL-81807, Preprint (1978).

On December 18, 1970, Baneberry, a 42-TJ (10-kt) nuclear device, was detonated at a depth of 278 m in hole U8d at the Nevada Test Site. A shock-induced fissure near ground zero opened and vented radioactive gases and debris into the atmosphere. This report presents calculational results describing the sequence of dynamic phenomena that produced the vent. The calculations predict the experimentally observed surface motion and long positive-velocity pulse. The surface fissure through which the material vented is the same radial distance from ground zero as the maximum horizontal displacement is calculated to be. Also, the calculations indicate an explosive-induced extension of the Baneberry fault to the surface, and this extension was observed in pictures of the surface motion and

later confirmed by postshot on-site inspection. The final calculated cavity radius is very close to the measured Baneberry cavity radius. Finally, the calculations indicate that an open fracture path was generated that runs from the cavity to the Baneberry fault, up the fault to the spall region, and then vertically to the surface. This vent path predicted by the calculations is consistent with the vent path found from the radioactivity in postshot drill holes. The extensions in computational capabilities in this work advance the state of the art for numerical simulation of the containment aspects of underground nuclear tests.

TERHUNE, R. W., H. D. Glenn, D. E. Burton, H. L. McKague, and J. T. Rambo, *Calculational Study of the Baneberry Event*, American Physical Society, June 11-13, 1979.

On December 18, 1970, Baneberry, a 10-kt nuclear device, was detonated at a depth of 278 m in hole U8d at the Nevada Test Site. A shock-induced fissure near ground zero opened and vented radioactive gases and debris into the atmosphere. This report presents the calculational results describing the sequence of dynamic phenomena that produced the vent. The calculations predict the long positive velocity pulse and the surface motion that were observed experimentally. The surface fissure through which the material vented is the same radial distance from ground zero as the maximum horizontal displacement is calculated to be. The calculations predict a final cavity radius that is very close to the measured Baneberry cavity radius. Finally, the calculations indicate that an open fracture path runs from the cavity to the Baneberry Fault, up the fault to the spall region, and then vertically to the surface. This was the vent path predicted by calculations and is consistent with the vent path found from the radioactivity in postshot drill holes. Because of our extensions in computational capabilities, we believe this report advances the state of the art for numerical simulation of the containment problems associated with underground nuclear tests.

TEWHEY, J. D., M. A. Chan, W. Kusameyer, and L. B. Owen, "Development of Injection Criteria

for Geothermal Resources," *Geotherm. Resources Counc. Trans.* 2, 649 (July 1978). (Lawrence Livermore Laboratory, Rept. UCRL-81007, Preprint 1978.)

The ability to inject large quantities of brine effluent will be an important factor in the development of liquid-dominated geothermal systems. Experimental studies have been conducted by the Earth Science Division of the Lawrence Livermore Laboratory (LLL) to evaluate injection of "spent" geothermal brine at the Salton Sea Geothermal Field (SSGF). The studies have dealt principally with the injectability of suspended solids that are produced in the brine during the energy conversion process. In the experimental plan, the subsurface medium was represented by membrane filters with pore diameters ranging from 0.4 to 10 microns and by sandstone core material. Changes in permeability with time were evaluated with respect to the following variables: (1) prefiltration of brine upstream from the core or membrane filter, (2) brine temperature (20°C to 100°C), (3) brine pH, and (4) confining pressure.

Tewhey, J. D., L. L. SCHWARTZ, D. O. Emerson, and W. J. Beiriger, "The Importance of Geosciences in Developing *In Situ* Technologies for Energy Resource Recovery," poster session presented at the Annual Meeting of the American Association for the Advancement of Science, February 12-17, 1978, Washington, D.C.

THIGPEN, L. and R. C. Y. Chin, *Waves in a Linear Viscoelastic Medium—Asymptotic Theory*, Lawrence Livermore Laboratory, Rept. UCRL-80760, Preprint (1978).

Uniformly valid asymptotic solutions are developed for the one-dimensional wave equation in a linear viscoelastic solid. In particular, the long-time behaviors resulting from an impulse, a unit step function, and a harmonic oscillation are investigated. The asymptotic solutions illustrate the effect of the dispersive-attenuation process. Results show a small-amplitude precursor, a diffusive main wave, and a boundary layer. The precursor

propagates at a speed corresponding to the instantaneous modulus and decays exponentially with distance. The main wave travels at a speed corresponding to the equilibrium modulus and spreads diffusively. The approximating equations using perturbation methods reveal that the decay of the precursor results from relaxation processes and that the diffusive behavior results from cumulative dispersion.

Thomsen, J. M., M. E. HEUSINKVELD, and J. B. Bryan, *Calculations for Miss Jade Underground Nuclear Test*, Lawrence Livermore Laboratory, Rept. UCRL-52579 (1978).

Thomsen, J. M., M. E. HEUSINKVELD, and J. L. M. Cortez, *Scaling of Shallowly Buried Nuclear Explosions*, Lawrence Livermore Laboratory, Rept. UCRL-52439 (1978).

Thorson, L. D. and J. G. MORSE, "Reservoir Engineering Study of a Portion of the Sulton Sea Geothermal Field," *Geotherm. Resources Counc. Trans.* 2, 471 (July 1978).

TOWSE, D., *Geoscience Parameter Data Base Handbook: Bedded Salt*, Lawrence Livermore Laboratory, Rept. UCRL-52557 (1978).

This handbook contains representative data useful for assessing radiological risks associated with repositories for high-level, transuranic, and spent-fuel wastes. The data will also be useful for deriving generic deep geological modeling parameters and as a standard for weighing other data presented in licensing applications for deep geological waste repositories. More data are now being developed by a subcontractor. Later revisions will contain mechanical and thermal data more relevant to facility design. The main text of this handbook (Sections 1 through 5) provide general information. Detailed tables of data are given in the appendices. Future editions will contain additional information on salt and on other media.

TOWSE, D., *Geologic Factors in Nuclear Waste Disposal*, Lawrence Livermore Laboratory, Rept. UCRL-52522 (1978).

