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Earth Sciences Division Collected Abstracts—1979

A. L. Henry
L. L. Schwartz

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Lawrence
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Earth Sciences Division Collected Abstracts—1979

A. L. Henry

L. L. Schwartz

Manuscript date: April 30, 1980

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EARTH SCIENCES DIVISION COLLECTED ABSTRACTS—1979

INTRODUCTION

This report is a compilation of abstracts of papers, internal reports, and talks presented during 1979 at national and international meetings by members of the Earth Sciences Division, Lawrence Livermore Laboratory. The arrangement is alphabetical (by author). For a 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 of the report provides useful cross references, while indicating major areas of research interest in the Earth Sciences Division.

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ABSTRACTS

ABEY, A. E., *Use of a General Nonlinear Least-Squares Fitting Program with Non-Closed Form Relationships*, Lawrence Livermore Laboratory Report UCID-18506 (1979).

A use for GNLS, a general nonlinear least-squares fitting program, is discussed. In this use GNLS determines a set of best parameters for relationships that cannot be written in closed form. This program can be useful for experimenters who need to determine experimental parameters by fitting non-closed form relationships to experimental data. Two examples are used to indicate how GNLS can be used for this type of problem.

Abey, A. E., W. B. DURHAM, and D. A. Trimmer, "Thermal Conductivity, Diffusivity and Expansion of Avery Island Salt at Pressure and Temperature," *Proceedings, 16th ITCC and 7th ITES Conference, Chicago, Illinois, November 7-9, 1979*; Lawrence Livermore Laboratory Report UCRL-83789 (1979).

ABEY, A. E., E. F. Lambson, A. J. Miller, I. J. Mohamad, G. A. Saunders, and L. M. Zammit-Mangion, "Acoustic Emission from Ferroelectric Crystals: Listening to Domain Walls Moving," paper presented at the *17th Annual Solid State Physics Conference, University of Warwick, 1979*; Lawrence Livermore Laboratory Report UCRL-83685 (Abstract) (1979).

Acoustic emissions (AE) are short duration elastic stress impulses, usually in the ultrasonic frequency range, propagated from localized sources within solids. AE proves to be a powerful new approach to the study of the dynamics of domain wall motion in ferroelectric $[Pb_5Ge_3O_{11}]$, Rochelle salt, TGS, $Gd_2(MO_4)_3$ and ferroelastic $[Pb_3(PO_4)_2]$ crystals. AE is observed in ferroelectric crystals undergoing hysteresis near saturation polarization. For $Pb_5Ge_3O_{11}$ in particular there is a reproducible threshold applied voltage above which AE pulses appear abruptly; this point is associated with the threshold voltage required to initiate sideways motion of the domain walls. Direct observation has been made of wall motion as AE onsets in the ferroelastic $Pb_3(PO_4)_2$.

An extensive series of experiments on ferroelectric crystals has been carried out to examine the effects on the threshold field and on the nature and intensity of the AE of sample thickness, composition, history, temperature and the rate of application of electric field. The location of noise sources is also being investigated.

ABEY, A. E., Y. K. Yogurtzu, A. J. Miller, and G. A. Saunders, "Studies of Higher Order Elastic Properties of Some Zinc Blende and Rock Salt Semiconductors," paper presented at the 7th International Conference AIRAPT High Pressure Technology, Le Creusot, France, July 30-August 3, 1979; Lawrence Livermore Laboratory Report UCRL-82573 (1979).

The velocity of ultrasonic waves as a function of pressure (up to 2 kbar) has been measured for single crystals of the zinc blende structure semiconductors GaP and HgTe and the rock salt structure PbTe, SnTe, and $\text{Ge}_{1-x}\text{Sn}_x\text{Te}$ alloys. The pressure derivatives of the second order elastic constants and the third order elastic constants obtained from the experimental results are compared and contrasted with those already measured for other zinc blende and rock salt structure crystals. Results are interpreted on the basis of the Keating model for bond bending and stretching in semiconductors under the influence of applied stress.

ABEY, A. E., Y. K. Yogurtzu, A. J. Miller, and G. A. Saunders, "Higher Order Elastic Constants of Zinc Blende Structure GaP and HgTe and of Rock Salt Structure PbTe, SnTe and $\text{Ge}_{0.08}\text{Sn}_{0.92}\text{Te}$," paper presented at American Physical Society Meeting, Chicago, January 21-24, 1980. Lawrence Livermore Laboratory Report UCRL-83482 (1979).

Hydrostatic pressure and one-dimensional stress were utilized in measuring the effect of stress on ultrasonic velocities in GaP, HgTe, PbTe, SnTe, and $\text{Ge}_{0.08}\text{Sn}_{0.92}\text{Te}$. Shear and compressional velocities were measured along various crystallographic directions as the stress level was varied. Third order elastic constants were obtained for PbTe, GaP, and HgTe

using the method of Thurston and Brugger. Pressure derivatives of second order elastic constants were determined for SnTe and $\text{Ge}_{0.08}\text{Sn}_{0.92}\text{Te}$. The results are compared with results for other materials with the same crystal structures.

Ackerman, F. J., J. H. CAMPBELL, J. H. Raley, and W. A. Sandholtz,
"Investigation of Critical Parameters in Modified In Situ Retorting,"
Lawrence Livermore Laboratory Report UCRL-83739 (Abstract) (1979).

AKELIA, J., "Diamond-Window High-Pressure Apparatus--A Tool to Investigate Phase Transformations at Lower Mantle Pressure," *Invited Lecture, National Geophysical Research Institute, India, January 29, 1979*; Lawrence Livermore Laboratory Report UCRL-82400 (Abstract) (1979).

The original diamond cell was made at the National Bureau of Standards by Wier and his group in 1959. In its simplest form, the diamond-window, high-pressure apparatus consists of two single-crystal, gem-quality diamonds in an opposed anvil configuration similar in concept to Bridgman anvils. Force is applied to the opposed anvils by variable means; e.g., by a spring-loaded lever arm assembly, by a mechanical piston and screw device, or by bellows.

Because of its simplicity, this device has become popular and various designs were developed. Phase transformation studies were made by x-ray powder diffraction techniques using this apparatus. However, as in any other opposed anvil device, the approximate parabolic pressure distribution across the diamond anvil face made the pressure estimates qualitative when force per unit area calculations were made. The accuracy of pressure estimation was increased by adding a second phase to the test sample (e.g., NaCl) whose equation-of-state is well known.

Recently, scientists at NBS have developed a simple but accurate method of measuring pressure in which the pressure dependence of the sharp ruby R fluorescence line is used. Mao and Bell extended the ruby scale to 100 GPa by measuring the lattice parameters of several metals as a function of pressure along with a ruby chip mixed in the sample.

Ming and Bassett have shown that samples held at high pressures in a diamond anvil pressure cell could be heated to high temperatures by means of a laser beam introduced through one of the transparent diamond anvils. A 7-J pulsed ruby laser could generate temperatures as high as 3000°C, and a 60-W CW YAG laser could produce sustained temperatures up to 2000°C.

The diamond-window, high-pressure apparatus has thus become a versatile tool for investigating phase transformations at pressures and temperatures corresponding to the lower mantle. Until now, knowledge of the earth's deep interior remained largely hypothetical, being derived from seismological and earthquake data, and also from observations in or near the earth's surface. Now, the diamond-anvil, high-pressure apparatus has opened up a new field of experimental geophysics and geochemistry for understanding the unknowns of the earth's mantle and possibly the core-mantle boundary.

AKELLA, J., "Estimates for the Pressure and Temperature of Equilibration of the Ultramafic Xenoliths in Kimberlites with Particular Reference to the Kimberlites of Wajrakharur, India," *Invited Lecture, Geology Department, Andhra University, India, January 16, 1979*; Lawrence Livermore Laboratory Report UCRL-82401 (Abstract) (1979).

A wide variety of garnet-bearing ultramafic xenoliths has been discovered in kimberlites, alkali olivine basalts, basanites, and nephelinites. It is an accepted view that these ultramafic xenoliths were brought up from the upper mantle. The xenoliths are generally lherzolites, pyroxenites, eclogites, and dunites.

Experimental phase equilibria studies can be used in estimating the P and T of equilibration of these nodules provided the original equilibria that were established in the upper mantle were not disturbed during eruption. Certain compositional variables among the minerals in the ultramafic nodules are sensitive functions of pressure and temperature. The P and T conditions of formation can be estimated, therefore, by equilibrating natural rock samples or mineral mixtures under known conditions and by studying the compositional variables in the minerals of simple synthetic systems that approximately model those in the natural rocks.

From the kimberlite pipe rocks of Wajrakharur, India, two eclogitic xenoliths, one diopside-phlogopite chip, and an ilmenite megacryst were recovered. Using the Mg-Fe partitioning data between the coexisting garnet and clinopyroxene, the eclogite chips from Wajrakharur give a temperature of equilibration of 945°C. Mg-Fe partitioning between the coexisting diopside and garnet inclusions in the ilmenite megacryst is used to estimate its temperature of equilibration which is 900°C using Akella and Boyd's data. Raheim and Green's data give a 20°C lower temperature.

The equilibration temperature for a variety of diopside-ilmenite nodules from South Africa ranged between 980°-1250°C. Thus, it is interesting to note that this ilmenite megacryst has a substantially lower equilibration temperature than most African intergrowths. Boyd and Nixon postulated that the discrete nodules and lamellar ilmenites are derived by crystallization of melts in the low-velocity zone of the mantle. On the other hand, if the ilmenite megacryst from Wajrakharur is a high-pressure phenocryst in a proto-kimberlitic magma, then the magma must be rather surprisingly cool.

AKELLA, J., "Friction Measurements in Piston-Cylinder Apparatus Using Quartz $\rightleftharpoons$ Coesite Transition," in *High-Pressure Science and Technology*, Vol. 1.

K. D. Timmerhaus and M. S. Barber, Eds. (Plenum Publishing Corp., New York, 1979).

The configuration for a high-pressure apparatus is generally a cylinder that is closed at one end and has a movable piston in the other. A specimen to be pressurized is placed inside the cylinder and is compressed by a piston, which is driven by the ram of a hydraulic press. A number of high-pressure apparatuses are in use for static high-pressure and high-temperature studies to 5.5 GPa and 2073 K. Of these, the end-loaded piston-cylinder apparatus has the simplest geometric configuration for directly measuring the pressure inside the cylinder. The pressure in the cylindrical WC pressure chamber is the product of the pressure on the ram driving the piston into the chamber and the ratio of the ram cross-section area to that of the piston. This pressure inside the cylinder is uncorrected for friction and is the nominal pressure. The basic apparatus is described by Boyd and England.

The effectiveness of solid-media high-pressure piston-cylinder apparatuses for studying phase equilibria has been limited by the uncertainty in determining the pressure on the sample. This uncertainty is mostly due to friction in the system. The relationship between load on a piston and the pressure on the sample is a complex function of friction between the cylinder wall and the piston, the mechanical properties of the pressure medium, and the differential loading of the high-pressure cell. In the cell, high-strength cell elements and large differential compaction of elements can cause one region to bear a disproportionate fraction of the total load applied.

Friction can be estimated from observations of some pressure-dependent variable within the cell over a range of applied pressure, both while the piston is moving in (compression) and moving out.

In this investigation, the value of friction was determined by monitoring the piston displacement as a function of nominal pressure on compression and decompression cycles at 1273 K. This value was compared with the friction value obtained by reversing the quartz $\rightleftharpoons$ coesite transition at 1273 and 1073 K in a talc-glass-alsimag cell described by Akella and Kennedy and a low-friction salt cell developed by Mirwald.

AKELLA, J., "Quartz $\rightleftharpoons$ Coesite Transition and the Comparative Friction Measurements in Piston-Cylinder Apparatus Using Talc-Alsimag-Glass (TAG) and NaCl High-Pressure Cells," *N. Jb. Miner. Mh.* H.5, 217 (1979) (Stuttgart, Mai).

The values of friction in a solid-media, high-pressure, piston-cylinder apparatus were determined by reversing the quartz $\rightleftharpoons$ 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 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.

AKELLA J., Q. Johnson, W. Thayer, and R. N. Schock, "Crystal Structure of the High-Pressure Form of Am," paper submitted to *Journal of the Less-Common Metals* (1979); Lawrence Livermore Laboratory Report UCRL-82136 (1979).

Below approximately 6.5 GPa, Am has been found to change from double-hexagonal close packed to face-centered cubic form. At about 11.0 GPa, a new set of diffraction lines was found. The structure of this phase is under investigation.

AKELLA, J., P. S. Rao, R. H. McCallister, F. R. Boyd, and H. O. A. Meyer, "Mineralogical Studies on the Diamondiferous Kimberlite of the Wajrakharur Area, Southern India," in *Kimberlites, Diatremes, and Diamonds: Their Geology, Petrology, and Geochemistry*, Vol. I, F. R. Boyd and H. O. A. Meyer, Eds. (American Geophysical Union, Washington, D.C., 1979), pp. 172-177.

Diamond-bearing kimberlites occur in Andhra Pradesh at Wajrakharur and Lattavaram. In general, the kimberlites at the surface are elliptical with their longer axes trending approximately N70°E. The pipes have intruded PC Dharwarschists, granites, and gneisses but have very limited surface exposure.

The kimberlite near Lattavaram is hard and compact, but slight differences in mineralogy are obvious in the two pipes at this locality. One kimberlite pipe consists predominantly of phenocrysts of olivine (Fo₉₂) partly serpentinized in a medium- to fine-grained groundmass of magnetite-rich spinel, chromite, phlogopite, and monticellite. Pectolite is also present. However, a remarkable feature of this kimberlite is the ubiquitous occurrence of needle-like crystals of nickel sulfide in the serpentine.

The second kimberlite at Lattavaram also is predominantly of serpentinized olivine, microilmenite, and minor garnet in a matrix of calcite, phlogopite, and opaque phases including Cr-rich ilmenite. Minor phases such as sphene and perovskite are also present. Olivine ranges between Fo₈₈ to Fo₉₂; and garnet is about 75% pyrope, 11% grossular with between 2.5 to 3 wt% Cr₂O₃. Up to the present time, a few mantle xenoliths have been recovered from drill cores, but crustal xenoliths (e.g., amphibolites) are not uncommon.

Akella, J., R. N. SHOCK, and Q. Johnson, "Crystal Structures of Am Up To 20.0 GPa," presented at AIRAPT, Le Creusot, France, July 30-August 3, 1979; Lawrence Livermore Laboratory Report UCRL-82729 (Abstract) (1979).

ANDERSON, G. D., "The Effects of Mechanical and Frictional Rock Properties on Hydraulic Fracture Growth Near Unbonded Interfaces," (SPE 8347), 54th Annual Fall Technical Conference of Society of Petroleum Engineers of AIME, Las Vegas, Nevada, September 23-26, 1979.

Experiments are being performed to study the growth of hydraulically driven cracks in the vicinity of an unbonded interface in rocks. The materials on either side of the interface may be the same or different. The materials used in these studies are Nugget sandstone from Utah (3-6% porosity) and Indiana limestone (12-15% porosity). The fracturing fluid is oil which is injected into the test specimens through high-pressure steel tubing. Blocks of the rock materials which are to be studied are held adjacent to one another in a hydraulic press so that a normal stress is set up across their mutual interface. A hydraulically driven crack is initiated in one of the blocks. It is found that the major parameters which affect hydraulic crack penetration into the adjacent block are the relative values of the mechanical strength and moduli of the rocks on either side of the interface, the finish of the interface surfaces, and the magnitude of the normal stress across the interface. To gain a better understanding of the mechanisms which control the growth of the cracks across the interfaces, experiments are being performed to study the frictional properties of these interface surfaces. The experiments involve the simultaneous measurement of the normal force across the interface and the applied force necessary to overcome friction to initiate displacement. These experiments indicate that, in addition to the normal force, the frictional force depends upon the surface finish and the presence of water in the rock.

ANDERSON, G. D., M. E. Hanson, and R. J. Shaffer, "Theoretical and Experimental Analyses of Hydraulic Fracturing," (METC/SP-79-6), *Proceedings of 3rd Eastern Gas Shales Symposium, Morgantown, West Virginia, October 1-3, 1979.*

We are conducting a joint theoretical/experimental research program on hydraulic fracturing. Experiments are being performed to study the growth of hydraulically driven cracks in the vicinity of an unbonded interface in rocks. Blocks of the rock materials which are to be studied are held adjacent to one another in a hydraulic press so that a normal stress is set up across their mutual interface. A hydraulically driven crack is initiated in one of the blocks. It is found that the major parameters which affect hydraulic crack penetration into the adjacent block are the relative values of the mechanical strength and moduli of the rocks on either side of the interface, the finish of the interface surfaces, and the magnitude of the normal stress across the interface. To gain a better understanding of the mechanisms which control the growth of cracks across the interfaces, experiments are being performed to study the frictional properties of these interface surfaces. The experiments involve the simultaneous measurement of the normal force across the interface and the applied force necessary to overcome friction to initiate displacement. These experiments indicate that in addition to the normal force, the frictional force depends upon the surface finish and the presence of water in the rock.

Newly developed numerical models have been applied to analyze some aspects of fracture propagation near well bonded material interfaces to determine if these interfaces can inhibit propagation. Results from these calculations indicate that, for fractures propagating from a lower modulus material toward an interface with a higher modulus material, the stress intensity factor at the tip near the interface decreases significantly as the tip approaches the interface. However, upon penetration of the interfaces into the higher modulus material, the stress intensity factor is seen to increase abruptly and arrive at a higher value than in the lower modulus material. Conversely, when the fracture is propagating from a lower modulus material toward a higher modulus material, the situation is reversed. The presence of existing fractures near the interface is seen to significantly reduce the effects of these phenomena.

Anderson, G. D., M. E. HANSON, R. J. Shaffer, W. Lin, D. F. Towse, M. P. Cleary, and B. C. Haimson, *LLL Gas Stimulation Program, Quarterly Progress Report, April through June 1979*, Lawrence Livermore Laboratory Report UCRL-50036-79-2 (1979).

Anderson, G. D., M. E. HANSON, R. J. Shaffer, L. D. Thorson, and D. N. Montan, "Theoretical and Experimental Analyses of Hydraulic Fracturing and Some Reservoir Response to the Stimulation," *Fifth Annual DOE Symposium on the Enhanced Oil and Gas Recovery and Improved Drilling Technology, Tulsa, Oklahoma, August 22-24, 1979*; Lawrence Livermore Laboratory Report UCRL-82578 (May 1979).

Anderson, G. D., M. E. Hanson, R. J. Shaffer, D. F. Towse, A. G. Duba, N. R. Burkhard, W. Lin, M. P. Cleary, and B. C. Hamison, *LLL Gas Stimulation Program Quarterly Progress Report January through March 1979*, Lawrence Livermore Laboratory Report UCRL-50036-79-1 (1979).

Anderson, G. D., and D. B. LARSON, "Plane Shock-Wave Studies of Porous Geologic Media," submitted to *Journal of Geophysical Research*; Lawrence Livermore Laboratory Report UCRL-80898, Rev. 1 (1979).

Anderson, G. D., and D. B. LARSON, "Plane Shock-Wave Studies of Westerly Granite and Nugget Sandstone," submitted to the *Journal of Geophysical Research*; Lawrence Livermore Laboratory Report UCRL-82264 (1979).

Anderson, G. D., R. J. SHAFFER, and M. E. Hanson, "Hydraulic Fracturing Near Interfaces," *ASME Energy Technology Conference, New Orleans, February 3-7, 1980*; Lawrence Livermore Laboratory Report UCRL-83419 (1979).

BONNER, B. P., and H. C. Heard, "Anelastic Response of Copper, Fused Silica, and Quartz Monzonite at High Pressure and Temperature," paper presented at *Seismic Wave Attenuation Conference, Stanford University, California, June 25-27, 1979*; Lawrence Livermore Laboratory Report UCRL-82562 (Abstract) (1979).

An apparatus has been constructed to study the relation between stress and time-dependent strain at low amplitudes in an internally heated gas pressure vessel capable of 1000 MPa (10 kbar) and 1200 K. Our general objective is to extend observation of mechanical loss of the phase lag in stress-strain and of the creep function (the strain-time response to a unit step in stress) to conditions representative of seismic wave propagation in the deep crust and upper mantle.

After equilibration at pressure and temperature, deviatoric stress is applied to the sample and strains are measured within the vessel. A programmable tractive electromagnet applies a uniaxial stress of up to 5.0 MPa to a 9-mm-diameter by 18-mm-long cylindrical jacketed sample. Samples are evacuated to 10^{-4} Torr and sealed in copper capsules with electron beam welds to ensure reproducible "dry" starting conditions. Strains are measured either by coaxial capacitance displacement transducers or by high-temperature resistance strain gauges bonded to the jacket surface with plasma-sprayed alumina. Phase-sensitive detection enhances the strain measurements. Peak sensitivities obtained thus far (at ambient pressure and temperature) are 2×10^{-8} in radial strain using the capacitors and 5×10^{-7} in longitudinal and transverse strain using the strain gauges. To estimate mechanical loss, the sample is driven in forced oscillation (far from resonance) at 0.5 to 3.0 Hz; the phase delay in strain relative to the forcing function is then measured. Time-dependent strain response to step changes in stress yields transient creep data which determine the creep function. Observation of both creep and phase lag can test the assumption that loss mechanisms are linear and thus independent of strain amplitude.

Preliminary data for polycrystalline copper, fused silica, and a quartz monzonite from Tuolumne County, California, have been obtained at 200 MPa to ~900K. At 200 MPa and 575 K, copper shows the strong relaxation reported in the literature ($Q^{-1} \approx 0.05$) at 1.5 Hz and strains of 5×10^{-6} . Creep curves are consistent with this high loss. Within the limits of the observations,

fused silica does not creep at stresses to 5.0 MPa to 900 K at 200 MPa for steps in strain of $\sim 3 \times 10^{-6}$. Due to the high modulus and low loss at all temperatures, the phase lag in strain could not be reliably determined for silica. Results for the quartz monzonite are fragmentary. The creep response indicates that strong relaxations ($Q^{-1} \geq 0.02$) are not present to ~ 900 K at 200 MPa. However, direct observations of the phase lag in strain suggest that the loss may reach $Q^{-1} = 0.02$ at the highest temperatures, ~ 900 K. These encouraging preliminary results indicate that the apparatus is suitable for detecting strong relaxations at high temperatures in rocks if such effects exist.

BONNER, B. P., and H. C. Heard, "Internal Friction and Transient Creep at High Pressure and Temperature," paper presented at *American Geophysical Union Meeting, Washington D.C., May 28-June 1, 1979*; Lawrence Livermore Laboratory Report UCRL-82390 (Abstract) (1979).

A versatile assembly has been constructed to study the relation between stress and time-dependent strain at low amplitudes in an internally heated gas pressure vessel capable of 1000 MPa (10 kbar) and 1200 K. A uniaxial stress of up to 5.0 MPa (50 bar) is applied to a 9-mm by 18-mm cylindrical jacketed sample by an internally mounted programmable electromagnet. Strains are measured either by coaxial capacitance displacement transducers or by high-temperature resistance strain gauges bonded to the jacket surface with plasma-sprayed alumina. Phase sensitive detection enhances the strain measurements; peak sensitivities thus obtained (at ambient pressure and temperature) are 2×10^{-8} in radial strain using the capacitors and 5×10^{-7} in longitudinal and transverse strain using the strain gauges. To estimate mechanical loss, the sample is driven in forced oscillation far from resonance at 0.5 to 3.0 Hz. The phase delay resulting from hysteresis in stress-strain is then measured. Time-dependent strain response to step changes in stress is observed to yield transient creep data. At 200 MPa (2 kbar) and 575 K, polycrystalline copper shows the strong relaxation reported in the literature ($Q^{-1} \approx 0.05$) at 1.5 Hz and strains of 5×10^{-6} . Creep curves are consistent with this high loss. These preliminary experiments on well-known materials (e.g., metals) indicate that the apparatus is suitable for detecting strong relaxations at high temperatures in rocks if such effects exist.

BONNER, B. P., and H. C. Heard, "Internal Friction and Transient Creep in Granitic Rocks at High Pressure and Temperature," presented at *IUGG Meeting in Canberra, Australia, December 2-17, 1979*; Lawrence Livermore Laboratory Report UCRL-83193 (Abstract) (1979).

An apparatus has been constructed to study the relation between stress and time-dependent strain at low amplitudes in an internally heated gas pressure vessel capable of 1000 MPa (10 kbar) and 1200 K. An internally mounted electromagnet applies a uniaxial stress of up to 5.0 MPa to a 9-mm-diameter by 18-mm-long cylindrical copper-jacketed sample. Strains are measured by high-temperature resistance strain gauges bonded to the jacket surface with plasma-sprayed alumina. Phase-sensitive detection enhances the strain measurements. Peak sensitivities obtained thus far (at ambient pressure and temperature) are 2×10^{-7} . To estimate mechanical loss, the sample is driven far from resonance at 0.5 to 3.0 Hz; the phase delay in strain relative to the forcing function is then measured. Time-dependent strain response to step changes in stress yields transient creep data which determine the creep function.

Preliminary results for quartz monzonite at 200 MPa and 1000 K show a strong temperature-dependent relaxation ($Q^{-1} \approx 0.05$) at least 200 K subsolidus.

BONNER, B. P., and F. M. Sears, "Ultrasonic Attenuation Measurement by Spectral Ratios Utilizing Signal Processing Techniques," submitted to *IEEE Geoscience Electronics*; Lawrence Livermore Laboratory Report UCRL-83679 (1979).

A new approach using signal averaging and signal processing is described for measuring ultrasonic attenuation of compressional (P) and shear (S) waves in highly attenuative (high Q^{-1}) materials. Broad-band ultrasonic pulses in the frequency range of 0.7 to 1.1 MHz are transmitted through a specimen to be characterized for comparison to a reference with low dissipation. Attenuation is calculated from the ratio of spectral amplitudes which are corrected for diffraction effects. An experimental example is given based upon measurements made on dry polycrystalline sodium chloride (halite or rock salt) from Avery Island, Louisiana. The measured Q_p of compressional waves is 46 ± 5.5 and Q_s of shear waves is 12 ± 0.3 . This is a through transmission technique which gives results for materials so lossy that multiple echoes cannot be detected.

BONNER, B. P., F. M. Sears, and M. Carroll, "Ultrasonic Attenuation Measurements in Polycrystalline NaCl Using Signal Averaging and Digital Processing," presented at *Annual Fall Meeting of the American Geophysical Union, San Francisco, December 3-7, 1979*; Lawrence Livermore Laboratory Report UCRL-83297 (Abstract) (1979).

Present methods for ultrasonic inspection of geological materials are limited by their inability to produce detailed quantitative information about the microstructure of the material. We utilize a digital spectral ratio technique to examine cracks in dry, polycrystalline sodium chloride from Avery Island, Louisiana, by studying the attenuation of P and S waves. Controlled heat treatment is used to induce thermal cracking for variation of the crack density. The attenuation dependence on frequency is examined in the range from 0.1 to 5.0 MHz. Test samples are 14.3 cm in diameter by 4.3 cm long with an average grain size of 0.5 cm. The large grain size allows study of the attenuation characteristics where the wavelength is much greater than the average grain size, approximately equal to the average grain size, and much smaller than the grain size.

