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EARTH SCIENCES DIVISION, COLLECTED ABSTRACTS—1977

MASTER

W. A. Quitiquit
G. P. Ledbetter
A. L. Henry

May 24, 1978

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MS. date: May 24, 1978

NOTICE

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EARTH SCIENCES DIVISION COLLECTED ABSTRACTS—1977

INTRODUCTION

This report is a compilation of abstracts of papers, internal reports, and talks presented during 1977 at national and international meetings by members of the Earth Sciences Division, Lawrence Livermore Laboratory. It is arranged alphabetically by author and includes a cross-reference by subject indicating the areas of research interest of the Earth Sciences Division, as follows.

ENERGY AND RESOURCES

- In situ processing
 - Coal gasification
 - Gas stimulation
 - Geothermal
 - Oil shale retorting
- Radioactive waste isolation
- Resources

GEOCHEMISTRY

- Computational methods
- Geochemical exploration
- Petrology

GEOPHYSICS

- Exploration geophysics
- Planetary interiors
- Seismology

PETROPHYSICS

- Cratering
- Equation-of-state modeling

Explosion phenomenology
Explosive fracturing
Massive hydraulic fracturing
Mechanical properties
Numerical analysis
Permeability
Rheological behavior
Shock-wave studies
Transport properties

MISCELLANY

PROFESSIONAL ROSTER

DIVISION LEADERSHIP:

R. N. Schock
L. L. Schwartz

PROJECT LEADERSHIP:

Reservoir Stimulation	M. E. Hanson
Oil Shale	A. E. Lewis
Radionuclide Migration/ Waste Isolation	L. D. Ramspott
Seismic Monitoring	H. C. Rodean
Nuclear Test	J. Toman

GEOLOGY

D. O. Emerson

I. Y. Borg
N. E. Burkhard
R. C. Carlson
M. A. Chan
J. J. Cohen
N. B. Crow
H. C. Ganow
J. M. Hanson
J. R. Hearst
N. W. Howard
D. J. Isherwood
P. W. Kasameyer
K. G. Knauss
D. L. Leach
G. P. Ledbetter
H. L. McKague
S. Mead
D. G. Miller
J. G. Morse
T. G. Naymik
L. B. Owen
K. P. Puchlik
B. J. Qualheim
T. L. Steinborn
R. Stone
H. A. Tewes
J. D. Tewhey
K. A. Tonnessen
D. F. Towse
J. L. Wagoner
T. J. Wolery

COMPUTATIONS

P. S. Brown

M. G. Austin
J. B. Bryan
D. E. Burton
T. R. Butkovich
M. E. Cunningham
H. Glenn
M. Heusinkveld
D. E. Maiden
D. N. Montan
J. T. Rambo
J. F. Schatz
R. J. Shaffer
C. M. Snell
R. P. Swift
R. W. Terhune
J. M. Thomsen
L. Thigpen
O. R. Walton

GEOPHYSICS

A. G. Duba

A. E. Abey
J. Akella
G. D. Anderson
B. P. Bonner
N. C. Burr
D. H. Chung
M. S. Costantino
L. Dengler
M. D. Denny
W. B. Durham
F. E. Followill
W. J. Hannon
H. C. Heard
A. Kusubov
D. B. Larson
E. M. Lilley
W. Lin
K. K. Nakanishi
A. J. Piwinski
N. L. Pruvost
P. W. Rodgers
R. F. Rohrer
E. S. Schaffer
D. L. Springer
D. A. Trimmer
H. C. Weed

OIL SHALE

A. J. Rothman

F. J. Ackerman
R. L. Braun
J. F. Carley
R. C. Y. Chin
B. Laswell
R. J. Mallon
J. Raley
W. A. Sandholtz
C. J. Sisemore

ABSTRACTS

ABEY*, A. E., "A Model for Predicting the Hydrostatic Loading and Unloading Relationship of Porous Materials Containing Various Amounts of Fluid," J. Geophys. Res. 82, 5418-5422 (1977). Lawrence Livermore Laboratory, Rept. UCRL-78290, Rev. 1, Preprint (1977).

An elastic-inelastic model is presented for the loading and unloading pressure-volume relationship of porous materials containing various amounts of fluid from 0 to 100% saturation. Distributions in both size and separation of connected and unconnected spherical and connected penny-shaped pores are assumed. The number of pores with a given size is assumed to be inversely proportional to the initial volume and independent of the separation between pores. The simple relationships relating the radius of a pore to the applied pressure are discussed. The pressure-volume relationship for the porous material with any saturation is calculated by using the input parameters, shear strength, shear modulus, matrix and fluid pressure-volume relationships, and the pressure-volume data for the dry material. Model predictions agree with the experimental data within experimental error for all saturations and at pressures up to 4 GPa (40 kbar) for Mt. Helen tuff.

ABEY, A. E., A Model for Predicting the Quasi-Static Hydrostatic or One-Dimensional Strain, Stress-Volume E.O.S. of a Partially Saturated Porous Material, (Am. Phys. Soc. Mtg. (San Diego, Mar. 1977). Lawrence Livermore Laboratory, Rept. UCRL-78961 Abstract (1977).

A distribution in both size and separation for spherical and penny-shaped pores is assumed to exist in a compressible matrix. The majority of the spherical pores and all the penny-shaped pores are interconnected and allow the movement of fluid between pores as pore crush-up takes place. The closure of spherical pores above a yield pressure is permanent while the closure of penny-shaped pores is elastic at all

*Names of senior authors appear in full caps. Abstracts follow the name of the senior author or, if the senior author is not a member of Earth Sciences Division, the first entry of the work.

pressure. The permanent closure of spherical pores is a function of maximum principal stress, mean matrix pressure, matrix shear strength, pore separation, and pore size. The elastic change for penny-shaped pores is a function of the matrix stress perpendicular to the pore's flat surface, the matrix shear modulus, pore separation, and pore radius. After calibration using the experimental dry hydrostat, the model can predict the hydrostatic and one-dimensional strain, stress-volume E.O.S. for all fluid saturations. Use of the model will be discussed using data for a common rock, tuff.

ABEY, A. E., and Dibley, L. L., An Apparatus for Deformation Tests at Intermediate Strain Rates - 10^{-2} to 10^{+2} sec $^{-1}$ and at High Pressure (Sixth Int. High Pressure Conf. (ATRAPT Boulder, Colorado, Jul. 1977)). Lawrence Livermore Laboratory, Rept. UCRL-79012 Preprint (1977).

A new apparatus has been designed and built to test deformation at strain rates from approximately 10^{-2} to 10^2 s $^{-1}$. The apparatus was designed for confining pressure up to 1 GPa, but so far interest has been in data obtained at pressures below 15 MPa. This unit is described in detail, and some one-dimensional stress data on Indiana limestone and 6061-T6 aluminum are presented.

Abey, A. E., KUHN, B. A., Lesure, D. R., Wallace, P. L., and Pereyra, R. A., Pressure-Induced Phase Transformation in Tailwind, Lawrence Livermore Laboratory, Rept. UCID-17534 (1977).

Abey, A., SCHATZ, J., Kusubov, A., Hearst, J., Snell, C., and Thigpen, L., Rock Mechanics Project Progress and Results: Rock Fracture and Pore Collapse, Lawrence Livermore Laboratory, Rept. UCID-17527 (1977).

Ackerman, F. J., and SANDHOLTZ, W. A., Operating Laboratory Oil Shale Retorts in an In-Situ Mode, prepared for Soc. of Petroleum Engineers 52nd Annual Meeting (Denver, Colorado, Oct. 9-12). Lawrence Livermore Laboratory, Rept. UCRL-79035 Preprint (Aug. 1977).

AKELLA, J., Friction Measurements in Piston-Cylinder Apparatus Using Quartz Coesite Transition; Sixth Int. High Pressure Conf. (AIRAPT, Boulder, Colorado, Jul. 1977). Lawrence Livermore Laboratory, Rept. UCRL-79559 Preprint (1977).

The values of friction in solid-media, high-pressure piston-cylinder apparatus was determined by reversing the quartz $\rightleftharpoons$ coesite transition at 1273 and 1073 K in compression and decompression quenching experiments. Both talc-glass-alsimag and low-friction salt high-pressure cells were used. These friction values were compared with that obtained by the piston-displacement technique.

The double value of friction measured by the piston-displacement technique is ~ 0.4 GPa at 1273 K and 3.1 GPa nominal pressure. With a salt cell, the double value of friction measured was 0.03 and 0.12 PGa at 1273 and 1073 K. The friction value at 1273 K with the talc-glass-alsimag cell was 0.25 GPa. The friction value obtained from the piston-displacement studies could be larger because of the hysteresis in the pressure medium, which may have failed to attain equilibrium before the displacement reading was taken. The difference may also be due to pressure gradients in the pressure medium; these gradients may not have reversed symmetrically when the direction of piston motion was changed.

AKELLA, J., McCallister, R. H., and Meyer, H. O. A., Diamondiferous Kimberlite of the Wajrakharur Area, Southern India, "Second. Int. Kimberlite Conf. Extended Abstr.", 1-3 (1977). (Lawrence Livermore Laboratory, Rept. UCRL-79948 Abstract (1977)).

Although diamond has been known in India from antiquity, the presence of kimberlite has been the subject of much speculation and controversy. However, in the late 19th century, igneous rocks, supposedly the hosts of diamond at Panna and Wajrakharur were described, but were discounted as being kimberlite. Subsequently, others studied the source of diamonds but generally considered that kimberlite was not present. However, in 1963 Rao and Phadtre after examining the geology and petrography for four igneous bodies near Wajrakharur, Andhra Pradesh concluded they were kimberlitic. We report here preliminary data on the mineralogy and mineral chemistry of phases from two of these diatremes and confirm the conclusion of Rao and Phadtre that these are kimberlites.

Four pipe-like bodies are located in the region of Wajrakharur; two are near this village and the other two are near Lattavaram, about 6 miles SSW of Wajrakharur. The bodies are somewhat oval in shape, trending roughly N70°E, and have intruded Pre-cambrian granite and gneiss. The material in the pipes is highly weathered near the surface and consists of serpentine, calcite, clay minerals, and fragments of crustal and local host country-rock.

At Lattavaram the kimberlite is somewhat more durable and compact than at Wajrakharur, and it is thus possible to distinguish slight mineralogical and petrographic differences between the two pipes. Rao and Phadtre report the occurrence of eclogite and peridotite xenoliths from this locality but unfortunately we have not yet been able to confirm this observation. For the most part xenoliths consist of amphibolite or other crustal fragments.

Petrographically, the two kimberlites near Lattavaram are distinct. One kimberlite (L1) consists of relatively small (average about 1 mm) phenocrysts of olivine in a very dark, fine grained matrix of serpentine, calcite, phlogopite, and magnetite-rich spinel. Minor monticellit and pectolite were also noted. Spinel in this rock appear to be of two types a minor number are rich in chromium (7-11 wt% Cr_2O_3) whereas the second group have generally about 2-4 wt% Cr_2O_3 .

The second kimberlite at Lattavaram (L2) is much more coarsely grained than L1. The phenocrysts of olivine are larger and more abundant although they are, for the most part, serpentinized. Ilmenite and garnet, the latter with very thick kelyphitic rims, are also present in this kimberlite. The ground mass consists predominantly of serpentine, calcite, minor phlogopite, and opaque phases, including spinel and ilmenite. Minor phases such as sphene and perovskite have also been observed.

Chemical analyses of various phases from the two kimberlites at Lattavaram are presented. the analyzed olivine in L1 is generally close to Fo_{92} whereas that in L2 ranges between Fo_{88} and Fo_{92} . the garnets in L2 kimberlite are predominantly pyrope with subsidiary almandine and grossular. The Cr_2O_3 is approximately 2.5 - 3.0 wt% in these garnets, which are also relatively low in CaO (~5 wt%). The ilmenites so far analyzed vary in chromium content with some containing up to 4 wt% Cr_2O_3 . These ilmenites rich in Cr_2O_3 also contain high amounts of MgO relative to the Cr-poor ilmenites.

Serpentinized olivine phenocrysts in L1 kimberlite are interesting in that the veins of serpentine contain numerous minute needles of a nickel sulfide phase. A maximum content of 72 wt% Ni was obtained for this mineral which strongly suggests it is heazlewoodite (Ni_3S_2). The occurrence of this phase is believed to be due to late stage sulfurization of the olivine accompanying serpentinization, with the Ni being derived from the original olivine (0.2 - 0.3 wt% NiO).

The geological occurrence, plus the petrographic character of these rocks, and the similarity of mineral compositions with other known kimberlites are sufficient evidence to support Rao and Phadtre in their conclusion that these are true kimberlites.

AKELLA, J., McCallister, R. H., and Meyer, H. O. A., Mineralogical Studies on the Diamoniferous Kimberlite of the Wajrakharur Area, Southern India, Lawrence Livermore Laboratory, Rept. UCRL-79948 Preprint (1977).

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 $\text{N}70^\circ\text{E}$. 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 between the two pipes at this locality. One kimberlite pipe consists predominantly of phenocrysts of olivine (Fo_{92}) 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 Fo_{88} to Fo_{92} ; and garnet is about 75% pyrope, 11% grossular with between 2.5 to 3 wt% Cr_2O_3 . Up to the present time, mantle xenoliths have not been found but crustal xenoliths (e.g., amphibolites) are not uncommon.

ANDERSON, G. D., and Larson, D. B., Laboratory Experiments on Hydraulic Fracture Growth near an Interface, to be presented at the Nineteenth U.S. Sympos. Rock Mech. (Stateline, Nevada, May 1978). Lawrence Livermore Laboratory, Rept. UCRL-80355 Abstract (1977).

Experiments were performed to study the growth of hydraulically driven cracks in the vicinity of an interface between two materials. The materials used in the study were Nugget sandstone from Utah (3-6% porosity), Indiana limestone (12-15% porosity), and polymethylmethacrylate (PMMA). The fracturing fluid was oil that was injected into the test specimen through high pressure tubing which was epoxied into the specimen. In some experiments two blocks of the same material or of two different materials were bonded together. In other experiments two blocks of the same material or of different materials were placed adjacent to one another without any bonding at the interface but with a normal stress applied across the interface. In both sets of experiments a hydraulically driven crack was initiated in one of the blocks so that it grew perpendicular to the interface. It was found that a crack would not cross a well-bonded interface in PMMA even when a 2000-psi normal load was placed across it. Cracks would cross a bonded interface from PMMA into Indiana limestone but not vice versa. Cracks would cross a bonded interface from Nugget sandstone to Indiana limestone but not vice versa. For certain finishes of the two faces, a crack would cross an unbonded interface in the rocks when a critical normal stress across the interface was reached.

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

ANDERSON, G. D., and Larson, D. B., Plane Shock Wave Studies of Geologic Media, Lawrence Livermore Laboratory, Rept. UCRL-52357 (1977).

Plane shock wave experiments have been conducted on eight geologic materials in an effort to determine the importance of time-dependent mechanical behavior. Of the eight rocks studied, only Westerly granite and nugget sandstone appear to show time independence. In the slightly porous materials (1-5%) rock, Mt. Helen tuff and Indiana limestone, time-dependent behavior is associated with the time required to close the available porosity. In water-saturated rocks, the time dependence arises because the water that is present shows no indication of transformation to the higher pressure ice phases, thus suggesting the possibility that a metastable form of water exists under dynamic conditions.

ANDERSON, G. D., and Larsen, D. B., "Shock Wave Compression of Nugget Sandstone," *Trans. Am. Geophys. Union* 58, 491 (1977). Lawrence Livermore Laboratory, Rept. UCRL-79193, Abstract (1977).

Nugget sandstone from Utah is 99 percent quartz with a density varying from 2.42 to 2.55 Mg/m³ (4.5 to 9.3 percent porosity). Plane shock wave experiments were performed on Nugget sandstone in the stress range between 0 and 9.0 GPa. The shock waves were produced by impact from 3-inch diameter flat, thick sandstone flyer plates which were accelerated by a 4-inch diameter gas gun. The targets were instrumented with electromagnetic particle velocity gages which were located on the impact surface and at three depths from the impact surface including the rear free surface. The Lagrangian particle velocity histories gave Hugoniot states behind the incident shock wave and stress-volume unloading paths through the rarefaction wave arising from the rear free surface. Unloading curves from the higher stress states indicate a permanent volume decrease while unloading from stress states below 1.6 PGa show little permanent volume change. A change in slope of the shock velocity-particle velocity ($U_s - u_p$) plot is observed in the vicinity of 1.5 GPa. It is suggested that this change in slope of the $U_s - u_p$ plot indicates the onset of pore collapse implying a matrix strength in the vicinity of 1.5 GPa.

Anderson, G. D., HANSON, M. E., Shaffer, R. J., Heard, H. C., and Montan, D. N., LLL Gas Stimulation Program, Quarterly Progress Report, January through March 1977, Lawrence Livermore Laboratory, Rept. 50036-77-1 (1977).

- Anderson, G. D., HANSON, M. E., Shaffer, R. J., Heard, H. C., Tonnessen, K. A., Montan, D. N., and Knutson, C. F., LLL Gas Stimulation Program, Quarterly Progress Report, April through June 1977, Lawrence Livermore Laboratory, Rept. UCRL-50036-77-2 (1977).
- Anderson, G. D., HANSON, M. E., Shaffer, R. J., Heard, H. C., and Emerson, D. O., LLL Gas Stimulation Program, Quarterly Progress Report, July through September 1977, Lawrence Livermore Laboratory, Rept. UCRL-50036-77-3 (1977).
- Anderson, G. D., HANSON, M. E., Shaffer, R. J., Hearst, J. R., Montan, D. N., Heard, H. C., and Emerson, D. O., Update on the LLL Gas Stimulation Program, Third Ann. ERDA Sympos. Enhanced Oil & Gas Recovery (Tulsa, Aug. 1977). Lawrence Livermore Laboratory, Rept. UCRL-79587 Preprint (1977).
- Beiriger, W. J., SCHWARTZ, L. L., Emerson, D. O., and Tewhey, J. D., The Importance of Geosciences in Developing In Situ Technologies for Energy Resource Recovery, presented at Amer. Assoc. Advanc. Sci. Annual Mtg. (Washington, D.C., Feb. 12-17, 1978). Lawrence Livermore Laboratory, Rept. UCRL-80218 Abstract (Oct. 1977).
- BONNER, B. P., Proposed Apparatus for Measuring Internal Friction in Rocks at High Temperatures and Pressures: A Design Analysis, Lawrence Livermore Laboratory, Rept. UCID-17589 (1977).

From many designs, we have selected an apparatus that measures internal friction in rocks at high temperatures ($\sim 800^{\circ}\text{C}$) and pressures (~ 1.0 GPa). Steady oscillations ($\sim 1.0\text{Hz}$) are induced in a jacketed sample while coaxial capacitive transducers monitor the resulting radial strain. Sample strains are continuously compared to the deformation of a low-loss standard, which acts as a stress transducer. The stress state produced is uniaxial stress. We use the theory of viscoelasticity to partition the loss into components depending on pure shear and dilatation. The theoretical results emphasize the importance of ultimately measuring each loss independently.

- Bonnier, B. P., DENGLER, L. A., Netherton, R., Piwinski A., and Trimmer, D. A., "Laboratory Investigations of Permeability Loss in Sedimentary Rocks," Trans. Am. Geophys. Union **58**, 539 (1977). Lawrence Livermore Laboratory, Rept. UCRL-79197 Abstract (1977).

BORG, I. Y., New Developments Affecting Supply of Oil to the Free World, Lawrence Livermore Laboratory, Rept. UCRL-52345 (1977).

The objective of this report is to update an earlier assessment of future world oil supply and demand. Recent exploration in Mexico and the North Sea indicates that these areas will contribute more to world supplies than anticipated; in the U.S., delayed leasing schedules and unsuccessful exploration in many areas on the outer continental shelf suggest a production potential below previous expectations; the fact that more and more OPEC nations are setting arbitrary production limits will also affect the future oil supply adversely; and early estimates of future Russian and Chinese exports seem now to have been overly optimistic.

In view of these and other new developments that affect worldwide demand for oil, world demand will probably exceed the supply by about 7 million bbl/day in 1990. Seasonal demands and growing markets for specific types of crude oil will create local shortages before that time. Thus, increasing prices and increasing competition for available supplies seem inevitable until syncrudes and other exotic energy sources become available in quantity.

BORG, I. Y., Use of Reserve/Resource Estimates by a National ERDA Laboratory, Symposium on Resource-Reserve Estimates, Fuel, and Energy Minerals (AAPG-SEPM Convention, Washington, D.C., Jun. 12-16, 1977). Lawrence Livermore Laboratory, Rept. UCRL-78689 Abstract (1977).

The 1973 embargo and subsequent price increases focused the attention of the nation and the national laboratories on reserve-resource data for energy fuels. Formation of ERDA emphasized the increased interest in long-range research and development (R&D) with the objective of developing novel energy sources.

Planning requires reconnaissance of the extent of this nation's reserves/resources, understanding of what these numbers mean, and a choice between the estimates available. The purpose is to recognize short supply, to estimate lead times available to develop alternative sources, and to indicate potential resources that require extensive, multidiscipline R&D efforts to develop.

The role of a national laboratory is to pursue long-range projects where initial investment of time and money may be unrealistic from industry's point of view. Nonetheless, industrial cooperation is vital to their success.

Before fruitful programs are selected, funded, and inaugurated, a new set of information pertaining to fossil reserves/resources is needed. Data tend to be specific and are usually difficult to garner from current sources such as API, AGA, NPC, or U.S. Geological Survey reports. They include information on attitude and thickness of continuous sections, e.g., of heavy-oil accumulations or oil shale; the data are crucial to the technology chosen for the development of the resource. The depth of the accumulations is pertinent as is location of the resource. Large accumulations in populated areas pose special problems as do diffuse resources spread over hundreds of square miles. There is no single recognized data bank containing information of this type. It is largely proprietary and uncollated. Increased cooperation between industry and government is needed in order to develop these novel fuels.