Before nuclear wastes can be disposed of safely in geologic media, the hydrology, chemistry, and geometry of the nuclear waste migration process must be analyzed. Hydrologic effects are determined by analyzing the porosity and permeability (natural and induced) of rock as well as pressures and gradients, dispersion, and the aquifer length. Chemistry parameters include radionuclide retardation factors and the waste dissolution rate. Geometric parameters (i.e., parameters with dimension) evaluated include repository layer thickness, fracture zone area, tunnel length, and aquifer length. The above parameters act as natural barriers or controls to nuclear waste migration, and are evaluated in three potential geologic media: salt, shale, and crystalline rock deposits. Parametric values are assigned that correspond to many existing situations. These values, in addition to other important inputs, are lumped as a hydrology input into a computer simulation program used to model and calculate (1) nuclear waste migration from the repository to the biosphere and (2) potential individual and population dose and radiation effects. These results are preliminary and show trends only; they do not represent an actual risk analysis.

Towse, D. F., R. A. HECKMAN, D. Isherwood, T. Harvey, and T. Holdsworth, *High Level Waste Repository Site Suitability Study—Status Report*, Lawrence Livermore Laboratory, Rept. UCRL-52633 (1978).

The disposal of high-level radioactive waste in an underground repository requires a means of determining the suitability of the repository site from the point of view of public health and safety. The main purpose of our study is to identify and analyze the physical factors that are important for making this determination. This work involves the analysis of relevant geologic events and their effects on geohydrologic parameters, the modeling of waste transport through the hydrologic system, and the calculation of associated radiologic risk.

A physical model has been developed for use in our studies of release scenarios. It consists of six horizontal layers whose parameters and dimensions we can vary to simulate a natural environment that is similar to many possible sites. The variables define the environment that determines the configurations and lengths of flow paths, as well as the

properties that influence flow rates and waste concentrations. Among other variations we can make are the composition and solubilities of the waste source and the climatic influences on water table levels, pressures, and pressure gradients. We can therefore study the effects of fractures around the repository, faults, solution breccia pipes, boreholes, and shorter aquifer paths to the biosphere.

In addition to the physical model, we have developed a series of computer simulation programs representing the mathematical models. We use these to calculate the performance of hypothetical repository sites.

Towse, D. F., T. R. DONICH, A. M. Kaufman, G. D. Sauter, and T. L. Steinborn, *Additional Media Studies for Site Suitability Criteria (Nuclear Waste Disposal)*, Lawrence Livermore Laboratory, Rept. UCID-17887 (1978).

Site suitability studies at LLL to date have considered repositories in bedded salt and shale. The models have been varied to include a number of dimensions, parameter values, histories, and potential failure modes. These model studies have enabled us to provide preliminary site suitability criteria based on parameter sensitivity calculations and to begin uncertainty analyses. In this report we consider domed salt, basalt, and crystalline rock, comparing these three media with each other and with bedded salt and shale. Comparisons are made on the basis of:

- The estimated level of effort required to develop models for these media that are similar in quality to those now available for bedded salt and shale. (The models must therefore consider regional and local migration of wastes, recharge of the repository, dissolution, and other special effects.)
- Our present state of knowledge about the important physical and chemical properties of these media and the estimated level of effort necessary to develop data bases for each that are comparable to the data base we currently have for bedded salt and shale.
- An evaluation of each medium as a suitable repository environment. (The evaluation is based on construction costs, colocation of other resources, availability of potential repository sites, retrievability of stored wastes, and suitability of physical and chemical properties.)

Trimmer, D., H. C. HEARD, W. Lin, B. Bonner and A. Duba, "Permeability of Generic Repository Rocks at Simulated *In Situ* Conditions," prepared for Sympos. Underground Disposal Radioactive Wastes, International Atomic Energy Agency, Otaniemi, Finland, July 1979.

Trimmer, D., W. Lin, B. Bonner, A. Duba and H. C. HEARD, "Permeability of Generic Repository Rocks at Simulated *In Situ* Conditions," Symp. Underground Disposal Radioactive Wastes, International Atomic Energy Agency, Otaniemi, Finland, July 1979.

WAGONER, J., *Hydrogeochemical and Stream Sediment Reconnaissance Basic Data Report for Millett NTMS Quadrangle, Nevada*, Lawrence Livermore Laboratory, Rept. UCRL-52641 (1978).

This report presents the results of geochemical reconnaissance sampling in the Millett $1^{\circ} \times 2^{\circ}$ quadrangle of the National Topographic Map Series (NTMS). We collected wet and dry sediment samples throughout the 18,770-km² arid to semiarid region and water samples at available streams, springs, and wells. Samples were collected between August and October 1976, and between July and October 1977. We present neutron activation analyses of uranium and trace elements and other measurements made in the field and laboratory in tabular hardcopy and microfiche format. The report includes seven full-size overlays for use with the Millett NTMS 1:250,000 quadrangle. Water sampling sites, sediment-sample total uranium and thorium concentrations, and Th/U ratios are shown on separate overlays. Samples were divided into 9 general rock types, according to the source rock from which the sediment was derived. Each group of samples was statistically treated as an independent population. Acidic volcanics and Tertiary non-marine elastic sediments have the highest background-uranium concentrations. In general, uranium correlates best with the rare-earth elements, hafnium, and thorium. Of all the elements, uranium is the best indicator of uranium mineralization in the Millett quadrangle. The highest uranium concentrations occur near silicic

volcanics and intrusive-metasedimentary contacts. The Th/U ratios define anomalous uranium concentrations; samples with a low Th/U ratio and high uranium are considered worthy of further study. Areas that warrant interest are near Tertiary silicic volcanics and near the Jurassic Austin Pluton quartz monzonite in the Toiyabe Range.

WEED, H. C., L. Dibley, and A. J. Piwinski, *A High Temperature Viscometer for Use at 100 kPa*, Lawrence Livermore Laboratory, Rept. UCRL-52477 (1978).

In this report we describe the design of a high-temperature rotational cup viscometer for use at 100 kPa. We include design criteria, a description of the apparatus, and the results of calibration against both a standard oil and a National Bureau of Standards glass to 1322 K.

WEED, H. C., D. G. Coles, D. J. Bradley, R. W. Mensing, and J. S. Schweiger, "Leaching Characteristics of Simulated Reactor Waste," Materials Res. Soc. Sympos., Boston, November, 1978.