Ultrasonic pulses are transmitted through the specimen to be characterized for comparison to a reference sample with low dissipation. Attenuation is calculated from the ratio of spectral amplitudes (analogous to the seismic technique) which are corrected for diffraction effects. A high-speed analog signal averager stacks repetitions of the ultrasonic pulse to improve the signal-to-noise ratio and to capture the 0.1 to $-5 \mu\text{s}$ ultrasonic signals for convenient digitization by a microcomputer. Using signal processing techniques, we calculate Q^{-1} as a function of frequency and crack density.

Bonner, B. P., H. C. HEARD, D. Trimmer, and A. Duba, "Permeability of Generic Repository Rocks at Simulated *In Situ* Conditions," paper presented at *Workshop on Low-Flow, Low Permeability Measurements in Largely Impermeable Rocks, Paris, France, March 19-21, 1979*; Lawrence Livermore Laboratory Report UCRL-82609 (Abstract) (1979).

Bonner, B. P., H. C. HEARD, D. Trimmer, W. Lin, and A. Duba, "Simultaneous Measurements of Permeability, Electrical Conductivity, and Ultrasonic Velocity in Igneous and Metamorphic Rocks," paper presented at American Geophysical Union Meeting, Washington, D.C., May 28-June 1, 1979; also, Lawrence Livermore Laboratory Report UCRL-82389 (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 Report UCRL-82086 (1979).

Braun, R. L., and A. E. LEWIS, "Retorting and Combustion Processes in Surface Retorts," Lawrence Livermore Laboratory Report UCRL-82085 (1979).

BROWN, P. S., and M. L. Lohmann, "Computer Modeling of the Voitenko Shock Tube Generator," Lawrence Livermore Laboratory Report UCRL-81701 (1979).

Two successful shock tube experiments were performed a year ago 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. Calculations using an arbitrary Lagrange-Eulerian computer code have been done to model the 10^5 -fold increase in air pressure in the Voitenko generator and the initial air flow down the shock tube. A detailed understanding of the Voitenko generator operation has been obtained. Very good agreement with the experiment has been calculated for the timing in the shock tube experiments, and the source of measured pressure oscillations has been explained.

BRYAN, J. B., D. E. Burton, and L. A. Lettis, Jr., "An Explosion Crater Comparable to Meteor Crater, Arizona," *Tenth Lunar and Planetary Science Conference, Johnson Space Center, Houston, Texas, March 19-23, 1979*; Lawrence Livermore Laboratory Report UCRL-82361 (Abstract) (1979).

What mechanisms were involved in the formation of the Barringer Crater in Arizona? Scientists have been seeking the answers to this and related questions, hoping to gain a better understanding of the formation of the nearly 90 impact craters identified on the Earth as well as craters observed on the Moon and other planetary bodies. Information about original impact conditions is important to improving our understanding of early planetary history and geological events leading to the present structure of our Earth. Little evidence remains of the actual mass and velocity of impacting projectiles which produced these craters. Physical evidence of the meteorite seldom survives the effects of the violent impact and subsequent weathering at those accessible sites on the Earth.

In contrast, craters produced by chemical or nuclear explosives have well-known energies and geometries. Researchers have estimated the mass and velocities of impacting projectiles based on the similarities between impact and explosive craters. In the last two decades sophisticated computer programs have been developed that model the dynamic behavior of geologic materials induced by the intense shock waves from chemical and nuclear explosions. Adequate initial information, including measured geological material properties, and the location and energy released by the explosive source enable these computer programs to accurately predict the dimensions of the resultant crater. Extending these computational tools to the study of impact cratering can produce valuable information about original impact conditions.

We have previously reported a computer simulation of the impact of the Canyon Diablo Meteorite forming the Barringer Crater which is approximately a mile in diameter. Assumptions included the vertical impact at 15 km/s (about 34,000 mph) of a 30-m x 30-m (about 100-ft) cylinder of iron weighing 1.7×10^8 kg (about 180,000 tons) on a limestone earth surface. This impact

has an energy equivalent of approximately 4.5 Mt or 4,500,000 tons of TNT. Our results are quite similar to the estimated pre-erosion dimensions for the Barringer Crater. In this impact cratering study the energy appeared to radiate from a point approximately 86 m (280 ft) below the original ground surface.

Recently, we have substantiated this estimated depth by calculating a 4.5-Mt explosion crater assuming an 86-m depth of burial. The computer model for the surrounding media remained unchanged. The resulting crater has nearly the same dimensions as the impact crater calculation.

Our studies have demonstrated that computer programs developed for explosive cratering studies can be adapted to the study of impact cratering. We have shown that the Barringer Meteor Crater could have been formed by the impact of a meteorite weighing 180,000 tons moving at 34,000 mph, with an equivalent explosive energy of 4.5 Mt. A crater very similar to the size of Barringer could be produced by burying a 4.5-Mt explosive at a depth of 280 ft.

BRYAN, J. B., D. E. Burton, and L. A. Lettis, Jr., "Calculational Comparisons of Explosion and Impact Cratering in Two Dimensions Using Barringer Crater as a Prototype," *Tenth Lunar and Planetary Science Conference, Johnson Space Center, Houston, Texas, March 19-23, 1979*; Lawrence Livermore Laboratory Report UCRL-82154 (Abstract) (1979).

Many similarities and differences between explosion and impact cratering were discussed in a recent volume. Explosion cratering data with relatively well-known energy sources have been used to estimate the unknown kinetic energies required to form large impact craters. These and other efforts to interrelate explosion and impact cratering data bases usually have been based on simplifying assumptions about kinetic energy coupling or transfer into the target material. Typically, explosion cratering studies employ depth-of-burst or height-of-burst as an independent variable which is important in determining the coupled kinetic energy and hence the excavated crater. Although impact cratering lacks an independent variable to serve in this role, investigators have utilized the concept of effective center of energy, apparent origin of shock, or effective depth-of-burst in their studies. Explosion crater size appears to be quite sensitive to depth-of-burst in the near subsurface to the

surface depth-of-burst region. This region contains most estimates of scaled effective depth-of-burst (SEDOB) for impact cratering. In an attempt to extend our understanding in this area, we have made quantitative comparisons of explosion and impact cratering using computer simulations.

In earlier cratering studies based on a two-dimensional finite difference calculation with the Eulerian SOIL computer code, we tentatively estimated an effective depth-of-burst (EDOB) for Barringer Crater (Meteor Crater, Arizona) to be about 85 m in a simulation of a 15-km/s impact for the Canyon Diablo Meteorite. Our value for EDOB is bounded by independent estimates of 64, 80, and 120 to 150 m (4 to 5 meteorite lengths). In order to further examine our estimate for EDOB, we performed an explosion cratering simulation.

Our computer simulation of explosion cratering employed the same computational tools, similar zoning in the finite difference computational mesh, and the same mathematical description for the limestone earth material. The initial conditions for the impact calculation included the 1.88×10^{16} J kinetic energy source as a cylindrical iron meteorite with a mass of 1.67×10^8 kg impacting normal to the ground surface at 15 km/s. By contrast, in the explosion calculation, the initial conditions included the 1.8×10^{16} J internal energy source as a sphere of vaporized limestone buried at a depth of 86.25 m. The initial radius was about 13 m and the pressure was near 1000 GPa (10 Mbar). The dynamic phase of each simulation, treating the stress wave propagation to a time of 0.4 s, was followed by a ballistic or throw-out extrapolation and a slope stability adjustment to calculate the final crater configuration. We observed similarities between the explosion and impact cratering calculations including not only the final crater dimensions but also the kinetic energy in the limestone, the late-time velocity field in the mound region, and the final ejecta distribution. The crater dimensions are in close agreement although the crater depth is slightly less for the explosion crater, suggesting that the depth-of-burst should be increased slightly.

Computer simulations can provide a basis for analyzing both the similarities as well as the differences of explosion and impact cratering. Thus far, our computer simulations suggest that the SEDOB for the Barringer Crater simulation with an impact velocity of 15 km/s onto limestone is about $50 \text{ m/Mt}^{1/3}$. This value is close to Oberbeck's experimental value of about

80 m $\text{Mt}^{1/3}$ for 2 km/s impacts onto quartz and sand and his suggestion that the SEDOB is reduced for higher velocity impacts. There is a large difference between the kinetic energy in our calculation 1.88×10^{16} J (4.5 Mt) and the kinetic energy of 870 J in Oberbeck's experiments. Our future calculations will analyze the sensitivity of these results to such parameters as depth-of-burst, total energy, and material type.

BRYAN, J. B., D. E. Burton, and L. A. Lettis, Jr. "Calculated Explosion and Impact Craters Produced by Multi-Megaton Energy Sources," *American Geophysical Society Spring Meeting 1979, Toronto, Canada*; Lawrence Livermore Laboratory Report UCRL-82388 (Abstract) (1979).

An explosion crater which closely matches the size and shape of an impact crater has been calculated. Our study treated explosion craters produced by 4.5-Mt (1.9×10^{16} J) charges buried 64, 86, and 109 m below the ground surface. These values are similar to earlier estimates of 64, 80, and 120 to 150 m by Johnson, Baldwin, and Shoemaker, respectively, for the effective depth of burst at Barringer Crater in Arizona. The explosion crater calculated for the 86-m depth-of-burst is very similar to the impact crater calculated for a 1.7×10^8 kg iron meteorite impacting at a velocity of 15km/s (4.5 Mt of kinetic energy). The energy coupling and crater size depend on the depth-of-burst. Increasing or decreasing the depth-of-burst by 22.5 m increases or decreases the crater radius (~ 505 m) by about 4%. Other crater dimensions are influenced in a similar manner. Our calculated results which assumed a 15-km/s impact velocity are consistent with earlier experimental impact and explosion cratering studies reported by Oberbeck for a 2-km/s impact velocity. These results suggest that the concept of "effective depth-of-burst" or "center of explosive energy" may be useful in relating impact and explosion craters.

BRYAN, J. B., D. E. Burton, and L. A. Lettis, Jr., "Computer Simulations of Meteorite Impacts and Explosions Which Form Craters the Size and Shape of Barringer Crater," 42nd Annual Meeting of Meteoritical Society, Heidelberg University, Heidelberg, Germany, September 3-7, 1979; Lawrence Livermore Laboratory Report UCRL-82800 (Abstract) (1979).

The data base of explosion-produced craters, with relatively well-known energy sources, has frequently been used by researchers to assist in estimating the energies involved in the formation of craters produced by impacting meteorites. In an effort to help quantify the relationship between impact and explosion craters, Oberbeck performed a series of cratering experiments. He used impact velocities near 2 km/s and energies of about 900 J in these laboratory-scale experiments in quartz sand. By varying the burial depth of the explosive, Oberbeck showed that an explosion buried at a scaled depth-of-burst near $0.66 \text{ m/(GJ)}^{1/3}$ produced a crater nearly identical to the 2-km/s impact with the same total energy.

Recently, we have performed explosion cratering calculations which were modeled after our previous calculations of the meteorite impact formation of Barringer Crater. In these calculations, patterned after Oberbeck's experiments, the energy source of 1.9×10^{16} J was buried at depths of 64, 86, and 109 m in limestone. The calculated final crater produced by the explosion buried at 86 m produced a crater nearly the same size and shape as was calculated for Barringer Crater in which a 1.7×10^8 kg iron meteorite was assumed to impact at 15 km/s. The other craters calculated for burial depths of 64 and 109 m were smaller and larger, respectively. Our results indicate that the effective depth-of-burst for a crater produced by a 15-km/s impact in limestone is about $0.32 \text{ m/(GJ)}^{1/3}$. This agrees with Oberbeck's suggestion that the effective scaled depth-of-burst for impact craters decreases for increasing values of impact velocity.

Bryan, J.B., D. E. BURTON, and L. A. Lettis, Jr., *Numerical Modeling of Spall Phenomena*, Lawrence Livermore Laboratory Report UCID-18289 (1979). (Text of presentation to DNA Spall Workshop, R&D Associates, Marina Del Rey, California, September 13, 1979).

Bryan, J. B., T. R. BUTKOVICH, and D. E. Burton, "Calculational Modeling of Explosive Fracture and Permeability Enhancement," *J. Energy Resour. Technol.* 101, 28 (1979).

BURKHARD, N. R., *Gravity Inversion Code*, Lawrence Livermore Laboratory Report UCID-18043 (1979).

The gravity inversion code applies stabilized linear inverse theory to determine the topography of a subsurface density anomaly from Bouguer gravity data. The gravity inversion program consists of four source codes: SEARCH, TREND, INVERT, and AVERAGE. TREND and INVERT are used iteratively to converge on a solution. SEARCH forms the input gravity data files for Nevada Test Site data. AVERAGE performs a covariance analysis on the solution. This document describes the necessary input files and the proper operation of the code.

BURKHARD, N. R., "The Resolution and Error of Iterative Algorithms for Linear Equations," Lawrence Livermore Laboratory Report UCRL-83023 (1979).

The resolution and error of iterative algorithms as applied to linear inversion problems are examined. Under certain conditions, the resolution and error of an iterative algorithm are identical with those obtained from generalized linear inversion. Iterative algorithms such as BPT (Back Projection Technique) are a viable alternative to generalized linear inversion when direct matrix inversion or pseudoinversion are impractical or impossible.

Burkhard, N.R., M. E. HANSON, G. D. Anderson, R. J. Shaffer, D. F. Towse, A. G. Duba, W. Lin, M. P. Cleary, and B. C. Hamison, *LLNL Gas Stimulation Program Quarterly Progress Report, January through March 1979*, Lawrence Livermore Laboratory Report UCRL-50036-79-1 (1979).

Burton, D. E., J. B. BRYAN, and L. A. Lettis, Jr., "An Explosion Crater Comparable to Meteor Crater, Arizona," *Tenth Lunar and Planetary Science Conference, Johnson Space Center, Houston, Texas, March 19-23, 1979*; Lawrence Livermore Laboratory Report UCRL-82361 (Abstract) (1979).

Burton, D. E., J. B. BRYAN, and L. A. Lettis, Jr., "Calculational Comparisons of Explosion and Impact Cratering in Two Dimensions Using Barringer Crater as a Prototype," *Tenth Lunar and Planetary Science Conference, Johnson Space Center, Houston, Texas, March 19-23, 1979*; Lawrence Livermore Laboratory Report UCRL-82154 (Abstract) (1979).

Burton, D. E., J. B. BRYAN, and L. A. Lettis, Jr., "Calculated Explosion and Impact Craters Produced by Multi-Megaton Energy Sources," *American Geophysical Society Spring Meeting 1979, Toronto, Canada*; Lawrence Livermore Laboratory Report UCRL-82388 (Abstract) (1979).

Burton, D. E., J. B. BRYAN, and L. A. Lettis, Jr., "Computer Simulations of Meteorite Impacts and Explosions Which Form Craters the Size and Shape of Barringer Crater," *42nd Annual Meeting of Meteoritical Society, Heidelberg University, Heidelberg, Germany, September 3-7, 1979*; Lawrence Livermore Laboratory Report UCRL-82800 (Abstract) (1979).

BURTON, D. E., J. B. Bryan, and L. A. Lettis, Jr., *Numerical Modeling of Spall Phenomena*, Lawrence Livermore Laboratory Report UCID-18289 (1979).
(Text of presentation to DNA Spall Workshop, R&D Associates, Marina Del Rey, California, September 13, 1979).

Pitfalls commonly encountered in numerically modeling spall phenomena with finite difference computer codes are discussed. Three purely numerical problems (zone size effects, continuous rezoning, and hourglass damping) and three constitutive problems (artificial viscosity, tensile failure, and void closure) are considered. This report gives three examples of numerically calculated spall: a controlled blasting configuration, a recalculation of the Sedan cratering event, and a simulation of the Baneberry event.

Burton, D. E., T. R. BUTKOVICH, and J. B. Bryan, "Calculational Modeling of Explosive Fracture and Permeability Enhancement," *J. Energy Resour. Technol.* 101, 28 (1979).

Burton, D. E., R. W. TERHUNE, H. D. Glenn, H. L. McKague, and J. T. Rambo, "Numerical Simulation of the Baneberry Event," *Nucl. Technol.* 46, 159 (1979).

BUTKOVICH, T. R., D. E. Burton, and J. B. Bryan, "Calculational Modeling of Explosive Fracture and Permeability Enhancement," *J. Energy Resour. Technol.* 101, 28 (1979).

With its underground explosion computer codes SOC and TENSOR, the Lawrence Livermore Laboratory is developing a capability for computer code prediction of fracture intensity and permeability enhancement far from a free face. Because the codes calculate fracture and not permeability, one must relate experimental measurements to a calculable parameter for fracture. High-explosive experiments in a coal outcrop and a multiple-charge experiment in a coal seam were designed to provide the needed data. Fracture intensity observed around the explosion centers is shown to be related to a calculated damage parameter ϵ_f . This parameter is actually the total failure-induced deviatoric strain. Intrinsic permeability, determined from hydraulic conductivity and calculated from results from slug tests in wells near the explosion, correlates at least qualitatively with the calculated residual tensile-fracture porosity, π_f . An important observation is that no tensile failure occurs for some distance from the explosion-formed cavity when spherical charges are employed, whereas tensile failure occurs near the cavity wall when cylindrical charges are used.

Butkovich, T. R., L. D. RAMSPOTT, L. B. Ballou, R. C. Carlson, D. N. Montan, J. E. Duncan, W. C. Patrick, D. G. Wilder, W. G. Brough, and M. C. Mayr, *Technical Concept for Test of Geologic Storage of Spent Reactor Fuel in the Climax Granite, Nevada Test Site*, Lawrence Livermore Laboratory Report UCRL-52796 (1979).

CAMPBELL, J. H., J. E. Raley, F. J. Ackerman, and W. A. Sandholtz,
"Investigation of Critical Parameters in Modified *In Situ* Retorting,"
Lawrence Livermore Laboratory Report UCRL-83739 (Abstract) (1979).

Recent results from operation of a 6000-kg simulated, modified retort show that high (up to 3 m/day) retorting rates can be achieved with high (85%) oil yield and acceptable ($<1000^{\circ}\text{C}$) maximum temperatures. These results were obtained with a bed of Colorado shale of broad ($-30 + 0.001$ cm) size range containing a stepped grade change from 75 to 150 lb/tonne . Process control by steam and air injection rates, as stipulated by pre-run model calculations, was demonstrated. Continuous estimation of retorting rate and oil yield from off-gas composition was also demonstrated during the operation.

CAMPBELL, J. H., F. T. Wang, S. W. Mead, and J. F. Busby, "Groundwater Quality Near an Underground Coal Gasification Experiment," *J. Hydro.* 44, 241 (1979).

Groundwater sampling and analysis have been carried out at the site of an underground coal gasification experiment conducted near Gillette, Wyoming. Water from more than 12 wells in the vicinity of the experiment has been sampled before, during, and up to 25 months following gasification. Water samples were analyzed for a variety of characteristics, including the presence of 70 inorganic species, phenolic materials, and volatile and semi-volatile organics. We find a greatly increased concentration of organic materials, particularly phenols, just outside the burn boundary and a variety of inorganic species issuing from within the residual ash bed. All detectable contaminants rapidly decreased in concentration with distance, although above-background levels of some materials were detected 30 m (100 ft) from the burn zone within 3 days of the gasification. Several important contaminants showed a large decrease in concentration with time due, probably, to adsorption. Our results suggest a simple physical picture of the development of groundwater pollution near an underground coal gasifier.

CARLEY, J. F., "Sample Size Required for Analysis of Oil Shale of Widely Varying Grade and Particle Size," Lawrence Livermore Laboratory Report UCRL-82078 (1979).

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., "Spontaneous Ignition in Preheated Beds of Spent Oil Shale," Lawrence Livermore Laboratory Report UCRL-83612 (1979).

Inert-gas preheating appears to be a good way to start the retorting of oil-shale rubbles *in situ*. This work was undertaken to determine a property that is important for that process: the temperature at which spent-shale char spontaneously ignites in air and diluted air. Spent Colorado oil shale obtained from inert-gas retorting of 118-lb/Mg (28-gal/ton) oil shale, was preheated with nitrogen in a small reactor, then exposed to oxygen/nitrogen mixtures for periods of about 20 min. Temperatures recorded from embedded thermocouples and the concentrations of carbon oxides in the effluent gas were followed as indicators of the ignition process. The factors explored in a 2^3 -factorial design were temperature of preheating, 300 and 350°C; average particle size, 0.46 and 1.80 cm; and concentration of oxygen in influent gas after changeover, 10.45 and 20.9 vol%. Two runs were made with the gas flow downward; in the other ten it was upward.

Rapidly rising temperatures, coupled with substantial concentrations of CO and CO₂ in the effluent gas, indicated that ignition did occur in all the runs. In three runs, temperatures close to 600°C were recorded and there

was evidence that even higher temperatures may have been reached in these and other runs. The rate of temperature rise increased with increasing oxygen concentration and particle size. CO and CO₂ both rose with increasing influent oxygen concentration, but the ratio of CO and CO₂ dropped sharply, possibly because of catalytic conversion of the one to the other. Responses were the same whether gas flow was upward or downward. The results obtained in this work, coupled with those of earlier simulation studies, indicate that inert-gas preheating should be a safe, economical and reliable method for initiating retorting in *in situ* oil shale rubbles.

CARLEY, J. F., and R. L. Braun, "Further Studies of Ignition of *In Situ* Oil-Shale Retorts with Hot Inert Gas," Lawrence Livermore Laboratory Report UCRL-82086 (1979).

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 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 (preheated) 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 Report UCRL-80984 (1979).

Carlson, R. C., L. D. RAMSPOTT, L. B. Ballou, D. N. Montan, T. R. Butkovich,
J. E. Duncan, W. C. Patrick, D. G. Wilder, W. G. Brough, and M. C. Mayr,
*Technical Concept for Test of Geologic Storage of Spent Reactor Fuel in the
Climax Granite, Nevada Test Site, Lawrence Livermore Laboratory Report
UCRL-52796 (1979).*

CARPENTER, D. W., T. L. Steinborn, and L. D. Thorson, *Groundwater Recharge
and Discharge Scenarios for a Nuclear Waste Repository in Bedded Salt,
Lawrence Livermore Laboratory Report UCID-18119 (1979).*

Twelve potential scenarios have been identified whereby groundwater may enter or exit a nuclear waste repository in bedded salt. The twelve may be grouped into four categories or failure modes: dissolution, fracturing, voids, and penetration. Dissolution modes include breccia pipe and breccia blanket formation, and dissolution around boreholes. Fracture modes include flow through preexisting or new fractures and the effects of facies changes. Voids include interstitial voids (pores) and fluid inclusions. Penetration modes include shaft and borehole sealing failures, undetected boreholes, and new mines or wells constructed after repository decommissioning. The potential importance of thermal effects on groundwater flow patterns and on the recharge-discharge process is discussed. The appropriate levels of modeling effort, and the interaction between the adequacy of the geohydrologic data base and the warranted degree of model complexity are also discussed.

CARPENTER, D. W., and D. F. Towse, *Seismic Safety in Nuclear-Waste Disposal,
Lawrence Livermore Laboratory Report UCID-18125 (1979).*

Seismic safety is one of the factors that must be considered in the disposal of nuclear waste in deep geologic media. This report reviews the data on damage to underground equipment and structures from earthquakes, the record of associated motions, and the conventional methods of seismic safety-analysis and engineering. Safety considerations may be divided into two classes: those during the operational life of a disposal facility, and those pertinent to the post-decommissioning life of the facility. Operational

hazards may be mitigated by conventional construction practices and site selection criteria. Events that would materially affect the long-term integrity of a decommissioned facility appear to be highly unlikely and can be substantially avoided by conservative site selection and facility design. These events include substantial fault movement within the disposal facility and severe ground shaking in an earthquake epicentral region. Techniques need to be developed to address the question of long-term earthquake probability in relatively aseismic regions, and for discriminating between active and extinct faults in regions where earthquake activity does not result in surface ruptures.

DENNISON, M., A. Duba, A. J. Irving, C. R. Thornber, and J. S. Huebner, "Electrical Conductivity of Aluminous Orthopyroxene," paper presented at *Tenth Lunar and Planetary Science Conference, Houston, Texas, March 19-23, 1979*; Lawrence Livermore Laboratory Report UCRL-82297 (Abstract) (1979).

The electrical conductivity of two aluminous orthopyroxenes from Alpine, Texas (ALP-8 and ALP-1) has been measured at 0.1-MPa pressure to 1050°C. Oxygen fugacity (f_{O_2}) was controlled using a $CO_2:CO$ ratio of 1.66:1. The orthopyroxenes occur as megacrysts in basalt, and are chemically homogeneous and free of exsolution and inclusions. Chemical compositions are given and include data for ferric iron based on Mössbauer spectroscopy of another orthopyroxene from the same locality. We assume that ferric iron contents re-equilibrate to much lower values at the f_{O_2} of the conductivity experiment.

The conductivity behavior for the ALP-8 as a function of temperature is illustrated. The conductivity of ALP-1 in the [100] direction has also been measured and is similar to that of ALP-8, but for clarity is not plotted. ALP-8 is more conductive than MF-1, the most conductive orthopyroxene studied by Huebner et al. Since the Alpine pyroxene has about three times more Al_2O_3 than MF-1, these results support the suggestion of Huebner et al. that the conductivity of pyroxenes may be dependent on Al_2O_3 content.

Since lunar mantle pyroxenes are likely to be subcalcic and relatively rich in Al_2O_3 , lunar temperatures calculated from the present conductivity data may be more representative than those calculated from the conductivity of

less Al_2O_3 -rich pyroxenes. Using available conductivity-depth data for the lunar interior and the conductivity-temperature data, we calculate (with some extrapolation) that the temperature at 500-km depth in the moon is between 890 and 1240°C. These limits are 100 to 200°C lower than limits calculated from orthopyroxenes with less Al_2O_3 .

DONICH, T. R., A. M. Kaufman, G. D. Sauter, T. L. Steinborn, and D. F. Towse, *Additional Media Studies for Site Suitability Criteria*, Lawrence Livermore Laboratory Report UCID-17887 (1979).

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.

Inasmuch as *in situ* tests are either underway or planned for the near future in other geologic environments in the United States, and since these environments may be recommended as waste repositories, work should begin immediately to produce results for these environments that are similar to those we have for the bedded media. Once the necessary data are available and the models developed, advanced analyses can be conducted in parallel with those on shale and bedded salt.

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 following basis:

1. 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.
2. 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.
3. An evaluation of each medium as a suitable repository environment. The evaluation is based on construction costs, collocation of other resources,

availability of potential repository sites, retrievability of stored wastes, and suitability of physical and chemical properties.

We have reached two principal conclusions on the basis of this study:

1. The funding necessary to bring our understanding of domed salt, basalt, and crystalline rock to a level comparable to our current understanding of bedded salt is estimated to be \$1,457,000, \$813,000, and \$1,742,000, respectively, for the three media. In each case, roughly 75% of the effort would be devoted to model development and analysis, 25% to data base development.

2. Basalt and crystalline rock are about equally suitable as waste repositories in terms of all criteria except the availability of potential repository sites, where crystalline rock has a clear advantage. Domed salt should yield substantially lower construction costs than basalt or crystalline rock, but it is inferior in the categories of colocated resources and waste retrievability, and probably suitability of chemical and physical properties.

The funding estimates reflect not only the effort and time required for each medium study, but also the probable DOE schedule for experimental pilot plant work and for potential repository development. The studies should begin simultaneously, allowing them to be completed in the order: basalt, domed salt, crystalline rock. Hydrology studies and systems model development will be an extension of work either already completed or in progress at LLL. If studies of other environments and media become necessary, they can be made in the same way.