As a consequence of study and reviews at Lawrence Livermore Laboratory, large on-going programs have evolved. They deal with in-situ coal gasification and oil-shale retorting, laser enrichment of uranium, utilization of geothermal brines, and a transportation program designed to develop alternate automotive fuels (MeOH, MeOH-gasoline, lithium-air-water battery) and alternate/hybrid engines for them.

Borg, I. Y., RAMSEY, W. J., and Thornton, R. L., Institutional Constraints and the Potential for Oil Shale Development, Lawrence Livermore Laboratory, Rept. UCIR-1169 (Jun. 1977).

We have assessed the importance of, and institutional restraints on the development of an oil shale industry. It seems clear that foreseeable depletion of domestic and worldwide crude oil resources will require the development of alternative hydrocarbon sources. Among the potential domestic, unconventional sources of hydrocarbons, oil from oil shale is on the threshold of commercialization.

The constraints on the oil shale industry fall rather naturally into two classes. Near-term constraints inhibit the establishment of any oil

shale industry. The long-term constraints determine the ultimate size of a mature industry.

Inability to meet current environmental regulations and uncertainty with respect to profitability are the principal near-term constraints. We believe these will be overcome.

It is certain that water availability, both withdrawals and storage capacity, will be an important long-term constraint. Air and water pollution and population pressures will also be important.

While it is impossible to quantify rigorously these constraints, we estimate that a mature shale oil industry would produce 2.5 million bbl/day of oil in the most likely case. In the unlikely event that near-term constraints remain in effect, there will be no oil shale industry. In what we believe to be the most optimistic case, the industry might produce 6.5 million bbl/day. Major, favorable water policy decisions would have to be made, and other constraints resolved, for this latter case to occur.

BORG, I. Y., Stone, R., Levy, H. B., and Ramspott, L. D., "Movement of Radioactivity Deposited at the U.S. ERDA Nevada Test Site," Transactions and Proceedings of Transfer of Nuclear Technology Conference (Atomic Energy Organization of Iran, Apr. 10-14, 1977). Lawrence Livermore Laboratory, Rept. UCRL-78670 Abstract (1977).

A condensation of the recently completed investigation of the geological, hydrological, and radio-chemical features of the U.S. Energy Research and Development Administration (ERDA) Nevada Test Site (NTS), which bears on radionuclide migration, will be presented. This study, which expended five man-years, incorporates a critical evaluation of all data and previously related studies of NTS, and also reports recent attempts to measure migration of radioactivity in the groundwater from a completely characterized source term.

The experience at the U.S. ERDA NTS, which relates to the migration of radionuclides in the groundwater, has analog with potential movement of radionuclides at radio-active waste burial sites, or movement subsequent to accidental spills or leaks at reactor sites.

For almost twenty years, radionuclides have been deposited underground at NTS as a consequence of nuclear device testing. More than 300 tests have

been detonated underground and 78 have been either near or below the water table. Migration at the test site has been studied in some detail and continues to be monitored in an effort to quantify the important parameters governing the movement or lack thereof.

To date, no radioactivity has been detected beyond the bounds of the NTS nor within any of the approximately 32 water wells within or around the boundaries of the site. All water used at the site continued to come from wells not far from areas of active underground testing. An approximate cumulative inventory of radioactivity deposited at NTS through June 30, 1975 reveals that about 13 kg of tritium has been deposited. The following yields were recorded 180 days after the initial deposition: 1.8×10^8 Ci of fission products, 1.3×10^8 Ci of tritium, 4.8×10^4 Ci of ^{239}Pu , 1.6 Ci of ^{235}U , and 5.6×10^6 Ci of miscellaneous activation products. These values may be in considerable error, particularly in the case of ^{239}Pu and ^{235}U , since arbitrary estimates have been made of the initial amount as well as the amount consumed during the experiments. For simplicity, the radioactivity associated with each explosion is assumed to have been deposited at the same time.

Movement of radioactivity has been minimal at NTS and relates to the general phenomenology of nuclear explosions that results in the capture of most refractory fission products and unspent fuel in lithological glasses produced by the explosion and the forceful ejection of water from the immediate vicinity of the explosion. Return of the water into the rubblized site inaugurates leaching processes and consequent mobilization of nuclides. The slow to moderate movement of the groundwater in the aquifer within NTS, 2 to 80 m/yr depending on locale, has contributed to the slow movement of the tritium, the most mobile of the radionuclides. Sorptive processes are especially important in retarding nuclide movement at NTS. The altered tuffaceous rocks, which comprise a large portion of the saturated zone, are rich in zeolites (cinoptilolite) and clays (montmorillonite and illite), which effectively absorb many radionuclides moving through the formation.

Burg, I. Y., and RAMSPOTT, L. D., Underground Nuclear Tests Below the Water Table as Waste Disposal Pilot Plants, Geological Society of America Annual Meeting, Symposium on Hydrogeology of Radioactive Waste Disposal (Nov. 7-9, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79632 Abstract (1977).

BRAUN, R. L., and Chin, R. C. Y., "Computer Model for In Situ Oil Shale Retorting: Effects of Input-Gas Properties," in Proc. of the 10th Oil Shale Symp., (Golden, Colorado, Apr. 20-21, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79033 Preprint (Mar. 1977).

A one-dimensional mathematical model has been developed for simulating the chemico-physical processes involved in the concurrent, vertical retorting of a rubblized bed of oil shale. Both hot-gas retorting and combustion retorting can be simulated. The flow rate of the gas stream and the composition and temperature of both the gas stream and the shale particles are calculated as a function of time and location in the retort. The rates of recovery of oil and water from the retort are also computed.

The model is used to predict commercial in-situ retorting phenomena for typical conditions of shale composition, particle size, packing fraction, and input-gas properties. The predicted effects of input-gas properties (flow rate, temperature, and composition) are examined in detail here. The model indicates that a gas input of air diluted with steam or CO_2 is effective in controlling the temperature and maximizing the oil yield, without causing the large decrease in retorting rate associated with the use of a mixture of air and recycled gas. The air-stream mixture is also attractive because it yields a retort product gas with a higher heating value.

BRAUN, R. L., and Chin, R. C. Y., Progress Report on Computer Model for In-Situ Oil Shale Retorting, Lawrence Livermore Laboratory, Rept. UCRL-52292 (Jul. 1977).

A one-dimensional mathematical model has been developed for simulating the chemico-physical processes involved in the concurrent, vertical retorting of a rubblized bed of oil shale. Included in the present model are those processes believed to have the greatest effects in either the hot-gas retorting mode or the combustion retorting mode. The physical

processes are: axial convective transport of heat and mass caused by the bulk gas flow, axial conductive transport of heat, heat transfer between the gas stream and the shale particles, and water evaporation and condensation. The chemical reactions in the shale particles are: decomposition of kerogen and carbonate minerals, reaction of carbon with CO_2 and O_2 , thermal degradation of oil, release of fixed water. The chemical reactions in the gas stream are: combustion of CO produced from the reaction of carbon with CO_2 , combustion of the fuel components in recycle gas, and oil combustion.

The governing equations are solved numerically by a semi-implicit, finite-difference method. Gas stream flow rate as well as the composition and temperature of both the gas stream and the shale particles are calculated as a function of time and location in the retort. Recovery rates of oil and water from the retort are also computed.

Braun, R. L., and CHIN, R. C. Y., Computational Aspects of Chemically Reacting Porous Medium Flows, presented at Amer. Math. Soc. Meeting #751 (Calif. Poly. Inst., San Luis Obispo, California, Nov. 11-12, 1977). Lawrence Livermore Laboratory, Rept. UCRL-80082 Abstract (1977).

BROWN, P. S., Burton, D. E., Butkovich, T. R., Schatz, J. F., Snell, C. M., Calculational Modeling of Explosive Fracture in Natural Resource Formations, presented at Amer. Assoc. Advanc. Sci. Annual Mtg. (Washington, D.C., Feb. 12-17, 1978). Lawrence Livermore Laboratory, Rept. UCRL-80212 Abstract (Oct. 1977).

High explosives may be used to fracture geological formations containing recoverable resources. Often the goal is to enhance permeability and thereby facilitate in situ recovery. We desire to predict the extent of fracture and its effect on permeability. Fracture is caused by complex interactions between the generated stress waves and the rock media. Experiments by themselves do not provide much information about these interactions; hence, we use computational models as a tool to study in detail how wave interactions lead to fracture. We have developed 1-D and 2-D Lagrangian wave propagation codes that model the constitutive-failure behavior of geologic materials and use multi-dimensional graphics to display the complex wave effects. Fracture parameters calculated by the codes have been related to observed extent of fracture and enhanced permeability in two

underground experiments in coal. We are now working on improving our models to better quantify the relationship between observed enhanced permeability and calculated fracture. This will improve our ability to predict these quantities for any charge configuration, explosive, or medium.

BRYAN, J. B., Snell, C. M., Heusinkveld, M., Burton, D. E., Bruce, A. L., Lettis, L. A., Jr., and Butkovich, T. R., Controlled Blasting Calculations and Experiments, ANS Topical Meeting, Energy and Mineral Resource Recovery (Colorado School of Mines, Golden, Colorado, Apr. 12-14, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79109 Preprint (1977).

A cooperative controlled blasting program was conducted by the U.S. Army Engineer Waterways Experiment Station (WES) and the Lawrence Livermore Laboratory (LLL). The Explosive Excavation Division of WES executed the field experiments in a granodiorite medium on Wilson Mesa at the Naval Weapons Center, China Lake, California. In-situ measurements of ground motion and stress were made during these detonations, and WES is analyzing the ground motion data. The Earth Sciences Division of LLL assisted with experimental designs and is performing dynamic computer calculations to model the blasting experiments. This controlled blasting program has been sponsored by the National Science Foundation, the Office of the Chief of Engineers, and the U.S. Energy Research and Development Administration.

Field experiments were designed using long cylindrical charges of high explosive typical of conventional blasting applications and selected to have geometrical symmetry which could be calculated using the two-dimensional TENSOR computer code. Subsurface measurements of acceleration, particle velocity, and stress at several depths and distances were made by WES. One blasting experiment included both pre-shot and post-shot coring to establish the fracture zone produced by the explosion. Several different chemical explosives were utilized in the experiments. The Chemistry Department of LLL characterized these explosives with laboratory experiments so that the explosive source could be properly prescribed in the computer calculations.

Laboratory tests, field data, and computer calculations have been used to develop the constitutive parameters of the granodiorite for the calculations. Both one-dimensional SOC and two-dimensional TENSOR computer calculations are being performed to simulate the field tests. Calculated

ground motion and material damage parameters are compared with field observations. Preliminary results indicate the such calculations provide a useful tool in understanding explosive-rock interactions.

Bryan, J. B., BUTKOVICH, T. R., and Burton, D. E., Calculational Modeling of Explosive Fracture and Permeability Enhancement, ANS Topical Meeting, Energy and Mineral Resource Recovery (Colorado School of Mines, Golden, Colorado, Apr. 12-14, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79114 (1977).

Bryan, J. B., BURTON, D. E., Lettis, L. A., Jr., Butkovich, T. R., and Bruce, A. L., Anisotropic Creation and Closure of Tension Induced Fractures, ANS Topical Meeting, Energy and Mineral Resource Recovery (Colorado School of Mines, Golden, Colorado, Apr. 12-14, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79578 (1977).

Bryan, J. B., WALTON, O. R., Snell, C. M., Thomsen, J. M., and Goodrich, M., Effects of Porosity, Strength and Water Content on Attenuation of Stresses Generated by Subsurface Explosions in Soils, ANS Topical Meeting, Energy and Mineral Resource Recovery (Colorado School of Mines, Golden, Colorado, Apr. 12-14, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79113 (1977).

BURTON, D. E., Lettis, L. A., Jr., Bryan, J. B., Butkovich, T. R., and Bruce, A. L., Anisotropic Creation and Closure of Tension Induced Fractures, ANS Topical Meeting, Energy and Mineral Resource Recovery (Colorado School of Mines, Golden, Colorado, Apr. 12-14, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79578 (1977).

A material model is presented that simulates the anisotropic creation and closure of tension-induced fractures. The relationship of the model to explosive-enhanced permeability of geologic formations is discussed. The model is introduced into a two-dimensional, finite-difference computer code, and the tensile fracture effects produced by a long cylindrical explosive charge detonated beneath a free surface are calculated.

Burton, D. E., BROWN, P. S., Butkovich, T. R., Schatz, J. F., Snell, C. M., Calculational Modeling of Explosive Fracture in Natural Resource Formations, presented at Amer. Assoc. Advanc. Sci. Annual Mtg. (Washington, D.C., Feb. 12-17, 1978). Lawrence Livermore Laboratory, Rept. UCRL-80212 Abstract (Oct. 1977).

Burton, D. E., BRYAN, J. B., Snell, C. M., Heusinkveld, M., Bruce, A. L., Lettis, L. A., Jr., and Butkovich, T. R., Controlled Blasting Calculations and Experiments, ANS Topical Meeting, Energy and Mineral Resource Recovery (Colorado School of Mines, Golden, Colorado, Apr. 12-14, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79109 Preprint (1977).

Burton, D. E., BURKOVICH, T. R., and Bryan, J. B., Calculational Modeling of Explosive Fracture and Permeability Enhancement, ANS Topical Meeting, Energy and Mineral Resource Recovery (Colorado School of Mines, Golden, Colorado, Apr. 12-14, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79114 (1977).

Burton, D. E., TERHUNE, R. W., Glenn, H. D., McKague, H. L., and Rambo, J. T., Calculational Examination of the Baneberry Event, presented at American Geophysical Union Spring Meeting (Miami, Florida, Apr. 17-21, 1978). Lawrence Livermore Laboratory, Rept. UCRL-52365 (1977).

Burton, D. E., TERHUNE, R. W., Glenn, H. D., and Rambo, J. T., Containment Analysis for the Simultaneous Detonation of Two Nuclear Explosives, Lawrence Livermore Laboratory, Rept. UCRL-52268 (1977).

Burton, D. E., BUTKOVICH, T. R., and Bryan, J. B., Calculational Modeling of Explosive Fracture and Permeability Enhancement, ANS Topical Meeting, Energy and Mineral Resource Recovery (Colorado School of Mines, Golden, Colorado, Apr. 12-14, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79114 (1977).

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., BROWN, P. S., Burton, D. E., Schatz, J. F., and Snell, C. M., Calculational Modeling of Explosive Fracture in Natural Resource Formations, presented at Amer. Assoc. Advanc. Sci. Annual Mtg. (Washington, D.C., Feb. 12-17, 1978). Lawrence Livermore Laboratory, Rept. UCRL-80212 Abstract (Oct. 1977).

Butkovich, T. R., BURTON, D. E., Lettis, L. A., Jr., Bryan, J. B., and Bruce, A. L., Anisotropic Creation and Closure of Tension Induced Fractures, ANS Topical Meeting, Energy and Mineral Resource Recovery (Colorado School of Mines, Golden, Colorado, Apr. 12-14, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79578 (1977).

Butkovich, T. R., BRYAN, J. B., Snell, C. M., Heusinkveld, M., Burton, D. E., Bruce, A. L., and Lettis, L. A., Jr., Controlled Blasting Calculations and Experiments, ANS Topical Meeting, Energy and Mineral Resource Recovery (Colorado School of Mines, Golden, Colorado, Apr. 12-14, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79109 Preprint (1977).

CARLEY, J. F., "Modeling of Vertical Pressure Distribution in Large In-Situ Retorts," in Proceedings of 10th Oil Shale Symp. (Colorado School of Mines, Golden, Colorado, Apr. 21-22). Lawrence Livermore Laboratory, Rept. UCRL-79039 Preprint (1977).

Deformation of hot oil shale and its consequent permeability loss depends upon rock pressure. This pressure distribution in oil shale rubble columns is therefore important to modified in-situ oil extraction from oil shale. Pressure distribution in freshly developed columns of oil shale rubble has been modeled using the theory of bins. Dependence of vertical

pressure on column geometry and shale properties was examined. A major finding is that, at room temperature for a given geometry and properties, pressure approaches an asymptotic limit regardless of overburden forces.

The model has been extended to include variations in density and frictional properties of shale that accompany the temperature changes occurring during retorting and this expanded model has been programmed for the CDC 7600 computer. Parametric studies with this program point up the urgent need for data on the dependence of interparticle frictional properties on temperature and pressure.

Directions of further development and improvement of this modeling effort are discussed.

CARLEY, J. F., and Thigpen, L., Modeling of Vertical Pressure Distribution in Large In-Situ Retorts, presented at 10th Oil Shale Symp. (Colorado School of Mines, Golden, Colorado, Apr. 21-22, 1978). Lawrence Livermore Laboratory, Rept. UCRL-79039 (1977).

Deformation of hot oil shale and its consequent permeability loss depends upon rock pressure. This pressure distribution in oil shale rubble columns is therefore important to modified in-situ oil extraction from oil shale. Pressure distribution in freshly developed columns of oil shale rubble has been modeled using the theory of bins. Dependence of vertical pressure on column geometry and shale properties was examined. A major finding is that, at room temperature for a given geometry and properties, pressure approaches an asymptotic limit regardless of overburden forces.

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Directions of further development and improvement of this modeling effort are discussed.

Carlson, R. C., and HEARST, J. R., The Gravimetric Density Formula for a Spherical Shell, Short Note in Geophysics 42, 7 (Dec. 1977), 1469. Lawrence Livermore Laboratory, Rept. UCRL-79157 Preprint (Feb. 1977).

Carlson, R. C., and TERHUNE, R. W., Site Characterization Requirements for Nuclear-Cratering Design, Lawrence Livermore Laboratory, Rept. UCRL-52253 (Mar. 1977).

CHAN, M. A., and Tewhey, J. D., Subsurface Structure of the Southern Portion of the Salton Sea Geothermal Field, Lawrence Livermore Laboratory, Rept. UCRL-52354 (Nov. 1977).

Subsurface correlation of sedimentary strata has been attempted among ten geothermal wells in the southern portion of the Salton Sea Geothermal Field. The spontaneous potential (SP) log has been the principal tool used for correlation purposes. The structure that emerges from the correlation diagrams is a shallow plunging syncline with an east-west axis perpendicular to the axis of the Salton Trough.

Chan, M., NETHERTON, R., and Piwinski, A. J., "Viscosity of Brine From the Salton Sea Geothermal Field, California, from 25°C to 90°C at 100 kPa," Trans. Am. Geophys. Union **58**, 1248 (1977). Lawrence Livermore Laboratory, Rept. UCRL-80016 (Dec. 1977).

Chan, M., PIWINSKII, A. M., and Netherton, R., Viscosity of Brines From the Salton Sea Geothermal Field, Imperial Valley, California, Lawrence Livermore Laboratory, Rept. UCRL-52344 (1977).

CHIN, R. C. Y., and Braun, R. L., Computational Aspects of Chemically Reacting Porous Medium Flows, presented at Amer. Math. Soc. Meeting #751 (Calif. Poly. Inst., San Luis Obispo, California, Nov. 11-12, 1977). Lawrence Livermore Laboratory, Rept. UCRL-80082 Abstract (1977).

Energy resource recovery processes such as oil shale retorting and coal gasification belong to the class of chemically reacting porous medium flow problems. Inherent in the flow phenomena are disparate time scales of the physical and chemical processes. This gives rise to a set of differential equations which are stiff in the sense of Miranker in that a system of differential equations is stiff on some interval if there exists a component of the solution which has rapid variation within that interval.

The computational aspects of a porous flow past a reacting solid undergoing pyrolysis will be discussed. An algorithm is proposed using a

fixed step size commensurate with the smoothly varying component of the solution and yet calculates accurately the rapidly varying component.

CHIN, R. C. Y., and Hedstrom, G. W., A Dispersion Analysis for Difference Schemes: Tables of Generalized Airy Functions, submitted to Mathematics of Computations. Lawrence Livermore Laboratory, Rept. UCRL-78668, Rev. 1 Preprint (Dec. 1977).

This paper contains graphs and tables of the function

$$A_{i,p,q}(\alpha,x) = \int_{-\infty}^{\infty} (2\pi)^{-1} \exp \{ i y^p/p - \alpha y^q/q + i x y \} dy$$

and its indefinite integral for $p = 3, 5, 7$, for $q = 2, 4, 6$, and for several values of α with $\alpha \geq 0$. It is shown how these tables should influence the choice of an artificial viscosity for a difference scheme for a linear hyperbolic equation.

CHIN, R. C. Y., Hedstrom, G. W., and Karlsson, K. E., A Simplified Galerkin Method for Hyperbolic Equations, submitted to Mathematics of Computations. Lawrence Livermore Laboratory, Rept. UCRL-77313, Rev. 1 (1977).

We modify a Galerkin method for nonlinear hyperbolic equations so that it becomes a simpler method of lines. The high order of accuracy is preserved. We present a linear wave analysis of the scheme and discuss some aspects of nonlinear problems. Our numerical experiments indicate that the addition of a proper artificial viscosity makes the method competitive with the common difference schemes, even when the solution has discontinuities.

CHIN, R. C. Y., and Thigpen, L., Waves in Linear Viscoelastic Medium - Asymptotic Theory, submitted to Geophysical Journal. Lawrence Livermore Laboratory, Rept. UCRL-79234 (1977).

Uniformly valid asymptotic solutions are developed for the one-dimensional wave equation in a linear viscoelastic solid. In particular, the long time behavior for an impulse, a unit step function, and a harmonic oscillation as the source is investigated. The asymptotic solutions illustrate the effect of the dispersive-attenuation process. Results show

a small amplitude precursor, a diffusive main wave, and a boundary layer. The precursor propagates at a speed corresponding to the instantaneous modulus and decays exponentially distance. The main wave travels at a speed corresponding to the equilibrium modulus and spreads diffusively. The approximating equations using perturbation methods reveals that the decay of the precursor is due to relaxation processes and the diffusive behavior is a result of cumulative dispersion.