Two methods for measuring the leach rates of simulated high level waste glass are compared. One is a modification of the standard IAEA method and the other is a one-pass method in which fresh leachant solution is pumped over the sample at a controlled flow rate and temperature. For times up to 3 days, there is close agreement between results from the two methods at 25.0°C. Leach rates from the one-pass method show no correlation with flow rate at 25.0°C, but at 75.0°C leach rate increases with flow rate. Np-237 rates at 75.0°C are greater than those at 25.0°C, but ²³⁹Pu rates at 75.0°C are less than or equal to those at 25.0°C. Resorption of ²³⁹Pu associated with (SiO₂)_x polymers at high temperature is suggested as a possible cause.

WEED, H. C. and A. J. Piwinski, "Viscosity of Silicate Melts at 101.3 kPa (1 atm) from 1373 to 1923 K," *Trans. Am. Geophys. Union* 59, 1219 (1978).

The dynamic viscosity (η) of anhydrous silicate melts was determined at 101.3 kPa from 1373 to 1923 K using a rotational cup viscometer of the Couette type. The rotational speed was between 0 and 16 rads/s. Bubble-free silicate glasses were prepared by repeated fusions in air of finely ground rock, followed by rapid quenching. Rock types, all obtained from the Department of Energy's Nevada Test Site in southern Nevada, include a basalt, a welded tuff, a vitric tuff, and an alluvium (a heterogeneous mixture of the above rock types). At 1673 $\pm$ 10 K, the viscosities increase in the order: basalt (η_B), tuff ($\sim 8.5 \eta_B$), and alluvium ($\sim 18.5 \eta_B$). In the relation $\ln \eta = A + B/T^{-1}$, B increases in the order: basalt ($\sim 3.0 \times 10^4$ K), alluvium ($\sim 3.5 \times 10^4$ K), and tuff ($\sim 3.8 \times 10^4$ K).

WEED, H. C., D. G. Coles, R. M. Mensing, and J. S. Schweiger, "Determination of the Dynamic Leaching Rate of ²³⁸Pu from Simulated Reactor Waste Glass," Sympos. Underground Disposal Radioactive Wastes, International Atomic Energy Agency, Otaniemi, Finland, July 1979.

To safely isolate radioactive waste in a geologic medium, it is necessary to estimate the rate of migration of radionuclides in the groundwater from the repository. An essential feature of such estimates is the strength of the source term used in the hydrologic calculations on which the estimates are based. This leaching study was undertaken to provide information from which the strength of the source term can be determined.

The experimental design for the factorial experiment is based on a split plot design with partial replication. The independent variables are time, temperature, flow rate, and solution composition. Dependent variables include the leaching rate of ²³⁹Pu. The apparatus is similar in function to that described by Coles *et al.*

The simulated reactor waste glass is a sodium zinc borosilicate glass prepared by Battelle Pacific Northwest Laboratories and identified by them as 76-68 Glass. The leach solutions are distilled water, 0.03M NaHCO₃ solution, and a synthetic brine solution.

Preliminary analysis indicates that for ²³⁹Pu, the leach rate R in g/(cm² $\times$ d) is a decreasing function of time t in days. After one day, the average value for R at 25°C is 2×10^{-6} . At 75°C, values of

R range from a low of 1.5×10^{-8} for slow flow rates to 3×10^{-6} for fast flow rates. Thus, for all three solutions, the leaching rate R is positively correlated with the flow rate at 75°C, but at 25°C the correlation between them is essentially random. However, the high temperature leaching rates are smaller than the room temperature rates for both low and medium flow. Thus, ^{239}Pu transport depends on flow rate only at high temperature, but is never greater at high temperature than at low temperature.

Weed, H. C., D. G. COLES, D. D. Jackson, and J. S. Schweiger, "Single-Pass Leaching of Nuclear Melt Glass by Groundwater, Part I," Am. Chem. Soc. Sympos. Radioactive Waste, Miami Beach, September 1978. (Lawrence Livermore Laboratory, Rept. UCRL-81617, Preprint, 1978).

Melt glass (fused rock containing fission and activation products and actinides) produced by three underground nuclear explosions has been leached at 25°C with groundwater obtained from a well near the explosion sites. Leaching was carried out in cells with the groundwater passing over glass particles (size range: 40-130 μm) at flow rates of 36 and 6.7 cm/day. With this dynamic flow-through system, the solid sample is continually exposed to fresh leaching solution in an attempt to simulate actual underground conditions. Radionuclide concentrations in the leachate were obtained at intervals of 1, 2, 3, 6, 11, 32, 38, 70, and 120 days after the leaching began. The fraction of radioactivity leached per day per m^2 surface area varied from 1.5

$\times 10^{-2}$ for ^{22}Na on Day 1 to 7.0×10^{-6} for ^{144}Ce on Day 120. Except for ^{144}Ce , leaching rates did not seem to depend significantly on flow rates.

Weed, H. C., S. C. MACLEAN, and D. G. Coles, *The Measurement of Sorption Ratios for Selected Radionuclides on Various Geologic Media*, Lawrence Livermore Laboratory, Rept. UCID-17928 (1978).

The distribution ratio R_D is measured in the same way as the sorption coefficient K_D , but differs from K_D in that R_D is not necessarily an equilibrium value. Distribution ratios (R_D) have been obtained for ^{85}Sr and ^{137}Cs on various geologic materials including limestone, basalt, dolomite, granite, tuff, and shale. R_D values for ^{95}mTc were determined on biotite, granite, tuff, and shale. The R_D values in this study obey the following inequalities:

$$\begin{aligned} R_D(\text{Pu}) &> R_D(\text{Cs}) \text{ except for biotite} \\ R_D(\text{Cs}) &> R_D(\text{Sr}) \text{ except for limestone} \\ R_D(\text{Sr}) &> R_D(\text{Tc}). \end{aligned}$$

Tc is not sorbed under the conditions of this study.

Weed, H. C., A. DUBA, A. J. Piwinski and M. Sansor, "The Electrical Conductivity of Sandstone, Limestone, and Granite," *Geophys. J. R. Astr. Soc.* 53, 583-597 (1978).