DUBA, A. G., "High Electrical Conductivity Does Not an Asthenosphere Make," paper presented at the *American Geophysical Union Meeting, Washington, D.C., May 28-June 1, 1979*; Lawrence Livermore Laboratory Report UCRL-82392 (Abstract) (1979).

The high electrical conductivity (σ) associated with the asthenosphere has been considered as an indication that the asthenosphere is partially molten. This model results from many laboratory measurements which show large increases in electrical conductivity associated with melting in rocks and minerals such as basalts, granites, and feldspars. However, recent laboratory results from measurements on olivines, pyroxenes, feldspars, and basalts under

controlled oxygen fugacity indicate that large increases in σ , similar to those observed on melting, are possible in the solid state. Further, the conductivity of some minerals such as olivine may actually decrease on melting. The conclusion of these laboratory studies is clear--electrical conductivity alone is not a reliable indicator of the state of geologic material.

DUBA, A. G., "Laboratory Electrical Conductivity Measurements and the Asthenosphere," paper presented at *Geophysical Research Symposium, Utrecht, Netherlands, January 10-11, 1980*; Lawrence Livermore Laboratory Report UCRL-82970 (Abstract) (1979).

Laboratory data indicate that the electrical conductivity of minerals, such as albite, and rocks, such as basalt and granite, increases several orders of magnitude on melting. Using these observations and physical models for conductivity based on possible melt geometries, one can explain a high conductivity anomaly associated with the asthenosphere as the result of partial melting. However, at least equally valid experiments show that the conductivity of minerals such as albite, and rocks such as basalt, can increase just as dramatically in the solid state, near, but below, melting, presumably due to order/disorder phenomena. The implication of this observation is that high conductivity anomalies can occur in an asthenosphere containing no partial melt phase. Thus, a mixture of refractory minerals and "frozen" partial melt just below the solidus could produce the same high conductivity as a mixture of refractory minerals and partial melt.

Duba, A. G., M. DENNISON, A. J. Irving, C. R. Thornber, and J. S. Huebner, "Electrical Conductivity of Aluminous Orthopyroxene," paper presented at *Tenth Lunar and Planetary Science Conference, Houston, Texas, March 19-23, 1979*; Lawrence Livermore Laboratory Report UCRL-82297 (Abstract) (1979).

Duba, A. G., M. E. HANSON, G. D. Anderson, R. J. Shaffer, D. F. Towse, N. R. Burkhard, W. Lin, M. P. Cleary, and B. C. Hamison, *LLNL Gas Stimulation Program Quarterly Progress Report January through March 1979*, Lawrence Livermore Laboratory Report UCRL-50036-79-1 (1979).

Duba, A. G., H. C. HEARD, D. Trimmer, and B. Bonner, "Permeability of Generic Repository Rocks at Simulated *In Situ* Conditions," paper presented at *Workshop on Low-Flow, Low Permeability Measurements in Largely Impermeable Rocks, Paris, France, March 19-21, 1979*; Lawrence Livermore Laboratory Report UCRL-82609 (Abstract) (1979).

Duba, A. G., H. C. HEARD, D. Trimmer, W. Lin, and B. Bonner, "Simultaneous Measurements of Permeability, Electrical Conductivity, and Ultrasonic Velocity in Igneous and Metamorphic Rocks," paper presented at *American Geophysical Union Meeting, Washington, D.C., May 28-June 1, 1979*; also, Lawrence Livermore Laboratory Report UCRL-82389 (1979).

DUBA, A. G., R. J. Lytle, and J. L. Willows, "Alternative Methods for Determining the Electrical Conductivity of Core Samples," *Rev. Sci. Instrum.* 50, 611 (1979).

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 on granite samples.

DUBA, A. G., and T. J. Shankland, "Fourth Workshop on Electromagnetic Induction Sees Launching of Proposed International Project," paper submitted to *Transactions of the American Geophysical Union*; Lawrence Livermore Laboratory Report UCRL-82156 (1979).

The Fourth Workshop on Electromagnetic Induction in the Earth and Moon was held in Murnau, West Germany, September 6-13, 1979. The workshop, part of Working Group III of IAGA, is devoted to probing electrical properties of the

earth from the deep crust on down as inferred (1) from magneto-tellurics (MT) in which both electrical and magnetic observations are made, and (2) from geomagnetic deep sounding (GDS) which uses purely magnetic variations.

Crustal Studies. The most striking, thorough work was evidenced by the Germans. The groups at Hannover headed by Losecke displayed exceptionally well-processed data from 50 sites that were used to locate the conductive "Zechstein base" at the top of the Permian in northern Germany which varied from 9 to 18 km in depth from south to north. As a geothermal investigation, this conducting layer was found to correlate well with contours of isotherms at 3-km depth, perhaps because of the effectiveness of this layer in transporting heat by fluid movement. Similar results with poorer correlations were given by Berchtold and Kemmerle of Munich for south-central Germany.

In tectonic regions there was continued observation of correlation between such features as the Great Glen Fault of Scotland and strong current channeling in the crust. This is a prominent effect in rift valleys such as that of East Africa, and it has now been noted also for the Rio Grande Rift.

Rift Tectonic Studies. Beblo of Munich presented a very detailed study of electrical properties of the crust beneath Iceland, which straddles the Mid-Atlantic Ridge. Off the ridge, the depth of the high conductivity region is 15-20 km and appears to be associated with the crust-mantle interface. However, it rises 3-5 km in depth beneath the neo-volcanic zone; the neo-volcanic zone is the on-land expression of the Ridge, and the presence of a shallow high conductivity layer (HCL) is consistent with its being a high-temperature indicator. This work was part of a competent Icelandic geophysical program at Munich that includes seismic and magnetic studies.

DUBA, A. G., T. J. Shankland, and U. Nitsan, "Optical Absorption and Radiative Heat Transport in Olivine at High Temperature," *J. of Geophys. Res.* 84, 1603 (1979).

The optical absorption spectra of natural single-crystal and polycrystalline olivine ($\text{Mg}_{1.84}\text{Fe}_{0.16}\text{SiO}_4$) have been measured in the wavelength range 300-8000 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 multiphonon 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 $10\text{--}15\text{ cm}^{-1}$ 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 $5 \times 10^{-3}\text{ cal/cm}\cdot\text{s K}$ (2 W/m K) at 1700 K and is only weakly dependent on temperature above 800 K. 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.

DURHAM, W. B., A. E. Abey, and D. A. Trimmer, "Thermal Conductivity, Diffusivity, and Expansion of Avery Island Salt at Pressure and Temperature," *Proceedings, 16th ITCC and 7th ITES Conference, Chicago, Illinois, November 7-9, 1979*; Lawrence Livermore Laboratory Report UCRL-83789 (1979).

Preliminary data on the thermal properties of a coarse-grained rock salt from Avery Island, Louisiana, indicate that hydrostatic pressure to 50 MPa has little effect on the thermal conductivity, diffusivity, and linear expansion at temperatures from 300 to 573 K. The measurements were made in a new apparatus under conditions of true hydrostatic loading. At room temperature and effective confining pressure increasing from 10 to 50 MPa, thermal conductivity and diffusivity are constant at approximately 7 W/m K and $3.6 \times 10^{-6}\text{ m}^2/\text{s}$, respectively. At 50 MPa and temperature increasing from 300 to 573 K, both conductivity and diffusivity drop by a factor of 2. Thermal linear expansion at 0 MPa matches that at 50 MPa, increasing from roughly $4.2 \times 10^{-5}/\text{K}$ at 300 K to 5.5×10^{-5} at 573 K. The lack of a pressure effect on all three properties is confirmed by previous work. Simple models of microcracking suggest that among common geological materials the lack of pressure dependence is unique to rock salt.

DURHAM, W. B., C. Froidevaux, and O. Jaoul, "Transient and Steady-State Creep of Pure Forsterite at Low Stress," *Phys. Earth Planetary Interiors* 19, 263 (1979).

Thirty-one single crystals of synthetic forsterite, Fo_{100} , were deformed in 69 compressional creep tests in a 0.1-MPa confining atmosphere of $\text{H}_2 + \text{Ar}$. The temperature ranged from 1753 to 2023 K and stress σ ($= \sigma_1 - \sigma_3$) from 1.5 to 37.8 MPa. Steady-state creep under these conditions follows an empirical law of the form: strain rate $\dot{\epsilon} = A\sigma^n \exp(-Q/RT)$ where A , n , and Q are constants. General characteristics of Fo_{100} creep--uniformity of strain, shape change as a function of orientation of σ , relative deformation resistance of different orientations--match those of natural olivine single crystals of composition Fo_{92} . Specific constants in the flow law, however, are distinctly new: for σ oriented along $[111]_c$ (equidistant from the three principal crystallographic axes), values for Fo_{100} are $n = 2.9 \pm 0.2$ and $Q = 0.67 \pm 0.03$ MJ/mol (160 ± 7 kcal/mol). A single law covers the range $3 < \sigma < 30$ MPa and $1753 < T < 1953$ K. Steady-state deformation is preceded by a transient period of strain softening. High strain rates at $\sigma \geq 10$ MPa render the transient barely resolvable; it apparently displaces the steady-state flow law by approximately -0.5% in strain. At $\sigma \leq 7.8$ MPa, the amount of strain imparted to a sample of the $[101]_c$ orientation is typically $< 0.1\%$ after 1 hr.

DURHAM, W. B., O. Jaoul, C. Froidevaux, and M. Michaut, *Oxygen Selfdiffusion in Forsterite: Implications for the High Temperature Creep Mechanism*, Laboratoire de Géophysique et Géodynamique Interne, Université de Paris Sud - Bât. 510, Orsay, France (1979).

The diffusivity of ^{18}O in forsterite Mg_2SiO_4 has been measured in the temperature range 1150 to 1600°C. The activation energy of oxygen self-diffusion in this silicate is found to equal 0.32 ± 0.04 MJ/mol (77 ± 10 Kcal/mol), and there is no dependence of the diffusivity upon the oxygen partial pressure surrounding the samples. The diffusion profiles were analyzed either with an ion probe or by means of the $^{18}\text{O} (p,\alpha) ^{15}\text{N}$ nuclear reaction. The latter method made use of a resonance in the cross section in the case of diffusion profiles shorter than 1000 Å; for diffusion

profiles up to 4 μm the same reaction was used, but in a nonresonant mode. New data on creep in forsterite and natural olivine are also given, including the influence of the oxygen partial pressure P_{O_2} . The latter is zero for forsterite and proportional to $(P_{O_2})^{1/6}$ for natural olivine. From this set of data we infer the possible relationship between diffusion and creep for this material. This relationship has to be more complicated than that predicted by simple climb mechanism.

Durham, W. B., and A. S. KUSUBOV, "Explosive-Induced Effects in Porous Sandstone under Confining Pressure," Lawrence Livermore Laboratory Report *Energy and Technology Review*, December 1979.

Durham, W. B., A. S. KUSUBOV, J. F. Schatz, R. N. Schock, and T. J. Ahrens, "Effect of Confining Pressure on Explosively Induced Damage in Porous Sandstone," presented at *American Geophysical Union Meeting, Washington, D.C., May 28-June 1, 1979*; Lawrence Livermore Laboratory Report UCRL-82384 (1979).

Durham, W. B., A. S. KUSUBOV, R. N. Schock, J. E. Schatz, and T. J. Ahrens, "Explosive-Induced Damage in Porous Sandstone," submitted to *Proceedings of 7th AIRAPT International High Pressure Conference, La Creusot, France, July 30-August 3, 1979*; Lawrence Livermore Laboratory Report UCRL-83448 (1979).

Ganow, H. C., S. W. MEAD, F. T. Wang, and D. H. Stuermer, "Environmental Studies of LLL's Hoe Creek II Underground Coal Gasification Experiment," Lawrence Livermore Laboratory Report UCRL-82409 (1979).

Ganow, H. C., S. W. MEAD, F. T. Wang, D. H. Stuermer, and R. Stone, "Ground-Water Effects of Underground Coal Gasification Experiments in Northeastern Wyoming," *54th Annual Fall Technical Conference of the Society of Petroleum Engineers of AIME, Las Vegas, Nevada, September 23-26, 1979*; Lawrence Livermore Laboratory Report UCRL-82466 (1979).

Glenn, H. D., R. W. TERHUNE, D. E. Burton, H. L. McKague, and J. T. Rambo,
"Numerical Simulation of the Baneberry Event," *Nucl. Technol.* 46, 159 (1979).

HANSON, J. M., "Tidal Pressure Response as a Reservoir Engineering Tool," paper presented at *Geothermal Resources Council Annual Meeting, Reno, Nevada, September 24-27, 1979*; Lawrence Livermore Laboratory Report UCRL-83012 (1979).

Fluid pressure oscillations resulting from tidal strain reflect hydrologic and elastic properties of a reservoir. Precise measurement and interpretation of these pressure fluctuations has the potential of being a useful quantitative reservoir engineering tool. Interpretations of reservoir response to tides have been to date of a qualitative nature. This is primarily due to the lack of resolving power of the spectral analysis techniques applied in the data interpretation. We have developed a procedure, based on the statistical nature of the noise in the signal, that overcomes most of these problems. The method quantifies the spectral resolution in terms of an absolute confidence level in both amplitude and phase of the spectral estimate. Analysis of one week of data from a well in the Salton Sea KGRA is presented.

Hanson, M. E., G. D. ANDERSON, and R. J. Shaffer, "Theoretical and Experimental Analyses of Hydraulic Fracturing," (METC/SP-79-6), *Proceedings of 3rd Eastern Gas Shales Symposium, Morgantown, West Virginia, October 1-3, 1979*.

HANSON, M. E., G. D. Anderson, R. J. Shaffer, W. Lin, D. F. Towse, M. P. Cleary, and B. C. Haimson, *LLL Gas Stimulation Program, Quarterly Progress Report, April through June 1979*, Lawrence Livermore Laboratory Report UCRL-50036-79-2 (1979).

This report summarizes the research and accomplishments of the LLL Gas Stimulation Program during the third quarter of FY 1979. We have continued to analyze dynamic fracture propagation near interfaces. We have also formulated the equations describing pressure evolution in a propagating hydraulic fracture, and the numerical simulation of several parameters in these equations has involved intensive study. Experimentally, we have continued our laboratory

molding of the aspects of fracturing near interfaces with primary emphasis on the effects of frictional interfaces. Frictional measurements on both sandstone and limestone have shown that the frictional coefficient for sandstone decreases with water saturation, but increases with limestone. Changes in viscosity of the fracturing fluids tend to slow the rate at which the breakdown point is reached. We are also measuring the mechanical and breakage characteristics of reservoir material from the Mesa Verde sections of the Piceance Basin. Cross plotting techniques are being applied to evaluate porosity from logs taken in the Bowdoin area in Montana.

HANSON, M. E., G. D. Anderson, R. J. Shaffer, L. D. Thorson, and D. N. Montan, "Theoretical and Experimental Analyses of Hydraulic Fracturing and Some Reservoir Response to the Stimulation," *Fifth Annual DOE Symposium on the Enhanced Oil and Gas Recovery and Improved Drilling Technology*, Tulsa, Oklahoma, August 22-24, 1979; Lawrence Livermore Laboratory Report UCRL-82578 (1979).

We are conducting a joint theoretical/experimental research program on hydraulic fracturing. Newly developed numerical models have been applied to analyze some aspects of fracture propagation near well-bonded material interfaces to determine if these interfaces can inhibit propagation. Results from these calculations indicate that, for fractures propagating from a lower modulus material toward an interface with a higher modulus material, the stress intensity factor at the tip near the interface decreases significantly as the tip approaches the interface. However, upon penetration of the interfaces into the higher modulus material, the stress intensity factor is seen to increase abruptly and arrive at a higher value than in the lower modulus material. Conversely, when the fracture is propagating from a lower modulus material toward a higher modulus material, the situation is reversed. The presence of existing fractures near the interface is seen to significantly reduce the effects of these phenomena.

Small scale laboratory experiments are being performed to study the growth of hydraulically driven cracks in the vicinity of unbonded interfaces in rocks. Blocks of the materials being studied are held adjacent to one another under a static load. A hydraulically driven crack is initiated in one of the

blocks. It is found that for blocks of the same material that penetration of the crack into the adjacent block is controlled by the normal stress across the interface and the finish of the interface surfaces. Experiments are performed to measure the frictional properties of the interfaces to better understand the mechanism of crack growth across the interface.

Well pressure test data from a MHF stimulated well in the Piceance Basin were analyzed. Analysis of that data indicated that the length of the fracture in the productive rock was of the order of the lens size. Additionally, the analysis showed that the fracture had a finite conductivity or there was fluid damage to the fracture faces, but it was impossible to uniquely determine if either mechanism was dominant.

HANSON, M.E., G. D. Anderson, R. J. Shaffer, D. F. Towse, A. G. Duba, N. R. Burkhard, W. Lin, M. P. Cleary, and B. C. Hamison, *LLL Gas Stimulation Program Quarterly Progress Report January through March 1979*, Lawrence Livermore Laboratory Report UCRL-50036-79-1 (1979).

This report summarizes the research and accomplishments of the LLL Gas Stimulation Program during the second quarter of FY 1979. We have used two-dimensional dynamic models to analyze some aspects of dynamic fracture propagation near bonded interfaces. In addition, we have used theoretical models to analyze aspects of a blunting process that occurs when a pressurized fracture contacts another fracture that lies at various angles to the created fracture. Friction coefficient measurements for Indiana limestone show 0.51 as an indicated mean value of the static frictional coefficient. We have experimentally determined effects of viscosity of the fracturing fluid under various principal stress states in a polyaxial stress cell. We have also completed some initial log analyses and comparisons with core for a well in the Piceance basin.

Hanson, M. E., R. N. SCHOCK, R. P. Swift, and O. R. Walton, "In Situ Fracture Related to Energy and Resource Recovery," paper prepared for presentation at VIIth International High Pressure AIRAPT Conference, Le Creusot, France, July 30-August 3, 1979, Lawrence Livermore Laboratory Report UCRL-82731 (1979).

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

We are developing and applying theoretical, numerical models to analyze the hydraulic fracturing process. Applications include: fracturing near interfaces, effects of existing fractures near interfaces, pore-pressure effects, and stress-field changes due to embedded lenses. 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 abruptly increases to a higher value than it had in the lower modulus material. When the situation is reversed the intensity factor increases as the tip approaches the interface and then abruptly decreases when the tip crosses the interface. Further calculations show that when existing cracks are present near the interface the effects of the change in material properties across the bonded interface are reduced. In addition, our analysis shows that increases in pore pressure due to leakage of fluids from the fracture into the surrounding media cause the stress-intensity factor to drop; a decrease in the stress-intensity factor means a reduction in the tendency to break. In other calculations we analyzed the stress-field disturbance caused by lenses of one material that are embedded in another material. These calculations show that in regions that are not tectonically relaxed the stress field is modified by the lenses. We conclude that the fracture geometry is modified by the presence of embedded lenses under these conditions.

Hanson, M. E., R. J. SHAFFER, and G. D. Anderson, "Hydraulic Fracturing Near Interfaces," *ASME Energy Technology Conference, New Orleans, Louisiana, February 3-7, 1980*; Lawrence Livermore Laboratory Report UCRL-83419 (1979).

HEARD, H. C., "Elastic, Thermal and Permeability Behavior of Generic Repository Rocks at *In Situ* Conditions," paper presented at *First Annual ONWI Information Meeting, Battelle, Columbus, Ohio, October 30-November 1, 1979*; also, Lawrence Livermore Laboratory Report UCRL-83221 (1979).

Accurate prediction of both the short-term and long-term response of an underground repository for high-level radioactive wastes requires knowledge of the *in situ* stress/strain field, the permeability, the time-dependent elastic/inelastic response, and the thermal behavior of the rock mass. Additional information needed includes the geometry and depth of the facility, the heat load and decay characteristics of the waste, and the effects of temperature on permeability. A calculational model based on the chemistry and physics of the operative processes is also needed. In support of the goal, laboratory measurements are being carried out on several generic rocks over a range of lithostatic pressures, deviatoric stresses and temperatures to be expected near a waste repository.

Elastic constants and thermal expansion of four coarse-grained igneous rocks are being measured at effective pressures to 50 MPa and temperatures to 300°C. These four are Climax stock quartz monzonite (NTS), Stripa granite (central Sweden), Westerly granite (Rhode Island) and Creighton gabbro (Sudbury, Canada). Sample sizes are 2.5-cm diameter by 6.5-cm length. Results of linear thermal expansion (α) measurements on the quartz monzonite indicate α ranges from 7×10^{-6} to $15 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$ and are nonlinearly dependent on both pressure and temperature. Optical and SEM observations together with the intrinsic behavior of the component minerals suggest that crack porosity is responsible for the increase α at likely repository conditions.

Thermal conductivity, diffusivity, heat capacity, and α are being determined on Avery Island salt (Louisiana), Climax quartz monzonite, and certain other rocks at lithostatic pressures at 50 MPa, temperatures to 300°C, and pore fluid pressures to 25 MPa. Large cylindrical samples are being tested: 13-cm-diameter by 23-cm-length. Preliminary results on salt with no pore fluid pressure indicate a thermal conductivity of $6 + 1 \text{ W m}^{-1} \text{ } ^\circ\text{C}^{-1}$ at 35°C, 10- to 40-MPa pressure. Diffusivity, heat capacity and α data have not yet been reduced.

Permeability, electrical conductivity, acoustic velocity, strain and displacement are being measured on large fractured and unfractured samples of White Lake gneissic granite (Ontario, Canada), Westerly granite, and Sudbury gabbro. Lithostatic pressures range to 50 MPa, pore fluid (water) pressures to 25 MPa and deviatoric stresses to 0.9 of the failure stress. The test temperature is 20°C and samples are 15-cm diameter by 28-cm length. Climax quartz monzonite, Montello granite (Wisconsin), and Stripa granite remain to be tested. Results for the initial three rocks indicate permeabilities of 10^{-16} to 10^{-20} cm² (10^{-8} to 10^{-12} D), depending on rock type, pressure, and stress. Electrical conductance and acoustic velocity are well-correlated with permeability and thus show promise as remote, nondisruptive indicators of permeability in situ.

HEARD, H. C., "Laboratory Measurements as Inputs to Modeling: Status and Needs," Lawrence Livermore Laboratory Report UCRL-82837 (1979).

The safe terminal storage of high-level radioactive wastes requires that they be isolated from the biosphere for the period that the material remains chemically toxic and/or the emitted radiation has decayed to an acceptable low level. Perhaps the most promising method of accomplishing this goal involves encapsulation of the solidified waste into canisters which are then emplaced underground in a stable rock formation for periods of 10^3 to 10^6 years, depending on whether the waste is in the form of reactor fuel rods or processed waste entrained in a solidified matrix. For purposes of possible waste retrieval, the underground facility must remain open for a period of $\sim 10^2$ years. After that, the workings would be backfilled and the site isolated.

Relationship of Laboratory Measurements to the Isolation Problem

Many believe the consequences of failure to isolate these wastes are so enormous that no relevant physicochemical property can remain unexplored and no serious design errors in the complete system can be tolerated.

As physical scientists and engineers, we have no comparable experience which would allow us to accurately predict the behavior of such a complex

system over these extended periods. The approach which offers the best chance of success in the near term would be to carry out relevant, high quality work simultaneously in each of the major scientific and engineering areas necessary for the complete waste storage system. Some of these problem areas are:

1. Characterization of the behavior of the waste material and placement of it into as inert a form as possible. This waste must be compatible with the rock type and characteristics of the site chosen.

2. Identify likely sites on a geological, geophysical basis. Determine characteristics of a site with minimal disruption of structural integrity.

3. Perform tests on that rock under carefully controlled conditions. Evaluate behavior as a function of scale; laboratory as well as field tests will be necessary. Test conditions must encompass as near as possible those expected over the isolation period, including identification of the responsible physicochemical processes.

HEARD, H. C., "Thermal Expansion and Inferred Permeability of Climax Quartz Monzonite to 300°C and 27.6 MPa," Lawrence Livermore Laboratory Report UCRL-83697 (1979); paper submitted to *International Journal of Rock Mechanics and Mining Sciences*.

The coefficient of linear thermal expansion (α) has been evaluated for Climax Stock quartz monzonite at effective pressures (P) of 0, 13.8, and 27.6 MPa (0 to 276 bars) and at temperature (T) from 19 to 300°C. The samples evaluated were deliberately chosen to include imperfections, such as healed fractures and large phenocrysts characteristic of the Climax pluton near the site of a high-level waste repository demonstration test at the Nevada Test Site. Values for α are neither constant with nor a simple function of T or P. For the range of T investigated, α range from 10 to 15 $\times 10^{-6} \text{ } ^\circ\text{C}^{-1}$ at 0 MPa, from 7 to 13 $\times 10^{-6} \text{ } ^\circ\text{C}^{-1}$ at 13.8 MPa and from 7 to 12 $\times 10^{-6} \text{ } ^\circ\text{C}^{-1}$ at 27.6 MPa. These values of α are greater than those expected for a similar but crack-free rock. Observations on the heated rock indicate that the thermal expansion is accompanied by new microcrack formation. At the temperatures to be expected in the wall rock near a waste canister, this increase in crack porosity is inferred to increase local permeability by factors of 2 to 5.

HEARD, H. C., A. Arieli, and A. K. Mukherjee, "Deformation Mechanisms in NaCl at Intermediate and Elevated Temperatures," paper presented at *109th AIME Annual Meeting, Las Vegas, Nevada, February 24-28, 1980*; also, Lawrence Livermore Laboratory Report UCRL-83705 (1979).

The flow stress dependence on temperature and strain rate of annealed, isotropic polycrystalline NaCl has been determined at temperatures of 296 to 673°K (0.28 to 0.63T_M) and strain rates of 10⁻¹ to 10⁻⁸s⁻¹. In the range of temperature between 0.28 and 0.44T_M, the deformation was rate-controlled by the lattice resistance to the dislocation motion. At higher temperatures (0.44-0.63T_M), dislocation climb was found to be the rate-controlling mechanism. The results obtained from this investigation were correlated with those obtained by other investigators in order to obtain a coherent picture of the deformation modes in polycrystalline NaCl.

Heard, H. C., and B. P. BONNER, "Anelastic Response of Copper, Fused Silica, and Quartz Monzonite at High Pressure and Temperature," paper presented at *Seismic Wave Attenuation Conference, Stanford University, California, June 25-27, 1979*; Lawrence Livermore Laboratory Report UCRL-82562 (Abstract) (1979).

Heard, H. C., and B. P. BONNER, "Internal Friction and Transient Creep at High Pressure and Temperature," paper presented at *American Geophysical Union Meeting, Washington, D.C., May 28-June 1, 1979*; Lawrence Livermore Laboratory Report UCRL-82390 (Abstract) (1979).

Heard, H. C., and B. P. BONNER, "Internal Friction and Transient Creep in Granitic Rocks at High Pressure and Temperature," presented at *IUGG Meeting in Canberra, Australia, December 2-17, 1979*; Lawrence Livermore Laboratory Report UCRL-83193 (Abstract) (1979).

HEARD, H. C., and C. F. Cline, "Mechanical Behavior of Polycrystalline BeO, Al₂O₃, and AlN at High Pressure," paper submitted to *Journal of Materials Science*; also, Lawrence Livermore Laboratory Report UCRL-82319 (1979).