Chin, R. C. Y., and BRAUN, R. L., "Computer Model for In-Situ Oil Shale Retorting: Effects of Input-Gas Properties," in Proc. of the 10th Oil Shale Symp. (Golden, Colorado, Apr. 20-21, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79033 Preprint (Mar. 1977).

Chin, R. C. Y., and BRAUN, R. L., "Numerical Model for Modified In-Situ Oil Shale Retorting," presented at 1977 Oil Shale Symp. (Golden, Colorado, Apr. 21-22), Lawrence Livermore Laboratory, Rept. UCRL-79033 Abstract (1977).

Chin, R. C. Y., and BRAUN, R. L., Progress Report on Computer Model for In-Situ Oil Shale Retorting, Lawrence Livermore Laboratory, Rept. UCRL-52292 (Jul. 1977).

CHUNG, D. H., Elasticity of Stishovite Revisited, presented at 6th Intl. Conf. on High Pressure (Boulder, Colorado, Jul. 1977). Lawrence Livermore Laboratory, Rept. UCRL-79058 Preprint (1977).

New elastic moduli for stishovite, which result from the self-consistent approximation based on an experimental study of AgCl-stishovite mixtures, are presented. This information is used to construct the solid equations of state of stishovite on the basis of phenomenological laws of the velocity-density-mean atomic weight relation and recent static and dynamic shock-compression data. A new interpretation of the composition of the earth's lower mantle is made. The author concludes that: (1) the bulk modulus of stishovite is indeed in the neighborhood of 3 Mb, consistent with the author's 1973-74 value ($K_s = 2.93 \pm 0.15$ Mb based on the VRH approximation scheme), and these values are in good agreement with recent static compression measurements of Olinger ($K = 2.88 \pm 0.13$ Mb) and Sato ($K = 2.98 \pm 0.05$ Mb if $K' = 0.7$, and $K = 2.81 \pm 0.02$ Mb if $K' = 5.00$); (2) the

bulk modulus of a "post-stishovite" material with an orthorhombic structure and a density of 4.435 gm/cm^3 can be estimated at $3.7 \pm 0.2 \text{ Mb}$ on the basis of the universal velocity-density relationship; and finally, (3) the periclase-wustite-post stishovite mixture with either olivine or pyroxene stoichiometry in the earth's lower mantle has seismic parameter and density values that are consistent with Birch's earth model.

CHUNG, D. H., "How is P_n Velocity Affected by Partial Melting?" Trans. Am. Geophys. Union 58, ⁿ439 (1977). Lawrence Livermore Laboratory, UCRL-79178, Abstract (1977).

The observed P_n velocity anomalies in the conterminous United States are restricted to the lithosphere, but the observed teleseismic delay-time variations are due principally to the regional variations in the physical state (thickness of low velocity zone and/or precent melt, etc.) of the asthenosphere. The observed low P_n velocity in such tectonically unstable mantle regions as the Basin & Range Province and the East Pacific Rise has been attributed to partial melting in the upper mantle, but it is shown here that the partial melting model alone cannot explain the seismologically observed low P_n velocities. I begin my analysis with the assumption that the observed low P_n velocities ($\sim 7.80 \text{ km/sec}$) in the western conterminous U.S. as compared to those of the eastern conterminous U.S. ($\sim 8.10 \text{ km/sec}$) are due entirely to the effect of partial melting. Partial melting in rock takes place along grain boundaries, and the molten component can be considered to be in the form of a thin film of liquid (geometrically resembling liquid-filled flat, penny-shaped crack). Various theories of the composite elasticity could apply to these observations. Among these theories, I use the Garbin-Knopoff theory for my illustration. Starting with 8.10 and 4.70 km/sec for α_0 and β_0 , respectively, for the shields, and the measured β_0 , respectively, for the shields, and the measured $\beta_1 = 4.59 \text{ km/sec}$, I find $\alpha_{1/3} = 8.02 \text{ km/sec}$ and the crack density parameter $(Nc/V) = 0.05$. This α_1 corresponds to a P_n velocity of 8.06 km/sec ; negligibly different from my original value of 8.10 km/sec . Evidently the partial melting alone cannot explain the seismologically observed low P_n velocities in such anomalous regions as the Basin and

Range Province, the Hoggar area, the Baikal Lake area, and the East Pacific Rise to name a few.

CHUNG, D. H., "LVZ, Partial Melting, and Chemical Changes in Tectonically Unstable Regions: The Basin & Range Province," Geol. Soc. Am. Abstr. with Programs 9(7), 928-929 (1977). Lawrence Livermore Laboratory, Rept. UCRL-80015, Abstract (1977).

Such technologically unstable regions as the Basin and Range Province and the East Pacific Rise, to name a few, are seismologically anomalous and they are characterized by low P_n velocities, distinctive travel-time and amplitude anomalies, and high attenuation of the seismic waves. The presence of a low velocity zone (LVZ) is now well recognized. Four possible mechanisms for the development of the LVZ with its apparent reduction in seismic wave velocities have been produced: (1) the predominance of the temperature effect over the pressure effect, (2) partial melting, (3) enrichment of iron, and/or (4) changes in the chemical and mineral composition of rock. A systematic study on the basis of the shield, tectonic, and oceanic geotherm models for various eclogite and peridotite upper mantles indicates that a change in chemical and mineralogical composition is necessary, in addition to partial melting, to account for the differences in P_n velocity between the Basin and Range Province and adjacent parts of North America. The LVZ under the Basin and Range Province is probably caused by downward chemical transition from the sub-Moho pyroclitic mantle material into a plagioclase-rich ophiolitic composition (old oceanic crust and upper mantle materials) and associated melting, and then into a peridotitic composition at the bottom of the LVZ. Any models of the upper mantle composition of this region must consider the effect of the vast amount of material subducted during the consumption of the offshore oceanic plates to the west over the last billion years or so, during which time most of this region was formed as a series of island arc - marginal basin episodes.

CHUNG, D. H., On the Geophysical and Geochemical Models of the Earth's Shields and Rift Zones, Lawrence Livermore Laboratory, Rept. UCRL-52238 (1977).

This report summarizes a collection of, synthesis of, and speculation on, the geophysical and geochemical models of the Earth's stable shields and rift zones. There are two basic crustal types, continental and oceanic, and two basic mantle types, stable and unstable. The crustal types are distinguished by their thickness of crust, and the two mantle types are distinguished by their stability and upper mantle velocities and travel-time residuals. The stable mantle is characterized by relatively high P_n and S_n velocities and the frequent absence of geophysical evidences for low velocity zone and the unstable mantle by low P_n and S_n velocities and a pronounced low velocity zone in the upper mantle. Both the crust and upper mantle play a strongly interactive role with surface geological phenomena ranging from the occurrence of mountains, ocean trenches, oceanic and continental rifts to geographic distributions of earthquakes, faults, and volcanoes. On the composition of the mantle, there is little doubt regarding the view that olivine constitutes a major fraction of the mineralogy of the Earth's upper mantle. To simulate the elasticity and composition of the Earth's lower crust and upper mantle, a systematic study of the elasticity and equation-of-state properties of such materials as peridotites, eclogites, pyroxenites, amphibolites, and various gabbros and basalts is needed. Also needed are measurements of attenuation of acoustic waves at seismic frequencies in these solids and partially molten peridotites and in olivine single-crystals, because such data are necessary to determine the nature of phenomena responsible for the existence of a low velocity zone in the upper mantle.

CHUNG, D. H., Phase Changes in the Earth's Mantle, Seminar (Univ. of Calif., Davis, Feb. 2, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79059 Abstract (1977).

The earth's mantle is divided into three major regions on the basis of the seismic velocity-depth distributions. In the upper mantle (first 30 to 400 km depth), velocity gradients are generally small, except in the vicinity of the low-velocity zone. In the transition zone (next 400 to 1100 km depth), velocity gradients are high on the average; most of the velocity increase in this region is concentrated in three distinctively narrow zones

around 400, 650, and 1050 km depth. The velocity gradients in these zones are so high that they often represent major seismic velocity discontinuities in the earth's mantle. Below 1050 km and extending down to the outer core boundary at about 2900 km lies the lower mantle, and this region of the earth is seismologically characterized by velocity gradients that are relatively small and uniform. In this talk, I propose to discuss some recent progress in research made in the effort to better understand these regions of the earth's interior with particular emphasis on the composition and physical properties of the mineral phases which are brought to be stable in the various regions of the mantle. Additional possible effects of phase changes in the dynamics of the earth's interior shall be discussed.

CHUNG, D. H., "P Velocity and Partial Melting--Discussion," Tectonophysics 42, T35-T42ⁿ(1977). Lawrence Livermore Laboratory, UCRL-78924 Preprint (1977).

The seismologically observed P_n velocity anomalies in the conterminous United States are restricted to the lithosphere, but the observed teleseismic delay-time variations are due principally to the regional variations in the physical state (i.e., thickness of low-velocity zone and/or percent melt, etc.) of the asthenosphere. The observed low P_n velocity has been attributed to partial melting in the upper mantle, but it is shown that the partial-melting model alone cannot explain the seismologically observed P_n velocities in such an anomalous region as the Basin and Range Province. The present structure of the Basin and Range Province is possibly a result of rifting in the western conterminous United States; under it there may lie a mixed structure of old crust and mantle materials. The low-velocity zone under the Basin and Range Province would then be caused by downward chemical transition from the sub-Moho pyroclitic mantle material into a plagioclase-rich ophiolitic (old oceanic crust and upper mantle) composition and associated melting and then into a peridotitic composition at the bottom of the low-velocity zone. This mixed material model, with partial melting, would explain the low P_n velocity and low seismic Q in the region, as well as other geophysical observations.

CHUNG, D. H., Time-Dependent Elastic Moduli of Stishovite. Is It Real?
Presentation, M.I.T. (Cambridge, June 7, 1977). Lawrence Livermore
Laboratory, Rept. UCRL-79180 Abstract (1977).

The belief that stishovite is a mineral present in the earth's mantle as a separate phase makes this material rather important in geophysics. Speculations and experiments on the elasticity and equation-of-state properties of stishovite abound, supported sometimes by assumptions of sufficient flexibility to accommodate any postulate. The value of K , for example, ranges from 7.14 to 2.5 Mb, and yet the elasticity of the earth's mantle has been worked out by some authors. Since the discovery of stishovite in 1960, the K value of this material has been estimated to be 4.35 Mb in 1963, 3.922 Mb in 1968, 3.659 Mb ($K' = 3.03$) in 1969, 3.37 Mb ($K' = 5$) in 1970, 3.0 Mb ($K' = 7$) in 1970, 3.546 Mb ($K' = 3.12$) in 1971, 3.43 Mb in 1972, 4.1 Mb ($K' = 3.4$) in 1973, 2.93 Mb in 1974, 2.88 Mb and 2.5 Mb in 1976, where (K') as indicated was assumed to find the K . A perusal of the literature reporting these values indicates that there is a time-dependent variation of K , i.e., 7.14 Mb in 1967, 3.43 in 1972, 2.93 in 1974, and 2.88 and 2.5 in 1976! Is it real? I present here a view that the observed spread in values of K is an artifice arising from two main difficulties: One, it is still a difficult task to produce stishovite in sufficient quantity and sinter it into a dense form without converting back to a low-pressure phase (or, the present state of crystal growth technology at high pressure and temperature cannot provide single-crystals large enough to make the acoustic measurements) and two, there are still well-known problems with measurement of acoustic velocities in small samples under pressure. The author then presents his prejudice that the VRH-based value of 2.93 (± 0.15) Mb is probably the right K for this material. Support to this conjecture comes not only from recent compression measurements, but also from use of the more rigorous composite theories like DGK's Self-Consistent Approximation, Kroner's average, and the Hashin-Shtrikman mean.

Chung, D. H., and GUBERNATIS, J. E., "Self-Consistent Approximation Applied to High-Pressure Phases," Trans. Am. Geophys. Union 58, 492 (1977). Lawrence Livermore Laboratory, UCRL-79179 Abstract (1977).

We calculate the effective elastic moduli of various high-pressure phases (hpp) using a self-consistent integral equation technique developed in the Doman-Gubernatis-Krumhansl (DGK) paper. Elastic moduli of the spinel phase of Fe_2SiO_4 , Fe_2GeO_4 , and Mg_2GeO_4 , and SiO_2 -stishovite, based on ultrasonic velocity measurements of AgCl -(hpp) composites, are found by use of the DGK method, the Kroner average, and the Hashin-Shtrikman (HS) mean and they are as follows:

	$\text{Mg}_2\text{GeO}_4(s)$	$\text{Fe}_2\text{GeO}_4(s)$	$\text{Fe}_2\text{SiO}_4(s)$	$\text{SiO}_2(r)$
ρ	41374	5.542	4.849	4.287
K_s (in Mb):				
DGK	1.79	1.64	2.10	2.82
Kroner	1.79	1.65	2.15	2.84
HS	1.90	1.71	2.25	3.19
VRH	1.89	1.78	2.05	2.93
μ (in Mb):				
DGK	0.83	0.57	0.66	1.27
Kroner	0.82	0.57	0.66	1.25
HS	0.99	0.64	0.76	1.67
VRH	1.03	0.73	0.81	1.69

For comparison, the published values based on the Voigt-Reuss-Hill (VRH) Approximation are included in the table above. The elastic constants of the matrix material (AgCl) and hpp material are very dissimilar. (The bulk modulus K_s of $\text{SiO}_2(r)$ is about 8 times that of AgCl , but the spreads among the elastic moduli resulting from different theories and that from VRH values are small for both μ and K_s . In fact, these spreads are much smaller than the apparent spreads among the measured moduli for these hpp materials by different investigators.

COHEN, J. J., Risk Assessment and Radioactive Waste Management, Lawrence Livermore Laboratory, Rept. UCRL-79293, (Aug. 1977).

Problems with radioactive waste management, both technological and administrative, have become a serious constraint in the development of nuclear power. An approach toward understanding these problems consists of

placing them in a perspective where the risks of radioactive waste management might be evaluated in relation to similar problems facing society so that consistent judgments can be made. RISK-COST-BENEFIT calculations are applied to problems of radwaste management in order to obtain a perspective on these problems for purposes of decision analysis.

Cohen, J. J., and KING, W. C., Interim Report to NRC on Radioactive Waste Classification, Lawrence Livermore Laboratory, Rept. UCID-17497 (Apr., 1977).

This report reviews the LLL effort to date in the development of a meaningful radioactive waste classification system. A three class system is proposed consisting of high, low, and nonwaste classes. A methodology for determination of interface levels for the waste classes is proposed.

Cohen, J. J., and TONNESSEN, K. A., Survey on Naturally Occurring Hazardous Materials in Deep Geologic Formations: A Perspective on the Relative Hazard of Deep Burial of Nuclear Wastes, Lawrence Livermore Laboratory, Rept. UCRL-52199 (Jan. 1977).

COSTANTINO, M. S., Recent Progress in High Pressure Research at Low Temperatures, invited lecture (Arizona State University, Tempe, Jan. 1977). Lawrence Livermore Laboratory, Rept. UCRL-79001 Abstract (1977).

A review of recent experimental advances in high pressure research at low and ultra-low temperatures will concentrate on equation-of-state measurements in hydrogen, nitrogen, and methane, and on molecular spectroscopy. Techniques and results for high-pressure superconductivity measurements will be mentioned briefly. Areas of current interest include a harmonic interaction in the simple rare gas solids and angle dependent potentials in molecular crystals. Several new and interesting techniques will be discussed.

COSTANTINO, M. S., Statistical Variation in Stress-Volumetric Strain Behavior of Westerly Granite, Lawrence Livermore Laboratory, Rept. UCRL-79422 Preprint (1977).

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

COSTANTINO, M. S., and Schock, R. N., An Empirical Relation for Dilatant Behavior in Brittle Rocks, Sixth Int. High Pressure Conf. (AIRAPT, Boulder, Colorado, Jul. 1977). Lawrence Livermore Laboratory, Rept. UCRL-79011 Preprint (1977).

We have developed a constitutive relation for stress-volume strain states in brittle, low porosity rocks under uniaxial compressive stress. Our analysis of laboratory data for a quartz sandstone, a granodiorite, and a granite yields the relation $\epsilon_v^e = a_0 + a_1\tau + b_0 \exp(b_1\tau)$ that fits volume strain to within 1% for stresses up to near the failure stress. The "excess volume strain," ϵ_v^e , is the difference between the volume strains under hydrostatic and nonhydrostatic loading conditions at the same mean stress, and τ is the shear stress. The fitting parameters a_i , b_i depend on the confining pressure, stress history, and sample microstructure.

The observed dilatant strain behavior can be explained by assuming two mechanisms of crack response. At low shear stresses, the linear deviation ($a_0 + a_1\tau$) from the hydrostat is due to the well-known elastic response of cracks to nonhydrostatic loading. Flat cracks with significant projections of their major axis perpendicular to the direction of the maximum principal stress σ_1 close at lower mean stresses than cracks with other orientations. Because these closed cracks no longer contribute to the volume strain, the mean stress-volume strain ratio $(\bar{\sigma}/d\varepsilon_v)$ increases relative to the hydrostat. At large shear stresses, favorably oriented cracks propagate with an increase in volume strain that is proportional to the existing volume strain $d\varepsilon_v/d\tau \propto \varepsilon_v$ so that $\varepsilon_v \propto \exp(b_1\tau)$. Crack growth continues until failure.

The fitting parameters a_1 and b_1 have not been correlated as yet with any measurable variables and, therefore, cannot be predicted. Nevertheless, the fact that dilatancy in three dissimilar rocks can be described so well by a single, simple relation suggests that the physics of dilatancy is dominated by two mechanisms, an elastic response of the crack distribution to stress and the propagation of existing cracks.

COSTANTINO, M. S. and Schock, R. N., An Empirical Relation for Dilatant Strain in Low Porosity Rock (Am. Nucl. Soc., Topical Mtg. (Golden, Colorado, Apr. 1977). Lawrence Livermore Laboratory, Rept. UCRL-79355, Abstract (1977).

Static stress-volume strain data from laboratory experiments on a granite, a granodiorite, and a sandstone undergoing uniaxial compression have been analyzed using curve fitting techniques. All three rocks are strong, brittle, and show no shear stress enhanced compaction. A single, simple relation

$$\varepsilon_v^d = a_0 + a_1\tau + b_0 \exp(b_1\tau)$$

is used to fit volume strain-shear stress data within 1% up to 90% of the failure stress. ε_v^d , the dilatant volume strain, is the difference in volume strains at a given mean stress under hydrostatic and nonhydrostatic loading conditions, τ is the shear stress, and the a_1 , b_1 are fitting parameters. The dilatant strain may be modeled as linear elastic crack closure at small τ that becomes dominated by crack propagation at large

t. This empirical relation should be useful in prediction of response of rocks to stress waves.

Crow, N. B. and KASAMEYER, P. W., Baseline Measurements of Geologic Events can Remove Potential Roadblocks to Geothermal Development, (presented at Amer. Assoc. Advanc. Sci., Annual Mtg., Washington, D.C., Feb. 12-17, 1978). Lawrence Livermore Laboratory, Rept. UCRL-80213 Abstract (Oct. 1977).

Cunningham, M. E., BRYAN, J. B., Burton, D. E. and Lettis, Jr., L.A., A Two-Dimensional Computer Simulation of Hypervelocity Impact Cratering: Some Preliminary Results for Meteor Crater, Arizona, Lawrence Livermore Laboratory, Rept. UCRL-80539 Abstract (1977).

DENGLER, L.A., Microcracks and Matrix Deformation in Stressed Gas-Bearing Sandstones, to be presented at Ann. Scanning Electron Microscope Sympos. (Los Angeles, Apr. 1978). Lawrence Livermore Laboratory, Rept. UCRL-80328 Abstract (1977).

The matrix structure in sandstones plays an important role in determining the quality of a natural gas reservoir. Graywacke sandstones from the Mesa Verde formation in northwest Colorado have low permeability values due to the presence of authigenic sheet silicates filling the available pore space. The Rio Blanco nuclear gas stimulation experiment in 1972 attempted to enhance permeability by explosively fracturing this reservoir rock.

The most direct way to assess the effect of stress on pore and crack structure is by scanning electron microscopy (SEM). This report presents SEM results of undeformed, laboratory and nuclear explosively-deformed Mesa Verde graywackes utilizing a relatively new method of sample preparation.

Tensional fracture surfaces have been used in the past to examine microporosity and authigenic clay structure. This method is most useful to study details of matrix morphology. However, it is difficult both to orient a fracture surface relative to fixed coordinate axes (such as principal stress directions) and quantitatively describe the observed structure. Ion milling of thick polished sections can, in part, solve both of these problems. This method of surface preparation involves polishing one side of a relatively thick slab of rock (up to 5 mm) and the removal of 10-30 μm of material by the mechanical abrasion of highly energetic argon ions. Ion

milling was originally used to prepare ultra-thin sections for transmission electron microscopy (TEM) and was first applied to SEM to look at micro-cavities in crystalline rock. It is quite effective in preserving both grain and pore structure in sedimentary rocks as long as the beam currents are kept low. Typical milling conditions used were 5 kV accelerating voltage, 10 μ A current, 20° tilt relative to the gun, and 10 hours milling time. Under these conditions, 10-20 μ m of material was removed during thinning.

In the undeformed rock, an intricate network of authigenic chlorite and kaolinite between grains causes the average pore size to be small. Chlorite platelets are typically oriented in random directions. Kaolinite crystals are stacked in extensive book structures, typically 10-20 μ m in length.