TOPICAL INDEX

LIST OF TOPICS REFERENCED

BASIC ENERGY SCIENCES
COMPUTATIONAL METHODS
CRATERING
ECONOMETRIC MODELING
ENERGY TECHNOLOGY DEVELOPMENT
 Environmental Effects
 Geothermal
 In Situ Coal Gasification

In Situ Oil Shale Retorting
Radioactive Waste Isolation
Reservoir Stimulation
Resource Evaluation
FRACTURE FLOW
GEOCHEMISTRY
 Aqueous Geochemistry
 Computational Methods
 High Pressure/Temperature Geochemistry
GEOLOGY

GEOLOGIC ENGINEERING

GEOPHYSICS

Crustal Properties
Equation of State
Exploration Geophysics
High Pressure/Temperature Geophysics
Mechanical Properties
Planetary Interiors
Seismology
Transport Properties

HIGH PRESSURE PHYSICS/EQUATION OF STATE

HYDROLOGY

MISCELLANEOUS

NUCLEAR REGULATORY COMMISSION

WASTE PROGRAM

Calculations
Geologic Characterization

NUCLEAR TEST VERIFICATION

General
Seismic Monitoring

PETROLOGY

SHOCK-WAVE PHYSICS

BASIC ENERGY SCIENCES

Shock Wave Generated Fractures Under Confining Pressure

A. S. KUSUBOV

Rock Fracture Under Confining Pressure

A. S. KUSUBOV

Effect of Simultaneous and Sequential Detonation on Explosive-Induced Fracture

R. P. SWIFT

Volumetric Response of Wet Porous Rock Based on Spherical Model

J. F. SCHATZ

COMPUTATIONAL METHODS

MOVIES: A Computer Code to Generate Contour Plots of Retort Temperature Data

F. J. ACKERMAN

Seismic Wave Propagation Modeled on a Digital Computer: Effect of Variation in Rock Properties

M. G. AUSTIN

LLL Retort Model (Modeled *In Situ* Retorts)

R. L. BRAUN

Results of the Computer Simulation of *In Situ* Oil Shale Retorting

R. L. BRAUN

Simultaneous Fluid-Solid Reactions in Porous Solids: Part I. Reactions between One Solid and Two Fluid Reactants

R. L. BRAUN

Numerical Solutions of Chemically Reacting Flows in Porous Media

R. L. BRAUN

The Application of a Digital Model for Evaluating the Bedrock Water Resources of the Maumee River Basin, Northwestern Ohio

T. G. NAYMIK

User's Manual for a Material Transport Code on the Octopus Computer Network

T. G. NAYMIK

User's Manual for a Two-Dimensional, Ground-Water Flow Code on the Octopus Computer Network

T. G. NAYMIK

An Application of a Method for Comparing One-Dimensional and Two-Dimensional Models of a Ground-Water Flow System

T. G. NAYMIK

Economic Models and Algorithms Used in the Livermore Economic Modeling System

J. T. RAMBO

Computer Code Documentation for the Livermore Economic Modeling System

J. T. RAMBO

User's Manual for the Livermore Economic Modeling System

J. T. RAMBO

Waves in a Linear Viscoelastic Medium—Asymptotic Theory

L. THIGPEN

CRATERING

Meteorite Impact Cratering on a Digital Computer: A Simulation of the Formation of Meteor (Barringer) Crater, Arizona

J. B. BRYAN

Meteorite Impact Cratering Modeled on a Digital Computer: Some Preliminary Results for Barringer Crater

J. B. BRYAN

Single-Charge Craters Excavated during Subsurface High-Explosive Experiments at Big Black Test Site, Mississippi

J. B. BRYAN

A Two-Dimensional Computer Simulation of Hypervelocity Impact Cratering: Some Preliminary Results for Meteor Crater, Arizona

J. B. BRYAN

Selected Surface-Motion Measurements from High-Explosive Cratering Experiments at Big Black Test Site in Mississippi during 1976-1977

R. F. ROHRER

ECONOMETRIC MODELING

Economic Models and Algorithms Used in the Livermore Economic Modeling System

J. T. RAMBO

Computer Code Documentation for the Livermore Economic Modeling System

J. T. RAMBO

User's Manual for the Livermore Economic Modeling System

J. T. RAMBO

ENERGY TECHNOLOGY DEVELOPMENT

Environmental Effects

Enhanced Oil Recovery by Combination Thermal Drive, Paris Valley, California

M. A. ADAMSON

Enhanced-Gas-Recovery Project, Gallia County, Ohio

M. ADAMSON

Enhanced Oil Recovery by Steam Injection, Cat Canyon, California

M. A. ADAMSON

An Environmental Geology Workshop for the Geysers-Calistoga Known Geothermal Resources Area

N. B. CROW

Monitoring Natural Subsidence and Seismicity in the Imperial Valley as a Basis for Evaluating Potential Aspects of Geothermal Production

N. B. CROW

Geotechnical Instrumentation Applied to *In Situ* Coal Gasification Induced Subsidence

H. C. GANOW

A Method of Using *In Situ* Porosity Measurements to Place an Upper Bound on Geothermal Reservoir Compaction

P. W. KASAMEYER

Baseline Measurements of Geologic Events Can Remove Potential Roadblocks to Geothermal Development

P. W. KASAMEYER

Environment Impact of the Coalginga Enhanced Oil Recovery Project

J. MC LEOD

LLL Environmental Studies of *In Situ* Coal Gasification, Annual Report Fiscal Year 1977

S. W. MEAD

Control Aspects of Underground Coal Gasification: LLL Investigations of Groundwater and Subsidence Effects

S. W. MEAD

Environmental Investigations of *In Situ* Coal Gasification Experiments

S. W. MEAD

Ground-Water and Subsidence Investigations of the LLL *In Situ* Coal Gasification Experiments

S. W. MEAD

Apparatus for Field Evaluation of Geothermal Effluent Injection

L. OWEN

Environmental Impact Assessment: Enhanced Gas Recovery by Massive Hydraulic Fracturing in Lincoln County, West Virginia

J. K. SCHNORR

Development of Injection Criteria for Geothermal Resources

J. D. TEWHEY

Geothermal

An Environmental Geology Workshop for the Geysers-Calistoga Known Geothermal Resources Area

N. B. CROW

Monitoring Natural Subsidence and Seismicity in the Imperial Valley as a Basis for Evaluating Potential Impacts of Geothermal Production

N. B. CROW

Thermoelastic Effects in Fracture Flow

J. M. HANSON

Predicting Production Temperature Using Tracer Methods

J. M. HANSON

Potential Uses for a High-Temperature Borehole Gravimeter

J. R. HEARST

A Method of Using *In Situ* Porosity Measurements to Place an Upper Bound on Geothermal Reservoir Compaction