The mechanical behavior of various types of BeO, Al₂O₃, and AlN have been investigated at confining pressures up to 1.25 GPa, at 25°C, and at strain rates of 3 to $7 \times 10^{-5} \text{ s}^{-1}$. The stress-strain data taken in uniaxial compressive-stress loading indicate the BeO aggregates undergo a transition from brittle fracture at low pressures to plastic flow at high pressures. Depending on the fabrication process, this transition pressure in BeO occurs at 0.4 to 0.7 GPa. Concurrently, the ultimate strength of BeO increases from 1.0 to 1.9 GPa at 0.1-MPa pressure to over 4.0 GPa at 1.0 GPa. Alumina remains brittle at all pressures up to 1.25 GPa; its strength increases from 4.5 GPa at 0.1-MPa pressure to over 6.0 GPa at 1.25 GPa. Aluminum nitride behaves similarly to BeO, having a brittle-ductile transition at 0.55 GPa. Its ultimate strength increases from 3.2 GPa at 0.1-MPa pressure to 4.7 GPa at 0.8 GPa.

The distortional strain energy (area under the stress-strain curve) absorbed by each material at pressure was calculated and compared to available data from the literature. Alumina shows a degraded energy absorption with pressure, but both BeO and AlN yield a strongly enhanced performance at moderate pressures. Beryllium oxide and AlN thus appear to be promising structural materials for certain applications where high strengths and ductilities are required at moderate pressures.

HEARD, H. C., and S. H. Kirby, "Activation Volume for Steady State Flow in Polycrystalline CsCl (Cesium Chloride Structure)," presented at *American Geophysical Union Meeting, Washington, D.C., May 28-June 1, 1979*; Lawrence Livermore Laboratory Report UCRL-82391 (Abstract) (1979).

Annealed polycrystalline samples of CsCl have been tested in triaxial compression at 200 to 400°C (T), at 50- and 400-MPa pressure (P), and at strain rates ($\dot{\epsilon}$) of 10^{-2} to 10^{-6} s^{-1} . Axial stress-strain data from these tests show an elastic-plastic behavior with minor work hardening occurring at lower temperatures and at higher rates.

At the values of T , P , and $\dot{\epsilon}$ investigated, the steady-state flow stress (σ) ranged from 1.3 to 65 MPa. Comparison of the stress-strain curves taken at similar T , $\dot{\epsilon}$, and at both pressures showed a two- to four-fold increase with P .

Measured values of $\dot{\epsilon}$, T , σ , and P from 30 tests were fit to $\dot{\epsilon} = A\sigma^N \exp[-(Q + PV^*)/RT]$ with V^* the activation volume for steady-state flow. A least-squares fitting routine was used to calculate A , N , Q , and V^* . At 1 std dev and in SI units, $\log A$ is -17.55 ± 0.64 , N is 4.10 ± 0.28 , Q is $149 \pm 10 \text{ kJ mol}^{-1}$, and V^* is $53 \pm 7 \times 10^{-6} \text{ m}^3 \text{ mol}^{-1}$. Larger deviations were observed when the data were fit to $\dot{\epsilon} = \beta \mu/T (\sigma/\mu)^N \exp[-Q + PV^*/RT]$ where μ is the shear modulus. Calculated V_C^* from Sherby and Simnad's empirical relation based on T_m/T and measured dT/dP on melting of the CsCl phase yields $98 \times 10^{-6} \text{ m}^3 \text{ mol}^{-1}$. Alternatively, V_C^* from Keyes' method based on the pressure dependence of the shear modulus and the bulk modulus is $28 \times 10^{-6} \text{ m}^3 \text{ mol}^{-1}$. Thus, if silicate and oxide minerals behave similarly, use of V_C^* derived from either melting behavior or from elastic moduli may lead to serious error in estimating rock flow behavior at depth.

HEARD, R. C., and W. Lin, "Mechanical Behavior of Devonian Shale at High Pressures," Lawrence Livermore Laboratory Report UCRL-83793 (1979).

Prediction of the effects of hydraulic or high-explosive fracturing for stimulation of fluid production from low permeability rocks requires a fracture model and certain equation-of-state (EOS) mechanical properties for input to the calculational codes. For such a study on the Devonian Shale of the eastern United States, we report here new EOS measurements taken on four shale members of this unit from 807- to 1233-m depth in the Columbia Gas Transmission well 20403, Huntington, West Virginia. For each member we have determined:

- (1) Tensile strength parallel and perpendicular to bedding, 0.1 MPa
- (2) Uniaxial stress failure envelope in compression to 300-MPa confining pressure, parallel and perpendicular to bedding
- (3) Uniaxial stress failure envelope in extension to 400- to 600-MPa confining pressure, parallel and perpendicular to bedding
- (4) Pressure-volume behavior to 4 GPa
- (5) Loading path in uniaxial strain (compression) beginning at 20- and 30-MPa confining pressure, loading direction both parallel and perpendicular to bedding

(6) Shear and compressional wave velocities to confining pressures of 1.0 GPa. Measurements were made parallel, at 45° , and perpendicular to bedding.

Results for (1) indicate, in general, there does not appear to be any discernable trend in tensile strength with either depth or between rock units (for the same orientation). Further, the tensile strength parallel to the bedding seems to be about two times that measured normal to bedding. Strengths and failure modes in compression and extension (2,3) show at low-moderate pressures; failure is brittle in all cases and is the result of combined tensile and shear fracture. For compression, at the highest pressures tested, these shale units frequently become ductile; that is, all deformation is quasi-uniformly distributed. For extension, however, brittle behavior dominates at all pressures. The extensile strengths are always lower than those of compression. Most units have only about a 10-20% strength anisotropy with loading direction. Loading parallel to bedding seems to be strongest (except at the lowest pressure) but more brittle than for perpendicular to bedding. Pressure-volume loading (4) indicates these rocks are rather incompressible: $6-10\% \Delta V/V_0$ at 2 GPa. For uniaxial strain loading (5), each shale unit follows a loading path subparallel to the compression failure envelope but at about one-half of that value. Large hysteresis occurs on unloading.

Acoustic velocities (6) increase more rapidly at low pressure (below 0.1 to 0.2 GPa) than at high pressure due to the preferential closing up of microcracks. The rock units show significant anisotropy in compressional wave velocity which decreases with pressure. For shear waves, the results do not show significant variation of anisotropy with pressure. Our results do not show significant variation of velocities with depth for any single unit.

HEARD, H. C., D. Trimmer, A. Duba, and B. Bonner, "Permeability of Generic Repository Rocks at Simulated *In Situ* Conditions," paper presented at *Workshop on Low-Flow, Low Permeability Measurements in Largely Impermeable Rocks, Paris, France, March 19-21, 1979*; Lawrence Livermore Laboratory Report UCRL-82609 (Abstract) (1979).

New laboratory data are reported on the effect of confining (lithostatic) pressure, pore-water pressure, and principal stress difference on permeability

of Westerly granite and White Lake gneissic granite. Permeabilities as low as 10^{-19} cm² (10^{-11} D) have been measured successfully, using a transient technique. Principal strains, electrical conductivity, and compressional velocity are determined simultaneously. Applied loads on the 15-cm-diameter by 28-cm-long test sample are controlled automatically and all data are taken by a microcomputer. Results on the gneissic granite indicate permeabilities of 10^{-18} to 10^{-19} cm² that appear to be unaffected either by effective pressure or by stress. The granite yields permeabilities of 4×10^{-16} cm² that decrease by a factor of two with pressure and vary by a factor of two with stress. When compared to the initial value, compressional velocities increase by 4% and conductivity decreases by 50% as pressure is increased to 50 MPa in the gneissic granite. In granite, these become 3% and 58%, respectively. At pressure, loading of the granite to 0.5 of failure stress increases conductivity by about 20%.

HEARD, H. C., D. Trimmer, W. Lin, A. Duba, and B. Bonner, "Simultaneous Measurements of Permeability, Electrical Conductivity, and Ultrasonic Velocity in Igneous and Metamorphic Rocks," paper presented at *American Geophysical Union Meeting, Washington, D.C., May 28-June 1, 1979*; also, Lawrence Livermore Laboratory Report UCRL-82389 (1979).

Fluid transport in low permeability rocks is critical to the safe underground storage of radioactive wastes. We report new permeability, electrical conductivity, acoustic velocity, and strain data taken at moderate lithostatic and pore water pressures, at moderate deviatoric stresses, and at 25°C. Test samples were 15 cm in diameter by 28 cm long, and both fractured and unfractured rocks were evaluated.

Among the rocks studied, there is a wide range in both permeability and the sensitivity of this permeability to stress or pressure. As an example, in an unfractured gneissic granite, we measure permeabilities of 10^{-18} to 10^{-19} cm² (10^{-10} to 10^{-11} D); these appear to be unaffected by pressure or stress. An unfractured granite yields permeabilities of 4×10^{-16} cm² which decrease by a factor of two with pressure but vary by a factor of two with stress. When compared to the initial value, compressional velocities increase by 4% and conductivity decreases by 50% as pressure is increased 50

MPa in the gneissic granite. In granite, these become 3% and 58%, respectively. At pressure, loading of the granite to 0.5 of failure stress increases conductivity by about 20%. In argillite, an increase of pressure from ambient to 50 MPa decreases the initial permeability of 10^{-16} cm^2 by a factor of 10^3 . The equivalent permeability for fractured argillite decreases from 10^{-12} cm^2 to $<10^{-17}$ over similar pressures.

HEARST, J. R., "Calibration of a Neutron Log in Partially Saturated Media," *SPWLA Twentieth Annual Well Logging Symposium, Tulsa, Oklahoma, June 3-6, 1979*; Lawrence Livermore Laboratory Report UCRL-81657 (1979).

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-diameter) dry holes and 30-cm-diameter 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, 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., *Technical Concept for Rock Mechanics Tests, Climax Granite*, NTS, Lawrence Livermore Laboratory Report UCID-18009 (1979).

If we are to believe our predictions of the thermomechanical behavior of the material surrounding a nuclear waste repository in granite, we must test the computational methods used in making the predictions. If thermal loadings appropriate to a real repository are used, thermally induced displacements and

the computational methods used in making the predictions. If thermal loadings appropriate to a real repository are used, thermally induced displacements and strains are quite small, and available geotechnical instrumentation is only marginally able to measure these effects to the accuracy desired to make thorough tests of the predictions. We outline a three-step program to address these issues:

1. Conduct experiments in which the thermal loading is large compared to that induced by a real repository. This will permit us to make accurate measurements with available instrumentation.
2. Simultaneously, develop improved instrumentation that will enable us to make accurate measurements of motions induced by thermal loadings appropriate to a real repository.
3. Finally, conduct a second set of experiments, with the improved instrumentation and thermal loading similar to that of a real repository in granite.

If we can predict the effects of this thermal loading to a few percent over distances of tens of meters for time periods of a few years, and demonstrate that these predictions are correct, we can have reasonable confidence that, using the same methods, we can predict the behavior over thousands of meters for hundreds of years to an order of magnitude. That accuracy should be satisfactory for those distances and times.

HEARST, J. R., J. W. Schmoker, and R. C. Carlson, "Effects of Terrain on Borehole Gravity Data," Lawrence Livermore Laboratory Report UCRL-80984 (1979).

The effect of terrain on gravity measurements in a borehole and on formation density derived from borehole gravity data is studied as a function of depth in the well, terrain elevation, terrain inclination, and radial distance to the terrain feature. The vertical attraction of gravity in a borehole g_T resulting from a terrain element is small at the surface and reaches an absolute maximum at a depth of about one and a half times the radial distance to the terrain element, then decreases at greater depths. The effect of terrain on calculated formation density is proportional to the vertical derivative of g_T and is maximum at the surface, passes through zero where $|g_T|$ is greatest, and reaches a second extremum of opposite sign to the first

and of much lower magnitude. Accuracy criteria for borehole-gravity terrain corrections show that elevation accuracy requirements are most stringent for a combination of nearby terrain features and near-surface gravity stations. Sensitivity to terrain inclination is also greatest for this combination. The measurement of the free-air gradient of gravity, commonly made slightly above the ground surface, is extremely sensitive to topographic irregularities within about 300 m of the measurement point. The density effect of terrain features 21.9 to 166.7 km from the well (Hammer's zone M through Hayford-Bowie's zone 0) is nearly constant with depth. At these distances the terrain correction will be equivalent to a dc shift of about $0.053 \text{ g/cm}^3/1000 \text{ m}$ of average elevation above or below the correction datum. The effect of topography beyond 166.7 km is not likely to exceed 0.01 g/cm^3 .

HEUSINKVELD, M., *Analysis of Slifer Data from Underground Explosions*, Lawrence Livermore Laboratory Report UCRL-52648 (1979).

We derive a formula describing the distance-time relationship of a shock wave moving outward from an underground explosion. We compare our calculated results with those computed using the LASL and BOTE formulas and with slifer data obtained from field experiments. We find that for many of the field events, our derived curve provides a better fit than do the LASL or BOTE formulas. We also present methods for the determination of the detonation energy W under three conditions: (1) where time and distance are known accurately, (2) where there is an unknown offset of time and distance, and (3) where there is an unknown offset of both time and distance. These methods are applied with moderate success to a set of (t,r) data supplied by Goldwire.

HOWARD, N. W., "The Continental Drilling for Scientific Purposes Data Management Program at Lawrence Livermore Laboratory," *Proceedings, Geoscience Information Society Symposium, Geological Society of America Annual Meeting, San Diego, California, November 4-7, 1979*; Lawrence Livermore Laboratory Report UCRL-82819 (1979).

Lawrence Livermore Laboratory was funded by the Office of Basic Energy Sciences of the Department of Energy (DOE/OBES) "to support the establishment

of a data and information unit on all DOE drilling activities, as a service for the entire scientific community." The effort is known as "The Continental Drilling for Scientific Purposes Data Management Program." The primary concern at this time is the collection of data on basement structures and deep continental basins, thermal regimes of the crust, mineral resources, and earthquakes and faulting. Satisfactory investigation of all these topics is dependent on data from deep, and therefore, expensive holes. An information system for existing and proposed deep drilling projects should be useful both for investigations of the particular concerns noted above, and for studies of the earth's crust in general. The data management program should promote the efficient use of limited funds for drilling deep holes. Given the knowledge of these deep holes, investigators may either use existing information, or propose experiments for planned holes that will--with perhaps only little extra expense compared with the cost of the hole--provide the data they need.

The LLL program is intended to improve dissemination of information on scientifically interesting holes. The program is operational but still under development. Data management systems are being reviewed to ascertain the most useful system. Data are being supplied by many individuals knowledgeable about existing and planned deep holes. Included among these individuals are members of the staff of the U.S. Geological Survey. Output of data now in the system is available on request.

HOWARD, N. W., LLL K Division Nuclear Test Effects and Geologic Data Base: Glossary and Parameter Definitions, Lawrence Livermore Laboratory Report UCID-18300, Part 1 (1979).

This report lists, defines, and updates Parameters in Dbase, an LLL test effects data bank in which data is stored from experiments performed at NTS and other test sites. Parameters are listed by subject and by number. Part 2 of this report presents the same information for parameters for which some of the data may be classified.

HOWARD, N. W., B. Grothaus, and H. McKague, "Subsurface Correlation of Tertiary-Quaternary Desert Alluvial Deposits, Northern Yucca Flat, Nevada," paper presented at *Cordilleran Section Meeting, Geological Society of America, San Jose, California (1979)*; Lawrence Livermore Laboratory Report UCRL-81872 (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 CO₂ 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. McKAGUE, and B. Grothaus, "Recognition of Faults in Tertiary-Quaternary Alluvium in Northern Yucca Flat, Nevada," paper presented at the *Cordilleran Section Meeting, Geological Society of America, San Jose, California (1979)*, Lawrence Livermore Laboratory Report UCRL-81873 (1979).

ISHERWOOD, D., R. A. Heckman, T. Holdsworth, D. F. Towse, and N. L. Dayen,
Site Suitability Criteria for Solidified High Level Waste Repositories,
Lawrence Livermore Laboratory Reports UCID-17830 and UCID-17831 (1979).

The Nuclear Regulatory Commission (NRC) is responsible for the management and disposal of nuclear wastes from licensed facilities. The agency also has licensing responsibility for long-term storage and disposal of high-level radioactive wastes from commercial operations and the Department of Energy.

In discharging its responsibilities, the NRC is developing a framework of regulations, criteria, and standards. Lawrence Livermore Laboratory (LLL) provides broad technical support to the NRC for developing this regulatory framework, part of which involves site suitability criteria for solidified high-level wastes (SHLW).

Both the regulatory framework and the technical base on which it rests have evolved in time. This document is the second report of the technical support project. It was issued as a draft working paper for a programmatic review held at LLL from August 16 to 18, 1977. It was printed and distributed solely as a briefing document on preliminary methodology and initial findings for the purpose of critical review by those in attendance. An earlier draft was generated as a briefing document for meetings with the NRC at LLL on March 22 and 23, 1977.

These briefing documents are being reprinted now in their original formats as UCID-series reports for the sake of the historical record. The LLL program has evolved rapidly and extensively. Some approaches that merited consideration during the initial stage of investigation have been discarded. New approaches have been tested. The models have been continuously refined and the data base updated with the accumulation of new information. Analysis results have evolved as both the models and data base have changed. As a result, the methodology, models, and data base in this document are severely outmoded.

In addition to these evolutionary programmatic changes, a major shift in program direction was mandated during FY 78 as a result of the Presidential decision to defer the reprocessing of spent reactor fuel. Emphasis was shifted from SHLW disposal to the study of spent-fuel disposal and retrieval in the environment of a deep geologic repository.

Isherwood, D., D. F. TOWSE, R. A. Heckman, T. Harvey, and T. Holdsworth, *High Level Waste Repository Site Suitability Study--Status Report*, Lawrence Livermore Laboratory Report UCRL-52633 (1979).

KNAUSS, K. G., and T. Ku, "Desert Varnish: Potential for Age Dating Via Uranium-Series Isotopes," accepted for publication in *Journal of Geology*; Lawrence Livermore Laboratory Report UCRL-82331 (1979).

Trace metals and natural radioisotopes were measured in an unusually thick and presumed ancient desert varnish from the Colorado Plateau in Utah. The U and Th concentrations in the sequence: varnish--altered rind--heartrock (sandstone of the Shinarump fm.) indicate that U with little accompanying Th is derived from external sources. The varnish forms a perfect closed system for ^{230}Th and ^{231}Pa with concordant equilibrium values for both $^{230}\text{Th}/^{234}\text{U}$ and $^{231}\text{Pa}/^{235}\text{U}$. Selective leaching of the ferromanganese oxides followed by analysis of both the leachate and silicate residue is proposed to allow age determinations.

KNAUSS, K. G., and T. Ku, "Radioactive Disequilibrium in Fissure-Filling Material and Its Implication in Dating of Manganese Nodules," *Colloques Internationaux du CNRS No. 289, La Génèse des Nodules de Manganèse* (1979), p. 289.

Study has been made of the uranium-series nuclides distribution in the interior of manganese nodules--in regions deeper than the outermost 3-4 mm where U-unsupported ^{230}Th and ^{231}Pa are normally found. Within experimental error, radioactive equilibrium among ^{238}U - ^{234}U - ^{230}Th prevails in most of the inner layers examined. The disequilibrium observed in a few cases is shown to result from infiltration of "young" sedimentary material (e.g., clay and carbonate) along diagenetically formed cracks or fissures. The extent of the disequilibrium indicates that the fissure-filling process was initiated at least 300,000 years ago. This age should constitute a lower limit for the age of the nodules. The observed logarithmic decrease of radioactivity with depth in nodules can be the combined effect of decay and

mixing process such as migration of material through fissures observed here. In this case, the accretion rates of nodules must be slower than those estimates obtained by assuming the logarithmic decrease as being solely due to radioactive decay.

KNAUSS, K. G., T. Ku, W. B. Bull, and S. T. Freeman, " ^{230}Th - ^{234}U Dating of Pedogenic Carbonates in Gravelly Desert Soils of Vidal Valley, Southeastern California," *Geol. Soc. Am. Bull.* 90, 1063 (1979).

Radioactive disequilibrium relationships among ^{230}Th , ^{234}U , and ^{238}U can be used to date pedogenic carbonates formed in regions of arid to semiarid climate. Samples suitable for dating consist of dense carbonate rinds around pebbles from the Cca soil horizon. Analogously, the method involves leaching the samples with dilute hydrochloric acid and measuring ^{238}U , ^{234}U , ^{230}Th , and ^{232}Th in both the leachate and residue fractions. As the soil carbonate commonly incorporates silicate mineral-bearing detritus, corrections are made to account for possible introduction of detrital ^{230}Th and ^{234}U into the acid leachate. The corrections are based on the assumptions that (1) the carbonate initially contains negligible amounts of ^{232}Th and ^{230}Th , or has a $^{230}\text{Th}/^{232}\text{Th}$ ratio similar to that in detrital minerals, (2) ^{238}U , ^{234}U , and ^{230}Th in the detrital silicate phase are in secular equilibrium with each other, and (3) the thorium isotopes in the detrital phase are not fractionated by the acid leaching. Application of the method to calcareous soils developed on upper Quaternary alluvial deposits of the eastern Mojave Desert in southern California gives ages that are internally consistent and that agree with the geomorphic and stratigraphic relative age relationships. Fourteen samples from an upper Pleistocene geomorphic surface, Q2b, yielded an average age of $83,000 \pm 10,000$ years. This age is confirmed by a different assessment of the data independent of the aforementioned assumptions. On one specimen two different layers of a pebble coating were dated, and a carbonate accumulation rate of about 1 mm/8,000 years was obtained. It is hoped that this study will serve as a basis for further research into the absolute dating of various types of impure carbonates of late Quaternary origin.

KNAUSS, K. G., R. Quong, N. D. Stout, L. B. Owen, "An Effective H_2S Abatement Process Using Geothermal Brine Effluents," *Trans. Geotherm. Resour. Council* 3, 557 (1979); Lawrence Livermore Laboratory Report UCRL-83010 (1979).

A simple and potentially inexpensive method for removal of H_2S from noncondensable gases evolved in geothermal flash processes has been successfully tested on a small scale in the field. The method consists of scrubbing the noncondensable gases of H_2S with brine effluents which contain relatively high concentrations of Pb, Zn, and Fe such as those of the Salton Sea and Brawley Geothermal Fields in the Imperial Valley, California. For plant applications, noncondensibles including H_2S would be ejected from a surface steam condenser (necessary to minimize the volume of liquid in contact with H_2S) and scrubbed with effluent brine just prior to preinjection clarification. The metal sulfide precipitates are removed in the clarification step, and the noncondensibles, less H_2S , are vented as usual.

KUSUBOV, A. S., and W. Durham, "Explosive-Induced Effects in Porous Sandstone under Confining Pressure," Lawrence Livermore Laboratory Report *Energy and Technology Review*, December 1979.

The fracturing of deeply buried rock is being explored as a means for recovering natural gas from underground reservoirs. Explosives provide one potential fracturing method. We have performed experiments and computer calculations to improve our understanding of the response of confined, partially water-saturated porous sandstone to explosive loading. We find that explosive loading is not effective for causing tensile fractures that could lead to increased permeability in deeply buried porous materials. The stress waves are attenuated by pore collapse and shear fracturing in a relatively small volume of material immediately around the explosion.

KUSUBOV, A. S., J. F. Schatz, W. B. Durham, R. N. Schock, and T. J. Ahrens, "Effect of Confining Pressure on Explosively Induced Damage in Porous Sandstone," presented at *American Geophysical Union Meeting, Washington, D.C., May 28-June 1, 1979*; Lawrence Livermore Laboratory Report UCRL-82384 (1979).

A laboratory study of high explosive-generated damage in porous sandstone has been conducted to study the effect of overburden pressure on crack formation and permeability enhancement. PETN charges (160-mg) were detonated in samples of Sego sandstone under confining pressures of 0.1, 24.0, and 48.0 MPa. The samples had a porosity of 26%, of which 75% was water-filled. The predominant effect of the explosion was compaction of the rock around the cavity. The maximum density increase was roughly 5%. Scanning electron microscopy of sample sections revealed that fracturing on the scale of grain sizes (100 to 200 μm) accompanied the compaction. Longer fractures were conspicuously absent. The cracking and compaction fell to background levels within approximately 2 radii of the cavity. A dependence on confining pressure was difficult to resolve. A numerical calculation based on a quasi-static equation-of-state of a similar sandstone predicts that the effect of confining pressure should be difficult to observe, the damage radius at 0.1 MPa being only a few percent larger than that at 48.0 MPa. The computer model also predicts a spherical region at 3 to 4 cavity radii where one component of the residual stress field is below overburden stress, rendering the rock in that region more susceptible to fracturing. The zone of compacted material around the cavity and the absence of through-going fractures suggest that ordinary explosions may not be effective in increasing permeability of "tight" gas sandstones at depth.

KUSUBOV, A. S., W. B. Durham, R. N. Schock, J. E. Schatz, and T. J. Ahrens, "Explosive-Induced Damage in Porous Sandstone," submitted to *Proceedings of 7th AIRAPT International High Pressure Conference, La Creusot, France, July 30-August 3, 1979*; Lawrence Livermore Laboratory Report UCRL-83448 (1979).

We have conducted a combined laboratory and computational effort to study the effect of overburden pressures on explosively damaged porous sandstone.

We found that it was difficult to establish a dependence on confining pressure. The predominant effect of the explosion was compaction around the cavity, and macroscopic fractures were conspicuously absent.

KUSUBOV, A. S., and R. P. Swift, "Technique to Study Multiple Fractures Produced at Intermediate Loading Rates," Lawrence Livermore Laboratory Report UCRL-83653 (Abstract) (1979).

A laboratory experiment has been developed to study the effects on hydrofracture caused by pressurizing a borehole at intermediate loading rates. The study is aimed at identifying loading conditions needed to initiate and sustain multiple fracture growth from a borehole. Controlled loading conditions are achieved by compressing fluid in a borehole with a piston engaged by a profiled cam mounted on a rotating shaft. The experimental apparatus provides sample confinement to 50-MPa pressure, borehole pressures up to 200 MPa with loading rates from quasi-static to 1 GPa/s, and pulse durations on the order of 1 to 50 ms. Observations from tests on a dense quartz sandstone under ambient confinement of 0.1 MPa are as follows: For quasi-static loading, the breakdown pressure is about 21 MPa with two fractures oriented at 180 degrees. For loading rates between 30 and 100 GPa/s, the breakdown pressure increases to about 40 to 45 MPa, and multiple fractures are observed. The technique provides a way to evaluate the tensile strength dependence on strain rate in the range from static to 100/s, and the results are indicative that communication in the tight gas and oil bearing media may be increased by hydrofracturing at intermediate loading rates.

LARSON, D. B., "Shock Wave Studies in Blair Dolomite," submitted to *Journal of Geophysical Research*; Lawrence Livermore Laboratory Report UCRL-80819 (1979).

Two types of shock wave experiments have been conducted on samples of Blair dolomite. The first employed a light-gas gun to produce uniaxial strain, while the second used a spherical high-explosive charge to cause radial divergent flow. Comparisons of data taken from these two types of experiments

(at strain rates of $10^6/s$ and $10^4/s$, respectively) with quasi-static data (at $10^{-4}/s$) show that Blair dolomite is strongly time-dependent in its behavior. This time-dependence appears over the entire stress interval from 0.24 to 5.33 GPa.

LARSON, D. B., *Spherical Wave Propagation in Elastic Media and Its Application to Energy Coupling for Tamped and Decoupled Explosions*, Lawrence Livermore Laboratory Report UCRL-52655 (1979).