Uniaxial strain testing causes plastic deformation of chlorite platelets, with both elongation and bending observed. Increased axial loading causes pronounced preferential orientation of platelets perpendicular to the direction of applied stress. Kaolinite deformation is restricted to separation and tilting along cleavage directions with no plastic deformation observable.

Nuclear explosively-deformed samples were recovered from the site of the Rio Blanco gas stimulation experiment and were located about 55 meters away from the bottom shot point. These samples contained long macroscopic fractures oriented perpendicular to the shock-front direction. In the vicinity of these fractures, chlorite deformation was similar to that observed in the laboratory-tested samples. Away from these areas, the sample appeared unstressed. Kaolinite deformation was slight, limited to toppling of the book structure and to separation of individual crystals.

DENGLER, L. A., Microstructure of Laboratory and Nuclear Explosively Deformed Gas-Bearing Sandstones, Sixth Int. High Pressure Conf. (AIRAPT, Boulder, Colorado, Jul. 1977) Lawrence Livermore Laboratory, Rept. UCRL-79021 Preprint (1977).

Pore structure and microfracturing is investigated in low permeability sandstones. An intricate network of clay minerals between grains causes the average pore size to be small in the undeformed rock. Laboratory testing causes sample compaction and short, unconnected cracks within grains.

Explosive deformation causes occasional narrow transgranular cracks. In both, the clay matrix exhibits compaction parallel to the direction of maximum principal stress.

DENGLER, L. A., Bonner, B. P., Netherton, R., Piwinski, A. J. and Trimmer, D. A., "Laboratory Investigations of Permeability Loss in Sedimentary Rocks," Trans. Am. Geophys. Union 58, 539 (1977). Lawrence Livermore Laboratory, Rept. UCRL-79197 Abstract (1977) .

Loss of formation permeability and porosity can occur by mechanical or chemical plugging of pores in reservoir rocks. We have begun an investigation of the mechanical plugging in sedimentary media at ambient temperatures due to injection of Salton Sea geothermal brine containing suspended solids. Our experiments have been performed on 100-mm-long, 25.4-mm-diameter right-circular cylinders of sandstone. Flow rates in St. Peter sandstone are reduced approximately 80% after the passage of 1500 pore volumes of brine through the sample. We have characterized the permeability loss by scanning electron microscopy (SEM), x-ray diffraction (XRD), optical microscopy (OM), and ultrasonic velocity (USV) techniques. SEM studies reveal that all available pore space is filled with fine-grained colloidal material, approximately 1 μm in diameter. XRD analyses of these deposits show that they are mostly amorphous, with only a small halite peak visible. Chemical analyses of the suspended solids in the reinjected brine indicate that silicon and iron are the main elements. The plugged specimens of the St. Peter sandstone show smaller P-wave velocities than untested samples saturated with brine. Much of this decrease can be explained by the density increase due to pore plugging. These results also imply a slight reduction in the elastic moduli of the sandstone matrix.

DENGLER, L. A. and Sprunt, E. S., "Cathodoluminescence of Some Quartzites from the Bergell Alps," Trans. Am. Geophys. Union 58, 1239 (1977). Lawrence Livermore Laboratory, Rept. UCRL-79959 Abstract (1977) .

Quartzites from the Bergell Alps are a sequence of deformed rocks whose metamorphic grade and dislocation structure are known from mineral assemblages and transmission electron microscopy studies (Liddell et al., 1976*). It is an ideal sequence to examine the color dependence of quartz

cathodoluminescence on temperature of deformation. The metamorphic facies of the samples studied varied from low greenschist to high amphibolite, with corresponding microstructures representative of cold working, recovery, and complete recrystallization. Quartz luminescence was uniform throughout a given sample. The nine samples we examined fell into three groups on the basis of color of luminescence. Group 1 samples luminesce a dull rusty red. Their microstructures are typical of cold-worked deformation with high dislocation densities and dense dislocation tangles. This microstructure is similar to that produced in laboratory experiments at 500 to 600°C. Samples in group 2, which luminesce a bluish-red, are recrystallized with low dislocation densities characteristic of hot working. Group 3 samples were from granite contacts, presumably a high-temperature environment. Their luminescence was bluer than group 2 samples. The observed change from red to blue in these three groups may be temperature related with low temperatures and mechanical deformation favoring red luminescence and high temperatures favoring blue.

DENGLER, L., Hoenig, G., Holt, A., Finger, M. and Kuhl, W., Hydrodynamic Modeling and Explosive Compaction of Ceramics, Sixth Int. Conf. High Energy Rate Fabrication (Essen, W. Germany, Sept. 1977). Lawrence Livermore Laboratory, Rept. UCRL-79345 Preprint (1977).

High-density ceramics with high-strength microstructure have been achieved by explosive compaction. Well characterized Al_2O_3 , AlN, and boron powders were explosively compacted in both cylindrical and flat-plate geometries. In cylindrical geometries we achieved compacted densities between 91 and 98% of theoretical. Microhardness measurements indicated that the strength and integrity of the microstructure was comparable to conventionally fabricated ceramics even though all samples with densities >90% theoretical contained macrocracks. Fractured surfaces evaluated by SEM showed evidence of boundary melting.

Equation-of-state data for porous Al_2O_3 were used to calculate the irreversible work done on the sample as a function of pressure. This was expressed as a percentage of the total sample which could be melted. Calculations show that very little melting can be expected in samples shocked to less than 3 GPa. Significant melting and grain boundary fusion can be expected in samples shocked to pressures >8 GPa.

Hydrodynamic modeling of right cylinder compaction with detonation at one end was attempted using a two-dimensional computer code. The complications of this analysis led to experiments using plane shock waves. Flat plate compaction assemblies were designed and analyzed by 2-D hydrodynamic codes. The use of porous shock attenuators was evaluated. Experiments were performed on aluminum oxide powders in plane wave geometry. Microstructure evaluations were made as a function of location in the flat plate samples.

Dengler, L. A. and SPRUNT, E. S., "Effects of Metamorphism on Quartz Cathodoluminescence," *Geol. Soc. Am. Abstr. with Programs* 9, 1138 (1977). Lawrence Livermore Laboratory, Rept. UCRL-80024 Abstract (1977) .

The cathodoluminescence of quartzites from the Johnson Spring Formation in Inyo County, California was studied to examine the relationship between luminescence and metamorphic grade. The Johnson Spring quartzites are a clean, Middle Ordovician equivalent to the widespread Eureka Quartzite Formation. These quartzites have been extensively faulted and intruded by three Jurassic plutons. Metamorphic grade varies from slightly altered through mechanically deformed to completely annealed near the plutons. The luminescence of the detrital quartz grains in the least deformed samples was heterogeneous, varying from dull red to blue. In contrast, quartz grains in the cold worked, mechanically deformed samples (schistose detrital grains, highly undulatory extinction, deformation lamellae, and polygonization at grain boundaries) luminesced a uniform rusty red throughout. There was no difference in the color of luminescence between the detrital grains and the new polygonal grains. The thermally deformed samples (totally recrystallized, exaggerated grain growth) luminesced a blue-violet. In the Johnson Spring Formation both mechanical and thermal deformation homogenizes cathodoluminescence in the sample as a whole. The color of this luminescence appears to be dependent upon the temperature of deformation and hence may be a valuable metamorphic indicator.

Dengler, L., PIWINSKII, A. J., Netherton, R. and Trimmer, D. A., "Injection Studies: Section 5.5.1 Results; Section 5.5.2 Failure Modes; Section

5.5.3 Field Experiments," in The LLL Geothermal Energy Program Status Report January 1976-January 1977, Lawrence Livermore Laboratory, Rept. UCRL-50046-76, A. L. Austin, A. W. Lundberg, L. B. Owen, G. E. Tardiff, Eds., p. 167-169 (Apr. 1977).

DENNY, M. D., The Installation of Horizontal Seismometers in the LLL Seismic Net and Their Calibration, Lawrence Livermore Laboratory, Rept. UCRL-52216 (January 1977).

We have upgraded the Lawrence Livermore Laboratory seismic net by installing two horizontal seismometers at each of the four LLL stations. These seismometers record radial and transverse ground motion from underground nuclear explosions at the Nevada Test Site and complement the vertical components which were installed several years ago. Each station now monitors three orthogonal components of ground velocity over a broad frequency band.

DUBA, A. G., "Electrical Conductivity of Coal and Coal Char, " Fuel 56 (1977) 441-443. Lawrence Livermore Laboratory, Rept. UCRL-78648 Preprint (1977) .

The electrical conductivity of coal, at either 1 kHz or d.c., was measured at 24°C on samples recovered from pyrolysis experiments aimed at modeling conditions during in situ gasification of coal. From an initial value of 10^{-3} S/m (when the coal is saturated with formation water), the conductivity decreases to 10^{-8} S/m when the coal is heated to 110°C in vacuum. This low value, presumably due to dehydration of the coal, prevails for samples heated as high as 500°C in dry argon. Samples of char recovered after pyrolysis to 800°C or more have a conductivity of 10^2 S/m. Capitalizing on the large contrast between the conductivities of coal and char produced during gasification, electrical probing may be a sensitive tool for monitoring "burn-front" progress during in situ coal gasification.

DUBA, A., Rock Properties Related to Assessment Methods, EPRI Geothermal Prog. Progress Rept. and Workshop (Kah-nee-ta, Oregon, Jul. 1977). Lawrence Livermore Laboratory, Rept. UCRL-79813 Summary (1977).

In order to interpret the data obtained from field geophysics measurements as well as well-logging tools which exist or may be developed for geothermal wells, laboratory data under relevant conditions must be available. Since the conditions of the laboratory measurement must closely simulate the reservoir environment, parameters which should be considered independent variables in relevant experiments include, but may not be limited to, rock type, mineralogy, structural state (cementation, fracturing, etc.), temperature, confining pressure, pore pressure, and pore-saturant chemistry. Correct interpretation of field data should provide information on the heat and fluid conductivity and capacity of the reservoir. The ideal situation would be one which provided spatial resolution of these properties in three dimensions.

Laboratory measurement of physical properties at the relevant conditions for a given reservoir should allow interpretation of routine and specialized field measurements. In order for these experiments to be useful, however, samples must be carefully characterized as to pore structure, chemistry and phase relationships before and after laboratory experiments are performed. Most meaningful physical property measurements need to be supported by petrographic studies including optical and scanning electron microscopy, chemical characterization by the electron microprobe, and definition of pore structure.

Laboratory measurements of physical properties of rocks under conditions which are relevant to most geothermal reservoirs are either sparse or nonexistent at present. The situation for electrical properties typifies the problem.

Some data do exist and are useful to gain "first cut" answers to questions concerning permeability, heat capacity, thermal diffusivity, and porosity. However, very few of the results summarized can be applied directly to a particular geothermal system. No complete data set in which pressure, temperature, and pore fluid composition and pressure are varied is available. One has to rely on extrapolation and analogy to get an estimate of the value of a parameter in a geothermal log. And when large expenditures of time and dollars depend on the proper interpretation of such logs, extrapolation and analogy will not suffice.

V_p , V_s and compressibility have been measured to about 100 MPa and 200°C on sandstones and siltstones, some of which were saturated with a KCl brine. In addition, the thermal conductivity at 133°C and 3 MPa confining pressure has also been determined on some of these rocks. Electrical conductivity to 200°C and an effective stress of about 7 MPa has been measured on shaly sandstones as a function of brine composition.

However, these studies have limited application to geothermal well-log and field survey interpretations. The paramount shortcoming is that the rock types studied have been limited to petroleum reservoir rocks. Igneous and metamorphic rocks have been studied over a much more limited range of pressure-temperature-saturant chemistry. Another shortcoming is the lack of simultaneous measurement of several physical properties on the same core. Cycling the sample in laboratory experiments produced changes in crack structure so that sequential information is unreliable for correlating changes in different physical properties when stress or temperature is cycled. Such correlations are essential if information on the permeability, porosity, or salinity of a geothermal reservoir is to be inferred from sonic and resistivity logs.

Laboratory data on the variation of the physical properties of reservoir constituents as a function of pressure, temperature, and saturant salinity would be invaluable in the interpretation of field measurements. If such data were available, we would be able to interpret geophysical data in terms of parameters the reservoir engineer needs to know -- the permeability and available porosity of the reservoir. In addition, these data could be useful for designing and interpreting monitoring tools to detect changes in reservoir properties during production. This information would be vital if reservoir stimulation schemes are evolved and employed in geothermal systems.

Specific measurements which need to be performed on typical reservoir rocks as a function of temperature, pressure, pore pressure, structural state of the rock, and pore fluid composition include, but should not be limited to:

- Ultrasonic velocities.
- Electrical conductivity.

- Permeability.
- Compressibility.
- Thermal conductivity.
- Heat capacity.
- Thermal expansion.

Simultaneous measurement of several properties and for various durations would be useful.

DUBA, A., Heard, H. C., Piwinski, A. J. and Schock, R. N., Geothermal Prospecting and the Electrical Conductivity Changes Associated with Melting, Panel Mtg. Expl. Meth. of Dry Hot Rock (Los Alamos, Jun. 1976). Los Alamos Scientific Laboratory, Rept. LA-6659-MS (1977), pp. 35-37. Lawrence Livermore Laboratory, Rept. UCRL-78261 Abstract (1977) .

The relevance of electrical conductivity surveys as an exploratory tool for partial melt zones within the Earth's crust and mantle is discussed using results from σ measurements prior to and during partial fusion, under controlled oxygen fugacity, of basalt and the plagioclase feldspar, albite. Field measurements of electrical conductivity anomalies have often been cited as evidence for the existence of melt at depth. Laboratory data on the large σ increase associated with melting of albite or basalt and granite, which contain plagioclase feldspar (albite is the sodium-end member of the solid solution series) as a major component, are listed as justification for this interpretation.

The σ of single-crystal albite measured at temperatures below melting as a function of time is compared with the σ of powdered albite measured upon melting. Data clearly show that the σ increases subsolidus, given sufficient time, to account for all the increase observed upon melting.

The σ measured at temperatures below melting and upon partial fusion of basalt under controlled oxygen fugacity is a complicated function of temperature, time, and oxygen fugacity. Generally, the σ decreases with time below approximately 900°C if oxygen fugacity is near the quartz-fayalite-magnetite buffer. Above 900°C, the σ increases with time for all oxygen fugacities studied. The σ change partial fusion ($T \approx 1050^\circ\text{C}$) is dependent upon the time the sample resided at temperatures below the beginning of melting.

Since the σ as a function of time for this basalt at three different oxygen fugacities at 1050°C behaves similarly to that of the albite, we suggest that the σ increase is related to disorder in the plagioclase rather than to partial melting. By analogy, we suggest that granite would behave similarly, if equilibrium were attained.

This argument suggests that field measurements cannot reliably distinguish between partial melt and a solid of similar composition, but slightly below the solidus. The situation is changed, however, if we assume a melt of basaltic composition present in a rock in which σ measured for olivines and pyroxenes under controlled fugacity as the most likely for the host rock, a σ contrast of two to four orders of magnitude would be observed between a zone where the σ is dominated by partial melt and one where the σ is controlled by either olivine or pyroxene.

DUBA, A., Heard, H. C., Schock, R. N. and Chakrabarty, M. R., "The Electrical Conductivity Tensor of Olivine under Controlled Oxygen Fugacity," Trans. Am. Geophys. Union 58, 1235-1236 (1977). Lawrence Livermore Laboratory, Rept. UCRL-80023 Abstract (1977).

The electrical conductivity tensor (σ) of olivine single crystals from San Carlos, Arizona, has been determined to about 2000 K as a function of oxygen fugacity controlled within the olivine stability field. At a given oxygen fugacity, $\Delta \log \sigma$ among the three principal directions is less than 0.2. This small difference in $\bar{\sigma}$ indicates that mantle anisotropy will not exert a significant influence on σ -T inversions. The temperature calculated using these results with available field data is in good agreement at 200 km with that inferred from the "pyroxene geotherm."

DUBA, A. G. and Ho, P. S., The Electrical Conductivity of Kemmerer Coal, Lawrence Livermore Laboratory, Rept. UCRL-52227 (1977).

To aid in the design of monitoring techniques for in situ coal gasification, we measured the electrical conductivity (σ) of coal that was saturated with tap water and 1-M-NaCl solution. Measurement as a function of time during drying in air and resaturation with tap water indicate an increase in σ presumably due to crack growth during drying. The σ

increases sharply upon saturation with salt solution and then increases more gradually as a function of time up to 96 hr. The laboratory data show that in coal is a function of the amount and conductivity of saturant present in the interconnected porosity.

Duba, A. and HORNADY, B., Earth Sciences Division, Annual Report--1976, Lawrence Livermore Laboratory, Rept. UCID-17476-76 (1977).

This compilation lists abstracts of papers, internal reports, and talks presented during 1976 at national and international meetings by members of the Earth Sciences Division, Lawrence Livermore Laboratory. A subject index is included.

DUBA, A. and Lytle, R. J., Use of Electrical Techniques to Monitor In Situ Processes, Am. Asso. Advanc. Sci. Ann. Mtg. (Washington, D.C., Feb. 1978). Lawrence Livermore Laboratory, Rept. UCRL-80211 Abstract (1977).

Measurement of electrical transmission, especially at high frequency (10^5 to 10^8 Hz), has a demonstrated potential for monitoring processes such as in situ coal gasification, oil shale retorting, and solution mining. Large changes in the electrical properties of coal and oil shale occur as the result of laboratory retorting. These studies also indicate that electrical measurements may be used to monitor fluid flow. Field measurements have detected the progress of the retort zone during in situ coal gasification and have been used also to follow the paths of injected fluids in coal seams. Between boreholes about 100 m apart, uncertainties in location of zones of interest may be as small as 0.5 m.

DUBA, A., Lytle, R. J. and Laine, E. F., Electrical Experiments Related to Monitoring In Situ Coal Gasification, Third Ann. Coal Conversion Sympos. (So. Tahoe, California, Jun. 1977). Lawrence Livermore Laboratory, Rept. UCRL-79265 Abstract (1977).

Laboratory and field investigations of the electrical properties of coal, its pore saturants, and pyrolysis products indicate that high-frequency electromagnetic studies are powerful tools for studying subsurface

phenomena. Laboratory and field studies of coal in the pre- and post-fractured state in saturants such as low and high conductivity groundwater and various NaCl solutions provide promising methods for locating fractures and studying local fluid flow phenomena. Laboratory and field studies of coal and its pyrolysis products have observed a large change in the electrical properties of coal during pyrolysis. This change may be used to delineate the reaction front during in situ gasification. The accuracy with which the location of the reaction zone or water velocity may be determined depends on hole spacing, frequency employed, and size of the anomaly.

DUBA, A., Piwinski, A. J., Santor, M. L. and Weed, H. C., The Electrical Conductivity of Sandstone, Limestone, and Granite, Lawrence Livermore Laboratory, Rept. UCRL-77314 Preprint (1977).

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

Duba, A. G., SHANKLAND, T. J. and Nitsan, U., "Radiative Heat Transfer in the Mineral Olivine: Effects of Optical Absorption, Refractive Index, Scattering, Temperature and f_{02} ," Trans. Am. Geophys. Union 58, 492-493 (1977). Los Alamos Scientific Laboratory, Rept. LA-UR 77-1374 (1977). Lawrence Livermore Laboratory, Rept. UCRL-79498 Abstract (1977) .

The effective radiative heat transfer conductivity of olivine ($(\text{Mg}_{.9}\text{Fe}_{.1})_2\text{SiO}_4$) has been calculated using optical absorption measurements on single and polycrystalline specimens at temperatures to 1400°C and under controlled oxygen fugacity (f_{O_2}), well within the stability field of the samples. The wavelength range was 0.3 to 8 micrometers (μm), completely spanning the "window" region of 1.5 to 4 μm . The transmission of the polycrystalline samples decreased substantially with heating due to scattering at air-crystal interfaces created by differential thermal expansion. Under mantle conditions, however, the most important scattering, that at grain boundaries, is shown to be strongly forward-directed and therefore to contribute negligibly to the opacity compared to absorption. Lack of knowledge of the temperature and wavelength dependence of the refractive index of olivine introduces a measurable uncertainty in the calculated values of K_r , but our results are in overall agreement with earlier measurements. The f_{O_2} near the center of the stability field of the samples decreased the opacity from that observed in natural crystals before heating, but the measurements were reproducible after temperature cycling.

Despite the fact that the calculated K_r is proportional to T^3 where T is absolute temperature, K_r increases gently from near zero at 300 K to about $5.10^{-3} \text{ cal cm}^{-1} \text{ s}^{-1} \text{ K}^{-1}$ ($2 \text{ W m}^{-1} \text{ K}^{-1}$) at 1700 K. The strong explicit temperature dependence is offset by a marked decrease of the photon mean free path as temperature rises.

Duba, A. and HEARD, H. C., "Stress, Strain, and Temperature Induced Permeability Changes in Potential Repository Rocks," National Waste Terminal Storage Program Conference on Waste Rock Interactions Y/OWI/SUB-77/14268 (Pennsylvania State Univ., University Park, 1977), pp. 43-44. Lawrence Livermore Laboratory, Rept. UCRL-79667 Abstract (1977) .

Duba, A., PIWINSKII, A. J. and Ho, P., "The Electrical Conductivity of Low and High Albite Throughout Its Melting Interval at 100 kPa," Canadian Mineralogist 15, 196-197 (1977). Lawrence Livermore Laboratory, Rept. UCRL-78777 Abstract (1977) .