P. KASAMEYER

Baseline Measurements of Geologic Events Can Remove Potential Roadblocks to Geothermal Development

P. W. KASAMEYER

Natural Fluid-Flow Patterns in the Salton Sea Geothermal Field

P. W. KASAMEYER

A Revised Estimate of Recoverable Thermal Energy in The Salton Sea Geothermal Resource Area

P. W. KASAMEYER

Reservoir Engineering Study of a Portion of the Salton Sea Geothermal Field

J. G. MORSE

Apparatus for Field Evaluation of Geothermal Effluent Injection

L. OWEN

Experimental Investigations of the Permeability of Sandstones to Hypersaline Brine from 70° to 90°C at 10.3 MPa Confining Pressure

A. J. PIWINSKII

The Effect of Diagenetic and Hydrothermal Alteration of Sound Propagation in Sedimentary Rocks from the Dunes Borehole, Imperial Valley, California

A. J. PIWINSKII

Development of Injection Criteria for Geothermal Resources

J. D. TEWHEY

***In Situ* Coal Gasification**

Modeling Permeability Enhancement from Explosive Fracture

T. R. BUTKOVICH

Predicting Underground Explosive Fracture and Permeability Enhancement

T. R. BUTKOVICH

Geotomography and Coal Gasification

A. DUBA

Geotechnical Instrumentation Applied to *In Situ* Coal Gasification Induced Subsidence

H. C. GANOW

Instrumentation for Evaluation of *In Situ* Recovery Projects

P. KASAMEYER

LLL Environmental Studies of *In Situ* Coal Gasification, Annual Report Fiscal Year 1977

S. W. MEAD

Control Aspects of Underground Coal Gasification: LLL Investigations of Ground-Water and Subsidence Effects

S. W. MEAD

Environmental Investigations of *In Situ* Gasification Experiments

S. W. MEAD

Ground-Water and Subsidence Investigations of the LLL *In Situ* Coal Gasification Experiments

S. W. MEAD

The Importance of Geosciences in Developing *In Situ* Technologies for Energy Resource Recovery

L. L. SCHWARTZ

Explosive-Induced Fracture Effects from Sequential and Simultaneous Detonations

R. P. SWIFT

***In Situ* Oil Shale Retorting**

A Computer Code to Generate Contour Plots of Retort Temperature Data

F. J. ACKERMAN

LLL Retort Model (Modified *In Situ* Retorts)

R. L. BRAUN

Results of the Computer Simulation of *In Situ* Oil Shale Retorting

R. L. BRAUN

Simultaneous Fluid-Solid Reactions in Porous Solids: Part I. Reactions between One Solid and Two Fluid Reactants

R. L. BRAUN

Numerical Solutions of Chemically Reacting Flows in Porous Media

R. L. BRAUN

Retorting and Combustion Processes in Surface Retorts

R. L. BRAUN

Further Studies of Ignition of *In Situ* Oil-Shale Retorts with Hot Inert Gas

J. F. CARLEY

Sample Size Required for Analysis of Oil Shale of Widely Varying Grade and Particle Size

J. F. CARLEY

Ignition of *In Situ* Oil-Shale Retorts with Hot Inert Gas

J. F. CARLEY

Instrumentation of Evaluation of *In Situ* Recovery Projects

P. KASAMEYER

Application of LLL Model to Surface Retort

A. E. LEWIS

Effect of Oil Wetting on Pressure Difference in Experimental Oil Shale Retorts

R. G. MALLON

Oil Degradation and Gas Evolution during the Retorting of Large Blocks of Oil Shale

R. G. MALLON

Evaluation of Retort Performance from Gas Data

J. H. RALEY

Use of Off-Gas Data for Retort Diagnosis and Control

J. H. RALEY

Results from Simulated Modified *In Situ* Retorting in Pilot Retorts

J. H. RALEY

Recent Experimental Developments in the Modified *In Situ* Oil Shale Program at Lawrence Livermore Laboratory

A. J. ROTHMAN

Experimental Work on Retorting of Oil Shale at Lawrence Livermore Laboratory

A. J. ROTHMAN

The Lawrence Livermore Laboratory Oil Shale Retorts

W. A. SANDHOLTZ

Simulated Modified *In Situ* Oil Shale Retorting

W. A. SANDHOLTZ

The Importance of Geosciences in Developing *In Situ* Technologies for Energy Resource Recovery

L. L. SCHWARTZ

Radioactive Waste Isolation

The Rock-Melt Approach to Nuclear Waste Disposal in Geological Media

J. J. COHEN

Measuring the Permeability of Eleana Argillite from Area 17, Nevada Test Site, Using the Transient Method

W. LIN

Determination of Rock Permeability Using the Transient Method

W. LIN

Waste Isolation Projects—FY 1977

L. D. RAMSPOTT

Laboratory and Field Measurements of Granitic Rocks Under Repository Stress Conditions

L. D. RAMSPOTT

Leaching Characteristics of Simulated Reactor Waste

H. C. WEED

Determination of the Dynamic Leaching Rate of ^{238}Pu from Simulated Reactor Waste Glass

H. C. WEED

Single-Pass Leaching of Nuclear Melt Glass by Groundwater, Part I

H. C. WEED

The Measurement of Sorption Ratios for Selected Radionuclides on Various Geologic Media

H. C. WEED

Reservoir Stimulation

Enhanced Oil Recovery by Combination Thermal Drive, Paris Valley, California

M. A. ADAMSON

Enhanced-Gas-Recovery Project, Gallia County, Ohio

M. ADAMSON

Environmental Impact Assessment: Enhanced Oil Recovery by Steam Injection, Cat Canyon, California

M. A. ADAMSON

Laboratory Experiments on Hydraulic Fracture Growth near an Interface

G. D. ANDERSON

Modeling Permeability Enhancement from Explosive Fracture

T. R. BUTKOVICH

Predicting Underground Explosive Fracture and Permeability Enhancement

T. R. BUTKOVICH

Microcracks and Matrix Deformation of Stressed Gas-Bearing Sandstones

L. A. DENGLE

Some Results from Continuum Mechanics Analyses of the Hydraulic Fracturing Process

M. E. HANSON

LLL Gas Stimulation Program, Quarterly Progress Report, April through June 1978

M. E. HANSON

LLL Gas Stimulation Program, Quarterly Progress Report, January through March 1978