The effects of variation in source and medium properties upon near and far field spectra for elastic waves are examined theoretically by considering spherical wave propagation in unbounded elastic media. This type of analysis, although idealized, provides insight into the relative effects of the various source and medium parameters on both tamped and decoupled explosions. Furthermore, it provides a basis for the interpretation of both field and laboratory experimental data obtained during spherical wave propagation in real media. In this report, I attempt to unify and present more completely the work that has been done on spherical wave propagation in elastic media. This is done in hopes that others may find the nondimensional forms of the solutions useful and some of the conclusions enlightening. Also included are a discussion of some of the limitations of the theory and examples of how this theory might be applied to spherical wave propagation in real media.

LARSON, D. B., and G. D. Anderson, "Plane Shock-Wave Studies of Porous Geologic Media," submitted to *Journal of Geophysical Research*; Lawrence Livermore Laboratory Report UCRL-80898, Rev. 1 (1979).

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 up to stress levels of about 4 GPa. 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. The strong time dependence observed in these materials would seem to preclude the use of quasi-static

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 high-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, "Plane Shock Wave Studies of Westerly Granite and Nugget Sandstone," submitted to the *Journal of Geophysical Research*; Lawrence Livermore Laboratory Report UCRL-82264 (1979).

Plane shock wave experiments were performed by using a light-gas gun on dry and water-saturated Westerly granite and dry Nugget sandstone. Changes in the slopes of the shock velocity vs particle velocity curves at 2 to 3 GPa and 1 to 2 GPa for dry granite and for dry sandstone, respectively, are attributed to the onset of pore collapse. However, there is little apparent loss of shear strength in either dry rock over the stress range of the experiments (i.e., 9.3 GPa in Westerly granite and 9.2 GPa in Nugget sandstone). Agreement between the shock wave data and quasi-static, uniaxial strain data for the dry rocks implies the absence of rate-dependence in uniaxial strain. The shock data on saturated granite agree well with those for dry granite, thus suggesting there was no loss in shear strength as a result of pore pressure buildup.

LEWIS, A. E., "Oil Shale: A Framework for Development," Lawrence Livermore Laboratory Report UCRL-83738 (1979).

The price escalation of petroleum in recent times has removed the economic barrier to shale oil production or soon will. A technological base for production is available which can be rapidly developed to the size and quality needed. The resource base in the Piceance Creek Basin of Colorado can support production of 1 to 5 million barrels of oil per day for hundreds of years.

Institutional problems are the major remaining impediment to the development of oil shale. The small part of the resource in private hands is economically marginal and cannot support large production rates or the most

efficient methods. The best land is owned by the federal government and is unavailable under present laws and policies. The lack of an integrated federal policy and an implementation plan prevents the development that is now technically and economically practical.

One possible solution is Piceance Basin Authority chartered by Congress to efficiently manage this resource and coordinate the federal governmental responsibility for oil shale resource development and conservation, water development, environmental control, and land use policy. It should be located in Colorado to help provide for an effective interaction with State and local authorities where both have responsibility.

Government lands must be made accessible on a scale suitable to the technology and in a way that is acceptable to industry and the public. Government and industry can then cooperate in a unitized, coordinated development of the resource and the area. With access to the resource and a clear government responsibility for area-wide noncommercial planning and development, industry can provide the technology and capital for production and marketing of shale oil on an economically competitive basis.

I believe that we will want production soon from oil shale, and for a long time to come. Now is the time to establish the objectives and the institutional framework necessary for both commercial production and noncommercial area development.

LEWIS, A. E., "Oil from Shale: the Potential, the Problems, and a Plan for Development," Lawrence Livermore Laboratory Report UCRL-83236 (1979).

A unitized management and development of the government-owned oil shale will make it technically and economically practical to obtain very large production rates (1 to 5×10^6 bbl/day) of shale oil from this source. The estimated price is below world prices and could be less than \$15/bbl. Private oil shale lands, on the other hand, provide a smaller though still important potential for production in terms of resource size and economic cost. Important differences exist in the nature of the oil-shale resource held by the government and that held by private companies. These differences are crucial not only in estimating production costs and incentives necessary for production but also in defining applicable technology.

Only a small part of the resource is in private hands, and these individual plots are too small to support large production rates. The technology applicable to these plots is estimated to be more costly than technology applicable to government land. The high cost (\$25 to \$30/bbl) and limited production potential of these private plots, as well as the economic risk of potential delay in obtaining permits and licenses, make these plots economically marginal. For these private lands, substantial government subsidy in one form or another will be required to get the first plant or two on line at a production rate of 100,000 bbl/day.

The failure of the federal government to provide a workable policy and an implementation plan for managing and developing the federal land prevents the development that is now technically and economically practical. Economic incentives provided by government will have no effect on this development, because they do not remove the present impediments.

If government lands are made accessible in an acceptable way and government and industry cooperate in a unitized, coordinated development of the resource, it will be possible to obtain economically competitive production at an early time without the need for the government to provide substantial economic incentives to industry for production and marketing of shale oil.

A Piceance Basin Authority (PBA) that is chartered by Congress should be established to efficiently manage this government resource as a single unit. This would allow efficient coordination of federal governmental responsibility for oil-shale resource development and conservation, water development, environmental control, and land use policy. Because of the magnitude of the development, the duration in time, and the fact that government organization and policy now constitute a blocking position in the development of this resource, this unitized operation is beyond the capability and area of responsibility of industrial corporations alone and, therefore, requires government action.

Production at a rate of 5×10^6 bbl/day can be maintained for four centuries in the Piceance Basin. We expect that actual production and marketing can best be accomplished by industry, but government must provide for an efficient, integrated basin development.

LEWIS, A. E., and R. L. Braun, "Retorting and Combustion Processes in Surface Retorts," Lawrence Livermore Laboratory Report UCRL-82085 (1979).

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 the loss of oil yield. We believe that application of this model can contribute to improvements in surface processing.

LIN, W., "Determination of Rock Permeability Using the Transient Method," Lawrence Livermore Laboratory Report UCRL-81644 (Abstract) (1979).

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 up-stream reservoir is observed. We have developed a transient method that is suitable for any size of specimen and reservoir. Pressures in the up-stream reservoir are calculated numerically as a function of time for the exact specimen and reservoir sizes used in the experiment, with various values of permeabilities, 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} D 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} D at effective pressures of about 1.0 MPa to 10^{-8} D at pressures of about 24 MPa.

Lin, W., M. E. HANSON, G. D. Anderson, R. J. Shaffer, D. F. Towse, A. G. Duba, N. R. Burkhard, M. P. Cleary, and B. C. Hamison, *LLL Gas Stimulation Program Quarterly Progress Report, January through March 1979*, Lawrence Livermore Laboratory Report UCRL-50036-79-1 (1979).

Lin, W., M. E. HANSON, G. D. Anderson, R. J. Shaffer, D. F. Towse, M. P. Cleary, and B. C. Haimson, *LLL Gas Stimulation Program, Quarterly Progress Report, April through June 1979*, Lawrence Livermore Laboratory Report UCRL-50036-79-2 (1979).

Lin, W., and H. C. HEARD, "Mechanical Behavior of Devonian Shale at High Pressures," Lawrence Livermore Laboratory Report UCRL-83793 (1979).

Lin, W., H. C. HEARD, D. Trimmer, A. Duba, and B. Bonner, "Simultaneous Measurements of Permeability, Electrical Conductivity, and Ultrasonic Velocity in Igneous and Metamorphic Rocks," paper presented at *American Geophysical Union Meeting, Washington, D.C., May 28-June 1, 1979*; also, Lawrence Livermore Laboratory Report UCRL-82389 (1979).

LIN, W., and C. Wang, "P-Wave Velocities in Rocks at High Pressure and Temperature and the Constitution of the Central California Crust," submitted to *Geophysical Journal*; Lawrence Livermore Laboratory Report UCRL-81249, Rev. 1 (1979).

Velocities of compressional waves are determined for central California rocks at pressures up to 0.7 GPa (7 kbar) and temperatures up to 450°C. These data are used to interpret the seismic velocity structure of the crust in the California Coast Ranges. The seismic data on both sides of the San Andreas fault are consistent with the following model: besides some patches of surface sediments, the upper 10 to 15 km of the crust on the northeast side consists of predominantly 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 on the southwest side, the entire crustal section 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.

Lohmann, M. L., and P. S. BROWN, "Computer Modeling of the Voitenko Shock Tube Generator," Lawrence Livermore Laboratory Report UCRL-81701 (1979).

MALLON, R. G., "Preparation and Injection of Grout from Spent Shale for Stabilization of Abandoned *In Situ* Oil Shale Retorts," Lawrence Livermore Laboratory Report UCRL-82455 (1979).

A procedure for stabilizing abandoned *in situ* oil shale retorts has been the subject of laboratory investigation. The procedure involves high-temperature treatment of surface processed shale followed by grinding, mixing with water, and injection underground. Laboratory results indicate that abandoned *in situ* retorts can be made strong enough to prevent subsidence, and sufficiently impermeable to greatly reduce groundwater flow. The underground injection also reduces the disposal of spent shale on the surface.

The exposure of spent oil shale to a temperature above that required for retorting results in the formation of a complex group of calcium silicates. A few of these compounds are hydraulic in nature; that is, they will form cohesive hydrates and become rigid and strong. By carefully choosing the time, temperature, and gaseous environment of exposure, the formation of hydraulic compounds can be maximized. Laboratory evidence indicates that the process chosen in this work results in the production of larnite, 2CaO SiO_2

and alite, 3CaO SiO_2 . These two compounds are hydraulic and are primarily responsible for strength in Portland cement. From x-ray examination, it appears that no other calcium silicates are formed in this process.

Samples were prepared using laboratory retorted shale as aggregate and high-temperature treated shale as grout to simulate underground injection. Tests on these samples showed that compressive strength continues to increase for several weeks after sample preparation. Permeability tests have also been performed on this material, and flow characteristics of the grout have been measured.

McKAGUE, H. L., B. Grothaus, and N. W. Howard, "Recognition of Faults in Tertiary-Quaternary Alluvium in Northern Yucca Flat, Nevada," paper presented at the *Cordilleran Section Meeting, Geological Society of America, San Jose, California (1979)*; Lawrence Livermore Laboratory Report UCRL-81873 (1979).

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/sq mi, in the hills surrounding Yucca Flat. This high number of faults plus the occurrence of low magnitude earthquakes around Yucca Flat indicate 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 has no surface expression, but has 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 are the most common technique. Electrical conductivity and downhole photography have been used successfully to identify faults in a single hole. Although the resolution is

nct 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., N. W. HOWARD, and B. Grothaus, "Subsurface Correlation of Tertiary-Quaternary Desert Alluvial Deposits, Northern Yucca Flat, Nevada," paper presented at *Cordilleran Section Meeting, Geological Society of America, San Jose, California (1979)*; Lawrence Livermore Laboratory Report UCRL-81872 (1979).

McKague, H. L., R. W. TERHUNE, H. D. Glenn, D. E. Burton, and J. T. Rambo, "Numerical Simulation of the Baneberry Event," *Nucl. Technol.* 46, 159 (1979).

Mead, S. W., J. H. CAMPBELL, F. T. Wang, and J. F. Busby, "Groundwater Quality Near an Underground Coal Gasification Experiment," *J. Hydrol.* 44, 241 (1979).

MEAD, S. W., F. T. Wang, H. C. Ganow, and D. H. Stuermer, "Environmental Studies of LLL's Hoe Creek II Underground Coal Gasification Experiment," Lawrence Livermore Laboratory Report UCRL-82409 (1979).

The Lawrence Livermore Laboratory has conducted two underground coal gasification experiments at its Hoe Creek site in northeastern Wyoming. During the Hoe Creek II experiment, roof collapse and the inadvertent gasification of an overlying coal seam resulted in the interconnection of three aquifers, including the two gasified coal seams. This situation has led to changes in the local hydrology and in the dispersal of reaction-product contaminants.

We have measured roof collapse with an array of subsurface geotechnical instruments, installed before gasification, and by means of post-burn coring operations. More than a dozen wells in and near the gasification cavity have

been monitored for water quality changes. Limited water quality analysis is carried out in the field, and detailed analysis is performed at U.S. Geological Survey laboratories and at LLL. The results of these measurements are providing a picture of contaminant distribution and movement through the interconnected aquifers.

MEAD, S. W., F. T. Wang, H. C. Ganow, D. H. Stuermer, and R. Stone, "Ground-Water Effects of Underground Coal Gasification Experiments in Northeastern Wyoming," *54th Annual Fall Technical Conference of the Society of Petroleum Engineers of AIME, Las Vegas, Nevada, September 23-26, 1979*; Lawrence Livermore Laboratory Report UCRL-82466 (1979).

The Lawrence Livermore Laboratory has carried out two underground coal gasification (UCG) experiments at its Hoe Creek site in Northeastern Wyoming. We are conducting environmental studies in conjunction with these UCG experiments, including an investigation of changes in local groundwater quality. Such changes are a consequence of the residual reaction products-- coal ash, char, some of the coal tars, and roughly 10% of the product gases-- which remain underground after gasification. When groundwater returns to the gasification zone, leaching and dissolution processes lead to the formation of a plume of contaminated groundwater, which begins to move through the coal seam. In addition, fissuring and roof collapse may destroy the integrity of the underground "reaction vessel" permitting contaminants to escape to the surface or into overlying aquifers. Our field investigations include groundwater quality monitoring near the UCG experiments, geotechnical measurements of ground deformations, and post-burn coring. Limited water quality analysis is performed in the field, and more extensive analysis, including GC-MS, is carried out at LLL and U.S. Geological Survey laboratories. The field program is augmented by laboratory measurements and modeling studies. We have monitored groundwater quality in wells near the first LLL experiment for a period of 2 years following gasification. A large number of contaminants were found in wells located up to 100 ft (30 m) from the burn zone, but concentrations have decreased substantially as a result of sorption by the coal. During the second gasification experiment (Hoe Creek II), roof collapse and the inadvertent gasification of an overlying coal seam caused the

interconnection of three aquifers, including the two gasified coal seams. We have measured the resulting changes in local hydrology and in the dispersal of reaction-product contaminants.

Miller, D. G., and J. A. RARD, "The Mutual Diffusion Coefficients of $\text{BaCl}_2\text{-H}_2\text{O}$ and $\text{KCl-H}_2\text{O}$ at 25° from Rayleigh Interferometry," Lawrence Livermore Laboratory Report UCRL-83065 (1979).

MILLER, D. G., J. A. Rard, L. B. Eppstein, and R. A. Robinson, "Mutual Diffusion Coefficients, Electrical Conductances, Osmotic Coefficients, and Ionic Transport Coefficients l_{ij} for Aqueous CuSO_4 at 25° ," accepted for publication by *Journal of Solution Chemistry*; Lawrence Livermore Laboratory Report UCRL-83465 (1979).

Experimental thermodynamic and transport data are presented for aqueous CuSO_4 solutions at 25°C from low concentrations to near saturation. Included are diffusion coefficients (Rayleigh interferometry), electrical conductances (DC method), and osmotic coefficients (isopiestic). These data and corresponding literature data are critically compared, as are literature density data. The resulting best values, together with previously compared transference number results, provide an extensive set of critically reviewed data for aqueous CuSO_4 . Onsager coefficients l_{ij} have been calculated for this salt and are compared with data for other valence types.

MILLS, J. M., S. Stein, and R. J. Geller, "Attenuation Measurements from Surface Waves and Free Oscillations and Their Implications," paper presented at the *IUGG 17th General Assembly, Canberra, Australia, December 11, 1979*.

We present a unified high quality data set for the attenuation of fundamental mode Rayleigh waves and fundamental and overtone spheroidal free oscillations covering the entire period range from 50 to 3000 sec. The data set is based on measurements from seven major earthquakes ranging in moment from 2×10^{27} to 2×10^{30} dyne-cm. Different techniques have been used for measurements in each of three period bands: traveling surface waves

of periods from 50 to 300 sec; unsplit free oscillation peaks for periods from 275 to 960 sec; and split free oscillation peaks from 1100 to 3200 sec.

The long period surface wave data are from the work of Mills and Hales. Group velocity and attenuation coefficients were measured using Rayleigh waves from Kurile Islands earthquakes. The data were recorded using WSSN seismometers prior to 1964 or HGLP stations. Global average attenuation and group velocity coefficients were calculated with equal weighting of nine great circle paths. The nine paths were evenly distributed in azimuth from the source and provide areal averages for group velocity and attenuation coefficients for each path which are independent of source mechanism. Global average attenuation coefficients calculated in this way are in good agreement at short periods with continental and oceanic measurements, and at long periods with measurements by Kanamori.

The unsplit spheroidal mode data are from the work of Geller and Stein. The data are derived from long period gravimeter records at seven stations of the IDA network for the 1977 Indonesian earthquake. The attenuation of fundamental spheroidal modes from ${}_0S_6 - {}_0S_{28}$ (962 to 275 sec period) was measured using a time domain decay method in a period range where normal mode splitting could be neglected. This data set forms the first set of measurements for these modes from multiple ultra long period records of a single earthquake, providing both excellent data and error bounds for each mode.

Attenuation data for the longest period spheroidal modes ${}_0S_2 - {}_0S_5$ are from the work of Stein and Geller. The data are from the Isabella strainmeter record of the 1960 Chilean earthquake, and the UCLA gravimeter record of the 1964 Alaskan earthquake. At these long periods, measurements of attenuation can be significantly biased by the effects of splitting, which introduce a complicated beating pattern in the time series for each mode. It is therefore not possible to derive a simple expression for the interference, either in the time or frequency domains, which will isolate the terms involving attenuation. Thus, to measure attenuation, time series were synthesized explicitly including the effects of splitting, and adjusted to find the best fitting values of Q^{-1} .

The combined data set for spheroidal (Rayleigh wave) modes is of high quality. All attenuation data are given in terms of Q^{-1} , a more natural unit than Q . An important property of the data set is the smooth transitions

between data from the three period ranges, demonstrating the lack of any bias introduced by different measurement techniques. We also present error bars for the attenuation at each period. The existence of such an integrated high quality data set covering this wide period range provides a major new tool for the study of attenuation as a function of depth within the earth.

The inversion of this data set for Q_B^{-1} as a function of depth in the earth is under way.

MILLS, J. M., S. Stein, and R. J. Geller, "Attenuation Measurements from Surface Waves and Free Oscillations and Their Implications," presented at *Conference on Seismic Wave Attenuation, Stanford University, California, June 25, 1979.*

We present a unified high quality data set for the attenuation of fundamental mode Rayleigh waves and fundamental and overtone spheroidal free oscillations covering the entire period range from 50 to 3000 sec. The data set is based on measurements from seven major earthquakes ranging in moment from 2×10^{27} to 2×10^{30} dyne-cm. Different techniques have been used for measurements in each of three period bands: traveling surface waves of periods from 50 to 300 sec; unsplit free oscillation peaks for periods from 275 to 960 sec; and split free oscillation peaks from 1100 to 3200 sec.

The long period surface wave data are from the work of Mills and Hales. Group velocity and attenuation coefficients were measured using Rayleigh waves from Kurile Islands earthquakes. The data were recorded using WWSSN seismometers prior to 1964 (when the instruments were shifted to a shorter period) or HGLP stations. Global average attenuation and group velocity coefficients were calculated with equal weighting of nine great circle paths. The nine paths were evenly distributed in azimuth from the source and provide areal averages for group velocity and attenuation coefficients for each path which are independent of source mechanism. Global average attenuation coefficients calculated in this way are in good agreement at short periods with continental and oceanic measurements and at long periods with measurements by Kanamori.

The unsplit spheroidal mode data are from the work of Geller and Stein. The data are derived from long period gravimeter records at seven stations of

the IDA network for the 1977 Indonesian earthquake. The attenuation of fundamental spheroidal modes from $0S_6 - 0S_{28}$ (962-275 sec period) were measured using a time domain decay method in a period range where normal mode splitting could be neglected. This data set forms the first set of measurements for these modes from multiple ultra long period records of a single earthquake, providing both excellent data and error bounds for each mode.

Attenuation data for the longest period spheroidal modes $0S_2 - 0S_5$ are from the work of Stein and Geller. The data are from the Isabella strainmeter record of the 1960 Chilean earthquake, and the UCLA gravimeter record of the 1964 Alaskan earthquake. At these long periods measurements of attenuation can be significantly biased by the effects of splitting, which introduce a complicated beating pattern in the time series for each mode. It is therefore not possible to derive a simple expression for the interference, either in the time or frequency domains, which will isolate the terms involving attenuation. Thus, to measure attenuation, time series were synthesized explicitly including the effects of splitting, and adjusted to find the best values of Q^{-1} .

The combined data set for spheroidal (Rayleigh wave) modes is presented. All attenuation data are given in terms of Q^{-1} , a more natural unit than Q . An important property of the data set is the smooth transitions between data from the three period ranges, demonstrating the lack of any bias introduced by different measurement techniques. We also present error bars for the attenuation at each period. The existence of such an integrated high quality data set covering this wide period range provides a major new tool for the study of attenuation as a function of depth within the earth.

Montan, D. N., M. E. HANSON, G. D. Anderson, R. J. Snaffer, and L. D. Thorson, "Theoretical and Experimental Analyses of Hydraulic Fracturing and Some Reservoir Response to the Stimulation," *Fifth Annual DOE Symposium on the Enhanced Oil and Gas Recovery and Improved Drilling Technology*, Tulsa, Oklahoma, August 22-24, 1979; Lawrence Livermore Laboratory Report UCRL-82578 (1979).

Montan, D. N., L. D. RAMSPOTT, L. B. Ballou, R. C. Carlson, T. R. Butkovich, J. E. Duncan, W. C. Patrick, D. G. Wilder, W. G. Brough, and M. C. Mayr, *Technical Concept for Test of Geologic Storage of Spent Reactor Fuel in the Climax Granite, Nevada Test Site*, Lawrence Livermore Laboratory Report UCRL-52796 (1979).

MORRISON, F. A., Jr., and S. K. Griffiths, "Low Peclet Number Heat and Mass Transfer from a Drop in an Electric Field," *J. Heat Transfer* 101, 484 (1979).

An electric field, when applied to a dielectric drop suspended in another such fluid, generates a circulating motion. The low Peclet number transport from the drop is investigated analytically using a regular perturbation expansion. A digital computer is used to obtain exact solutions to the resulting equations. These solutions yield accurate results up to a Peclet number of at least 60.

MORRISON, F. A., Jr., and S. K. Griffiths, *The Permeability of Granular Beds Emplaced in Vertical Drill Holes*, Lawrence Livermore Laboratory Report UCRL-52674 (1979).

To determine the permeabilities of granular materials emplaced in vertical drill holes used for underground nuclear tests, we conducted an experiment at the USDOE Nevada Test Site (NTS). As the hole is being filled, falling material increases pressure above and within the granular beds beneath. When the filling operation starts or stops, a transient pressure response occurs within the beds; we measured this response in beds of various compositions. The permeabilities after emplacement were found by matching analytical predictions of the response to these data. This information is useful in assuring the containment of nuclear tests conducted in such drill holes.

MORRISON, F. A., Jr., and J. M. Laude, "Stability of Flow from a Nuclear Cavity," *J. Fluids Eng.* 101, 335 (1979).

The stability of multicomponent flow through porous media is investigated. The flow results from an underground nuclear explosion. The effects of condensation, gravity, fluid mobilities, and heat transfer are considered. Marginal stability conditions and an expression for the decay rate of instabilities are obtained.

MORRISON, F. A., Jr., and M. B. Stewart, "Small Reynolds Number Electro-hydrodynamic Flow Around Drops and the Resulting Deformation," *J. Appl. Mech.* 46, 510 (1979).

Low Reynolds number flow in and about a droplet is generated by an electric field. Because the creeping flow solution is a uniformly valid zeroth-order approximation, a regular perturbation in Reynolds number is used to account for the effects of convective acceleration. The flow field and resulting deformation are predicted.

NAKANISHI, K. K., *Computer Code for the Transfer Function of Seismic Systems*, Lawrence Livermore Laboratory Report UCID-18071 (1979).

A computer code has been written to compute amplitude and phase transfer functions for various mechanical and electromagnetic seismic systems using analytical functions found in the literature. It can be used to compute transfer functions for the World-Wide Standard Seismic Network (WWSSN) system, the Seismic Research Observatory (SRO) system, the Lawrence Livermore Laboratory (LLL) system, the Wiechert system, the Wood-Anderson system, and other user-specified systems.

NAKANISHI, K. K., and F. Schwab, "Correlation Between Seismic Arrivals and Normal Modes in Synthetic Seismograms," Lawrence Livermore Laboratory Report UCRL-82383 (Abstract) (1979).

Computation of synthetic seismograms by the summation of normal modes has been used by many investigators to generate both surface and body wave arrivals. The results of these calculations show that there is a direct correlation between distinctive features in the dispersion and excitation spectra and various guided waves such as Lg, Sa, and Sn. These arrivals are found to be correlated to stationary phases in the group velocity curve and to relative peaks in the excitation spectrum. Modern computer graphics provide an excellent means of determining whether this correlation also holds for seismic arrivals such as S and sS. When amplitude excitation is plotted against group slowness and frequency for each mode in a three-dimensional representation, the correlation seen for Lg, Sa, and Sn appears to be more striking than that for S and sS. The summation of normal modes that form the arrivals is illustrated by use of three-dimensional graphical representations involving the phase spectrum as well as the amplitude excitation and the dispersion.

OWEN, L. B., *Correcting the Plotting Symbol Positioning Error in Tektronix GRAPH PLOT 50 Software (4050A07 Series B)*, Lawrence Livermore Laboratory Report UCID-18234 (1979).

The Graph Plot 50 (GP-50) software is an extremely useful package for rapid preparation of graphs. However, the current version of the software has a coding error which results in a serious misalignment of plotting symbols with respect to the actual position of data points in a user-defined x-y coordinate system. When graphs are produced using the series 4050 CRT screen one plotting symbol (+) is properly located, but most other characters are offset along the x- and/or y-axis. When graphs are produced using the Model 4662 digital plotter, all plotting symbols are misaligned on the y-axis.

A simple modification to GP-50 has been devised for eliminating the symbol positioning error. The eight most frequently used plotting symbols (X,x,0,o,*,+,0 and .) are automatically compensated to ensure proper

positioning when output is created on either the series 4050 screen display or the 4662 plotter. Other keyboard characters can be used as plotting symbols, if desired, but automatic positioning compensation is not provided.

OWEN, L. B., R. T. Hasbrouck, and R. Netherton, "An Automated System for Membrane Filtration and Core Tests," paper presented at *Geothermal Resources Council Annual Meeting, Reno, Nevada, September 24-27, 1979*; Lawrence Livermore Laboratory Report UCRL-83009 (1979).

An existing manually operated LLL system for obtaining data on injectability of geothermal effluents has been automated. Membrane filters and core samples are exposed to geothermal brine at representative injection pressure and formation confining pressure to study the potential effects of scaling and suspended solids deposition on the performance of injection wells. An electronic controller provides for operation under conditions of either constant differential pressure or constant flow. A data logger is used to obtain continuous records of all major system parameters. The new system is being used to assess the injectability of effluents produced by Magma Power Company's reaction clarifier-filter preinjection treatment facility operated in conjunction with the Geothermal Loop Experimental Facility at the Salton Sea Geothermal Field, Southern California.