- Duba, A. G., SCHOCK, R. N., Heard, H. C. and Stromberg, H. D., "The Electrical Conductivity of Polycrystalline Olivine and Pyroxene under Pressure," in High-Pressure Research, Applications in Geophysics, M. H. Manghnani and S. Akimoto, Eds. (Academic Press, New York, 1977), pp. 39-51. Lawrence Livermore Laboratory, Rept. UCRL-78048 Preprint (1977)
- Durham, W. B., SWIFT, R. P., Schatz, J. F., Hearst, J. R. and Kusubov, A., Effect of Simultaneous and Sequential Detonation on Explosive-Induced Fracture Nineteenth U.S. Sympos. Rock Mech. (Lake Tahoe, Nevada, May 1978) Lawrence Livermore Laboratory, Rept. UCRL-80390 Abstract (1977).
- Emerson, D. O., HANSON, M. E., Shaffer, R. J., Anderson, G. D., Heard, H. C., Knutson, C. and Haimson, B., LLL Gas Stimulation Program, Quarterly Progress Report, July through September 1977, Lawrence Livermore Laboratory, Rept. UCRL-50036-77-3 (Oct. 1977).
- Emerson, D. O., HANSON, M. E., Shaffer, R. J., Hearst, J. R., Anderson, G. D., Montan, D. N. and Heard, H. C., Update on the LLL Gas Stimulation Program, submitted to 3rd Ann. ERDA Symp. on Enhanced Oil and Gas Recovery (Tulsa, Oklahoma, Aug. 30-Sept. 1, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79587 Preprint (Jul. 1977).
- Emerson, D. O., SCHWARTZ, L. L., Tewhey, J. D. and Beiriger, W. J., The Importance of Geosciences in Developing In Situ Technologies for Energy Resource Recovery, (presented at Amer. Assoc. Advanc. Sci. Annual Mtg., Washington, D.C., Feb. 12-17, 1978). Lawrence Livermore Laboratory, Rept. UCRL-80218 Abstract (Oct. 1977).
- Ganow, H. C., GREENLAW, R. C., and Langland, R. T., Subsidence and Stability Studies for Underground Coal Gasification, Lawrence Livermore Laboratory, Rept. UCID-17674 (Oct. 1977).

By excavating roof elements in a tensile state of stress, we have improved the nonlinear finite-element techniques previously used for predicting subsidence at the Hoe Creek underground coal gasification site. To supplement the finite element approach, we have applied some elasticity solutions to the problem in a nondimensional parametric formulation. The elastic solutions indicate the extent of the induced tensile zone in a roof, and we have used this zone to predict the arch height in an underground cavity. The arch heights found by this method compare favorably with those found by the finite element method with extraction of roof elements.

Finally, we have conducted a series of laboratory core tests to determine material properties of Hoe Creek rock samples to provide better data both for future subsidence studies and for calibration of predicted subsidence with field measurements during and after coal gasification experiments.

Glenn, H. D., and TERHUNE, R. W., Estimate of Earth Media Shear Strength at the Nevada Test Site, Lawrence Livermore Laboratory, Rept. UCRL-52358 (Nov. 1977).

Glenn, H. D. and TERHUNE, R. W., Estimate of Residual Shear Strength Around Explosive Sources in Earth Media, to be presented at 19th Symposium on Rock Mechanics (Stateline, Nevada, May 1-3, 1978). Lawrence Livermore, Laboratory, Rept. UCRL-80393 Abstract (1977).

Glenn, H. D., TERHUNE, R. W., Burton, D. E., McKague, H. L. and Rambo, J. T., Calculation Examination of the Baneberry Event, to be presented at American Geophysical Union Spring Meeting (Miami, Florida, Apr. 17-21, 1978). Lawrence Livermore Laboratory, Rept. UCRL-52365 (1977).

Glenn, H. D., TERHUNE, R. W., Burton, D. E. and Rambo, J. T., Containment Analysis for the Simultaneous Detonation of Two Nuclear Explosives, Lawrence Livermore Laboratory, Rept. UCRL-52268 (1977).

GROTHAUS, B. and Howard, N., Correlation of Alluvial Deposits at the Nevada Test Site, Lawrence Livermore Laboratory, Rept. UCRL-52335 (Sept. 1977).

Because characteristics of rock layers and problems in drilling must be studied before radioactive waste can be safely contained, an evaluation was made of methods for correlating alluvial deposits at Yucca Flat of the Nevada Test Site (NTS). Although correlation of Tertiary volcanic tuff beds at the NTS has been successfully achieved, correlation of stratigraphic zones in the overlying alluvium has posed technical difficulties. We have evaluated several methods of correlating alluvial deposits from drillholes, including electric resistivity logs (E logs), visual examination of sidewall samples and comparison of their carbonate (CO_2) content, downhole stereo photography for identifying debris flow deposits, caliche age-dating, and specific yield and permeability measurements of deposits. For predicting the thickness of zones having similar physical properties in the alluvium, E log measurement were found to be the most useful of these methods.

HANSON, M. E., Stimulation of the Tight Western Gas Reservoirs, Lawrence Livermore Laboratory, Rept. UCID-17369 (Jan. 1977).

Hydraulic fracturing and high-explosive stimulation are the two principal methods that have been used to stimulate production of oil and gas reservoirs in the United States. Since the late 1940s, hydraulic fracturing has become the primary well-completion and cleanup method used in this country. The use of high explosives to increase production has declined, but still remains a viable method for reservoirs in which permeability is primarily fracture controlled. In these cases, the effective diameter of the explosive cavity has to be of the order of the primary fracture spacing. Nuclear explosives have also been tried in tight western reservoirs, but with varying results.

HANSON, M. E., Heard, H. C., Hearst, J. R. and Shaffer, R. J., LLL Gas Stimulation Program, Quarterly Progress Report, October through December 1976, Lawrence Livermore Laboratory, Rept. UCRL-50036-76-4 (Feb. 1977).

In this quarter, we continued work on the elastic/porous flow model for simulating the hydraulic fracturing process; the early forms of the model were applied in analyzing the effects of some aspects of the strain and stress field resulting from a pressurized hydraulic fracture. In addition, using cores from a well drilled recently in West Virginia, we measured the low- and medium-stress mechanical properties of Devonian shales. These data will be used as input to theoretical models designed to analyze various stimulation processes. Finally, sonic-log data taken in a West Virginia Devonian shale well were analyzed.

HANSON, M. E., McKee, C. R. and Terhune, R. W., Explosive Enhancement of Permeability, presented at Sixth AIRAPT Intl. High Pressure Conf. (Univ. of Colorado, Boulder, Colorado, Jul. 25-29, 1977). Lawrence Livermore Laboratory, Rept. UCRL-78207 Rev. 1 (May 1977).

Relationships describing the permeability enhancement caused by explosive detonations in boreholes have been derived and combined to yield

$$k = k_c \left(\frac{r_d^{-3f-3}}{r_d^{-f-m} + n_o/n_c} \right)^2 + k_o ,$$

for the case in which the stress decays asymptotically as a power law; k_c and n_c represent permeability and fracture density at the edge of the pulverized region near the cavity wall; f is a geometric attenuation factor; m is the dissipation due to real material effects; k_o is the original permeability, n_o the initial fracture density, and r_d the scaled radius. This relationship has been compared with available measurements from the American "Hardhat" nuclear shot, the French nuclear events in Hoggar granite, and a chemical explosive shot in coal near Kemmerer, Wyoming. Significant correlation between theory and experimental measurements is observed. A comparison between single and multiple detonations shows that permeability enhancement falls off steeply near the shot; however, enhancement can be considered midway between two shots spaced 10 cavity radii apart. The degree to which enhancement can be significant depends on material properties and initial fracture density. Porosity distribution from the explosive is the dominant parameter in permeability enhancement.

HANSON, M. E., Shaffer, R. J., Anderson, G. D., Heard, H. C. and Montan, D. N., LLL Gas Stimulation Program, Quarterly Progress Report, January through March 1977, Lawrence Livermore Laboratory, Rept. UCRL-50036-77-1 (May 1977).

During this quarter, we have further developed our elastic/porous-flow model for simulating the hydraulic fracturing process. The elastic parts of the model have been used to analyze surface deformations and some aspects of the stress/strain field resulting from a hydraulic fracture. We have explored various iteration schemes for solving the elastic parts of the problem more quickly. The incomplete Cholesley-conjugate gradient method has proved considerably faster than a point iteration scheme, although it requires more computer memory. The model in its present state includes coupling between the stress field and the pore pressure (as described by Terzaghi equations). Crack permeability is defined as a function of aperture.

Another ongoing project is our study of the medium-stress mechanical properties of Devonian shale cores from West Virginia. This work must be completed before we can hope to calculate the effects of hydraulic fracturing with any degree of precision.

We are analyzing the Rio Blanco, nuclear, gas-stimulation experiments with a view to interpreting important reservoir parameters. We have also begun laboratory hydraulic fracturing experiments.

HANSON, M. E., Shaffer, R. J., Anderson, G. D., Heard, H. C., Tonnessen, K. A., Montan, D. N. and Knutson, C. F., LLL Gas Stimulation Program, Quarterly Progress Report, April through June 1977, Lawrence Livermore Laboratory, Rept. UCRL-50036-77-2 (Aug. 1977).

This report summarizes the research and accomplishments of the LLL Gas Stimulation Program during the third quarter of fiscal year 1977. Work has continued on two models that stimulate, respectively, the local and distant effects of the hydraulic fracturing process. We have performed laboratory hydraulic fracturing experiments that indicate that precracks in the borehole and external stresses affect the fracture orientation and fracture initiation pressure considerably. We are studying the depositional environment of "Western tight gas sands" and are attempting to correlate sand characteristics with the genesis of the rock containing the gas. Parametric theoretical reservoir analyses have been performed to determine the effects of fracture conductivity on production in a large, tight, gas reservoir. These analyses indicate that productivity decreases significantly with a decrease in fracture conductivity. We have also completed environmental assessments for several ERDA-sponsored, field gas-stimulation experiments.

HANSON, M. E., Shaffer, R. J., Anderson, G. D., Heard, H. C., Emerson, D. O., Knutson, C. and Haimson, B., LLL Gas Stimulation Program, Quarterly Progress Report, July through September 1977, Lawrence Livermore Laboratory, Rept. UCRL-50036-77-3 (Oct. 1977).

This report summarizes the research and accomplishments of the LLL Gas Stimulation Program during the third quarter of FY 1977. Work has continued on the two theoretical models that stimulate, respectively, the local and

distance effects of the hydraulic fracturing process. Application and analysis have indicated that, for a penetrating fluid, the stress intensity factor tends to decrease as the pore pressure increases. Laboratory fracturing experiments indicate that for no precrack in the borehole, the hydraulic fluid pressure necessary to initiate a crack is relatively insensitive to the applied load on the block. Other laboratory experiments have been performed to test the sensitivity of the principal stress magnitudes on the fracture orientation. We have also completed a rock geometry and mechanics study of the Western tight gas sands. A summary of this study is included here and is being published under separate cover.

HANSON, M. E., Shaffer, R. J., Hearst, J. R., Anderson, G. D., Montan, D. N., Heard, H. C. and Emerson, D. O., Update on the LLL Gas Stimulation Program, submitted to 3rd Ann. ERDA Symp. on Enhanced Oil and Gas Recovery (Tulsa, Okla., Aug. 30-Sept. 1, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79587 Preprint (Jul. 1977).

This report discusses the progress and current state of the Lawrence Livermore Laboratory research program on stimulation of tight gas reservoirs. The program is primarily theoretical modeling and laboratory experimental; however, the application and interpretation of geophysical logging is an essential part of it. In their current state of development, the theoretical hydraulic-fracturing models show that, as pore pressure increases, the matrix stress around a fracture becomes more tensile. Laboratory experiments, which use unconfined specimens, show that both the characteristics of a layer and the mechanical properties of the adjacent materials control some long-sweep acoustic-velocity logs. Preliminary analysis of these logs indicates gas-producing fractures intersecting the well bore. The logs also indicate that other fractures either are nonproductive or do not intersect the well bore. Mechanical measurements of the Devonian shale indicate fairly uniform mechanical characteristics; however, a degree of mechanical anisotropy was noted for sections oriented horizontally or vertically with respect to the shale structure. Reservoir analyses of the Rio Blanco nuclear stimulation experiment and the nearby massive hydraulic fracturing (MHF) experiment indicate that characteristic lens dimensions were 40 to 60 ft (12 to 18 m) vertically and 400 to 600 ft (120 to 180 m) horizontally.

HEARD, H. C., Prediction of the Closure Behavior of Terminal Radioactive Waste Storage Vaults in Salt Bodies at Depth, invited lecture, Rockstore Conf. (Stockholm, Sept. 1977); invited lecture Kavernen-Bau Betriebs (Hannover, Sept. 1977). Lawrence Livermore Laboratory, Rept UCRL-79976 Abstract (1977).

The flow law governing steady-state behavior of polycrystalline salt has been determined on artificial aggregates deformed in the laboratory at temperatures ranging from 23⁰-400⁰C, stresses from 500 to 16 bars, and strain rates of 10⁻¹ to 10⁻⁸ s⁻¹. At stresses greater than about 150 bars, the deformation mechanism responsible for steady-state flow is dislocation glide (slip). All data are well fit by $\log \dot{\epsilon} = 4.5(+0.3) - 26.0(+1.1)/2.3 RT + \sigma/46.9(+1.5)$ where $\dot{\epsilon}$ is the steady-state strain rate (s⁻¹), R is the gas constant, T is temperature (K), and σ is stress (bars). The stated uncertainties are reported at the one standard deviation level. At all lower stresses, the data are well correlated to $\log \dot{\epsilon} = -5.6(+0.4) = 23.5(+0.9)/2.3 RT + 5.5(+0.2) \log \sigma$ where the operative mechanism is dislocation glide and climb (polygonization). These results have been correlated with observations of flow in naturally occurring salt bodies (e.g., Zechstein salt, North Germany). Prediction of the steady-state flow behavior of natural salt on the basis of these laboratory measurements on artificial salt aggregates yields results that agree well within the uncertainties of the above flow equations. For example, steady-state room closure rates of $7-9 \times 10^{-12}$ s⁻¹ are observed at the 700 mm level of the Asse #2 mine (Wolfenbützel, North Germany) where temperatures are 30⁰C and lithostatic stresses are about 150 bars. When this range of strain rates and temperature for the Asse #2 mine are used together with the observed steady-state flow equation for slip to calculate the closure stress, the resulting values are 145-153 bars, depending upon the initial values of rate.

On the basis of these laboratory-determined flow laws, closure rates for opening in natural salt in this region are both stress- and temperature-dependent; thus, the duration of operation of vaults used for terminal radioactive waste storage may be accurately predicted. For example, at an ambient temperature of 30⁰C with no emplaced wastes, vaults at 600-800 m will remain open for 2500 to 1000 years, depending on depth. With

emplacement of hot wastes, if the surrounding temperatures in the salt rise to 50°C at those depths, vault closure occurs at 220 to 70 years. At 100°C, closure could occur over durations as short as 1.6 to 0.3 years.

Heard, H. C., BARBER, D. J., Paterson, M. S. and Wenk, H. -R., "Stacking Faults in Dolomite," *Nature* 269, 789-790 (1977). Lawrence Livermore Laboratory, Rept. UCRL-79979 Preprint (1977) .

Dolomite, an important rock-forming mineral, is a mixed carbonate possessing trigonal symmetry ($R\bar{3}$), with alternate layers of Mg and Ca atoms separated by planes containing the carbonate groups. Its ordered structure offers the possibility of extended planar faults of low energy and Barber¹ has shown evidence for stacking disorder in dolomite of high metamorphic grade. There is no previous evidence, however, for the creation of extended faults as a direct result of deformation processes. We have prepared single crystals, approximately 25 mm in cross section and 10 mm long, and tested them in compression at temperatures up to 800°C while subjected to a confining pressure of either 3 or 7 kbar. Specimens were mostly oriented to give a large resolved shear stress on the basal planes while minimising the stress for mechanical twinning on the $f \equiv \{0112\}$ planes. (We use four-digit indices for planes and directions referred to the structural hexagonal unit cell, with $c = 16.01$ Å and $a = 4.81$ Å.) It has been shown (optically) that slip on (0001) and twinning on $\{0112\}$ are common modes of deformation on dolomite. Using TEM methods, Barber has shown that slip on $\{0112\}$ can also occur in dolomite. The current observations were also made by high voltage transmission electron microscopy, using sections which were thinned first mechanically and then by ion bombardment.

The extended planar faults are generated by slip on the basal planes and when viewed with the electron beam aligned parallel to a $\langle 2110 \rangle$ direction, they are visible edge-on as very fine lines of low contrast. They are thus easily distinguishable from long screw-type basal dislocations which are profuse in most samples. By tilting a foil of known orientation, (2110), through a measured angle about the (0110) zone axis (the line of intersection of a fault with the foil plane) and knowing the foil thickness, the fault plane has been shown to be unequivocally (0001). Local specimen

thickness was determined easily because of the pressure of small cleavage cracks on $\{1014\}$.

Although observations were taken at 1,000 kV and dolomite is elastically anisotropic, the clarity of contrast changes strongly suggests that we can calculate the displacement vector R in the usual manner, taking $g \cdot R = n$, where n must be zero or an integer for zero contrast with a given reciprocal lattice vector g . Using the above data, this gives as a likely value for R the vector $1/3 \ 1100$, which is not a proper translation vector of the dolomite structure. As might be anticipated, the vector lies in the basal plane and, for example, when applied to a magnesium atom, translates it at 30° to the normal $(\bar{1}2\bar{1}0)$ slip vector to a position directly above a calcium atom. This creates a stacking fault in the structure (not an antiphase boundary): the stacking fault is removed with a further displacement of $1/3 \ 0110$, giving

$$1/3 \ (\bar{1}100) + 1/3 \ (01\bar{1}0) = 1/3 \ (\bar{1}2\bar{1}0).$$

which is the normal slip vector of length $4.81 \text{ \AA}$. This reaction, of course, identifies the observed partial dislocations. We have found that such stacking faults occur extensively in dolomite crystals compressed at temperatures of $300\text{--}500^\circ\text{C}$.

We have also observed that faint fringe contrast is sometimes created by the passage of dislocations on the $\{0112\}$ slip planes. We have failed, however, to find a diffraction vector which brings the fringes into strong contrast and the fringes do not always terminate at dislocations but sometimes extend throughout the active part of the slip plane. It thus seems that the faint fringes, which indicate residual elastic strain, may be associated with a small fractional displacement vector, as occurs in orthopyroxene.

Evidence for stacking faults generated by slip in carbonates is new and it further emphasises the differences in mechanical behavior between dolomite and calcite. Until the work of Turner and Orozco on metamorphic calcite there was no firm evidence for basal slip in calcite, although it is the favoured low-temperature mechanism in dolomite. Braillon and Serughetti have reported small (0001) planar faults in calcite but have attributed them to growth twinning. Our results, which demonstrate the existence of extensive stacking faults in dolomite, together with partial dislocations, are therefore novel and important.

HEARD, H. C. and Duba, A., "Stress, Strain and Temperature Induced Permeability Changes in Potential Repository Rocks," National Waste Terminal Storage Program Conference on Waste Rock Interactions Y/OWI/SUB-77/14268 (Pennsylvania State University, University Park, 1977), pp. 43-44. Lawrence Livermore Laboratory, Rept. UCRL-79667 Abstract (1977) .

Terminal storage of high-level radioactive wastes requires placement of the solidified materials in a stable environment devoid of circulating groundwater. This implies initially that the potential repository rock is of low permeability and that subsequent to excavation of the vault, this permeability will not increase excessively. It also implies that the thermal field resulting from the emplaced waste canisters will not lead to structural problems or larger permeability increases with time. The goal of this work is to assess the permeability characteristics of coarse-grained igneous rocks as affected by pressure, deviatoric stress, and temperature.

In order to predict the long-term behavior of these rocks, both virgin and fractured, we are measuring the permeability and all principal strains resulting from an imposed deviatoric stress under various simulated lithostatic pressures. In addition, we are evaluating compressional as well as shear velocities and electrical conductivity along these principal directions. These simultaneous measurements are being made initially at 25°C on a 15-cm-diameter by 30-cm-long sample in a pressure apparatus controlled by a mini-computer. Correlation of these data with similar field observations should then allow simplified exploration for a suitable repository site as well as the prediction of the response of a mined cavity with both distance and time at this site.

After emplacement of the waste canisters, the mechanical stability and hydrologic integrity of this mined repository will be directly influenced by the fracturing of the surrounding rock, which results from local temperature differences and the thermal expansion of that rock. Temperatures (and, hence, these differences) in the vicinity of the repository are expected to be affected by the presence of pore fluids (single- or two-phase) in the rock, the heat capacity, and the thermal conductivity of this system. In turn, these are all dependent upon lithostatic pressure, pore pressure, and stress. Thermal expansion (and fracturing) will also be affected by the lithostatic (and effective) pressure, the deviatoric stress field, and the

initial anisotropy of the rock. We will outline the laboratory program for the determination of heat capacity, thermal conductivity, and thermal expansions under pressure for a broad spectrum of potential repository rock types.

HEARD, H. C., Wenk, H. -R. and Barber, D. H., "Experimental Deformation of Dolomite Single Crystals to 800°C," Trans. Am. Geophys. Union 58, 1238-1239 (1977). Lawrence Livermore Laboratory, Rept. UCRL-80017 Abstract (1977) .

The stress-strain behavior of oriented single crystals of dolomite has been determined at 0.7-0.8 GPa (7-8 kb) and 25° to 800°C. Two orientations were deformed, the first to favor (0001) = c slip and the second to favor twinning on {0221} = f.

For the first orientation and below 500°C, HVEM studies show slip predominates and is concentrated in broad zones with a high density of screw dislocations parallel to (2110) = a. In petrographic thin sections, these slip zones are associated with intense localized fracturing. HVEM studies reveal presence of c stacking faults with a displacement vector $R = 1/3$ (0110) indicating that average slip in the a direction can take place by movement of partial dislocations. Critical resolved shear stresses for c slip increase monotonically from 77 MPa at 25°C to 130 MPa at 500°C. At 300°-500°C, prismatic kink bands are observed and minor f slip also occurs. At 500°-800°C, c slip is accompanied by increasing f slip. Resolved shear stress increases more slowly at these temperatures; at 800°C it becomes 143 MPa.