M. E. HANSON

LLL Gas Stimulation Program, Quarterly Progress Report, October through December 1978

M. E. HANSON

Theoretical and Experimental Research on Hydraulic Fracturing

M. E. HANSON

Some Continuum Considerations of the Hydraulic Fracturing Process

M. E. HANSON

LLL Gas Stimulation Program Quarterly Progress Report, July through September 1978

M. E. HANSON

Some Theoretical and Experimental Considerations of the Hydraulic Fracturing Process and Supporting Research

M. E. HANSON

Environmental Impact of the Coalbed Gas Enhanced Oil Recovery Project

J. MC LEOD

Enhanced Gas Recovery by Massive Hydraulic Fracturing in Lincoln County, West Virginia

J. K. SCHNORR

The Importance of Geosciences in Developing *In Situ* Technologies for Energy Resource Recovery

L. L. SCHWARTZ

Explosive-Induced Fracture Effects from Sequential and Simultaneous Detonations

T. P. SWIFT

Resource Evaluation

A Revised Estimate of Recoverable Thermal Energy in the Salton Sea Geothermal Resource Area

P. KASAMEYER

Reservoir Engineering Study of a Portion of the Salton Sea Geothermal Field

J. G. MORSE

Hydrogeochemical and Stream Sediment Reconnaissance Basic Data Report for Winnemucca NTMS Quadrangle, Nevada

K. P. PUCHLIK

Raw Data Report Smoke Creek Desert Basin Orientation Study Lovelock and Susanville 1° × 2° NTMS Area, Nevada

K. P. PUCHLIK

Raw Data Report Winnemucca Dry Lake Basin Orientation Study Nevada

K. P. PUCHLIK

Hydrogeochemical and Stream Sediment Reconnaissance Basic Data Report for Millett NTMS Quadrangle, Nevada

J. WAGONER

FRACTURE FLOW

Modeling Permeability Enhancement from Explosive Fracture

T. R. BUTKOVICH

Predicting Underground Explosive Fracture and Permeability Enhancement

T. R. BUTKOVICH

Thermoelastic Effects in Fracture Flow

J. M. HANSON

Predicting Production Temperature Using Tracer Methods

J. M. HANSON

Natural Fluid-Flow Patterns in the Salton Sea Geothermal Field

P. W. KASAMEYER

GEOCHEMISTRY

Aqueous Geochemistry

Geochemistry and Radionuclide Migration

D. ISHERWOOD

Calculated Radionuclide Migration from a Geologic High Level Waste Repository

D. J. ISHERWOOD

A Critical Review of Retardation Factors Used to Predict Radionuclide Migration

D. ISHERWOOD

Hydrogeochemical and Stream Sediment Reconnaissance Basic Data Report for Winnemucca NTMS Quadrangle, Nevada

K. P. PUCHLIK

Raw Data Report Smoke Creek Desert Basin Orientation Study Lovelock and Susanville 1° × 2° NTMS Area, Nevada

K. P. PUCHLIK

Raw Data Report Winnemucca Dry Lake Basin Orientation Study, Nevada

K. P. PUCHLIK

High Level Waste Repository Site Suitability Study Status Report

D. F. TOWSE

Hydrogeochemical and Stream Sediment Reconnaissance Basic Data Report for Millett NTMS Quadrangle, Nevada

J. WAGONER

Leaching Characteristics of Simulated Reactor Waste

H. C. WEED

Determination of the Dynamic Leaching Rate of ²³⁸Pu from Simulated Reactor Waste Glass

H. C. WEED

Single-Pass Leaching of Nuclear Melt Glass by Groundwater, Part I

H. C. WEED

The Measurement of Sorption Ratios for Selected Radionuclides on Various Geologic Media

H. C. WEED

Computational Methods

Calculated Radionuclide Migration from a Geologic High Level Waste Repository

D. J. ISHERWOOD

High Pressure/Temperature Geochemistry

Reexamination of the Quartz-Coesite Transition at 1272 and 1973 K

J. AKELLA

Partitioning of Cr, Ti, and Al Between Olivine, Spinell, and Liquid Under Controlled f_{O_2} Conditions

J. AKELLA

Reinvestigation of Quartz-Coesite Transition in Piston Cylinder Apparatus Using Talc-Alsimag-Glass (TAG) and NaCl High-Pressure Cells

J. AKELLA

GEOLOGY

Subsurface Correlation of Tertiary-Quaternary Desert Alluvial Deposits, Northern Yucca Flat

N. W. HOWARD

Recognition of Faults in Tertiary-Quaternary Alluvium in Northern Yucca Flat, Nevada, Quaternary Faulting Symposium

H. L. MC KAGUE

Geoscience Parameter Data Base Handbook: Bedded Salt

D. TOWSE

Geologic Factors in Nuclear Waste Disposal

D. TOWSE

GEOLOGIC ENGINEERING

Geotechnical Instrumentation Applied to *In Situ* Coal Gasification Induced Subsidence

H. C. GANOW

A Method of Using *In Situ* Porosity Measurements to Place an Upper Bound on Geothermal Reservoir Compaction

P. W. KASAMEYER

Environmental Studies of *In Situ* Coal Gasification Annual Report Fiscal Year 1977

S. W. MEAD

Control Aspects of Underground Coal Gasification: LLL Investigations of Ground-Water and Subsidence Effects

S. W. MEAD

Environmental Investigations of *In Situ* Coal Gasification Experiments

S. W. MEAD

Ground-Water and Subsidence Investigations of the LLL *In Situ* Coal Gasification Experiments

S. W. MEAD

GEOPHYSICS

Crustal Properties

P-Wave Velocities in Rocks at High Pressure and Temperature and the Crustal Constitution of the Central California Coast Ranges

W. LIN

Equation of State

Shock Wave Compression of Limestone and Tuff

G. D. ANDERSON

Shock Wave Studies of Blair Dolomite

D. B. LARSON

Plane Shock Wave Studies of Porous Geologic Media

D. B. LARSON

Volumetric Response of Wet Porous Rock Based on Spherical Model

J. F. SCHÄTZ

Exploration Geophysics

Geotomography and Coal Gasification

A. DUBA

An Apparatus for Simultaneously Measuring Electrical Conductivity and Oxygen Fugacity