Owen, L. B., K. G. KNAUSS, R. Quong, and N. D. Stout, "An effective H_2S Abatement Process Using Geothermal Brine Effluents," *Trans. Geotherm. Resour. Council* 3, 557 (1979); Lawrence Livermore Laboratory Report UCRL-83010 (1979).

OWEN, L. B., F. Locke, and R. Quong, "Lawrence Livermore Laboratory Test Facilities at the Salton Sea Geothermal Field, Southern California," invited contribution to a *Geologic Society of America Fieldtrip Guidebook: Geology and Geothermics of the Salton Trough* (1979); Lawrence Livermore Laboratory Report UCRL-83428 (1979).

The Lawrence Livermore Laboratory has been funded by the DOE (and its precursor organizations) for the last seven years to investigate problems relating to the utilization of high-temperature, hypersaline geothermal brine characteristic of the Salton Sea Geothermal Field (SSGF) in Southern California. The SSGF was chosen as the locale for this work because the size of the resource and its proximity to highly populated Southern California cities made the impact of its development on the energy problem potentially great. The technical areas chosen for investigation were selected to best match the scientific resources of the Laboratory, in this case chemistry, materials science, and the geosciences. A parallel mechanical engineering effort to design a unique energy conversion machine provided the initial impetus for our work.

Typical brines are produced at wellhead temperatures in excess of 200°C with totally dissolved solids ranging from 18 to 30 wt%. A major portion of LLL's geothermal activities has been field-oriented. We have studied methods for controlling scale deposition (based on chemical pretreatment of hot brine), corrosion of well casing and power plant materials, H₂S abatement, and preinjection treatment of spent brine effluents. Our reservoir assessment activities have included a program to test production and injection wells that were used to support the jointly operated (DOE-SDG&E-Magma Power Company) Geothermal Loop Experimental Facility (GLEF). We have also assessed total geothermal reserves in the Salton Sea Known Geothermal Resource Area based on a geophysical model of the resource. To test the model, we designed and then implemented a sub-sea temperature gradient survey, across the southern end of the Salton Sea, via a subcontract to the Institute of Geophysics and Planetary Sciences, University of California, Riverside.

Owen, L. B., E. RABER, and J. E. Harrar, "Using Surface Waters for Supplementing Injection at the Salton Sea Geothermal Field, Southern California," *Geothermal Resources Council 1979 Annual Meeting, Reno, Nevada, September 24-27, 1979*; Lawrence Livermore Laboratory Report UCRL-83011 (1979).

OWEN, L. B., E. Raber, C. Otto, R. Netherton, R. Neurath, and L. Allen, *An Assessment of the Injectability of Conditioned Brine Produced by a Reaction Clarification--Gravity Filtration System in Operation at the Salton Sea Geothermal Field, Southern California*, Lawrence Livermore Laboratory Report UCID-18488 (1979).

A Demonstration Reaction Clarifier--Gravity Filtration System with a 1600-gpm throughput capability was in operation at the joint DOE-SDG&E-Magma test facility located in the Salton Sea Geothermal Field, Southern California, during the summer of 1979. The system, which was designed to condition spent effluent from a 10-MWe-size geothermal power plant, removes supersaturated dissolved species and residual suspended solids from brine prior to subsurface brine disposal via injection wells. We established the post-processing chemical stability of conditioned effluents by means of anaerobic incubation tests at 90°C. The effect of residual dissolved polymer, which might be used for the purpose of scale control in upstream power plant components on the efficiency of reaction clarification, was also evaluated. Membrane filtration and core tests were used to assess the injectability of processed brine.

We found that the clarifier-filter operational procedures and system design permitted oxygenation of the brine by air intrusion. This resulted in partial stabilization of dissolved silica and precipitation of oxides of iron. As a consequence, conditioned brine injectability was poor. However, elimination of the air intrusion problem would result in a substantial improvement in brine quality. Residual amounts of dissolved polyaminoethylene (20 ppm, by weight), a powerful silica inhibitor in brine was shown, by means of bench-scale tests carried out at ~90°C, to improve the efficiency of the clarification process where the additive appears to function as a flocculent.

Patrick, W. C., L. D. RAMSPOTT, L. B. Ballou, R. C. Carlson, D. N. Montan, T. R. Butkovich, J. E. Duncan, D. G. Wilder, W. G. Brough, and M. C. Mayr, *Technical Concept for a Test of Geologic Storage of Spent Reactor Fuel in the Climax Granite, Nevada Test Site*, Lawrence Livermore Laboratory Report UCRL-52796 (1979).

PIWINSKII, A. J., *Deep Structure of the Earth's Crust and Upper Mantle in the USSR According to Geophysical and Seismological Data, Part I*, Lawrence Livermore Laboratory Report UCID-18099 (Abstract) (1979).

During the past two decades, data have been acquired via the Soviet Deep Seismic Sounding (DSS) program and from converted waves of earthquakes which help to elucidate the nature of the deep structure of the earth's crust and upper mantle in the territory of the Soviet Union. Results of these geophysical and seismological investigations and various earth-structure models are presented.

PIWINSKII, A. J., "Experimental Petrological Investigations Bearing on the Genesis of the Idaho Batholith and Related Ore Deposit," *Invited Guest Lecture, University of Idaho, and Idaho Bureau of Mines, Moscow, Idaho, May 4-5, 1979*; Lawrence Livermore Laboratory Report UCRL-82329 (Abstract) (1979).

The Idaho Batholith comprises an area of approximately 16×10^3 sq mi and is located in central Idaho. Emplaced in Middle Cretaceous, the batholith is a composite; it consists of the following rock types as estimated by Larsen and Schmidt: quartz gabbro (1%), tonalite (9%), granodiorite (23.5%), quartz monzonite (64.5%), and microgranite (1%). The average bulk composition of the Idaho Batholith is approximately quartz monzonite as compared to granodiorite and tonalite for the Sierra Nevada Batholith and Southern California Batholith, respectively.

Phase equilibrium relationships for granitoid rocks from the California Batholiths have been determined in the presence of excess water to 1 GPa. Complete fusion patterns have been determined for gabbro, tonalite, granodiorite, quartz monzonite, and granite. Electron microprobe analyses of liquids in equilibrium with crystals and vapor at 200-MPa water pressure reveal that the normative anorthite content and the tenor of MgO and FeO in the liquids increase with temperature. Concordance between the trends of liquid compositions and those illustrated by batholithic crystalline rocks suggest, but do not prove, that liquid-crystal equilibria was the operative petrogenetic process that produced the crystalline rocks of the batholiths.

Ancillary hypersolidus and subsolidus quenching experiments on calc-alkaline plutonic rocks between 0.125 and 1.0 GPa indicate that iron fractionates into the vapor phase. Subsolidus polythermal experiments on intermediate and basic compositions corroborate the movement of iron in the vapor phase and the nucleation of hematite at 500°C. The experimental data thus support the generation of iron-bearing ore fluids that give rise to contact metasomatic iron ore deposits which occur near batholiths.

Piwinskii, A. J., and N. D. STOUT, "Enthalpy and Heat Capacity of Silicate Melts at Atmospheric Pressure from 1520 to 2560 K," presented at *Annual Fall Meeting of American Geophysical Union, San Francisco, December 3-7, 1979*; Lawrence Livermore Laboratory Report UCR-63280 (1979).

PIWINSKII, A. J., and N. D. Stout, "The Entropy of Silicate Melts at Atmospheric Pressure from 1520 to 2560 K," presented at *Annual Fall Meeting, American Geophysical Union, San Francisco, California, December 3-7, 1979*; Lawrence Livermore Laboratory Report UCRL-83281 (Abstract) (1979).

The entropy, $S_T - S_{298}$, of anhydrous silicate melts was calculated from enthalpy data which were determined at 0.1 MPa from 1520 to 2560 K using a drop calorimeter. The rock types, all obtained from the Department of Energy's Test Site in southern Nevada, include basalts, welded tuffs, rhyolite, and sedimentary alluvium. Starting materials in all the experiments were bubble-free glasses prepared by repeated fusions in air of finely ground rock, followed by rapid quenching. Rock compositions in weight percent are: For basalt Uel8q#2,

SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	TiO ₂	Na ₂ O	K ₂ O	H ₂ O ⁺	H ₂ O ⁻
59.78	17.82	4.86	4.29	7.64	1.63	3.45	1.47	0.06	<0.11

For welded tuff Ue20u (330),

SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	TiO ₂	Na ₂ O	K ₂ O	H ₂ O ⁺	H ₂ O ⁻
75.58	14.66	1.15	0.90	0.61	0.28	2.57	3.77	0.28	0.08

For the basalt between 1520 and 2550 K,

$$S_T - S_{298} \text{ (J/g} \cdot \text{K)} = 1.015 \ln T + 2.576 \times 10^{-5} T - 5.79.$$

For the welded tuff between 1740 and 2560 K,

$$S_T - S_{298} \text{ (J/g} \cdot \text{K)} = 1.370 \ln T - 7.806.$$

Using the Lacy network-forming index R, where $R=O/(Si+Al)$ and is the ratio of molecular percent of nonbridging oxygens to the network-forming cations, as a structure-sensitive indicator, the silicate melt entropy data suggest that the structure of the highly siliceous tuff melt changes more rapidly than the structure of the less-polymerized basaltic melt between 1520 and 2560 K.

PIWINSKII, A. J., and H. C. Weed, "Dynamic Viscosity of Some Silicate Melts to 1688°C under Atmospheric Pressure," submitted to *Ber. der Bunsen Gell. fur Phys. Chem*; Lawrence Livermore Laboratory Report UCRL-83126 (Abstract) (1979).

The dynamic viscosity of six anhydrous silicate melts, obtained by fusing rocks collected from the Department of Energy's Nevada Test Site, has been measured from 1120 to 1688°C under atmospheric pressure using a rotational cup viscometer of the Couette type. The melts exhibit Newtonian behavior in this temperature interval. Melt viscosities decrease in the order: tuff > alluvium > basalt. Activation energy for viscous flow in the interval 1120 to 1688°C ranges from 268 to 397 kJ.

Piwinskii, A. J., H. C. WEED, and L. L. Dibley, *An Experimental Study of the Dynamic Viscosity of Some Anhydrous Silicate Melts to 1953 K at 150 kPa*, Lawrence Livermore Laboratory Report UCRL-52757 (1979).

PUCHLIK, K. P., *The Use of Thorium-Uranium Ratios as A Guide to Uranium Exploration in the Basin and Range*, Lawrence Livermore Laboratory Report UCRL-52469 (1979).

Thirteen hundred stream sediment samples were collected from the Winnemucca NTMS sheet during a recent hydrogeochemical survey for uranium in the Northern Basin and Range. Uranium was determined by neutron activation and delayed neutron counting. Twenty-five additional elements were determined by neutron activation. The problem in reviewing the data for such a large-scale survey is to sort the background uranium concentrations from the anomalous values that may warrant attention. This is especially important when dealing with samples from a highly varied and mixed population of rock types. For example, sediment samples with >5-ppm uranium may represent anomalous values in a carbonate terrain but at the same time constitute background values in or near outcrops of rhyolitic rocks and silicic intrusives.

Uranium tends to be oxidized to the comparatively soluble uranyl ion, permitting easy mobilization in surficial processes. The uranium is lost slowly from igneous rocks over a long period of time while the relatively insoluble thorium shows no significant changes. This rate of loss of uranium vs thorium varies with parent rock composition, mineralogy and texture. Thus, high values of uranium in sediments also high in thorium may represent concentration in either primary or secondary resistate phases. Conversely, concentration of uranium relative to thorium in sediments may be related to deposition or sorption from waters. It is these latter uranium values which may be important in deleting areas of interest. Therefore in defining a hydromorphic anomaly, the ratio of relatively insoluble thorium to soluble uranium was considered.

Th/U concentration ratios were computed for samples with a uranium content >5 ppm. Samples having Th/U values in the lower 10 percentile delineated almost all the known uranium occurrences in the region. These samples also correspond well with areas of fluvial and lacustrine beds associated with ash fall tuffs. Correlation analysis shows little association of uranium with other elements due to the high element variability in these sediments. Of greater interest are the remaining anomalous areas that were also detected. The analysis for these samples corresponds well to the known

geochemistry of carbonates. Uranium values in carbonates are generally low and since no known uranium occurrences exist near these samples these areas therefore warrant further investigation.

Finally, the above sites of low Th/U were deleted from the sample set containing >5-ppm uranium. Correlation coefficients were then computed for the remaining samples with relatively high Th/U. The results show a correlation of uranium with thorium, rubidium, and cerium. Even though many of these samples contain uranium values in the upper quartile of the data, these elemental associations suggest that the uranium is in either primary or secondary resistate phases and is thus of little interest.

PUCHLIK, K. P., S. Grotch, and D. Leach, "Evaluation of Medium-Sand Sediment Fraction as a Sampling Medium in a Geochemical Reconnaissance for Uranium in Arid Regions of the Great Basin, Western United States," submitted to *Journal of Geochemical Exploration; Lawrence Livermore Laboratory Report UCRL-82773* (1979).

The use of the fine-sediment fraction (~20 mesh or finer) from areas where eolian transport is important may present serious problems in a low-density geochemical reconnaissance for uranium. One such area where eolian transport is important is the semiarid Great Basin. This study evaluates the medium-sand fraction (500 to 1000 μ m) as an alternative sample medium that can minimize "eolian contamination" in a uranium reconnaissance in the Great Basin province in the western United States.

PUCHLIK, K. P., D. L. Leach, and D. Cazes, *Artillery Peak Orientation Study, Mohave County, Arizona*, Lawrence Livermore Laboratory Report UCRL-52675 (1979).

We present the results of an orientation study of uranium concentrations in the Artillery Peak quadrangle, Arizona, a part of the Prescott $1^{\circ} \times 2^{\circ}$ quadrangle of the National Topographic Map Series (NTMS). Uranium concentrations, as well as those of 25 other elements, were measured by

neutron activation analysis of wet, dry, and rock samples collected throughout the region. Uranium is found in veins and disseminations in the Precambrian rocks and in carbonaceous, tuffaceous lacustrine rocks of the Tertiary Artillery Formation. Data suggest that uranium is associated with resistate mineral phases. Data also show that stream sediment samples may not be an accurate way to determine uranium concentrations in poorly exposed lacustrine deposits similar to those in the Artillery Formation. Analytical data and field measurements are presented in tabular hardcopy and microfiche format; full-size overlays are included for use with the Artillery Peak NTMS Quadrangle map and show water sample sites, water-sample uranium locations, sediment sample sites, and sediment-sample total uranium concentrations.

PUCHLIK, K. P., D. L. Leach, and R. K. Glanzman, "Geochemical Exploration for Uranium in Playas," Lawrence Livermore Laboratory Report UCRL-82737 (1979).

Playas and closed basin lakes contain unique geochemical environments for the entrapment and concentration of mobile chemical elements. For this reason, playas may be considered as potentially favorable areas for the accumulation of uranium. We investigated playa sediments to determine their value as possible sample media for determining the presence of significant accumulations of uranium in the basins and playas. Instrumental neutron activation analyses were made on near-surface (0-50 ft) sediments, pore fluids, and both surface and groundwater in closed basins at Winnemucca Dry Lake, Smoke Creek, Roach Lake, Columbus Marsh, and Clayton Valley, Nevada, and Sevier Lake, Utah.

Playa sediments at spring discharge areas contain up to 58-ppm uranium. Evaporation and mobilization processes were found to limit the use of playa sediments as geochemical sampling media for uranium. However, other metals such as zinc, tungsten, and gold may have a geochemical signature in the playas. Most playas have little uranium resource potential. However, there are certain conditions that would make some playas more favorable for the accumulation of uranium. These conditions include: (1) presence of precursor carbonate-rich saline lakes, (2) nearby uranium-rich source rocks, (3) restricted groundwater discharge into the playa, (4) localized precipitation

mechanisms or phases in the playa, (5) large drainage basin and adequate precipitation, and (6) stability of a hydrologically closed basin for a long period of time.

PUCHLIK, K. P., D. L. Leach, and S. G. Schultz, "Geochemistry of Uranium in Stream Sediments of the Artillery Peak Quadrangle, Mohave County, Arizona," submitted to *USGS Contributions to Geology*; Lawrence Livermore Laboratory Report UCRL-83401 (1979).

The Artillery Peak quadrangle, Arizona, was the site of an orientation study to determine if dry stream sediments could be used to detect uranium in lacustrine units of the Artillery Formation. The area was chosen because it is typical of the Cenozoic lake-bed basin-fill deposits that have been exploration targets in west-central Arizona. Information obtained here could be applied to a regional reconnaissance for uranium in similar Cenozoic pluvial and lacustrine environments in the southwestern United States.

This report centers on two drainages west of Artillery Peak that contain the Masterson and Lucky Four uranium claim groups. The Artillery lacustrine units are well-exposed and have been little disrupted by mineral exploration. Although no uranium minerals were observed on the surface, anomalous areas were defined by scintillometer traverses. Furthermore, drilling has reported carnotite at shallow depths. Composited stream-sediment samples were collected at 400-m intervals down both drainages. Uranium was determined by neutron activation and delayed-neutron counting. Twenty-five additional elements were determined by neutron activation. Selected samples were sieved to several size fractions; partial extraction of uranium was obtained using a cold acetic-acid hydrogen-peroxide leach. Mineralogy was determined by optical methods.

Uranium concentrations in stream sediments draining the Artillery Formation within the study area are slightly greater than for sediments derived from other rock types in the quadrangle. Within these two drainages, other elements having significantly higher concentrations in stream sediments from the Artillery Formation include Fe, Th, Dy and to a lesser extent, Hf, Co, Mg. Uranium in these same sediments correlates best with thorium. The

uranium occurrences in these Artillery Peak drainage areas were not indicated in the stream sediments either by the total uranium concentrations or by partially extractable uranium obtained by hydrogen-peroxide acetic-acid leach.

The highest uranium concentrations in stream sediments from the Artillery Formation generally are in the 60- to 250- μ m fraction. Nonmagnetic heavy minerals are most abundant in this size fraction. Partially extractable uranium is consistently low (less than 5 to 10%) in all size fractions, suggesting that little adsorbed uranium is present.

The results of this study suggest that uranium concentration in stream sediments from the two drainages west of Artillery Peak are dominated by uranium in resistate mineral phases derived from the Artillery Formation, possibly the basal arkosic unit, or from the Precambrian rocks. The low concentration of total and acid-extractable uranium in stream sediments near the uranium occurrences may be due to low levels of mobile uranium at the prospect outcrops. Possibly the exposed lacustrine units have been leached of more mobile uranium by the action of rainwater. These results suggest that stream-sediment samples may not be an effective exploration method for poorly exposed uranium deposits in lacustrine units similar to those in the Artillery Formation.

QUALHEIM, B., *Hydrogeochemical and Stream Sediment Special Reconnaissance Report for the Deep Creek Mountains, Nevada and Utah*, Lawrence Livermore Laboratory Report UCRL-52686 (1979).

This report represents the results of the reconnaissance sampling of the Deep Creek Mountains of western Utah. The Deep Creek range is located in the northwest corner of the Delta NTMS 1:250,000 and the southwestern corner of the Tooele NTMS 1:250,000 sheets and covers an area of 1750 km². Samples collected in this study include dry and wet stream sediments and water from available streams, wells, and springs. The samples were analyzed for uranium, as well as 15 to 20 trace elements, using neutron activation techniques. In addition, field and laboratory measurements were made on the water samples. Analytical data and field measurements are presented in tabular hardcopy and microfiche format. Water-sample site locations, water-sample uranium concentrations, sediment-sample site locations, and sediment-sample uranium concentrations are shown on separate overlays.

QUALHEIM, B., *Hydrogeochemical and Stream Sediment Reconnaissance Report for the Lovelock NTMS Quadrangle, Nevada*, Lawrence Livermore Laboratory Report UCRL-52677 (1979).

This report presents the results of the geochemical reconnaissance sampling in the Lovelock $1^{\circ} \times 2^{\circ}$ quadrangle of the National Topographical Map Series (NTMS). We collected wet and dry sediment samples throughout the 18,854-km², arid-to-semiarid area and water samples at available streams, springs, and wells. Neutron activation analysis of uranium and trace elements and other measurements made in the field and laboratory are presented in tabular hardcopy and microfiche format. The report includes five full-size overlays for use with the Lovelock NTMS 1:250,000 quadrangle. Water sampling sites, water-sample uranium concentrations, water-sample conductivity, sediment sampling sites, and sediment-sample total uranium and thorium concentrations are shown on the separate overlays. We include general geological and structural descriptions of the area and delineate known uranium occurrences in this quadrangle.

QUALHEIM, B., *Hydrogeochemical and Stream Sediment Reconnaissance Report for the Tonopah NTMS Quadrangle, Nevada*, Lawrence Livermore Laboratory Report UCRL-52676 (1979).

This report presents the results of the geochemical reconnaissance sampling in the Tonopah $1^{\circ} \times 2^{\circ}$ quadrangle of the National Topographical Map Series (NTMS). We collected wet and dry sediment samples throughout the 19,000-km², arid-to-semiarid area and water samples at available streams, springs, and wells. Neutron activation analysis of uranium and trace elements and other measurements made in the field and laboratory are presented in tabular hardcopy and microfiche format. The report includes five full-size overlays for use with the Tonopah NTMS 1:250,000 quadrangle. Water sampling sites, water-sample uranium concentrations, water-sample conductivity, sediment sampling sites, and sediment-sample total uranium and thorium concentrations are shown on the separate overlays. We include general geological and structural descriptions of the area and delineate known uranium occurrences in this quadrangle.

RABER, E., and S. E. Haggerty, "Zircon-Oxide Reactions in Diamond-Bearing Kimberlites," in *Kimberlites, Diatremes and Diamonds: Their Geology, Petrology, and Geochemistry* Vol. 1, F. R. Boyd and F. O. A. Meyer, Eds. (American Geophysical Union, Washington, D.C., 1979).

In a petrographic and electron microprobe study of zircons (ZrSiO_4) intergrown with ilmenite (FeTiO_3) and/or rutile (TiO_2) from kimberlites in southern Africa we have established: (1) the compositions of ilmenites associated with zircons have a narrow range in MgO (8-10 wt%) and in Cr_2O_3 (0.02-0.85 wt%) contents which may be indicative of a characteristic P-T regime; (2) subsolidus reactions, along with the zircon-ilmenite interfaces, yield an exotic mineral assemblage consisting of zirconolite ($\text{CaZrTi}_2\text{O}_7$), Ti-rich baddeleyite ($[\text{TiZr}]_2\text{O}_2$), and diopside ($\text{CaMgSi}_2\text{O}_6$) in association with calcite (CaCO_3); (3) ilmenite/rutile-zircon assemblages consist of zirconolite + baddeleyite + diopside at ilmenite-zircon interfaces, and baddeleyite + sphene (CaTiSiO_5) at rutile-zircon interfaces (both assemblages are in association with calcite); (4) rutile-zircon assemblages consist only of Zr-armalcolite ($[\text{FeMg}]_2\text{Ti}_2\text{O}_5$) and ilmenite when not in association with calcite. We propose that assemblages along calcite-associated interfaces are the result of reactions due to the availability of a carbonatitic fluid which induced an intercrystalline reaction between zircon and either ilmenite or rutile. This is the first reported occurrence of terrestrial zirconium-bearing armalcolite. Based on phase equilibria studies the conditions inferred for the coexisting mineral assemblages are $T = 1450\text{-}1550^\circ\text{C}$, $P = 8\text{-}12$ kbar, and $f\text{O}_2 < 10^{12}$ atm. The Ti/Zr ratios of zirconolites are evaluated as a possible geothermometer, but it is recognized that the application to kimberlites is limited because of the indeterminate effects of pressure.

RABER, E., S. E. Haggerty, and C. W. Naeser, "A New Method of Fission-Track Dating for Kimberlitic Zircons," paper prepared for *Earth and Planetary Science Letters*; Lawrence Livermore Laboratory Report UCRL-83338 (1979).

At present, the only reliable method for dating kimberlites is a lengthy and specialized hydrothermal procedure that extracts ^{206}Pb and ^{238}U from low-uranium zircons. This paper describes in detail a second successful

method, the fission-track dating of low-uranium, kimberlitic zircons. This technique involves mounting, polishing, and etching whole zircon crystals, and thereby overcomes the earlier limitations and difficulties of track dispersion and underetching. The use of whole crystals also provides detailed information on uranium zoning and allows direct comparisons with fission-track uranium distribution studies done on lunar samples.

Fission-track ages of zircons from five African kimberlites are reported, including Kimberley Pool (90.3 ± 6.5 m.y.), Orapa (87.4 ± 5.7 and 92.4 ± 6.1 m.y.), Nzega (51.1 ± 3.8 m.y.), Koffiefontein (90.0 ± 8.2 m.y.), and Val do Queve (133.4 ± 11.5 m.y.). In addition, we report the first radiometric ages (707.9 ± 59.6 and 705.5 ± 61.0 m.y.) of zircons from the Lofa kimberlite in northwest Liberia. The fission-track ages agree well with earlier age estimates from the U/Pb method. Because most crystals examined in this study are zoned with respect to uranium, statistical methods have been employed that show good linear correlation (by regression analysis) and constant uranium concentration (by analysis of variance) among all of the areas measured in an individual crystal.

RABER, E., L. B. Owen, and J. E. Harrar, "Using Surface Waters for Supplementing Injection at the Salton Sea Geothermal Field, Southern California," presented at *Geothermal Resource Council 1979 Annual Meeting, Reno, Nevada, September 24-27, 1979*; Lawrence Livermore Laboratory Report UCRL-83011 (July 1979).

The flash-steam conversion cycle is most suitable for electric power production at the SSGF. However, large-scale development of the SSGF may require use of makeup water supplements to injected brine for a viable reservoir pressure maintenance program. Since steam condensate will probably be required to satisfy power plant cooling needs, local surface waters have been evaluated for their potential use as sources of injection makeup. We found that direct injection of untreated makeup water is not feasible because of high suspended solids loading and potential incompatibility problems. However, mixtures of ambient temperature makeup water and higher temperature ($80-90^{\circ}\text{C}$) brine effluent, in a 1:4 mass ratio are potentially injectable following processing by reaction clarification and granular media filtration.

Raber, E., L. B. OWEN, C. Otto, R. Netherton, R. Neurath, and L. Allen, *An Assessment of the Injectability of Conditioned Brine Produced by a Reaction Clarification--Gravity Filtration System in Operation at the Salton Sea Geothermal Field, Southern California*, Lawrence Livermore Laboratory Report UCID-18488 (1979).

RABER, E., and R. E. Thompson, "The Processing of High Salinity Brines for Subsurface Injection," *International Conference of Geotechnical and Environmental Aspects of Geopressure Energy, Sea Island, Georgia, January 13-16, 1980*; Lawrence Livermore Laboratory Report UCRL-83122, Rev. 1 (1979).

The most significant environmental concerns in the development of geothermal/geopressured energy are aspects of reservoir pressure maintenance resulting from the withdrawal of enormous volumes of formation waters and the disposal of highly saline brines (up to 28% NaCl). Therefore, large-scale utilization of these resources will require reinjection of spent brine effluents as the most environmentally acceptable method of disposal. We have recently been involved in evaluating different chemical pretreatments and filtration methods as a possible means of clarifying and improving the injectivity of hypersaline brines. This work involved extensive field tests at three strategic petroleum reserve sites (Bryan Mound in Texas, West Hackberry, and Bayou Choctaw in Louisiana). Although the methodology and processing techniques used in this study can be applied elsewhere, the results are unique and specific to high-salinity brines (30-33% NaCl). These brines, which are low in silica, hydrogen sulfide, and other toxic trace metals, compare favorably with geothermal/geopressured waters from Louisiana. Studies done elsewhere include only treatment of undersaturated solutions of seawater with salinities up to 8% NaCl, although reactor-clarification has been suggested for the silica saturated hypersaline brines in the Imperial Valley, California.