For the second orientation, we observe extensive f twinning by HVEM and optical microscopy. Critical resolved shear stresses also increase monotonically from 95 MPa at 150°C to 150 MPa at 700°C.

Our results confirm the increase in strength with temperature up to 500°C for c slip. However, our data do not agree with their reported decrease in strength with temperature for f twinning.

Heard, H. C., DUBA, A., Piwinski, A. J. and Schock, R. N., Geothermal Prospecting and the Electrical Conductivity changes Associated with Melting, Panel Mtg. Expl. Meth. of Dry Hot Rock (Los Alamos, Jun. 1976) Los Alamos Scientific Laboratory, Rept. LA-6659-MS (1977), pp. 35-37. Lawrence Livermore Laboratory, Rept. UCRL-78261 Abstract (1977) .

- Heard, H. C., DUBA, A., Schock, R. N. and Chakrabarty, M. R., "The Electrical Conductivity Tensor of Olivine under Controlled Oxygen Fugacity," Trans. Am. Geophys. Union 58, 1235-1236 (1977). Lawrence Livermore Laboratory, Rept. UCRL-80023 Abstract. (1977) .
- Heard, H. C., HANSON, M. E., Shaffer, R. J., Anderson, G. D. and Montan, D. N., LLL Gas Stimulation Program, Quarterly Progress Report, January through March 1977, Lawrence Livermore Laboratory, Rept. 50036-77-1 (1977).
- Heard, H. C., HANSON, M. E., Shaffer, R. J., Anderson, G. D., Tonnessen, K. A., Montan, D. N. and Knutson, C. F., LLL Gas Stimulation Program, Quarterly Progress Report, April through June 1977, Lawrence Livermore Laboratory, Rept. UCRL-50036-77-2 (1977).
- Heard, H. C., HANSON, M. E., Shaffer, R. J., Anderson, G. D. and Emerson, D. O., LLL Gas Stimulation Program, Quarterly Progress Report, July through September 1977, Lawrence Livermore Laboratory, Rept. UCRL-50036-77-3 (1977).
- Heard, H. C., HANSON, M. E., Hearst, J. R. and Shaffer, R. J., LLL Gas Stimulation Program, Quarterly Progress Report, October through December, 1976, Lawrence Livermore Laboratory, Rept. UCRL-50036-76-4 (1977).
- Heard, H. C., HANSON, M. E., Shaffer, R. J., Hearst, J. R., Anderson, G. D., Montan, D. N. and Emerson, D. O., Update on the LLL Stimulation Program Third Ann. ERDA Sympos. Enhanced Oil & Gas Recovery (Tulsa, Aug. 1977) Lawrence Livermore Laboratory, Rept. UCRL-79587 Preprint (1977).
- Heard, H. C., SCHOCK, R. N., Duba, A. G. and Stromberg, H. D., "The Electrical Conductivity of Polycrystalline Olivine and Pyroxene under Pressure, in High-Pressure Research, Applications in Geophysics, M. H. Manghnani and S. Akimoto, Eds. (Academic Press, New York, 1977), pp. 39-51. Lawrence Livermore Laboratory, Rept. UCRL-78048 Preprint (1977) .
- Heard, H. C. and THIGPEN, L., The Vertical Stress Distribution in Oil Shale Aggregate Columns During Retorting, Lawrence Livermore Laboratory, Rept. UCRL-79978 Preprint (1977).
- Heard, H. C. and TRIMMER, D. A., Compaction and Permeability Behavior of Oil Shale Aggregates at Elevated Temperatures, Lawrence Livermore Laboratory, Rept. UCRL-80141 Preprint (1977).

HEARST, J. R., Current Well Logging Research at Lawrence Livermore Laboratory, presented at Southern California Well Logging Society Meeting. (Long Beach, California, Sept. 20, 1977). Lawrence Livermore Laboratory, Rept. UCRL-80021 Abstract (1977).

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

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

Some time ago we used Monte Carlo calculations to study the effect of bulk density on neutron log readings, and calculated that the effect is significant. We have constructed a hydrogen content test facility to simulate partially saturated media with several bulk densities for the same water content. Preliminary measurements in this facility tend to confirm the Monte Carlo calculations. Additional calculations indicate that the use of Al_2O_3 in part of the facility does not significantly affect the result.

A machine to drill sidewall cores approximately 1 m into the walls of Nevada Test Site emplacement holes has been built and successfully tested. The cores appear to contain undistributed material.

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

HEARST, J. R., "Estimation of Dip and Lateral Extent of Beds with Borehole Gravimetry," Geophysics 42, 5 (Aug. 1977), pp. 990-994, Lawrence Livermore Laboratory, Rept. UCRL-78087 (1977).

Simple expressions for the estimation of dip or lateral extent of a bed whose extent is large compared to its thickness has been developed. Let ρ_{CA} be the apparent density contrast between the bed and its surroundings as measured by a borehole gravimeter and ρ_{CT} the true density contrast measured by a gamma-gamma density log. Then for a dipping bed:

$$\rho_{CA} \approx \rho_{CT} \cos^2 \alpha,$$

where α is the dip angle.

For a horizontal bed of finite extent:

$$\rho_{CA} \approx \rho_{CT} \left[1 - \frac{2 \tan^{-1} \frac{t}{w}}{\pi} \right],$$

where t/w is the ratio of the bed thickness to its horizontal extent. For dipping beds of finite lateral extent the expression is more complicated. Numerical solutions were obtained and graphed.

HEARST, J. R., "On the Range of Investigation of a Borehole Gravimeter," Transactions of 18th Annual Symposium of the Society of Professional Well Logging Analysts (Houston, Texas, June 5-8, 1977). Lawrence Livermore Laboratory, Rept. UCRL-78875 Preprint (Feb. 1977).

Concepts of the range of investigation of a borehole gravimeter are reviewed. It is shown that the maximum sensitivity to a mass point at a horizontal distance R from a borehole occurs at a vertical distance $Z = R/\sqrt{2}$. Thus, the angle of maximum sensitivity is about 50° from the vertical. It is also shown that the absolute value of the gravitational effect decreases with increasing R . There are two maxima of the vertical gradient of gravity (at $Z = 0$ and at $Z = \sqrt{3}/2 R$). The minimum distance required between gravimeter stations to obtain a usable measurement can be determined. The slab radius R for which the gravitational effect of a horizontal slab is equal to 45%, 90%, etc., of that of an infinite Horizontal slab is a function of the measurement spacing. The closer the measurement spacing, the more information obtained.

HEARST, J. R. and Carlson, R. C., "The Gravimetric Density Formula for a Spherical Shell," Short Note in Geophysics 42, (Dec. 1977), pp. 1469. Lawrence Livermore Laboratory, Rept. UCRL-79157 Preprint (Feb. 1977).

The formula for the gravimetric density (ρ) of material, between two stations a vertical distance Z apart in a borehole, is

$$\rho = \frac{1}{4\pi k} \left(F - \frac{\Delta g}{\Delta Z} \right), \quad (1)$$

where k is the gravitational constant, F the free air gradient (the derivative of gravity with respect to depth in the absence of matter), and Δg the change in gravity. This formula is generally derived by integrating the vertical component of gravity caused, at a measuring point, by an infinite horizontal plate of thickness t , and then doubling it to account for one measuring point above and below the plate. This results in

$$\Delta g = 4\pi k \rho t. \quad (2)$$

In fact, however, the earth is not made up of infinite horizontal plates; it can perhaps more reasonably be regarded as a series of spherical shells. It is therefore instructive to derive the expression for the change in gravity associated with passing through one of these spherical shells.

Imagine that two gravity measurements are made, the first at radius r_i from the center of the earth, and the second at radius r_0 , where $r_0 > r_i$. By Gauss's theorem, the measurement at r_i does not see the shell, and the measurement at r_0 sees it as if its mass were concentrated at the center of the earth. Thus,

$$\Delta g = \frac{4}{3}\pi \rho k \frac{(r_0^3 - r_i^3)}{r_0^2}, \quad (3)$$

where ρ is the density of the shell. If we take

$$r_i = r_0 - dr, \quad (4)$$

and expand, then

$$\Delta g = \frac{4}{3}\pi \rho k \frac{(3r_0^2 dr - 3r_0 dr^2 + dr^3)}{r_0^2}. \quad (5)$$

Neglecting higher-order terms in dr (the second-order term is of the order of 10^{-5} times the first-order term), we obtain

$$\Delta g = 4\pi k \rho dr. \quad (6)$$

If we let $t = dr$, we get equation (2). Thus, the formula in equation (1) is equally valid for a spherical earth. This is reassuring.

This result is, of course, only of theoretical and academic interest. Certain aspects of the practical case, in which the material between stations is nonuniform, nonhorizontal, and finite, are discussed in another article.

Hearst, J. R., HANSON, M. E., Heard, H. C. and Shaffer, R. J., LLL Gas Stimulation Program, Quarterly Progress Report, October through December 1976, Lawrence Livermore Laboratory, Rept. UCRL-50036-76-4 (Feb. 1977).

Hearst, J. R., HANSON, M. E., Shaffer, R. J., Anderson, G. D., Montan, D. N., Heard, H. C. and Emerson, D. O., Update on the LLL Gas Stimulation Program, submitted to 3rd Ann. ERDA Symp. on Enhanced Oil and Gas Recovery (Tulsa, Oklahoma, Aug. 30-Sept. 1, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79587 Preprint (Jul. 1977).

Hearst, J. R., SCHATZ, J. F., Kusubov, A., Abey, A. E., Snell, C. M. and Thigpen, L., Rock Mechanics Project Progress and Results: Rock Fracture and Pore Collapse, Lawrence Livermore Laboratory, Rept. UCRL-17527 (May 1977).

Heusinkveld, M., BRYAN, J. B., Snell, C. M., Burton, D. E., Bruce, A. L., Lettis, L. A., Jr. and Butkovich, T. R., Controlled Blasting Calculations and Experiments, ANS Topical Meeting, Energy and Mineral Resource Recovery, (Colorado School of Mines, Golden, Colorado, Apr. 12-14, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79109 Preprint (1977).

HOWARD, J. H. and Towse, D., History of Exploitation at Salton Sea Geothermal Field, California, presented at Amer. Assoc. of Petroleum Geologists Annual Meeting (Washington, D.C., Jun. 1977). Lawrence Livermore Laboratory, Rept. UCRL-78862 (1977).

Geologically and historically, the Salton Sea Geothermal field is among the most interesting in the world. Structure of the field reflects the interaction of the East Pacific Rise and the North American plate and includes a series of active northwest-trending strike-slip faults. The stratigraphic section includes a series of lacustrine and braided-stream deposits of the ancestral Colorado River. The reservoir is liquid

dominated. Temperatures as high as 630°F (332°C) have been reported. Porosities are as much as 30% at shallow depths but decrease rapidly with increasing depth and temperature. Fractures are an important factor in flow. Permeabilities lie in the range of a few hundred millidarcys. Estimates of the electric-eye potential range from 8000 to 800 megawatt-centuries.

Attempts at energy recovery began in 1927; in addition, considerable effort has been devoted to minerals recovery. Carbon dioxide for refrigeration was taken from the field from 1932 to 1954. During the early 1960s, a serious but unsuccessful effort was made to recover other minerals, including potassium chloride.

Attempts to exploit the energy from this resource continue today. ERDA, San Diego Gas and Electric Co., and Imperial Magma Co. are evaluating a flashed-stream-binary-exchange power-production system. In addition, Lawrence Livermore Laboratory under contract to ERDA is evaluating still other innovative energy-recovery schemes, including the "total flow" system, which holds promise of greater efficiency of energy production. Interest in minerals recovery continues, but no major effort has been fielded in recent years.

HOWARD, N. W., "The Lawrence Livermore Laboratory Nuclear Test Effects and Geologic Data Bank," in Proc. of the Eleventh Mtg., Geoscience Information Society 7 (Falls Church, Virginia, 1977). Lawrence Livermore Laboratory, Rept. UCRL-78799 (1977).

Data on the geology of the USERDA Nevada Test Site have been collected for the purpose of evaluating the possibility of release of radioactivity at proposed underground nuclear test sites. These data, including both the rock physical properties and the geologic structure and stratigraphy of a large number of drill-hole sites, are stored in the Lawrence Livermore Laboratory Earth Sciences Division Nuclear Test Effects and Geologic Data Bank. Retrieval programs can quickly provide a geological and geophysical comparison of a particular site with other sites where radioactivity was successfully contained. The data can be automatically sorted, compared, and averaged, and information listed according to site location, drill-hole construction, rock units, depth to key horizons to the water table, and

distance to faults. These programs also make possible ordered listings of geophysical properties (interval bulk density, overburden density, interval velocity, velocity to the surface, grain density, water content, carbonate content, porosity, and saturation of the rocks). In this paper, we discuss the characteristics and capabilities of this data bank.

Howard, N. and GROTHAUS. B., Correlation of Alluvial Deposits at the Nevada Test Site, Lawrence Livermore Laboratory, Rept. UCRL-52335 (Sept. 1977).

ISHERWOOD, D., Preliminary Report on Retardation Factors and Radionuclide Migration, Lawrence Livermore Laboratory, Rept. UCRL-17551 (Aug. 1977).

The available data on distribution coefficients for the biologically important radionuclides present in high level-waste were used to estimate retardation factors (K_f) for a mass transport hydrological model. The radionuclides were divided into three groups: fission products with no sorption ($K_f = 1$), fission products with sorption ($K_f = 10^2$), and the actinides and their daughter products ($K_f = 10^4$). Minimum and maximum values were assigned the latter two groups. Uncertainties as a function of time were estimated at $\pm$ an order of magnitude.

ISHERWOOD, D., The Geochemical Barrier to Radionuclide Migration From a Nuclear Waste Repository, Amer. Geophy. Union Fall Mtg. (San Francisco, California, Dec. 5-9, 1977). Lawrence Livermore Laboratory, Rept. UCRL-80013 Abstract (1977).

Effective isolation of nuclear waste in a deep geological repository can be described in terms of interacting multiple barriers. The simplest to define is the geometric barrier; i.e., the physical isolation of the waste at some depth within the rock unit. Of greater complexity is the hydrologic barrier; i.e., parameters which determine the waste dilution factors and groundwater flow rates. The least understood is the geochemical barrier, identified as a series of waste/water/rock interactions involving sorption (ion exchange), membrane filtration, hydrolysis, precipitation and complexing. Of these, sorption is the primary geochemical control.

The mass transport hydrologic model tested the relative importance of the various parameters. Sorption was quantitatively expressed in the model

as the retardation factor; that is, the relative velocity of the groundwater to the radionuclides. (Retardation factors can be estimated from the ion exchange distribution coefficients for individual radionuclides.) A parameter sensitivity analysis showed the model to be most sensitive to the chemistry. Changes in the retardation factors produced dramatic changes in the radionuclide concentrations. This was particularly true for the long-lived nuclides. Those with short half-lives were effectively isolated by the combined efforts of the geometric and hydrologic barriers.

The importance of low solubilities in limiting radionuclide concentrations in groundwater was also evaluated. Solubilities based on thermodynamic calculations show a number of the radionuclides have equilibrium concentrations within those limits now considered acceptable by the federal government. However, the theoretical solubilities of Th and Sn are below concentrations actually found in natural waters. This is no doubt due to the formation of unidentified soluble complexes.

KASAMEYER, P. W. and Crow, N. B., Baseline Measurements of Geologic Events can Remove Potential Roadblocks to Geothermal Development, presented at Amer. Assoc. Advanc. Sci., Annual Mtg. (Washington, D.C., Feb. 12-17, 1978). Lawrence Livermore Laboratory, Rept. UCRL-80213 Abstract (Oct. 1977).

Large-scale production of electricity from geothermal fluids in southern California may possibly cause adverse environmental effects such as water pollution, earthquakes, or subsidence. The LLL Imperial Valley Environmental Project, in cooperation with several organizations, is making baseline measurements of water chemistry, seismology, and surface elevation before production starts. Natural geologic events have been observed which might have been considered environmental effects of production had full production been in progress. Documentation of the variability of natural geologic activity is reducing the risk that public reaction to a natural event will stop production. One event was an earthquake swarm. Fewer than 40 earthquakes per month were detected near the Niland field in five months. Over 300 earthquakes occurred in the sixth month. Assuming the events had a stationary Poisson distribution, the change in seismicity is highly improbable. Because the natural seismicity rate is variable it is

not a practical discriminant between natural and production-related events. The depths-of-focus or source-mechanism may be a better discriminant.

KASAMEYER, P., Thorson, L. and McKee, C., "Modeling Thermal and Flow Fronts for Arbitrary Well Arrays, Geothermal Resources Council, Transactions 1, (May 1977), p. 163-165. Lawrence Livermore Laboratory, Rept. UCRL-79353 (Apr. 1977).

A computer code has been developed, that uses an analytical solution for the pressure distribution to calculate fluid flow patterns within an arbitrary array of geothermal production and injection wells. The approximate location of the thermal front due to reinjection is also calculated. The code has been used to evaluate well use at the Magma-SDG&E geothermal site in the Salton Sea Geothermal Field.

KASAMEYER, P. W., "Resistivity Survey," in The LLL Geothermal Energy Program Status Report January 1976-January 1977, Lawrence Livermore Laboratory, Rept. UCRL-50046-76, Section 5.3.1, A. L. Austin, A. W. Lundberg, L. B. Owen, G. E. Tardiff, Eds. (Apr. 1977), p. 135.

KASAMEYER, P. W., "Seismic Refraction Survey," in The LLL Geothermal Energy Progra Status Report January 1976-January 1977, Lawrence Livermore Laboratory, Rept. UCRL-50046-76, Section 5.3.3, A. L. Austin, A. W. Lundberg, L. B. Owen, G. E. Tardiff, Eds. (Apr. 1977), p. 138.

KASAMEYER, P. W., "Thermal History of Injected Effluents", in The LLL Geothermal Energy Program Status Report January 1976-January 1977, Lawrence Livermore Laboratory, Rept. UCRL-50046-76, Section 5.4.3, A. L. Austin, A. W. Lundberg, L. B. Owen, G. E. Tardiff, Eds. (Apr. 1977), p. 153.

KASAMEYER, P. W. and Schatz, J. F., "Well-Log Resistivity Evaluation," in The LLL Geothermal Energy Program Status Report January 1976-January 1977, Lawrence Livermore Laboratory, Rept. UCRL-50046-76, Section 5.3.2, A. L. Austin, A. W. Lundberg, L. B. Owen, G. E. Tardiff, Eds. (Apr. 1977), p. 136.

KASAMEYER, P. W. and Schroeder, R. C., "Thermal Depletion of Geothermal Reservoirs with Fracture and Pore Permeability," in The LLL Geothermal Energy Program Status Report January 1976-January 1977, Lawrence Livermore Laboratory, Rept. UCRL-50046-76, Section 5.4.2, A. L. Austin, A. W. Lundberg, L. B. Owen, G. E. Tardiff, Eds. (Apr. 1977), p. 150.

KASAMEYER, P. W., Thorson, L. D. and McKee, C. R., "Heat and Mass Transport in Liquid-Dominated Geothermal Reservoirs," in The LLL Geothermal Energy Program Status Report January 1976-January 1977, Lawrence Livermore Laboratory, Rept. UCRL-50046-76, Section 5.4.1, A. L. Austin, A. W. Lundberg, L. B. Owen, G. E. Tardiff, Eds. (Apr. 1977), p. 148.

KASAMEYER, P. W. and Younker, L. W., "Temperature-Gradient Analysis," in The LLL Geothermal Energy Program Status Report January 1976-January 1977, Lawrence Livermore Laboratory, Rept. UCRL-50046-76, Section 5.3.4, A. L. Austin, A. W. Lundberg, L. B. Owen, G. E. Tardiff, Eds. (Apr. 1977), p. 139.

Kasameyer, P. W., OWEN, L. B., Netherton, R. and Thorson, L. D., Predicting the Rate by Which Suspended Solids Plug Geothermal Injection Wells, prepared for Third Annual Stanford Geothermal Workshop on Geoth. Reservoir Eng. (Stanford University, Dec. 14-16, 1977). Lawrence Livermore Laboratory, Rept. UCRL-80529 (Dec. 1977).

KNAUSS, K. G., Ku, T. -L. and Moore, W. S., "Radium and Thorium Isotopes in the Surface Waters of the East Pacific and Coastal Southern California," to be published in Earth Planet. Sci. Lett. 39 (Apr. 1978). Lawrence Livermore Laboratory, Rept. UCRL-79949, Rev. 1 Preprint (Dec. 1977) .

A fiber extraction technique is used to concentrate Ra and Th isotopes from 1000 liters or more of seawater. Natural ^{226}Ra and ^{234}Th are used as yield tracers. In the Equatorial Pacific the ^{228}Ra activity of surface water varies from 2G to 1 dpm/10000 kg and generally decreases away from continental shelf areas. Across the Peru Current System, this decrease is modeled as one-dimensional diffusion and indicates the possibility of two flow regimes with distinct characteristics mixing lengths and apparent eddy diffusivities of 10^5 and 10^7 cm^2/sec . The perturbing effect of advection and equatorial upwelling west of the Galapagos Islands are noted. Off the coast of Southern California a vertical ^{228}Ra distribution gives an apparent diffusivity of $1.6 \text{ cm}^2/\text{sec}$ for the upper thermocline. ^{226}Ra concentrations near the coast appear to be higher than the open ocean values at comparable depths, which may reflect supply of this isotope from continental shelf sediments and/or upwelling. The insoluble daughter/soluble parent activity ratios $^{228}\text{Th}/^{228}\text{Ra}$ and $^{234}\text{Th}/^{238}\text{U}$ in the Equatorial Pacific surface water display latitudinal trends which may be

correlated with productivity variations. Near the coast of California these ratios reflect the differing oceanographic conditions north and south of Pt. Conception indicating a mean chemical removal time constant on the order of 4 months for Th and other highly reactive elements within the Southern California Bight. The ^{232}Th content of seawater sampled is less than 0.1 $\mu\text{g}/1000\text{ l}$; most of the published values for seawater ^{232}Th could well be too high. A comparison of the two methods of determining ^{228}Ra (via ^{228}Ac and via ^{228}Th) made on 64 seawater samples shows that the time delay required by the ^{228}Th method is more than compensated by its better analytical simplicity and precision.