A. DUBA

Recent Well Logging Research at Lawrence Livermore Laboratory

J. R. HEARST

BIFUR II, A Program for Calculating Borehole Gravity Caused by Two-Dimensional Structure

J. R. HEARST

Effects of Terrain on Borehole Gravity Data

J. R. HEARST

Laboratory Studies of an Improved Carbon/Oxygen Log

J. R. HEARST

Calibration of a Neutron Log in Partially Saturated Media

J. R. HEARST

Potential Uses for a High-Temperature Borehole Gravimeter

J. R. HEARST

Instrumentation for Evaluation of *In Situ* Recovery Projects

P. KASAMEYER

High Pressure/Temperature Geophysics

Optical Absorption and Radiative Heat Transport in Olivine at High Temperature

A. G. DUBA

Permeability of Generic Repository Rocks at Simulated *In Situ* Conditions

H. C. HEARD

Capabilities for Measuring Physicochemical Properties at High Pressure

H. C. HEARD

Rock Fracture Under Confining Pressure

A. S. KUSUBOV

Shock Wave Generated Fractures Under Confining Pressure

A. S. KUSUBOV

Effect of Simultaneous and Sequential Detonation on Explosive-Induced Fracture

R. P. SWIFT

A High Temperature Viscometer for Use at 100 kPa

H. C. WEED

Viscosity of Silicate Melts at 101.3 kPa (1 atm) from 1373 to 1923 K

H. C. WEED

Mechanical Properties

Laboratory Experiments on Hydraulic Fracture Growth near an Interface

G. D. ANDERSON

Shock Wave Compression of Limestone and Tuff

G. D. ANDERSON

Simultaneous Fluid-Solid Reactions in Porous Solids: Part I. Reactions between One Solid and Two Fluid Reactants

R. L. BRAUN

Numerical Solutions of Chemically Reacting Flows in Porous Media

R. L. BRAUN

Modeling Permeability Enhancement from Explosive Fracture

T. R. BUTKOVICH

Predicting Underground Explosive Fracture and Permeability Enhancement

T. R. BUTKOVICH

Statistical Variation in Stress-Volumetric Strain Behavior of Westerly Granite

M. S. COSTANTINO

Microcracks and Matrix Deformation in Stressed Gas-Bearing Sandstones

L. A. DENGLER

Creep Behavior of Forsterite at Low Stress

W. B. DURHAM

Mechanisms of Plastic Flow in Olivine

W. B. DURHAM

Some Results from Continuum Mechanics Analyses of the Hydraulic Fracturing Process

M. E. HANSON

Theoretical and Experimental Research on Hydraulic Fracturing

M. E. HANSON

Some Continuum Considerations of the Hydraulic Fracturing Process

M. E. HANSON

Some Theoretical and Experimental Considerations of the Hydraulic Fracturing Process and Supporting Research

M. E. HANSON

Shock Wave Generated Fractures Under Confining Pressure

A. S. KUSUBOV

Rock Fracture Under Confining Pressure

A. S. KUSUBOV

Shock Wave Studies of Blair Dolomite

D. B. LARSON

Plane Shock-Wave Studies of Porous Geologic Media

D. B. LARSON

Laboratory and Field Measurements of Granitic Rocks under Repository Stress Conditions

L. D. RAMSPOTT

Volumetric Response of Wet Porous Rock Based on Spherical Model

J. F. SCHATZ

Effect of Simultaneous and Sequential Detonation on Explosive-Induced Fracture

R. P. SWIFT

Explosive-Induced Fracture Effects from Sequential and Simultaneous Detonations

R. P. SWIFT

Planetary Interiors

Parametric Studies of the Earth's Upper Mantle

D. H. CHUNG

Attenuation in the Upper Mantle of the Basin and Range Province

D. H. CHUNG

Electrical Conductivity of Orthopyroxene: Measurements and Implications

A. G. DUBA

Electrical Conductivity of Pyroxene and the Lunar Temperature Profile

A. G. DUBA

Electrical Condition in Upper Mantle Rocks and Minerals

A. G. DUBA

Seismology

Seismic Waves Propagation Modeled on a Digital Computer: Effect of Variation in Rock Properties

M. G. AUSTIN

Seismic Experiments at Yucca Lake, Test Execution Report, the Rayleigh Wave Experimental Program

A. S. KUSUBOV

The Effects of Variations in Source and Medium Parameters upon Far Field Spectra

D. B. LARSON

P-Wave Velocities in Rocks at High Pressure and Temperature and the Crustal Constitution of the Central California Coast Ranges

W. LIN

Propagation of Lg Waves across Eastern Europe and Asia

A. J. PIWINSKII

Waves in a Linear Viscoelastic Medium—Asymptotic Theory

L. THIGPEN

Transport Properties

Microcracks and Matrix Deformation in Stressed Gas-Bearing Sandstones

L. A. DENGLER

The Electrical Conductivity of Sandstone

A. G. DUBA

Geotomography and Coral Gasification

A. G. DUBA

Some Problems with the Electrical Conductivity of Basalt

A. G. DUBA

An Apparatus for Simultaneously Measuring Electrical Conductivity and Oxygen Fugacity

A. G. DUBA

Optical Absorption and Radiative Heat Transport in Olivine at High Temperature

A. G. DUBA

Alternative Methods for Determining the Electrical Conductivity of Core Samples

A. G. DUBA

Electrical Conductivity of Pyroxene and the Lunar Temperature Profile—A Petrologic Approach

A. G. DUBA

Electrical Conductivity of Orthopyroxene: Measurements and Implications

A. G. DUBA

Electrical Conduction in Upper Mantle Rocks and Minerals

A. G. DUBA

Electrical Conductivity of Orthopyroxene: Measurements and Implications

A. G. DUBA

Permeability of Generic Repository Rocks at Simulated *In Situ* Conditions

H. HEARD

Measuring the Permeability of Eleana Argillite from Area 17, Nevada Test Site Using the Transient Method

W. LIN

Determination of Rock Permeability Using the Transient Method

W. LIN

Relationships among Permeability, K, Porosity, η , and Formation Factor

W. LIN

Experimental Investigations of the Permeability of Sandstone to Hypersaline Brine from 70° to 90°C at 10.3 Mpa Confining Pressure

A. J. PIWINSKII

The Effect of Diagenetic and Hydrothermal Alteration on Sound Propagation in Sedimentary Rocks from the Dunes Borehold, Imperial Valley, California