RALEY, J. H., "Evaluation of Retort Performance from Gas Data," Lawrence Livermore Laboratory Report UCRL-82079 (1979).

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 pilot, 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 steam reactions, gas bypassing and kerogen conversion. Both intraretort and off-gas data may also be employed to monitor operation of surface retorts.

RALEY, J. H., "Monitoring Oil Shale Retorts by Off-Gas Alkene/Alkane Ratios," Lawrence Livermore Laboratory Report UCRL-82457 (1979).

Data from 125- and 6000-kg oil shale pilot retorts indicate that off-gas ethene/ethane and propene/propane ratios are useful for monitoring retort performance. Information supplied by these ratios may be particularly valuable for *in situ* retorts. Since response time is short, the ratios may be useful for control as well as diagnosis of retort operation. The pilot retort data show that, for a smoothly operating combustion retort, the ratios provide an estimate of the effective shale heating rate. Rough operation, indicated by wide fluctuations in peak temperature, is reflected by fluctuations in the ratios. Particularly high ratios indicate exposure of oil to excessive temperature and/or oxygen with resultant loss of oil yield. A relationship between elevated ratios and oil loss via conversion to gaseous hydrocarbons is demonstrated for retorting of shale blocks immersed in a bed of smaller shale particles.

Chemical interpretation of the data is made by comparison with the thermal cracking of n-hexadecane and pyrolysis of polyethylene. A free radical, chain reaction scheme is proposed. The dependence of alkene/alkane values on heating rate is attributed to competition between carbon-carbon bond cleavage vs hydrogen atom-transfer processes. The contribution of oxidation reactions to elevated alkene/alkane values is also discussed.

Raley, J. H., J. H. CAMPBELL, F. J. Ackerman, and W. A. Sandholtz,
"Investigation of Critical Parameters in Modified *In Situ* Retorting,"
Lawrence Livermore Laboratory Report UCRL-83739 (Abstract) (1979).

Rambo, J. T., R. W. TERHUNE, H. D. Glenn, D. E. Burton, and H. L. McKague,
"Numerical Simulation of the Baneberry Event," *Nucl. Technol.* 46, 159
(1979).

RAMSPOTT, L. D., *Climax Granite Test Results*, Lawrence Livermore Laboratory
Report UCID-18502 (1979).

The Lawrence Livermore Laboratory, as part of the Nevada Nuclear Waste Storage Investigations (NNWSI) program, is carrying out *in situ* rock mechanics testing in the Climax granitic stock at the Nevada Test Site. Although LLL is heavily involved in planning and execution for a test storage of spent reactor fuel in the Climax granite and in the planning and design for a Rock Mechanics Test Facility, this report will cover only those field data taken to date that address thermomechanical modeling for a hardrock repository. The results to be discussed include thermal measurements in a heater test that was conducted from October 1977 through July 1978, and stress and displacement measurements made during and after excavation of the canister storage drift for the Spent Fuel Test (SFT) in the Climax granite. Associated laboratory and field measurements will be summarized.

RAMSPOTT, L. D., "Laboratory and Field Measurements of Granitic Rocks under Repository Stress Conditions," presented at *Society for Experimental Stress Analysis (Spring Meeting)*, San Francisco, California, May 20-25, 1979;
Lawrence Livermore Laboratory Report UCRL-82004, Rev. 1 (Abstract) (1979).

An underground repository for high-level nuclear waste differs from ordinary underground excavations such as mines or tunnels because it must withstand heat loads as high as 50 W/m^2 averaged over several km^2 . Local concentrations of heat in storage drifts are greater by a factor of 5 for an excavation ratio of 20%. The highest thermal gradients will exist around the

boreholes in which waste canisters are stored; the borehole walls may be as hot as 200°C. The stress field in the undisturbed rock is initially altered by the excavation. Thermomechanical stresses are imposed due to thermal expansion further modifying the *in situ* stresses. Altering the stress field in a rock mass produces a potential for rock fracture, which may negatively affect the ultimate isolation of the nuclear waste from the biosphere or (in the short term) the retrievability of the waste canisters.

Although there are centuries of experience with underground openings in rock, the thermomechanical stress problem has little precedent, and research programs have been established to study the problem. The Lawrence Livermore Laboratory has a program of laboratory and field measurements combined with mathematical modeling. The goal is to understand the effects of thermomechanical stress and to produce a predictive capability for the design of a nuclear waste repository in granitic rock. To date there are two laboratory projects and three field tests, with additional field tests being planned.

One laboratory project involves the measurement of rock permeability, stress, strain, electrical conductivity, and acoustic velocity during a single test loading. These measurements are made on large (15-cm-diameter by 28-cm-long) cylindrical specimens through a range of confining pressures, pore (water) pressures, and deviatoric stresses that might exist at depths of up to 2000 m.

The basic goal of these measurements is to systematically explore the effects of applied stress on rock permeability of both sound and fractured rock specimens. This will allow us to develop working hypotheses to account for the very low permeabilities of deeply buried rocks. At the same time, systematic data will be developed on the stress-strain relationships and the variation of electrical conductivity and acoustic velocity with applied stress. The former will serve as input to rock mechanics models, and the latter, to the development of remote monitoring techniques.

A second laboratory project involves measuring rock thermal properties as a function of temperature to 500°C and confining pressure to 200 MPa in the presence of pore fluid. Such data are needed for predictive calculations of the effects of waste emplacement. The thermal parameters measured are conductivity, diffusivity, heat capacity, and the linear expansion coefficient.

The relation of the linear thermal expansion coefficient to rock temperature and confining pressure is particularly important for calculations of stresses due to introduction of the thermal load. Additional measurements are planned to obtain the elastic moduli and Poisson's ratio as functions of temperature, pressure, and pore pressure because these are also necessary for stress calculations.

The three field tests are all located in the Climax granitic stock at the DOE Nevada Test Site. An available vertical shaft provides access to a horizontal drift complex at a depth of 420 m below ground surface. A set of *in situ* thermal properties tests and permeability tests was conducted in an existing drift in FY 1978. A test of retrievable geologic storage of spent fuel assemblies is under construction, with initial loading of spent fuel scheduled for 1980. Additional rock mechanics tests are being planned.

The field tests to date have not included the measurement of rock stress, or even strain. However, the effects of thermally induced stress are clear in the permeability tests, where the permeability declined as the rock temperature increased, and then increased to pretest levels as the rock cooled. Our initial interpretation of the data is that microcracks were closed under elevated stress levels induced by the heating.

Similar stress effects may have occurred in the thermal properties tests. The thermal conductivity derived from the data is about 3.0 W/mK, about 15% higher than the mean value of laboratory measurements without confining pressure. Measurements were made both parallel and perpendicular to the principal fracture direction of the rock, with insignificant variation. Although the rock temperature at the borehole wall peaked at about 350°C, all data could be matched to within a few percent using the 3.0 W/mK conductivity. Laboratory measurements without confining pressure show a 12 to 23% decline of the thermal conductivity of typical granites as temperature increases from 0 to 200°C. The few data (none for granite) available for thermal conductivity as a function of confining pressure show conductivity to increase with increasing pressure by less than 10^{-5} /bar. Therefore, combined effects of *in situ* stress, construction stress (the boreholes and mine opening), and thermally induced stress may counter the temperature rise-effect somewhat. Stress and/or strain measurements on future field tests plus the systematic laboratory measurements described above should enable us to address these hypotheses.

RAMSPOTT, L. D., Ed., *Waste-Isolation Projects, FY 1978*, Lawrence Livermore Laboratory Report 50050-78 (1979).

This report describes Lawrence Livermore Laboratory activities during FY 1978 in support of the National Waste Terminal Storage Program. Current projects at LLL fall into three categories: (1) field testing, (2) laboratory rock mechanics measurements, and (3) laboratory studies of sorption and leaching.

Field test activities conducted in the Climax granite at the Nevada Test Site included electrical heater tests, preparation for a spent-fuel-storage test, and planning for a series of rock mechanics tests. The heater tests determined the *in situ* thermal properties of Climax granite and its *in situ* permeability as a function of rock temperature.

The two main laboratory rock mechanics projects involved (1) measurement of the permeability, electrical conductivity, and acoustic velocity of 15-cm-diameter cores of granitic rocks over a range of confining pressure, pore (water) pressure, and deviatoric stress, and (2) measurement of rock thermal properties as a function of temperature and confining pressure in the presence of pore fluids to 770 K and 220 MPa.

The leaching studies made use of an LLL-designed, single-pass leaching apparatus with three solutions, two leach temperatures, and three flow rates. The material evaluated was Np-Pu-doped simulated waste glass from Battelle Pacific Northwest Laboratories. The sorption studies involved standard static measurements of the equilibrium distribution coefficient (K_d) for various radionuclides on a variety of rocks, and flow-through-core studies of dynamic sorption.

RAMSPOTT, L. D., L. B. Ballou, R. C. Carlson, D. N. Montan, T. R. Butkovich, J. E. Duncan, W. C. Patrick, D. G. Wilder, W. G. Brough, and M. C. Mayr, *Technical Concept for a Test of Geologic Storage of Spent Reactor Fuel in the Climax Granite, Nevada Test Site*, Lawrence Livermore Laboratory Report UCRL-52796 (1979).

We plan to emplace spent fuel assemblies from an operating commercial nuclear reactor in the Climax granite at the U.S. Department of Energy's Nevada Test Site. In the generic test, 11 canisters of spent fuel will be

emplaced with 6 electrical simulator canisters in a storage drift 420 m below the surface and their effects compared. Two adjacent drifts will contain electrical heaters, operated to simulate the temperature-stress-displacement fields of a large repository. In this report, we describe the test objectives, the technical issues, the site, the preoperational measurement program, thermal and mechanical response calculations, the characteristics of the spent fuel, the field instrumentation and data-acquisition systems, and the system for handling spent fuel.

RAMSPOTT, L. D., and F. Holzer, Eds., *Proceedings of a Workshop on Thermomechanical Modeling for a Hardrock Waste Repository, Berkeley, California, June 25-27, 1979*; Lawrence Livermore Laboratory Report UCAR-10043 (1979).

These proceedings summarize the discussions, conclusions, and recommendations reached in a workshop on Thermomechanical Modeling for a Radioactive Waste Repository in hard crystalline rock from June 25-27, 1979, in Berkeley, California. The workshop was arranged and chaired by the Lawrence Livermore Laboratory under the sponsorship of the Office of Nuclear Waste Isolation (ONWI) and the DOE. About 100 participants from national laboratories, universities, private companies, and government organizations spent 2-1/2 days exchanging information and developing a set of conclusions and recommendations. The objectives of the workshop were as follows:

1. Identify the key issues connected with modeling and validating the response of a hard rock repository to the emplaced waste source.
2. Identify status and needs, and develop a list of recommended activities, in order of priority, which would serve as programmatic input to ONWI and DOE for future consideration and implementation.

The agenda for the workshop is given. Discussions covered modeling and calculations, laboratory and field measurements of properties and effects, instruments and techniques, and field experimentation for validation and model testing. Emphasis was placed on the thermomechanical response of the rock to the radioactive waste source emplaced within it. Hydrologic and radionuclide transport properties were specifically excluded, because they were to be the subject of a subsequent workshop.

During the first day and following an introduction, a set of prepared papers established the present state of the art and provided a point of reference for the discussions that followed. Technology was addressed in the morning and results from field experiments were given in the afternoon. Extended summaries of these papers are given in a later section of these proceedings.

On the morning of the second day, the attendees broke up into four different workshops, each dealing with a separate aspect of the overall problem:

1. Codes and Methods.
2. Laboratory Measurements.
3. Field Measurements.
4. *In Situ* Tests and Model Validation.

In the afternoon, the participants held a joint session and heard progress reports from each of the four workshop discussion leaders. This session served as a means for providing cross-cutting input and coordination. Recommendations and priority lists were then developed during the individual afternoon sessions.

On the morning of the third day, participants assembled again in joint session to hear final reports and recommendations for the workshop leaders, followed by discussion and comment from those presenting papers and from the audience. After the meeting adjourned at noon, workshop leaders drafted a summary of conclusions and recommendations. These drafts were subsequently expanded and are presented in a later section. There is a listing of workshop organizers, discussion leaders, recorders, and participants in the individual workshop sessions. The complete attendance list together with affiliations and addresses is given.

RAMSPOTT, L. D., J. D. Tewhey, D. G. Coles, H. C. Weed, J. S. Schweiger, and R. Stone, *FY78 Annual Technical Report of Lawrence Livermore Laboratory's Participation in the DOE-NV Project: Radionuclide Migration in the Ground*, Lawrence Livermore Laboratory Report UCID-18259-78 (1,9).

Activities by the Lawrence Livermore Laboratory in support of the Department of Energy, Nevada Operations Office for the Radionuclide Migration in the Ground program include:

1. Laboratory study of single-pass leaching of nuclear melt glass by NTS groundwater.

2. Design of field and laboratory distillation apparatus to concentrate water samples in order to detect low levels of radionuclides.

3. Feasibility studies for *in situ* tracer studies at NTS.

4. Periodic sampling and analysis of water from sites of NTS nuclear tests.

5. Geochemical studies of melt glass from NTS underground nuclear tests.

This report describes the results during FY 1978 for these activities.

RARD, J. A., and D. G. Miller, "The Mutual Diffusion Coefficients of $\text{BaCl}_2\text{-H}_2\text{O}$ and $\text{KCl-H}_2\text{O}$ at 25° from Rayleigh Interferometry," Lawrence Livermore Laboratory Report UCRL-83065 (1979).

The volume-fixed mutual diffusion coefficients of $\text{BaCl}_2\text{-H}_2\text{O}$ and $\text{KCl-H}_2\text{O}$ have been measured to an accuracy of 0.1-0.2%, from dilute solutions to near saturation, using free diffusion Rayleigh interferometry. These diffusion coefficients are compared to other available diffusion data for these systems, measured by the conductometric and optical methods. The new data extend previously available optical results to higher and lower concentrations, and confirm that the diffusion coefficients of $\text{BaCl}_2\text{-H}_2\text{O}$ are unusually low, relative to the other alkaline earth chlorides, at moderate and high concentrations. The effect of cation hydration on the diffusion coefficients of alkali and alkaline earth chloride solutions is briefly discussed.

Rard, J. A., D. G. MILLER, L. B. Eppstein, and R. A. Robinson, "Mutual Diffusion Coefficients, Electrical Conductances, Osmotic Coefficients, and Ionic Transport Coefficients l_{ij} for Aqueous CuSO_4 at 25° ," accepted for publication by *Journal of Solution Chemistry*; Lawrence Livermore Laboratory Report UCRL-83465 (1979).

RODEAN, H. C., *Elastic Wave Radiation from Spherical Sources*, Lawrence Livermore Laboratory Report UCRL-52867 (1979).

The subject of this study is the radiation of spherical compressional waves from a spherical cavity in an ideal elastic solid. The equations for the radiation source and field are written in terms of the reduced displacement potential. The source equation is studied in terms of characteristic frequencies, corresponding periods and wavelengths, and damping. The field equations for the stresses, strains, radial displacement, etc., are reviewed with regard to the respective transitions between the near and far fields. The natural parameters for defining the dynamic source and field characteristics are $2b/R$ and b/a in some cases and a/R in others, where a = compressional wave velocity, b = shear wave velocity, and R = cavity radius. Transient solutions for stresses, strains, radial displacement, etc., include damped sinusoidal oscillations. The initial and final value theorems for the Laplace transform are used to obtain solutions for τ (the reduced time) $\rightarrow 0$ + (high-frequency, far-field) and $\tau \rightarrow \infty$ (zero-frequency, near field).

RODEAN, H. C., *ISC Events from 1964 to 1976 At and Near the Nuclear Testing Ground in Eastern Kazakhstan*, Lawrence Livermore Laboratory Report UCRL-52856 (1979).

We studied seismic events from 1964 to 1976 at and near the Nuclear Testing Ground (NTG) in Eastern Kazakhstan using data published by the International Seismological Centre (ISC) in the United Kingdom. During this period, the ISC detected 129 events concentrated in three testing areas within the NTG. We estimated the detection performance of the network of stations that reported to the ISC during these years, and used our performance assessment to estimate the number of events within a magnitude range that may have been missed by the ISC. In addition, we examined the apparent origin times of these events with respect to their identity (earthquake or explosion), the relations between errors of calculated origin time and location, the apparent Soviet practice for timing the detonation of

explosions, and the geophysical significance of the mean origin times within the minute. The identity of event 760320 is considered on the basis of its ISC origin time and location, the results of studies by other investigators, and its location close to a major fault that is clearly visible in Landsat imagery.

RODEAN, H. C., *Optimum Frequencies for Regional Detection of Cavity-Decoupled Explosions*, Lawrence Livermore Laboratory Report UCRL-52690 (1979).

This report examines the natures of compressional (P) waves that originate in the crust, propagate in the crust and upper mantle, and are observed as Pg, Pn, and $\bar{P}$ waves at regional distances. The discussion includes the observed variations of amplitude with epicentral distance for these waves as well as an estimate of values for the specific dissipation function Q_α in different regions. We studied theoretical source and propagation functions for direct, reflected, and head waves as approximations for the observed Pg, $\bar{P}$, and Pn, respectively. We conclude that the classical (critically refracted) head wave is not very significant in regional observations, and that the related interference head wave and diving wave are more likely observed as Pn. Using an assumed seismic noise spectrum and the constant Q_α model for seismic attenuation, we derive relations for the frequencies corresponding to maximum signal-to-noise ratio for the classical and interference head waves and for the direct, reflected, and diving waves. The relations among seismic frequency, epicentral distance, anelastic attenuation, and explosion yield are illustrated for a simple source and propagation model.

Rodean, H. C., R. W. TERLUNE, and C. M. Snell, *Enhanced Coupling and Decoupling of Underground Nuclear Explosions*, Lawrence Livermore Laboratory Report UCRL-52806 (1979).

ROTHMAN, A. J., "Recent Experimental Developments in Retorting Oil Shale at the Lawrence Livermore Laboratory," Lawrence Livermore Laboratory Report UCRL-83569 (1979).

The Lawrence Livermore Laboratory is engaged in a program aimed at extraction of oil from oil shale *in situ*. The experimental program is briefly described. Retorting results obtained in pilot above-ground retorts are reviewed. Combustion retorting of small (1-2 cm) particles of narrow size distribution gives yields near 95% of assay, and appears to be reasonably understood and predictable by model calculations. Results on retorting behavior of nonuniform sized particles are less well-understood. Reasons for this behavior are examined, and appear to be related to nonuniform gas flow. The effect of steam on retorting is considered.

In Part II we examine more recent retort runs and especially the effects of nonuniform size particles. We relate the loss of oil yield to the mechanisms of combustion, cracking and coking. We show how the alkene/alkane ratio in the off-gas is related to loss of oil yield and utilize this ratio to study mechanisms and predict yields in retorts. We review the behavior of retorting and combustion fronts and show that these are a reflection of nonuniform retorting and burning. In turn these nonuniform effects are related to bed structure resulting in nonuniform gas flow. To clarify the role of nonuniform flow, we have utilized tracer measurements to model dispersion in retorts. We discuss qualitatively some very large effective dispersion coefficients in our beds of nonuniform particle size. Finally we show that rubble bed structure may be characterized before retorting by a "steam-logging" technique. Both retorting and combustion behaviors are shown to relate closely to the bed structure as determined by steam-logging.

SANDHOLTZ, W. A., "Some Relationships of Thermal Effects to Rubble Bed Structure and Gas Flow Patterns in Oil Shale Retorts," Lawrence Livermore Laboratory Report UCRL-83740 (1979).

Conventional tracer measurements in packed beds rely on detection of specific molecular species to characterize bed structure and measure fluid dispersion under varied flow conditions. The work reported here demonstrates

the use of temperature sensors such as thermocouples to develop similar kinds of information from thermal data.

In packed beds, such as batch oil shale retorts in which the process is driven by heat transfer from a flowing medium to the rubble, much can be inferred about bed and void structure and flow patterns from the time/temperature relationships among thermocouple arrays placed in the bed. The use of temperature data as a bed diagnostic tool in oil shale retorting experiments is shown. The close relationships in combustion retorting between the steam front and the retorting front are illustrated. This thermal logging technique has proved useful in understanding laboratory retorting experiments and predicting retort performance.

Sandholtz, W. A., J. H. CAMPBELL, J. H. Raley, and F. J. Ackerman,
"Investigation of Critical Parameters in Modified *In Situ* Retorting,"
Lawrence Livermore Laboratory Report UCRL-83739 (Abstract) (1979).

SANDHOLTZ, W. A., and T. R. Galloway, "Comparison of Flow Nonuniformities in Oil Shale Pilot Retorts with Those Predicted by Numerical Flow Simulations," Lawrence Livermore Laboratory Report UCRL-82132 (1979).

The primary obstacle to commercial recovery of shale oil is the presence of flow nonuniformities in *in situ* oil shale retorts. In an effort to evaluate the causes of these nonuniformities, we have compared flow data from an experimental retort with computer flow simulation. We found that in areas where the large-scale sweep efficiency was adequate, local nonuniform flow was caused by (1) channeling in regions of high permeability (i.e., along the retort wall and around larger blocks), (2) acceleration in flow around cross-section blockages, and (3) exothermic chemical reactions that change the gas viscosity.

Schock, R. N., J. AKELLA, Q. Johnson, and W. Thayer, "Crystal Structure of the High-Pressure Form of Am," paper submitted to *Journal of the Less-Common Metals* 1979; Lawrence Livermore Laboratory Report UCRL-82136 (1979).

SCHOCK, R. N., A. Duba, and R. L. Stocker, "The Effect of Oxygen Fugacity on Electrical Conductivity and Defect Production in Olivine," paper submitted to *American Geophysical Union Meeting, San Francisco, California, December 3-7, 1979*; Lawrence Livermore Laboratory UCRL-83320 (Abstract) (1979).

The electrical conductivity of single crystal olivines from the Red Sea (Fo_{91}) and San Carlos (Fo_{92}) has been measured as a function of oxygen fugacity and temperature. San Carlos peridot exhibits p-type semiconductor behavior at 1200°C , atmospheric pressure in both the $[001]$ and $[010]$ directions. At the reducing limit of the olivine stability field, the conductivity in both orientations has little if any f_{O_2} dependence. The electrical conductivity of Red Sea peridot is weakly n-type semiconducting at 1200°C , weakly n-type to f_{O_2} independent at 1300°C , and shows a conductivity minimum at both 1400 and 1500°C . San Carlos is about an order of magnitude better conductor than Red Sea in the $[001]$ direction at 1200°C and $10^{-5}\text{Pa}f_{\text{O}_2}$. These observations can be interpreted in terms of a defect model incorporating the following assumed features:

1. The olivines have fixed but different cationic ratios.
2. The mobilities of conduction-band electrons μ_e' , electron hopping between iron ions in magnesium sites $\mu_{\text{Fe}_{\text{Mg}}}$, and ionic mobilities μ_I are in the order $\mu_e' > \mu_{\text{Fe}_{\text{Mg}}} > \mu_I$.
3. Impurities are not significant contributors to the conduction process.

Based on this model the charge neutrality condition in stoichiometric olivine is magnesium Frenkel defects. Under nonstoichiometric conditions, and if no associated defects are present, magnesium vacancies and silicon interstitial are indicated as being responsible for charge neutrality. Thus electrical conductivity in natural olivines of upper mantle composition appears to be both electronic and ionic, with Mg-Si nonstoichiometry having an important influence on electrical conductivity.

SCHOCK, R. N., M. E. Hanson, R. P. Swift, and O. R. Walton, "In Situ Fracture Related to Energy and Resource Recovery," paper prepared for presentation at *VIIIth International High Pressure AIRAPT Conference, Le Creusot, France, July 30-August 3, 1979*; Lawrence Livermore Laboratory Report UCRL-82731 (1979).

Many resources require fracturing of rock before recovery. This is often accomplished by energy deposition under *in situ* conditions. The mechanical properties of the medium, confining pressure, pore fluid pressure, temperature, and energy deposition rate are among the important factors leading to an understanding and prediction of fracture production. Recent experimental and modeling studies have improved understanding of the effects of confining pressure on explosive-induced fracturing in small-scale blocks, effect of timing of multiple explosives, rate of pressurization on hydraulic fracture production, changing material properties on hydraulic pressure-produced fracture initiation and orientation, and material properties on rubble behavior after fracturing.

SCHOCK, R. N., Q. Johnson, and J. Akella, "Crystal Structures of Am Up To 20.0 GPa," presented at *AIRAPT, Le Creusot, France, July 30-August 3, 1979*; Lawrence Livermore Laboratory Report UCRL-82729 (Abstract) (1979).

The crystal structure of Am has been characterized up to 20.0 GPa using a diamond-anvil, high-pressure apparatus. The normal form of Am stable at 1 atm and room temperature is dhcp. This form undergoes two phase transformations below 20.0 GPa. The first transformation occurs at 6.5 ± 1.0 GPa, and the second at 11.0 ± 1.0 GPa. The structural behavior of Am in relation to lanthanides will be discussed.

Schock, R. N., A. S. KUSUBOV, W. B. Durham, J. E. Schatz, and T. J. Ahrens, "Explosive-Induced Damage in Porous Sandstone," submitted to *Proceedings of 7th AIRAPT International High Pressure Conference, Le Creusot, France, July 30-August 3, 1979*; Lawrence Livermore Laboratory Report UCRL-83448 (1979).

Schock, R. N., A. S. KUSUBOV, J. F. Schatz, W. B. Durham, and T. J. Ahrens, "Effect of Confining Pressure on Explosively Induced Damage in Porous Sandstone," presented at *American Geophysical Union Meeting, Washington, D.C., May 28-June 1, 1979*; Lawrence Livermore Laboratory Report UCRL-82384 (1979).

Shaffer, R. J., G. D. ANDERSON, and M. E. Hanson, "Theoretical and Experimental Analyses of Hydraulic Fracturing," (METC/SP-79-6), *Proceedings of 3rd Eastern Gas Shales Symposium, Morgantown, West Virginia, October 1-3, 1979*.

Shaffer, R. J., M. E. HANSON, G. D. Anderson, W. Lin, D. F. Towse, M. P. Cleary, and B. C. Haimson, *LLL Gas Stimulation Program, Quarterly Progress Report, April through June 1979*, Lawrence Livermore Laboratory Report UCRL-50036-79-2 (1979).

Shaffer, R. J., M. E. HANSON, G. D. Anderson, D. F. Towse, A. G. Duba, N. R. Burkhard, W. Lin, M. P. Cleary, and B. C. Haimson, *LLL Gas Stimulation Program Quarterly Progress Report, January through March 1979*, Lawrence Livermore Laboratory Report UCRL-50036-79-1 (1979).

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

SHAFER, R. J., M. E. Hanson, and G. D. Anderson, "Hydraulic Fracturing Near Interfaces," *ASME Energy Technology Conference, New Orleans, Louisiana, February 3-7, 1980*; Lawrence Livermore Laboratory Report UCRL-83419 (1979).