KNAUSS, K. G., Nary, Q. and Ku, T. -L., Groundwater Investigation using Uranium Isotopes in the Mojave Desert, submitted to Jour. of Geophys. Res. Lawrence Livermore Laboratory, Rept. UCRL-80450 Preprint (Dec. 1977).

The uranium isotopic character of the Mojave River (surface and subsurface flow) was determined from its source in the San Bernardino Mountains to its sink in the central Mojave Desert. Within the Mojave River Groundwater Basin samples taken from Troy Dry Lake and surrounding sources of local recharge allow calculation of relative mixing proportions using uranium tracer techniques. Uranium concentrations range from 0.2 to 30 ppb while activity ratios ($\text{U-234}/\text{U-238}$) range from 0.9 to 1.80. Two thermal springs on Paradise Range show uncommonly low activity ratios of 0.52 and 0.39, the latter value being less than the lower limit explainable by Th-234 ejection (uranium isotopes, groundwater).

KUSUBOV, A. S., Schatz, J. F. and Ahrens, T. J., Shock Wave Generated Fractures Under Confining Pressure, prepared for Gen. Mtg. Am. Phys. Soc. (San Francisco, Jan. 1978). Lawrence Livermore Laboratory, Rept. UCRL-80295 Abstract (1977).

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

Kusubov, A., SCHATZ, J., Hearst, J., Abey, A., Snell, G. and Thigpen, L., Rock Mechanics Project Progress and Results: Rock Fracture and Pore Collapse, Lawrence Livermore Laboratory, Rept. UCID-17527 (1977).

Kusubov, A., SWIFT, R. P., Schatz, J. F., Durham, W. B., and Hearst, J. R., Effect of Simultaneous and Sequential Detonation on Explosive-Induced Fracture, Nineteenth Sympos. Rock Mech. (Lake Tahoe, Nevada, May 1978). Lawrence Livermore Laboratory, Rept. UCRL-80390 Abstract (1977).

Lacey, C. S., REE, F. and Walton, O., "EOS of mixtures," in H-Division Quarterly Report, January through March 1977, Lawrence Livermore Laboratory, Rept. UCRL-50028-77-1 (1977).

LARSON, D. B., Explosive Energy Coupling in 15 Geologic Materials, Lawrence Livermore Laboratory, Rept. UCRL-79427 Preprint (1977).

Small-scale high-explosive experiments, using spherical charges as energy sources, were conducted on 15 geologic materials. Explosive coupling parameters, derived from the resulting data, were used in comparing explosive energy coupling values and in determining the relationship between coupling and the properties of materials. For rocks and soils with significant dry porosity, the dissipation of energy resulting from the crushing of pores dominates all other inelastic mechanisms until a stress is reached that corresponds to matrix strength. The large difference in coupling values between water and water-saturated rock suggests that two-component interactions attenuate the wave in saturated rocks. The difference between water, ice, and ice-saturated soils is attributed to dissipation of energy in the melting transition.

LARSON, D. B., The Relationship of Rock Properties to Explosive Energy Coupling, Lawrence Livermore Laboratory, Rept. UCRL-52204 (1977).

We have conducted small-scale high explosive experiments with spherical charges as energy sources in 15 geologic materials. Gages, placed radially from the source, recorded particle velocity and stress time histories. Data from these experiments provide evidence of a shock-induced melting transition in ice-saturated materials as well as evidence for the collapse of a family of similar pores at 3 GPa in Westerly granite. We compared coupling

efficiency using peak particle velocity and peak stress attenuation as a function of radius. The strongest coupling is observed in water and in consolidated rocks. We attribute the deviation from ideal elastic behavior observed in these materials to viscosity and finite strain, and, in the case of consolidated rock, to microcracks and other grain boundary effects. The weaker coupling observed in the other materials is related to other material properties. The weakest coupling is observed in materials with large amounts of dry porosity. In addition, strength is an important coupling parameter because it limits the radius for major inelastic response. Other material properties observed to cause major effects on coupling include multiple-component interactions in water-saturated rocks and phase transformation in ice-saturated soils.

Larson, D. B. and ANDERSON, G. D., Laboratory Experiments on Hydraulic Fracture Growth near an Interface to be presented at the Nineteenth U.S. Sympos. Rock Mech. (Stateline, Nevada, May 1978). Lawrence Livermore Laboratory, Rept. UCRL-80355 Abstract (1977).

Larson, D. B. and ANDERSON, G. D., Plane Shock Wave Studies of Geologic Media, Lawrence Livermore Laboratory, Rept. UCRL-52357 (1977).

Larson, D. B. and ANDERSON, G. D., "Shock Wave Compression of Nuggett Sandstone," Trans. Am. Geophys. Union 58, 491 (1977). Lawrence Livermore Laboratory, Rept. UCRL-79193 Abstract (1977) .

LEACH, JR., D. L., Application of Geochemical Data to the Development of Uranium Resource (presented at Amer. Assoc. Advanc. Sci., Annual Mtg., (Washington, D.C., Feb. 12-17, 1978). Lawrence Livermore Laboratory, Rept. UCRL-80219 Abstract (Oct. 1977).

Uranium is mobile under most geological environments; therefore, uranium in stream waters and sediments provides information on surficially exposed uranium occurrences while uranium in groundwater is effective in identifying subsurface uranium occurrences. This provides a rapid, effective method to identify new uranium resources. To conduct an effective geochemical survey, a sampling program must be devised that is specific for a geological environment. In addition to uranium, sufficient geochemical data must be developed so that true uranium anomalies can be determined from

background levels and false anomalies. Uranium saturation calculation, ion ratios, and various statistical methods are useful for interpreting uranium in waters. The interpretation of uranium in sediments is greatly facilitated by multi-element analyses provided by neutron activation analysis and emission spectrometry. These data permit mineralogical and chemical characterization of the sediments and provide a basis for predicting anomalous uranium concentrations.

LEACH, JR., D. L., Geothermal Reconnaissance for Uranium in the Arid Regions of the Western United States, ERDA Symp. (Grand Junction, Colorado, Mar. 15-16, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79241 Preprint (1977).

In developing the sampling strategy for the seven western states, the Lawrence Livermore Laboratory (LLL) divided the region into geologic and physiographic provinces.

A large part of the LLL region of responsibility lies within the arid to semi-arid Basin and Range province. This region is characterized as an area of rather complex geology with internal drainage. The desert-like conditions in many parts of this region result in a unique set of problems which requires a unique reconnaissance program. In this paper, I will describe some of the features of the LLL program which are keyed to the desert environment in the northern Basin and Range province.

LEACH, JR., D. L. and Benson, L. V., "Hydrogeochemistry of Uranium in the Walker River Basin, California and Nevada," submitted to the Jour. of Geochemical Exploration. Lawrence Livermore Laboratory, Rept. UCRL-79282 Preprint (1977).

This report describes the hydrogeochemistry of uranium in surface and ground water within the Walker River Basin. The specific objectives are to (1) describe the geochemical transport system which governs the distribution of uranium by water in this environment, (2) evaluate the use of widely-spaced surface and ground water samples as an effective means of detecting uranium anomalies, (3) describe the seasonal changes in uranium concentration, and (4) evaluate the effects of mining and agricultural activities on the transport and occurrence of uranium.

LEDBETTER, G. P., Nordyke, M. D., A Bibliography of Published Material Related to the Soviet PNE Program, Lawrence Livermore Laboratory, Rept. UCRL-52362 (Nov. 1977).

Scientists in the Soviet Union have published many papers that provide details about the Soviet program for the peaceful use of nuclear explosions. Over the years much of this material has been gathered at the Lawrence Livermore Laboratory into what has become a sizeable collection. The present bibliography provides a useful record of the material available in that collection.

LEWIS, A. E. and Rothman, A. J., Modified In-Situ Technology - Experimental Results at Lawrence Livermore Laboratory and Present Status, presented at Amer. Nuclear Soc. Topical Meeting on Energy and Mineral Recovery Research (Golden, Colorado, April 12-14). Lawrence Livermore Laboratory, Rept. UCRL-79149 Abstract (1977).

An experimental effort is in progress to obtain a comprehensive understanding of the retort process. Recent results have increased understanding of the mechanism of yield loss, decomposition of carbonate minerals, and the reaction of char with O_2 and CO_2 . A computer model has been compared successively with retort experiments and is proving useful in optimizing the process and in designing further experiments. A summary of experimental and model results will be presented.

Lewis, A. E., ROTHMAN, A. J., Experimental Work on Oil Shale at LLL and Predictions of Retorting Characteristics of Oil Shales, presented at 11th Israel Conf. on Mechanical Engineering 1977, Technion - Israel Instit. of Tech. (Technion City, Haifa, Israel, Jul. 11-12). Lawrence Livermore Laboratory, Rept. UCRL-79630 Abstract (1977).

Lewis A. E., ROTHMAN, A. J., Lawrence Livermore Laboratory Oil Shale Project Quarterly Report. March-June 1977, Lawrence Livermore Laboratory, Rept. UCRL-16986-77-2 (1977).

LIN, W., Compressible Fluid Flow Through Rocks of Variable Permeability, Lawrence Livermore Laboratory, Rept. UCRL-52304 (1977).

The effectiveness of coarse-grained igneous rocks as shelters for burying radioactive waste can be assessed by determining the rock

permeabilities at their in situ pressures and stresses. We used analytical and numerical methods to solve differential equations of one-dimensional fluid flow through rocks with permeabilities from 10^4 to 1 nD. In these calculations, we used upstream and downstream reservoir volumes of 5, 50, and 500 cm³. The optimal size combinations of the two reservoirs were determined for measurements of permeability, stress, strain, acoustic velocity, and electrical conductivity on low-porosity, coarse-grained igneous rocks.

McKague, H. L., TERHUNE, R. W., Glenn, H. D., Burton, D. E. and Rambo, J. T., Calculational Examination of the Baneberry Event, to be presented at American Geophysical Union Spring Meeting (Miami, Florida, Apr. 17-21, 1978). Lawrence Livermore Laboratory, Rept. UCRL-52365 (1977).

MEAD, S. W., Campbell, J. H. and Stephens, D. R., Ground-Water Quality Effects of an Underground Coal Gasification Experiment, submitted to the Proc. of the 3rd Annual Underground Coal Conversion Symp. (Fallen Leaf Lake, California, Jun. 6-9, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79867 Preprint (1977).

Ground-water sampling and analysis have been carried out at the site of an in situ coal gasification experiment conducted by the Lawrence Livermore Laboratory (LLL) near Gillette, Wyoming. An important environmental question associated with the in situ gasification of coal concerns the possibility that reaction products (ash and tars) left underground following the gasification process may lead to the contamination of local ground waters. In an effort to clarify the significance of this problem, we have sampled the water from more than 12 wells in the vicinity of an underground gasification experiment before, during, and up to 6 months following gasification. Water samples were analyzed in the field and at LLL, U. S. Geological Survey, and Research Triangle Institute for a variety of characteristics, including the presence of 70 inorganic elements and compounds, phenolic materials, dissolved organic carbon, and volatile organics. We find a greatly increased concentration of phenolic materials (450 mg/l) just outside the burn boundary, and a variety of inorganic species issuing from within the residual ash bed. All contaminants decrease rapidly with distance, although above-background levels of some species were

detected 100 feet from the burn zone. Several important contaminants showed a large decrease in concentration with time, possibly a result of adsorption.

MILLER, D. G., Ionic Interactions in Transport Processes as Described by Irreversible Thermodynamics, Faraday Discussion #64 presented a Ion-Ion and Ion-Solvent Interactions meeting (Oxford, England, Sept. 13-15, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79624 (1977).

The application of irreversible thermodynamics to transport in electrolyte solutions is reviewed. The linear "Onsager" coefficients l_{ij} should provide a general and more fundamental insight into ion-ion and ion-solvent interactions than special-case coefficients like the conductance. The implications of non-zero l_{ij} , $i \neq j$, are discussed. Selected l_{ij} values for binary and ternary systems are presented, including new results for CuSO_4 . Estimation methods for l_{ij} for ternary and higher order systems are reviewed.

MILLER, D. G., Piwinskii, A. J. and Yamauchi, R., Geochemical Equilibrium Codes: A Means of Modelling Precipitation Phenomena in the Salton Sea Geothermal Field, prepared for 1977 SPE-AIME Intl. Symposium on Oilfield and Geothermal Chemistry (La Jolla, California, Jun. 27-28, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79056 Preprint (Apr. 1977).

We have used the Helgeson-Herrick geochemical code to predict which minerals will precipitate from Salton Sea Geothermal Field brines. The code's predictions of sulfide-amorphous silica precipitation from the Magmamax No. 1 brine are in good agreement with field tests of scaling, although the observed silicate scale matrix is in amorphous form, rather than the numerous crystalline forms predicted by the code. The code's predictions of scale precipitation from wells with different brine compositions are also in good agreement with field tests. The code appears to be a useful screening tool, despite reservations about the use of purely thermodynamic predictions in systems with important kinetic constraints.

MILLER, D. G., Piwinski, A. J. and Yamauchi, R., The Use of Geochemical-Equilibrium Computer Calculations to Estimate Precipitation from Geothermal Brines, Lawrence Livermore Laboratory, Rept. UCRL-52197 (Jan. 1977).

We have used the Helgeson-Herrick geochemical code to calculate the solubility of NaCl, KCl, and KCl-NaCl in water and to predict which minerals will precipitate from Salton Sea Geothermal Field brines. The code's predictions of sulfide-silicate precipitation from the Magmamax No. 1 brine are in good agreement with field tests of scaling, although the observed sulfide-silicate scale matrix is in amorphous form, rather than the crystalline form predicted by the code. The code's predictions of scale precipitation from wells with different brine compositions are also in good agreement with field tests. The code appears to be a useful screening tool, despite reservations about the use of purely thermodynamic predictions in systems with important kinetic constraints. We have suggested several ways to improve and apply the code in the future.

Montan, D. N., HANSON, M. E., Shaffer, R. J., Anderson and Heard, H. C., LLL Gas Stimulation Program Quarterly Progress Report, January through March 1977, Lawrence Livermore Laboratory, Rept. UCRL-50036-77-1 (May 1977).

Montan, D. N., HANSON, M. E., Shaffer, R. J., Anderson, G. D., Heard, H. C., Tonnessen, K. A. and Knutson, C. F., LLL Gas Stimulation Program, Quarterly Progress Report, April through June 1977, Lawrence Livermore Laboratory, Rept. UCRL-50036-77-2 (Aug. 1977).

Montan, D. N., HANSON, M. E., Shaffer, R. J., Hearst, J. R., Anderson, G. D., Heard, H. C. and Emerson, D. O., Update on the LLL Gas Stimulation Program, submitted to 3rd Ann. ERDA Symp. on Enhanced Oil and Gas Recovery (Tulsa, Okla., Aug. 30-Sept. 1, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79587 Preprint (Jul. 1977).

MORSE, J. G., Well Interference Study of the Multi-Layered Salton Sea Geothermal Reservoir, Proc. of the Third Annual Stanford Geothermal Reservoir Engineering Workshop (Stanford University, Dec. 1977). Lawrence Livermore Laboratory, Rept. UCRL-80385 Summary (1977).

A well interference testing program of the Salton Sea Geothermal reservoir is being conducted as part of a resource evaluation study by the

Earth Sciences Geothermal Industrial Support Program of the Lawrence Livermore Laboratory. Studies to date indicate the reservoir rock to be composed of layered sequences of shales and sands. Wells involved in the testing program are being used in support of, or are in the vicinity of, the MAGMA-SDG&E Geothermal Loop Experimental Facility (GLEF), located in the Salton Sea Geothermal Field (SSGF). Between these wells, a shale layer has been correlated which appears to divide the reservoir into an upper and lower portion. Other thick sand and shale sequences may provide additional stratification. This report describes work in progress on a well testing program designed to determine the horizontal and vertical transmissivity and storage parameters between wells in the vicinity of the GLEF. These tests are being conducted with the cooperation and support of Magma Power Company and San Diego Gas and Electric Company.

MORSE, J. G. and Owen, L. B., Adapting Coaxial Cablehead Assemblies for Use in Geothermal Wells, to be presented at 85th Nat. Mtg. of AIChE (Philadelphia, PA, June 4-8, 1978). Lawrence Livermore Laboratory, Rept. UCRL-80152 Abstract (Nov. 1977).

Cablehead assemblies, used in conjunction with wellbore pressure-temperature tools, fail frequently in geothermal applications. Injection of halogenated chlorofluorocarbon grease into cablehead assemblies eliminates problems caused by entry of corrosive brine and gases. A continuous 60 day test (180°F, 20% TDS) was successfully completed at the Salton Sea Geothermal Field.

MORSE, J. G. and Schroeder, R. C., "Reservoir Evaluation," in The LLL Geothermal Energy Program Status Report January 1976-January 1977, Lawrence Livermore Laboratory, Rept. UCRL-50046-76, Section 5.4.5, A. L. Austin, A. W. Lundberg, L. B. Owen, G. E. Tardiff, Eds. (Apr. 1977), p. 159.

OWEN, L. B., Chemical Modification of Hypersaline Geothermal Brine for Scale Control, presented at Amer. Assoc. Advanc. Sci., Annual Mtg. (Washington, D.C., Feb. 12-17, 1978). Lawrence Livermore Laboratory, Rept. UCRL-80215 Abstract (Oct. 1977).

Prototype thermal energy conversion systems processing geothermal brine can be jeopardized by severe scaling problems that arise when the brine

undergoes evaporative cooling. Field studies in the Imperial Valley, Southern California have demonstrated that massive siliceous scaling can be prevented when brine, while still at wellhead conditions, is acidified with hydrochloric acid. Preliminary evaluations indicate that reagent requirements for acidification add about one to two mills per kilowatt hour to the price of power depending upon the energy conversion system employed. The rationale for scale control by acidification was based on the premise that the polymerization-condensation kinetics that control the rate of silica precipitation are pH-dependent.

OWEN, L. B., "Properties of Siliceous Scale from the Salton Sea Geothermal Field," Geothermal Resources Council, Transactions 1 (May 1977), p. 235. Lawrence Livermore Laboratory, Rept. UCRL-79350 (1977) .

Evaporative concentration of depressurized hypersaline brine from the Salton Sea Geothermal Field (SSGF) results in rapid deposition of siliceous scale (heavy metal sulfides and iron-rich amorphous silica) on brine-exposed surfaces. The scaling problem is aggravated by high flow rates typical of producing wells in the SSGF (nominally 1.8×10^5 kg brine/hour) because even a minuscule mass transfer of dissolved constituents from brine to scale is sufficient to rapidly clog flow lines and render valves and other critical components of energy conversion systems inoperable. In view of the complexity of natural brines at high temperature and pressure, a field-oriented experimental program was initiated with supporting laboratory studies of scale compositions and microstructures. Results of these activities were supplemented by appropriate literature reviews in order to identify effective control measures that might subsequently be evaluated in the field.

OWEN, L. B., Digiallonardo, S. L., Shell, Jr., E. O. and Steele, W. J., An Integrated Approach to the Analysis of Scale Deposits From the Salton Sea Geothermal Field, presented at 10th Annual Technical Mtg., Intl. Metallorgraphic Soc. (Houston, Texas, June 19-20, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79295 (Mar. 1977).

Thermal energy-electric power conversion schemes utilizing geothermal brine can be jeopardized by rapid formation of scale in process equipment,

well casings, and flowlines as brine undergoes flash evaporation. In 1973, development of a TOTAL FLOW system for use at the Salton Sea Geothermal Field (SSGF), Imperial County, California, was initiated at Lawrence Livermore Laboratory. This process involves the expansion of total wellhead production (liquid plus steam) through nozzles designed to efficiently convert the thermal energy of the fluids to kinetic energy. The resulting high velocity exhaust streams are then used to drive an impulse turbine. However, preliminary field tests with simulated turbine components indicated that nozzle and blade scaling was going to be a serious problem. In order to better understand the deposition process, scale samples from the SSGF were characterized by optical microscopy and a variety of instrumental techniques.

Polished sections were prepared with vacuum impregnation techniques optimized to control bleeding and disruption of deposits on metallic or polymeric substrates. These sections were then examined by optical and scanning electron microscopy. Chemical compositions were subsequently obtained with the electron microprobe. Replication techniques were not satisfactory for ultrastructure determinations by transmission electron microscopy because of the low tensile strength of scale and the resulting contamination of replicas with extracted material. However, excellent results were obtained by viewing thin edges of scale fragments directly.

These studies indicated that scales are composed of a variety of well crystallized heavy metal sulfides and metallic minerals (primarily native silver) entrained within or growing upon a fine-grained, iron-rich amorphous silica matrix. The sulfides were never observed adhering directly to metallic or polymeric substrates; basal scale layers were either silica-rich or intimate intergrowths of amorphous silica and sulfide minerals. These relationships suggested that initial silica deposition was required for subsequent adhesion of sulfides. Sulfide morphologies were also indicative of diffusion controlled growth rather than precipitation and subsequent incorporation in scale of large sulfide crystals ($> 1 \mu\text{m}$ diameter). Once sulfide nucleation occurred within the silica matrix, further growth was supported by diffusion of sulfide and metal ions at the scale-brine interface. Electron microscopy demonstrated that the silica matrix presented an ideal environment for sulfide nucleation as it was comprised to

1 to 5 nm colloidal silica particles aggregated in the form of a porous gel-type network.