A. J. PIWINSKII

HIGH PRESSURE PHYSICS/ EQUATION OF STATE

Capabilities for Measuring Physicochemical Properties at High Pressure

H. C. HEARD

Quasi-Isentropic Compressibility of Hydrogen

A. S. KUSUBOV

HYDROLOGY

The Application of a Digital Model for Evaluating the Bedrock Water Resources of the Maumee River Basin, Northwestern Ohio

T. G. NAYMIK

User's Manual for a Material Transport Code on the Octopus Computer Network

T. G. NAYMIK

User's Manual for a Two-Dimensional, Ground-Water Flow Code on the Octopus Computer Network

T. G. NAYMIK

An Application of a Method for Comparing One-Dimensional and Two-Dimensional Models of a Ground-Water Flow System

T. G. NAYMIK

Additional Media Studies for Site Suitability Criteria

T. L. STEINBORN

High Level Waste Repository Site Suitability Study—Status Report

D. F. TOWSE

MISCELLANEOUS

The Chemical Composition and Temperature of Vega

L. A. DREILING

A Code for Generating Presentation Viewgraphs

R. J. KNOX

Earth Sciences Division Collect Abstracts—1977

W. A. QUITQUIT

Sphere Drag at Mach Numbers from 0.3 to 2.0 at Reynolds Numbers Approaching 10⁷

D. G. MILLER

NUCLEAR REGULATORY COMMISSION WASTE PROGRAM

Permeability of Generic Repository Rocks at Simulated *In Situ* Conditions

B. BONNER

Radiological Performance Objectives Derived from Public Values for Nuclear Waste Management

J. J. COHEN

Suggested Nuclear Waste Management Radiological Performance Objectives

J. J. COHEN

Determination of a Radioactive Waste Classification System

J. J. COHEN

Determination of Acceptable Risk Criteria for Nuclear Waste Management

J. J. COHEN

An Evaluation of the Effect of Natural Background Radiation on Cancer Incidence

J. J. COHEN

Review of Issues Relevant to Acceptable Risk Criteria for Nuclear Waste Management

J. J. COHEN

Permeability of Generic Repository Rocks at Simulated *In Situ* Conditions

H. C. HEARD

Geochemistry and Radionuclide Migration

D. ISHERWOOD

Calculated Radionuclide Migration from a Geologic High Level Waste Repository

D. J. ISHERWOOD

A Critical Review of Retardation Factors Used to Predict Radionuclide Migration

D. ISHERWOOD

User's Manual for a Material Transport Code on the Octopus Computer Network

T. G. NAYMIK

User's Manual for a Two-Dimensional, Ground-Water Flow Code on the Octopus Computer Network

T. G. NAYMIK

An Application of a Method for Comparing One-Dimensional and Two-Dimensional Models of a Ground-Water Flow System

T. G. NAYMIK

Additional Media Studies for Site Suitability Criteria (Nuclear Waste Disposal)

D. F. TOWSE

Geoscience Parameter Data Base Handbook: Bedded Salt

D. TOWSE

Geologic Factors in Nuclear Waste Disposal

D. TOWSE

High Level Waste Repository Site Suitability Study—Status Report

D. F. TOWSE

NUCLEAR TEST PROGRAM

Calculations

Calculations for Miss Jade Underground Nuclear Test

M. E. HEUSINKVELD

Scaling of Shallowly Buried Nuclear Explosions

M. E. HEUSINKVELD

Analysis of Depth of Burial Criteria for Containment

R. W. TERHUNE

Calculational Study of the Baneberry Event

R. W. TERHUNE

Numerical Simulation of the Baneberry Event

R. W. TERHUNE

Estimate of Residual Shear Strength Around Explosion Cavities in Earth Media

R. W. TERHUNE

Geologic Characterization

Recent Well Logging Research at Lawrence Livermore Laboratory

J. R. HEARST

BIFUR II, A Program for Calculating Borehole Gravity Caused by Two-Dimensional Structure

J. R. HEARST

Effects of Terrain on Borehole Gravity Data

J. R. HEARST

Laboratory Studies of an Improved Carbon/Oxygen Log

J. R. HEARST

Calibration of a Neutron Log in Partially Saturated Media

J. R. HEARST

Subsurface Correlation of Tertiary-Quaternary Desert Alluvial Deposits, Northern Yucca Flat

N. W. HOWARD

Recognition of Faults in Tertiary-Quaternary Alluvium in Northern Yucca Flat, Nevada

H. L. MC KAGUE

NUCLEAR TEST VERIFICATION

General

Parametric Studies of the Earth's Upper Mantle

D. H. CHUNG

Attenuation in the Upper Mantle of the Basin and Range Province

D. H. CHUNG

A Review of Soviet Studies Related to Peaceful Underground Nuclear Explosions

W. LIN

A High Temperature Viscometer for Use at 100 kPa

H. C. WEED

Viscosity of Silicate Melts at 101.3 kPa (1 atm) from 1373 to 1923 K

W. C. WEED

Seismic Monitoring

Seismic Wave Propagation Modeled on a Digital Computer: Effect of Variation in Rock Properties

M. G. AUSTIN

Seismic Experiments at Yucca Lake, Test Execution Report, the Rayleigh Wave Experimental Program

A. S. KUSUBOV

The Effects of Variations in Source and Medium Parameters upon Far Field Spectra

D. B. LARSON

Propagation of Lg Waves Across Eastern Europe and Asia

A. J. PIWINSKII

Waves in a Linear Viscoelastic Medium Asymptotic Theory

L. THIGPEN

PETROLOGY

Effects of Metamorphism on Quartz Cathodoluminescence

L. A. DENGLE

SHOCK WAVE PHYSICS

Shock Wave Compression of Limestone and Tuff

G. D. ANDERSON

Computational Studies of a Voitenko Compressor

P. S. BROWN

Mach 130 Air Shock Attenuation Studies

H. D. GLENN

Shock Wave Generated Fractures under Confining Pressure

A. S. KUSUBOV

Rock Fracture under Confining Pressure

A. S. KUSUBOV

Effect of Simultaneous and Sequential Detonation on Explosive-Induced Fracture

A. S. KUSUBOV

Shock Wave Studies of Blair Dolomite

D. B. LARSON

Plane Shock-Wave Studies of Porous Geologic Media

D. B. LARSON