In order to determine the parameters and reservoir characteristics which control the geometry of massive hydraulic fractures in a reservoir we are conducting theoretical and experimental studies of pressure driven fractures

near interfaces that separate differing materials. We have applied dynamic and equilibrium finite element models to study fracturing in the vicinity of interfaces. We find that when a crack propagates in material A toward a well-bonded interface at half the dilatational wave speed there is an amplification in the likelihood of crack penetration into material B. This amplification increases as material A becomes stiffer relative to B. In our equilibrium calculations, we find that the stress intensity factor of the leading crack tip decreases as the crack approaches a stiffer material and increases as the crack approaches a more flexible material. Additionally, we find that when existing cracks are present near the interface the effects of the change in material properties are reduced. In our equilibrium analyses with unbonded interfaces, where shear stresses are transmitted via friction, we find that a decrease in the coefficient of friction reduces the likelihood of crack penetration into the adjacent material when both materials are identical; however, decreasing friction tends to draw the crack toward the interface. Experimentally, we have measured friction coefficients and hydrofracture penetration characteristics in Indiana limestone and Nugget sandstone. We find that there is a least stress required across the interface for a hydrofracture to cross the interface. This stress depends on rock type, interface surface finish, and water content.

Shaffer, R. J., M. E. HANSON, G. D. Anderson, L. D. Thorson, and D. N. Montan, "Theoretical and Experimental Analyses of Hydraulic Fracturing and Some Reservoir Response to the Stimulation," *Fifth Annual DOE Symposium on the Enhanced Oil and Gas Recovery and Improved Drilling Technology*, Tulsa, Oklahoma, August 22-24, 1979; Lawrence Livermore Laboratory Report UCRL-82578 (1979).

Stone, R., L. D. RAMSPOTT, J. D. Tewhey, D. G. Coles, H. C. Weed, and J. S. Schweiger, *FY78 Annual Technical Report of Lawrence Livermore Laboratory's Participation in the DOE-NV Project: Radionuclide Migration in the Ground*, Lawrence Livermore Laboratory Report UCID-18259-78 (1979).

Stone, R., S. W. MEAD, F. T. Wang, H. C. Ganow, and D. H. Stuermer, "Ground-Water Effects of Underground Coal Gasification Experiments in Northeastern Wyoming," *54th Annual Fall Technical Conference of the Society of Petroleum Engineers of AIME, Las Vegas, Nevada, September 23-26, 1979*; Lawrence Livermore Laboratory Report UCRL-82466 (1979).

Stout, N. D., K. G. KNAUSS, R. Quong, and L. B. Owen, "An Effective H_2S Abatement Process Using Geothermal Brine Effluents," *Trans. Geotherm. Resour. Council* 3, 557 (1979); Lawrence Livermore Laboratory Report UCRL-83010 (1979).

STOUT, N. D., and A. J. Piwinski, "Enthalpy and Heat Capacity of Silicate Melts at Atmospheric Pressure from 1520 to 2560 K," presented at *Annual Fall Meeting of American Geophysical Union, San Francisco, December 3-7, 1979*; Lawrence Livermore Laboratory Report UCRL-83280 (1979).

The enthalpy, $H_T - H_{298}$, and heat capacity, C_p , of anhydrous silicate melts were determined at 0.1 MPa from 1520 to 2560 K using a drop calorimeter. The rock types, all obtained from the Department of Energy's Test Site in southern Nevada, include basalts, welded tuffs, rhyolite, and sedimentary alluvium. Starting materials in all the experiments were bubble-free glasses prepared by repeated fusions in air of finely ground rock, followed by rapid quenching. Rock compositions in weight percent are:

For basalt Uel8#2,

SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	TiO_2	Na_2O	K_2O	H_2O^+	H_2O^-
59.78	17.82	4.86	4.29	7.64	1.63	3.45	1.47	0.06	<0.21

For welded tuff Ue20u (330),

SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	TiO_2	Na_2O	K_2O	H_2O^+	H_2O^-
75.58	14.66	1.15	0.90	0.61	0.28	2.57	3.77	0.28	0.08

For the basalt between 1520 and 2550 K,

$$H_T - H_{298} \text{ (J/g)} = 1.015 T + 1.288 \times 10^{-5} T^2 - 363.9 \text{ with 1 S.D.} = 5.65 \text{ J/g and } \chi^2 = 0.022 \text{ and}$$

$$C_p \text{ (J/g} \cdot \text{K)} = 1.015 + 2.576 \times 10^{-5} T.$$

For the welded tuff between 1740 and 2560 K,

$$H_T - H_{298} \text{ (J/g)} = 1.370 T - 686.0 \text{ with 1 S.D.} = 20.8$$

$$\text{J/g and } \chi^2 = 0.225 \text{ and } C_p \text{ (J/g} \cdot \text{K)} = 1.370.$$

Stout, N. D., and A. J. PIWINSKII, "The Entropy of Silicate Melts at Atmospheric Pressure from 1520 to 2560 K," presented at *Annual Fall Meeting, American Geophysical Union, San Francisco, California, December 3-7, 1979*; Lawrence Livermore Laboratory Report UCRL-83281 (Abstract) (1979).

Swift, R. P., and A. KUSUBOV, "Technique to Study Multiple Fractures Produced at Intermediate Loading Rates," Lawrence Livermore Laboratory Report UCRL-83653 (Abstract) (1979).

Swift, R. P., R. N. SCHOCK, M. E. Hanson, and O. R. Walton, "In Situ Fracture Related to Energy and Resource Recovery," paper prepared for presentation at *VIIth International High Pressure AIRAPT Conference, LeCreusot, France, July 30-August 3, 1979*; Lawrence Livermore Laboratory Report UCRL-82731 (1979).

TERHUNE, R. W., H. D. Glenn, D. E. Burton, H. L. McKague, and J. T. Rambo, "Numerical Simulation of the Baneberry Event," *Nucl. Technol.* 46, 159 (1979).

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. Calculational results describe the sequence of dynamic phenomena that very likely 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 approximately 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. 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 roughly 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., and L. R. Moreno, *Containment Calculation for Burzet*, Lawrence Livermore Laboratory Report UCRL-52784 (1979).

Burzet is a proposed intermediate-yield underground test of a nuclear explosive at the Nevada Test Site. The possible existence of a high Paleozoic scarp and fault within 100 m of the proposed working point created concern as to their effect on the containment of the radioactive gases. A calculation of the expected stress wave interaction at the scarp and fault demonstrates that the effects are negligible. Results of the calculation are those expected from an event in a homogeneous media and are thus consistent with good containment experience on numerous previous detonations of similar yield, depth of burial, and medium properties.

TERHUNE, R. W., C. M. Snell, and H. C. Rodean, *Enhanced Coupling and Decoupling of Underground Nuclear Explosions*, Lawrence Livermore Laboratory Report UCRL-52806 (1979).

We studied the seismic coupling efficiency of nuclear explosions in granite by means of computer calculations as a function of scaled explosion source radius. The scaled source radii were varied from $0.1 \text{ m/kt}^{1/3}$ (point source) to $20 \text{ m/kt}^{1/3}$ (representing a nearly full decoupling cavity). It was found that seismic coupling efficiency is at a maximum when the scaled source radius is approximately $2 \text{ m/kt}^{1/3}$. The primary cause of this maximum in seismic wave source strength is the effect of initial source radius on peak particle velocity and pulse duration of the outgoing elastic wave. A secondary cause is that rock vaporization (an energy sink) does not occur for scaled source radii somewhat greater than $1 \text{ m/kt}^{1/3}$. Therefore, for scaled

source radii greater than $1 \text{ m/kt}^{1/3}$, there is additional energy available for seismic wave generations. Available data for some nuclear explosions at the Nevada Test Site do not provide sufficient evidence either to support or negate the enhanced coupling that is indicated by calculations at scaled source radii of 1 to $2 \text{ m/kt}^{1/3}$.

Tewhey, J. D., L. D. RAMSPOTT, D. G. Coles, H. C. Weed, J. S. Schweiger, and R. Stone, *FY78 Annual Technical Report of Lawrence Livermore Laboratory's Participation in the DOE-NV Project: Radionuclide Migration in the Ground*, Lawrence Livermore Laboratory Report UCID-18259-78 (1979).

Thorson, L. D., D. W. CARPENTER, and T. L. Steinborn, *Groundwater Recharge and Discharge Scenarios for a Nuclear Waste Repository in Bedded Salt*, Lawrence Livermore Laboratory Report UCID-18119 (1979).

Thorson, L. D., M. E. HANSON, G. D. Anderson, R. J. Shaffer, and D. N. Montan, "Theoretical and Experimental Analyses of Hydraulic Fracturing and Some Reservoir Response to the Stimulation," *Fifth Annual DOE Symposium on the Enhanced Oil and Gas Recovery and Improved Drilling Technology*, Tulsa, Oklahoma, August 22-24, 1979; Lawrence Livermore Laboratory Report UCRL-82578 (1979).

TOWSE, D. F., *Geoscience Parameter Data Base Handbook*, Lawrence Livermore Laboratory Report UCRL-52557 (1979).

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 an LLL subcontractor. Later revisions

will contain mechanical and thermal data more relevant to facility design. An earlier broad treatment of this material is now in preparation for publication as a separate document.

The main text of this handbook, Sections 1 through 5, provides general information. Detailed tables of data are given in the appendices.

This edition of the handbook deals with data for the bedded salt environment. Future editions will contain additional information, on salt and on other media.

The literature on the bedded salt environment as it relates to nuclear waste disposal is voluminous, but much of it is redundant and qualitative. Unfortunately, there is a dearth of reliable quantitative data useful for analysis of waste management options.

The reader should be cautioned that much of the geologic data recorded for other purposes is not suited for waste management analysis and that using such data could produce serious errors and false conclusions. Data recorded specifically for waste management purposes is also site specific, not generic. Such data were intentionally collected because the site was or is under serious consideration for repository licensing (e.g., Lyons, Kansas, and the Waste Isolation Pilot Plant in New Mexico). The reader should also be aware that most of the currently available data reflect not true *in situ* conditions, but, rather, laboratory conditions.

TOWSE, D. F., "Solving the Geologic Issues in Nuclear Waste Disposal," *Annual Meeting of the American Institute of Professional Geologists, Lafayette, Louisiana, September 21, 1979*; Lawrence Livermore Laboratory Report UCRL-83285 (1979).

Technical problems with nuclear waste disposal are largely geological. If these are not solved, curtailment of nuclear power development may follow, resulting in loss of an important element in the national energy supply.

Present knowledge and credible advances are capable of solving these problems provided a systems view is preserved and a national development plan is followed.

This requires identification of the critical controllable elements and a systematic underground test program to prove those critical elements. Waste

migration can be understood and controlled by considering the key elements in the system: the system geometry, the hydrology, and the waste-rock-water chemistry.

The waste program should (1) identify and attack the critical problems first, (2) provide tests and demonstration at real disposal sites, and (3) schedule elements with long lead-times for early start and timely completion.

Towse, D. F., and D. W. CARPENTER, *Seismic Safety in Nuclear-Waste Disposal*, Lawrence Livermore Laboratory Report UCID-18125 (1979).

Towse, D. F., T. R. DONICH, A. M. Kaufman, G. D. Sauter, and T. L. Steinborn, *Additional Media Studies for Site Suitability Criteria*, Lawrence Livermore Laboratory Report UCID-17887 (1979).

Towse, D. F., M. E. HANSON, G. D. Anderson, R. J. Shaffer, A. G. Duba, N. R. Burkhard, W. Lin, M. P. Cleary, and B. C. Hamison, *LLL Gas Stimulation Program Quarterly Progress Report, January through March 1979*, Lawrence Livermore Laboratory Report UCRL-50036-79-1 (1979).

Towse, D. F., M. E. HANSON, G. D. Anderson, R. J. Shaffer, W. Lin, M. P. Cleary, and B. C. Haimson, *LLL Gas Stimulation Program, Quarterly Progress Report, April through June 1979*, Lawrence Livermore Laboratory Report UCRL-50036-79-2 (1979).

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 Report UCRL-52633 (1979).

The high-level waste management system has been defined as: solidification of high-level waste and interim storage, transportation to the repository site, handling and emplacement of the waste until the repository is

sealed, and the future history of the sealed repository. Each component can be analyzed separately and modeled with a consistent set of assumptions. The risks associated with each component can then be minimized by identifying the critical factors. Thus, the overall risk from waste management processes can be minimized. Activities that could occur and initiate risk within the system must be considered in modeling.

Historically, the approach to a nuclear system has been to identify the components of a facility whose failure could threaten public health and safety, and to require multiple barriers against radiation release, strict quality control, and safety features that could be engineered into the facility. For containment of waste for geologic times substantial reliance must be placed on natural existing conditions. Physical characteristics, geologic behavior patterns of prospective sites, and estimated time constraints must be defined and analyzed. Therefore, assessing the suitability of a repository site for high-level waste storage becomes a complex problem with many interrelated, but not always well-defined, factors.

LLL is currently performing a multicycle systems analysis approach to the problem of site suitability through development of different models, including a physical model and mathematical models. This approach allows data development and model development to proceed in parallel. Each progressive cycle more clearly defines the parameters and their uncertainties, further refines the models developed, and validates assumptions and approximations used.

A six-layer horizontal model was developed whose parameters and dimensions can be varied to simulate the natural environment of many potential repository sites. The geologic-hydrologic properties that influence groundwater flow rates and waste concentrations, as well as variables that determine the configurations and lengths of flow paths were incorporated and analyzed.

The mathematical models were developed to calculate the performance of hypothetical repository sites. The ORIGEN, WASTE, and BIDOSE programs were employed to calculate and evaluate the inventory of important nuclides, the amount of radioactive waste released, and the expected individual and population radiation doses, respectively.

This report describes the analytical methods employed, the parameter data base used, and the preliminary results obtained.

TOWSE, D. F., D. Isherwood, R. A. Heckman, T. Holdsworth, and N. L. Dayen, *Site Suitability Criteria for Solidified High Level Waste Repositories*, Lawrence Livermore Laboratory Reports UCID-17830 and UCID-17831 (1979).

Trimmer, D. A., W. B. DURHAM, and A. E. Abey, "Thermal Conductivity, Diffusivity and Expansion of Avery Island Salt at Pressure and Temperature," *Proceedings, 16th ITCC and 7th ITES Conference, Chicago, Illinois, November 7-9, 1979*; Lawrence Livermore Laboratory Report UCRL-83789 (1979).

Trimmer, D., H. C. HEARD, A. Duba, and B. Bonner, "Permeability of Generic Repository Rocks at Simulated *In Situ* Conditions," paper presented at *Workshop on Low-Flow, Low Permeability Measurements in Largely Impermeable Rocks, Paris, France, March 19-21, 1979*; Lawrence Livermore Laboratory Report UCRL-82609 (Abstract) (1979).

Trimmer, D., H. C. HEARD, W. Lin, A. Duba, and B. Bonner, "Simultaneous Measurements of Permeability, Electrical Conductivity, and Ultrasonic Velocity in Igneous and Metamorphic Rocks," paper presented at *American Geophysical Union Meeting, Washington, D.C., May 28-June 1, 1979*; also, Lawrence Livermore Laboratory Report UCRL-82389 (1979).

WAGONER, J. L., *Hydrogeochemical and Stream Sediment Reconnaissance Basic Data Report for Millett NTMS Quadrangle, Nevada*, Lawrence Livermore Laboratory Report UCRL-52641 (1979).

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 nine 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 nonmarine clastic 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.

WAGONER, J. L., *Hydrogeochemical and Stream Sediment Reconnaissance Basic Data Report for Williams NTMS Quadrangle, Arizona*, Lawrence Livermore Laboratory Report UCRL-52671 (1979).

This report presents the result of geochemical reconnaissance sampling in the Williams 1° x 2° quadrangle of the National Topographic Map Series (NTMS). We collected wet and dry sediments throughout the 18,500-km² arid-to-semiarid region and water samples at available streams, springs, and wells. Samples were collected between August 1977 and January 1978. We present the results of neutron activation analyses of uranium and trace elements and other field and laboratory analyses in tabular hardcopy and microfiche format. The report includes six full-size overlays for use with the Williams NTMS 1:250,000 quadrangle. We divided sediment samples into five general groups according to the source rock from which the sediment was derived; we treated these groups as independent populations. Background uranium concentrations for the quadrangle are relatively low, ranging from 1.91 to 2.40 ppm, with the highest associated with the Precambrian igneous and

metamorphic complexes of the Basin and Range province. Uranium correlates best with the rare-earth elements and iron, scandium, titanium, and manganese. Known uranium occurrences are not readily identified by the stream sediment data.

Walton, O. R., R. N. SCHOCK, M. E. Hanson, and R. P. Swift, "In Situ Fracture Related to Energy and Resource Recovery," paper prepared for presentation at *VIIth International High Pressure AIRAPT Conference, LeCreusot, France, July 30-August 3, 1979*; Lawrence Livermore Laboratory Report UCRL-82731 (1979).

WEED, H. C., F. Bazan, J. H. Rego, and J. S. Schweiger, "Sorption of Radionuclides on Sandstone in Water and in Brine," presented at *American Chemical Society Meeting in Houston, Texas, March 23-28, 1979*; Lawrence Livermore Laboratory Report UCRL-83589 (Abstract) (1979).

Sorption ratios have been calculated from measured transport rates of ^{85}Sr , $^{95\text{m}}\text{Tc}$ and ^3H as tritiated water in St. Peter Sandstone cores, using sandstone-equilibrated water or brine as the transporting medium. Cores are 26-mm diameter $\times$ 25-mm length. During the transport experiment, steady flow is first established along the core. Then a short pulse of a mixed radionuclide solution is injected at the inlet face, transported along the core, and collected in the effluent as a function of time. Transport rates are calculated from the concentration vs time curves for the effluent and the concentration vs distance curves for the core. Sorption ratios (K_d) are calculated from the transport rates assuming a retardation factor of unity for tritiated water and linear sorption isotherms for ^{85}Sr and $^{95\text{m}}\text{Tc}$ on St. Peter Sandstone. For experiments lasting up to 7200 min, $K_d = 0$ for $^{95\text{m}}\text{Tc}$ in both sandstone-equilibrated water and concentrated brine. For ^{85}Sr , $K_d = 0.18$ to $1.4 \text{ cm}^3/\text{g}$ in sandstone-equilibrated water, but $K_d = 0$ in concentrated brine.

WEED, H. C., D. G. Coles, D. J. Bradley, R. W. Mensing, J. S. Schweiger, and J. H. Rego, "Leaching Characteristics of Actinides from Simulated Reactor Waste, Part 2," presented at *Materials Research Society Annual Meeting, Cambridge, Massachusetts, November 26-30, 1979*; Lawrence Livermore Laboratory Report UCRL-81147 (1979).

Leach rates for ^{237}Np and ^{239}Pu are investigated with a single-pass leaching system. The factorial experimental design uses several combinations of solution composition and flow rate; and two temperatures, 25 and 75°C. The 25°C results are compared with those from a modified IAEA procedure. At 25°C, leach rates decrease with time. Agreement between results from the single-pass and modified IAEA methods is fair with WIPP brine leachant, good with NaHCO_3 , and good with distilled H_2O . Leach rates are approximately independent of flow rates at room temperature, but increase with flow rates at high temperature. Rates from ^{237}Np increase with temperature, but those for ^{239}Pu either decrease or do not change with temperature.

WEED, H. C., D. G. Coles, and J. S. Schweiger, "Single-Pass Leaching of Nuclear Melt Glass by Groundwater, Part II.," presented at *American Chemical Society Annual Meeting in Houston, Texas, March 23-25, 1979*; Lawrence Livermore Laboratory Report UCRL-81617, Part II (1979).

Nuclear explosion melt glass has been continuously leached with NTS groundwater for 420 days. A single-pass dynamic flow system was used in order to simulate actual underground conditions. The experimental details and preliminary data for the first 120 days of leaching of only one of the three glass samples have been presented earlier. This discussion presents the final data for all three glass samples leached during the experiment. Leaching was carried out at flow rates of 36 and 6.7 cm/day and at 25°C. The samples ranged from 40 to 130 μm in particle size and contained from 65 to 100% glass. The highest leaching rate observed was for ^{22}Na and varied from $1.5 \times 10^{-2} \text{ day}^{-1} \text{ m}^{-2}$ on Day 1 to $6 \times 10^{-5} \text{ day}^{-1} \text{ m}^{-2}$ on Day 420. The lowest flow rate observed was for ^{144}Ce and varied from $1.5 \times 10^{-5} \text{ day}^{-1} \text{ m}^{-2}$ on Day 1 to $4.5 \times 10^{-6} \text{ day}^{-1} \text{ m}^{-2}$ on Day 420.

Cerium-144 showed the greatest dependence of leaching rate on flow rate. Mechanisms are presented which describe the leaching behavior of the glasses with respect to radionuclides observed in the leachate. Surface effects as observed by SEM on the glass particles after the leaching was terminated are also discussed.

WEED, H. C., and D. D. Jackson, *Design of a Variable Flow-Rate, Single-Pass Leaching System*, Lawrence Livermore Laboratory Report UCRL-52785 (1979).

We have designed leaching systems for experiments on several kinds of solids, including glassy debris from underground nuclear explosions at NTS (puddle glass), refractory compositions for retention of radioactive nuclear reactor waste, and spent reactor fuel. The system used on puddle glass has a continuously variable flow rate from 13 to 460 cm³/day, a temperature range from 25 to 75°C, operating capacity for up to 20 simultaneous experiments, and one-pass operation with continuous exposure of samples to fresh solution. Results obtained on puddle glass are in qualitative agreement with those on silicate glasses designed for isolation of nuclear reactor waste.

Weed, H. C., and A. J. PIWINSKII, "Dynamic Viscosity of Some Silicate Melts to 1688° under Atmospheric Pressure," submitted to *Ber. der Bunsen Gell. fur Phys. Chem*; Lawrence Livermore Laboratory Report UCRL-83126 (Abstract) (1979).

WEED, H. C., A. J. Piwinskii, and L. L. Dibley, *An Experimental Study of the Dynamic Viscosity of Some Anhydrous Silicate Melts to 1953 K at 150 kPa*, Lawrence Livermore Laboratory Report UCRL-52757 (1979).

The dynamic viscosity of six anhydrous silicate melts, obtained by fusing various rocks collected from the Department of Energy's Nevada Test Site, has been measured from 1393 to 1953 K at 150 kPa. These silicate melts exhibit Newtonian behavior in this temperature interval. Experimental results

indicate that tuff viscosity > alluvium viscosity > basalt viscosity. At 1673 K, viscosities of Schooner tuff ($Ue20\mu-330'$), alluvium ($U10ba$), and Danny Boy basalt ($Ue18q\#2$) are 28,460 Pa·s, 4,820 Pa·s, and 12.6 Pa·s, respectively. Activation energies for viscous flow in the interval 1393-1953 K range from 268 to 393 kJ/mole.

Weed, H. C., L. D. RAMSPOTT, J. D. Tewhey, D. G. Coles, J. S. Schweiger, and R. Stone, *FY78 Annual Technical Report of Lawrence Livermore Laboratory's Participation in the DOE-NV Project: Radionuclide Migration in the Ground*, Lawrence Livermore Laboratory Report UCID-18259-78 (1979).

WEED, H. C., J. S. Schweiger, and J. Rego, "Experimental Retardation Factors and Sorption Ratios for Sr-85, Tc-95m, and H-3 in Thirsty Canyon Tuff at 10-MPa Confining Pressure and 25°C," presented at *Annual Fall Meeting, American Geophysical Union, San Francisco, California, December 3-7, 1979*; Lawrence Livermore Laboratory Report UCRL-83289 (Abstract) (1979).

Transport rates of Sr-85, Tc-95m, and H-3 as tritiated water have been measured on Thirsty Canyon Tuff cores at 10-MPa confining pressure and 25°C, with tuff-equilibrated water. Cores are 26-mm diameter by 25-mm length. After establishment of steady flow through the core, a short pulse of radionuclide solution is injected at the inlet face, transported along the core, and monitored in the effluent solution as a function of time. Retardation factors are calculated from the concentration vs time curve for the effluent solution and the concentration profile for the core. For run times up to 11,000 minutes, most Sr-85 remains in the core, tritiated water and Tc-95m appear simultaneously in the effluent, and Tc-95m also remains in low concentration in the core. Retardation factors are 1 for tritiated water and Tc-95m in the effluent, and (244 ± 125) for Sr-85. The corresponding sorption ratio values are $K_d = 0$ for tritiated water and Tc-95m in the effluent, and $(29 \pm 14) \text{ cm}^3/\text{g}$ for Sr-85. Possible causes for the retention

of Tc-95m in the core included irreversible sorption, precipitation as TcO_2 , or trapping in dead-end pore spaces. These results can be applied directly to radionuclide transport calculations.

WILDER, D. G., "Influence of Jointing on Stress and Strain Response during Underground Excavation for Test Storage of Spent Reactor Fuel," submitted to *Journal of Geological Society of America*; Lawrence Livermore Laboratory Report UCRL-82742 (1979).

Jointing appears to have controlled the *in situ* response of granitic rock to underground excavation for test storage of spent reactor fuel. Three parallel drifts were excavated 427 m (1400 ft) below ground in quartz monzonite containing steeply dipping, slightly open joints oriented roughly parallel and perpendicular to the drifts with shallow dipping, healed joints and steeply dipping, intensely jointed zones oriented oblique to the drifts. Stress and strain responses to excavation of the central drift were monitored by instrumentation located in both intensely and moderately jointed rock. Displacements measured in intensely jointed rock were four times the displacement predicted by finite element analysis but only 20% of predicted values in moderately jointed rock. Reductions in vertical compressive stresses measured in the pillar near the central drift rib were 1.5 times greater in moderately jointed rock than in intensely jointed zones. Many joints on the interior ribs of the outer drifts opened surficially; however, a few open joints appeared to extend deeply into the pillar parallel to intense jointing.

It was concluded that arching over the drifts coupled with discrete block motions along zones of intense jointing were responsible for the anomalous responses.

Wilder, D. G., L. D. RAMSPOTT, L. B. Ballou, R. C. Carlson, N. N. Montan, T. R. Butkovich, J. E. Duncan, W. C. Patrick, W. G. Brough, and M. C. Mayr, *Technical Concept for a Test of Geologic Storage of Spent Reactor Fuel in the Climax Granite, Nevada Test Site*, Lawrence Livermore Laboratory Report UCRL-52796 (1979).

WOLERY, T. J., "Computer Simulation of Temperature-Dependent Equilibrium Precipitation," presented at *Geothermal Resources Council 1979 Annual Meeting, Reno, Nevada, September 24-27, 1979*; Lawrence Livermore Laboratory Report UCRL-83013 (1979).

The EQ3/EQ6 software package contains two computer codes (EQ3 and EQ6) and data files which form a useful tool in modeling precipitation from geothermal fluids caused by heating or cooling. The data files contain information on 140 aqueous species and nearly 150 minerals, and permit calculations over the temperature interval 0-350°C. Assumption of homogeneous thermodynamic equilibrium in aqueous solution permits calculation of the driving forces for precipitation as measured by the affinity ($\log Q/K$) for each such reaction. Further assumption of precipitation and heterogeneous equilibrium for any mineral whose affinity would otherwise exceed a value of zero permits determination of the identity of the precipitates, their masses and volumes, and the temperature ranges in which they form.

We have used the EQ3/EQ6 capability to determine the effects of temperature increase on formation of precipitates from Salton Sea water.

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