On the basis of these observations, it was hypothesized that inhibition of silica deposition would control scaling, even in cases where the bulk of deposits consisted of heavy metal sulfides. A scale-preventive measure, based on modification of brine pH prior to energy conversion, was subsequently developed and successfully tested at the SSGF.

Owen, L. B. and GOLDBERG, A., Pitting Corrosion and Scaling of Carbon Steels in Geothermal Brine, submitted to Materials Performance and presented at 150th Fall Mtg. Electrochemical Soc. Inc. (Las Vegas, Nevada, Oct. 1976). Lawrence Livermore Laboratory, Rept. UCRL-79508 Preprint (1977).

An evaluation was made of pitting corrosion failures of surface pipeline and wellhead casing exposed to hypersaline brine in the Salton Sea Geothermal Field. Uniform corrosion, pitting corrosion, and various forms of highly localized, selective attacks were observed. The corrosion product (Fe_3O_4) was covered with a transition zone of mixed corrosion product-scale that graded into a scale-rich deposit. The scale, consisting of heavy metal sulfides dispersed in an Fe-rich amorphous silica matrix, was deposited as the brine cooled. The possible roles of the outer scale deposit, the intermediate transition zone, and the inner corrosion product on either abetting or deterring corrosion are discussed. We propose that cracks, resulting from thermal stresses induced during periods of intermittent operation, form in the scale permitting the infusion of oxygen during shutdown intervals. This contributes to localized accelerated pitting resulting in perforation of the pipe and casing walls. The importance of environmental (pH, E_H , composition, heterogeneity) and material (composition, casting, thermomechanical history, microstructure, surface condition) variables that influence the formation of different morphologies is discussed and compared with related observations cited in the literature.

Owen, L. B. and GRENS, J. Z., "Field Evaluation of Scale Control Methods: Acidification," Geothermal Resource Council, Transactions 1 (May 1977), p. 119. Lawrence Livermore Laboratory, Rept. UCRL-79351 (1977) .

Brine modification experiments carried out during the Summer and Fall of 1976, at the Salton Sea Geothermal Field confirmed that siliceous scale formation is a pH-dependent process. The rationale for scale control was based on the premise that sulfide activity products and rates of silica polymerization and aggregation are reduced in acidic solutions. When separated brine from the Magmamax No. 1 Well (nominal conditions: 200-230°C; 220-320 psig; pH 5.4-5.8) was acidified with sufficient hydrochloric acid to reduce the pH of expanded brine (1 atm, 102°C) to values between 1.5-5.0, scaling of simulated TOTAL FLOW turbine components was eliminated.

OWEN, L. B., Kasameyer, P. W., Netherton, R. and Thorson, L. D., Predicting the Rate by Which Suspended Solids Plug Geothermal Injection Wells, prepared for Third Annual Stanford Geothermal Workshop on Geoth. Reservoir Eng. (Stanford University, Dec. 14-16, 1977). Lawrence Livermore Laboratory, Rept. UCRL-80529 (Dec. 1977).

Standard membrane filtration tests have been used by the oil industry for more than 20 years to evaluate injection well performance. Published analytical models are also available for relating filtration data to injector lifetimes. We have utilized these techniques to evaluate injection at the Salton Sea Geothermal Field, Southern California. Results indicate that direct injection into reservoir zones with primary porosity is not feasible unless 1 μ m or larger particulates formed during or after the energy conversion process are removed.

Owen, L. B., AUSTIN, A. L., Lundberg, A. W. and Tardiff, G. E., The LLL Geothermal Energy Program status report January 1976-January 1977. Lawrence Livermore Laboratory, Rept. UCRL-50046-76 (Apr. 1977).

OWEN, L. B., Grens, J. Z. and Snell, Jr., E. O., "Scale-Control Tests," The LLL Geothermal Energy Program Status Report January 1976-January 1977, Section 4.4, Lawrence Livermore Laboratory, Rept. UCRL-50046-76, A. Austin, A. W. Lundberg, L. B. Owen, G. E. Tardiff, Eds. (Apr. 1977), p. 78-87.

Owen, L. B., HILL, J. H., Otto, Jr., C. J., Morris, C. J. and Quong, R., Brine Chemistry and Suspended Solids, The LLL Geothermal Energy Program Status Report January 1976-January 1977, Section 4.5, Lawrence Livermore Laboratory, Rept. UCRL-50046-76 (Apr. 1977), p. 87-98.

Owen, L. B. and MORSE, J. G., Adapting Coaxial Cablehead Assemblies for Use in Geothermal Wells, to be presented at 85th Nat. Mtg. of AIChE (Philadelphia, Pennsylvania, June 4-8, 1978). Lawrence Livermore Laboratory, Rept. UCRL-80152 Abstract (Nov. 1977).

OWEN, L. B., Quong, R., Digiallono, S., Snell, E. O. and Steele, W. J., "Scale Studies," The LLL Geothermal Energy Program Status Report January 1976-January 1977, Section 4.2, Lawrence Livermore Laboratory, Rept. UCRL-50046-76, A. L. Austin, A. W. Lundberg, L. B. Owen, G. F. Tardiff, Eds. (Apr. 1977), p. 58-73.

PIWINSKII, A. J., Dengler, L., Netherton, R. and Trimmer, D., "Injection Studies," LLL Geothermal Energy Program Status Report, January 1976-January 1977, A. Austin et al., Eds., Lawrence Livermore Laboratory, Rept. UCRL-50046-76 (1977), pp. 167-171.

Preliminary laboratory core-flushing experiments were conducted to evaluate the potential for permeability and porosity losses induced by the injection of expanded brine effluents with suspended solids. These experiments involved the passage of untreated and unfiltered brine effluents from the Magmamax No. 1 well through sedimentary media under ambient temperatures and differential pressure of approximately 35 MPa. The brine was originally collected in a plastic-lined drum and stored for several weeks prior to use. Suspended solids consisted of colloidal silica with iron oxides and minor quantities of heavy-metal sulfides.

PIWINSKII, A. J., Duba, A. and Ho, P., "The Electrical Conductivity of Low and High Albite Through Its Melting Interval at 100 kPa," Canadian Mineralogist 15 (1977) 196-197. Lawrence Livermore Laboratory, Rept. UCRL-78777 Preprint (1977) .

The electrical conductivity (σ) of single-crystal Amelia albite has been measured parallel to the b axis under controlled oxygen fugacity near the qfm buffer up to 1406 K. Two specimens were used in the investigation. One was held at temperatures between 1353 and 1384 K for a total of 3200 hours in order to produce maximum-disordered monoclinic albite. These temperatures were below the reported melting point of albite, 1391 K. The other sample, triclinic ordered albite, was cycled between 673 and 1223 K, temperatures below the triclinic-monoclinic inversion.

The σ of high albite (monoclinic) during melting at 1406 K as a function of time and frequency (ν) is shown. It is clear that the σ of high albite increases on melting by approximately half a order of magnitude at 1 to 10 kHz, but decreases at all ν 's below 1 kHz during the first hundred hours.

The σ of low albite (triclinic) during melting at 1406 K as a function of time and frequency is shown. The σ was found to increase at all ν 's. The σ measured at 1 and 10 kHz increased by approximately 2.5 orders of magnitude, and the σ measured at 2000 Hz increased by approximately two orders of magnitude.

These results indicate that the crystal structures of low and high albite preceding melting exert a control over both the ν -dependence of the σ observed on melting and the magnitude and direction of the conductivity change. These new data further qualify the observation of Khitarov & Slutskii regarding the sharp increase (approximately two decades in σ attributed to melting in albite. In systems such as $\text{NaAlSi}_3\text{O}_8$ which exhibit order-disorder phenomena, the degree of disorder attained prior to melting may control the σ change upon melting. Thus, we may expect to observe such features, upon melting, in rocks such as basalt which contain plagioclase feldspar as a major constituent.

PIWINSKI, A. J. and Miller D. G., "Geochemical Code Calculations," in LLL Geothermal Energy Program Status Report, January 1976-January 1977, A. Austin et al., Eds., Lawrence Livermore Laboratory, Rept. UCRL-50046-76 (1977), pp. 100-102.

The Helgeson-Herrick code has been used to predict chemical equilibria in complex, Salton Sea-type, high-salinity geothermal brine to determine its usefulness for brine problems. The code was employed to survey the effects of changing both brine pH and oxidation state for some initial brine compositions. Emphasis so far has been focused on determining the phases that precipitate from these brines at 60, 100, 150, 200, and 250°C as a function of pH and oxidation potential; the latter is used to establish a boundary condition (i.e., either very reducing or very oxidizing). Precipitation reactions at intermediate temperatures cannot be considered, because the code does not follow continuously cooling regimes. Furthermore,

Permeabilities of 10.2-cm-long, 2.5-cm-diameter Kayenta (porosity, $20.7 \pm 1.66\%$) and St. Peter (porosity, $13.6 \pm .13\%$) sandstones to Magmamax No. 1 brine containing suspended solids were determined from 70° to 90°C at 10.3 MPa confining pressure. Measurements were performed with no filters, with one $10\text{-}\mu\text{m}$ filter, and with two $10\text{-}\mu\text{m}$ filters inserted upstream of the core sample. In all cases, there was a dramatic decrease in permeability within the first hour of flow or few hundred pore volumes of flow through the core. Experiments, which were conducted with no filters or with one filter, yield permeabilities which represent both the rock and the two to three mm amorphous silica-iron layer on the top face of the core. The experimental results show that, if the Salton Sea Geothermal Field were composed of porous sedimentary formations similar to Kayenta sandstone, long-term injection of unmodified Magmamax brine would not be feasible. In the case of acidified brine, most of the permeability decline may result from the mobilization of silica.

PIWINSKII, A. J. and Netherton, R., Permeability of Kayenta Sandstone to Hypersaline Brine at 10.3 MPa Confining Pressure and Temperatures to 90°C , Third Ann. Workshop Geothermal Reservoir Engineering (Stanford University, Dec. 1977). Lawrence Livermore Laboratory, Rept. UCRL-80383 Summary (1977).

The ability to inject "spent" geothermal brine may be a critical and perhaps limited factor in the development of fluid-dominated geothermal resources. In order to understand and evaluate changes in formation permeability and porosity at depth as a result of injection of brine effluents, experiments were carried out (70° - 90°C at 10.3 MPa confining pressure) in conjunction with the ongoing brine chemistry and materials evaluation effort at the Lawrence Livermore Laboratory Field Test Station located in the Salton Sea Geothermal Field, Imperial Valley, California.

PIWINSKII, A. J., Netherton R. and Chan, M., Viscosity of Brines from the Salton Sea Geothermal Field, Imperial Valley, California, Lawrence Livermore Laboratory, Rept. UCRL-52344 (1977).

The viscosity of chemically-analyzed brines from the Salton Sea Geothermal Field was measured from 5° to 90°C at 100 kPa. Data indicate

in its present form, the code cannot be used to estimate absolute amount of precipitation, nor can it consider relative differences in chemical reaction rates.

Accurate chemical analyses were available for brine produced by the Sinclair No. 4 and Magmamax No. 1 wells. These compositions were then recalculated to nominal reservoir states by assuming appropriate wellhead qualities. An example of output from a typical computer run is shown for the case of reducing Magmamax No. 1 brine.

In general, the number of different mineral precipitates increases significantly as temperature decreases and pH increases. Siliceous scales consist of various kinds of crystalline heavy-metal sulfides dispersed within, or growing on, a fine-grained amorphous silica matrix. However, most of the predicted phases (largely silicates) are not observed in the matrix in the form of adsorption complexes on colloidal silica.

The failure of predicted substances to appear is not surprising and can be attributed primarily to the code's inability to consider kinetic data. This shortcoming can be partially resolved by "calibrating" the code, for a given chemical system, by interacting with scale-deposition experiments. When this is done, important scaling reactions can be predicted with some confidence, and valuable insights are gained with respect to scaling processes.

For instance, with lower pH, the code predicts and field observations confirm that the heavy-metal sulfide content of siliceous scales decreases. Other calculations indicate that heavy-metal sulfides can be eliminated by raising the oxidation potential of brine, but at the risk of precipitating oxides or sulfates.

We are currently studying the feasibility of using the Helgeson-Herrick code to model brine-rock interactions that might cause chemical plugging of reservoir rocks adjacent to injection wells. Although there are many problems associated with its use, this code can be a valuable analytical tool, useful in understanding complex chemical systems.

PIWINSKII, A. J. and Netherton, R., An Experimental Investigation of the Permeability of Kayenta and St. Peter Sandstones to Hypersaline Brine in the Temperature Interval 70°C-90°C at 10.3 MPa Confining Pressure, Lawrence Livermore Laboratory, Rept. UCRL-52382 (1977).

that these multicomponent solutions are slightly more viscous than a 3.5 M NaCl solution in this temperature interval.

Piwiński, A. J., NETHERTON, R. and Chan, M., "Viscosity of Brine from the Salton Sea Geothermal Field, California, from 25°C to 90°C at 100 kPa," Trans. Am. Geophys. Union 58, 1248 (1977). Lawrence Livermore Laboratory, Rept. UCRL-80016 Abstract (1977) .

The viscosity of natural, chemically-analyzed brine obtained from wells in the Salton Sea Geothermal Field, California, was determined at 100 kPa using a portable viscometer. 500 ml samples were obtained from both Woolsey and Magmamax No. 1 wells and heated in a constant temperature bath to $\pm 0.5^\circ\text{C}$. Viscosities were obtained of unmodified Woolsey and Magmamax No. 1 brine is approximately twice that of water at 30°C. Below 30°C, the viscosity of unmodified Woolsey and Magmamax No. 1 brine increases markedly to precipitation of iron-rich amorphous silica and heavy metal sulphides from these brines which contain approximately 20% total dissolved solids. Acidification of Magmamax No. 1 brine to a pH of 4.5 not only decreases its viscosity relative to unmodified brine, but also inhibits solids production at the lower temperatures.

PIWINSKII, A. J., Dengler, L., Netherton, R. and Trimmer, D. A., "Injection Studies: Section 5.5.1 Results; Section 5.5.2 Failure Modes; Section 5.5.3 Field Experiments," in The LLL Geothermal Energy Program Status Report January 1976-January 1977, Lawrence Livermore Laboratory, Rept. UCRL-50046-76, A. L. Austin, A. W. Lundberg, L. B. Owen, G. E. Tardiff, Eds. (Apr. 1977), p. 167-169.

Piwiński, A. J., DENGLER, L. A., Bonner, B. P., Netherton, R. and Trimmer, D. A., "Laboratory Investigations of Permeability Loss in Sedimentary Rocks," Trans. Am. Geophys. Union 58, 539 (1977). Lawrence Livermore Laboratory, Rept. UCRL-79197 Abstract (1977) .

Piwiński, A. J., DUBA, A., Heard, H. G. and Schock, R. N., Geothermal Prospecting and the Electrical Conductivity Changes Associated with Melting (Panel Mtg. Expl. Meth. of Dry Hot Rock (Los Alamos, June 1976) Los Alamos Scientific Laboratory, Rept. LA-6659-MS (1977), pp. 35-37. Lawrence Livermore Laboratory, Rept. UCRL-78261 Abstract (1977) .

Piwinskii, A. J., DUBA, A., Santor, M. and Weed, H. C., The Electrical Conductivity of Sandstone, Limestone, and Granite, Lawrence Livermore Laboratory, Rept. UCRL-77314 Preprint (1977).

Piwinskii, A. J., MILLER, D. and Yamauchi, R., The Use of Thermodynamic Equilibrium Codes for Estimating Precipitation from Geothermal Brines, Lawrence Livermore Laboratory, Rept. UCRL-52197 (1977).

Piwinskii, A. J., MILLER, D. and Yamauchi, R., Thermodynamic Equilibrium Codes: A Means of Modelling Precipitation Phenomena in the Salton Sea Geothermal Field Int. Sympos. Soc. of Pet. Eng. Am. AIME (San Diego, June 1977). Lawrence Livermore Laboratory, Rept. UCRL-79056 Preprint (1977); SPE Rept. 6604. 167-172 (1977).

Piwinskii, A. J. and SCARFE, C. M., "Physics and Chemistry of Silicate Melts and Magmas " Trans. Am. Geophys. Union 58 (1977), pp. 155-156; Canadian Mineralogist 15 (1977), pp. 133-134. Lawrence Livermore Laboratory, Rept. UCRL-76595 Abstract (1977) .

Modeling physiochemical magmatic processes occurring within the earth's crust and mantle can provide valuable insight into the generation, evolution, and emplacement of igneous rocks. A fundamental prerequisite is a knowledge of the properties of silicate melts and magmas. However, properties such as diffusion, nucleation, crystal growth, viscosity, electrical conductivity, volatile component solubility, thermodynamics, and structure have been neglected in the past and are not well understood for most melts of geological interest. In order to discuss some of the most recent work in these areas, a session was convened which would bring together geochemists, geophysicists, and material scientists currently working on experimental and theoretical aspects of silicate melts and magmas. The one-day session was held during the Annual Joint Meeting of the Geological and Mineralogical Associations of Canada, Edmonton, May 19-21, 1976.

Piwinskii, A. J., WEED, H. C. and Keller, P., Time Dependent Electrical Parameters of Rock-Solution Systems: Part I Int. Sympos. Soc. Pet. Eng. Am. AIME (San Diego, Jun. 1977). Lawrence Livermore Laboratory, Rept. UCRL-79013 Preprint (1977); SPE Rept. 6609 (1977), pp. 213-220.

PUCHLIK, K. P., Collection and Preparation of Wet and Dry Stream-Sediment Samples, Lawrence Livermore Laboratory, Rept. UCRL-79240 Preprint (Mar. 1977).

This paper discusses the collection and preparation of sediment samples in the Basin and Range Province.

The sample site locations for stream sediments must be related to the nature of the geology and the mobility of uranium in a given environment. In the Basin and Range we have chosen to emphasize stream sampling along the range front. In valleys, dry sediments are collected only along major drainages and only if range front sampling does not provide adequate coverage.

The collection of the sediment involves the gathering of a composite sample from five locations, five yards apart. In the case of dry sediment, the sample is sieved at the sampling site using a No. 3 sieve. The 0.5-to-1.0-mm size fraction appears to be more useful than finer fractions because the smaller sizes are subject to wind transport and commonly are enriched in resistate minerals.

The samples are then placed into polyethylene bags and returned to the laboratory. At the sample processing laboratory, the samples are placed in pyrex drying pans to be oven dried at $105^{\circ} \pm 5^{\circ}\text{C}$ and then sieved, blended and split. Three grams of the 500 to 1000 micrometer sample fraction are placed in polyethylene bags, sealed, weighed, and loaded into INAA rabbits for analysis.

PUCHLIK, K. P., Holder, B. E. and Smith, C. F., Lawrence Livermore Laboratory Hydrogeochemical and Stream Sediment Reconnaissance, Raw Data Report, Roach Lake Orientation Study, Kingman 10 x 20 NTMS Area, Nevada, NURE, Lawrence Livermore Laboratory, Rept. UCID-17681 (Dec. 1977).

This report presents the results of the Roach Lake Basin, Nevada, orientation study in the Kingman 10 x 20 quadrangle of the National Topographic Map Series (NTMS). Wet, dry, and playa sediment samples were collected throughout the 420 km² semi-arid, closed basin. Water samples were collected at the few available wells and springs. In addition to neutron activation analysis for uranium and 15 to 20 trace elements on all

samples, field and laboratory measurements were made on water samples. Analytical data and field measurements are presented in tabular hardcopy and fiche format. Four full-size overlays for use with the Kingman NTMS 1:250,000 quadrangle are included. Water site locations, water sample uranium concentration, sediment site locations, and sediment sample total uranium concentrations are shown on the separate overlays. A general description of the area and the rock type distribution is presented.

PUCHLIK, K. P., Holder, B. E. and Smith, C. F., Lawrence Livermore Laboratory Hydrogeochemical and Stream Sediment Reconnaissance, Raw Data Report, Cave Valley Orientation Study, Lund 1° x 2° NTMS Area, Nevada, NURE, Lawrence Livermore Laboratory, Rept. UCID-17648 (Nov. 1977).

This report presents the results of the Cave Valley, Nevada, orientation study in the Lund 1° x 2° quadrangle of the National Topographic Map Series (NTMS). Wet, dry, and playa sediment samples were collected throughout the 360 km² semi-arid, closed basin. Water samples to neutron activation analysis for uranium and 15 to 20 trace elements on all samples, field and laboratory measurements were made on water samples. Analytical data and field measurements are presented in tabular hardcopy and fiche format. Four full-size overlays for use with the Lund NTMS 1:250,000 quadrangle are included. Water site locations, water sample uranium concentration, sediment site locations, and sediment sample total uranium concentration are shown on the separate overlays. A general description of the area and the rock type distribution is presented.

QUALHEIM, B. J., Geological Exploration of Potential Underground Coal Gasification Sites in the Powder River Basin of Wyoming and Montana, Lawrence Livermore Laboratory, Rept. UCRL-52237 (Mar. 1977).

This report summarizes the information obtained from exploratory drilling of potential coal-gasification sites in the Powder River Basin of Wyoming and Montana. Our objectives were to obtain stratigraphic descriptions of the coal-bearing strata from cuttings and geophysical logs, determine the hydrologic characteristics of the coal and associated strata, and see if there were drilling and logging problems associated with the deep, thick coal seams.

During this work, it was decided to do preliminary hydrologic and gasification experiments on the shallower Felix coal before proceeding to more deeply buried coals. Geologic exploration of the shallow coal included determination of the lithology and stratigraphy and the measurement of the natural coal fracture orientation.

The types of information obtained in the exploratory program included 1) geophysical borehole logs, 2) lithologic and stratigraphic logs derived from drill cutting samples, 3) drilling rate data, 4) stratigraphic columns showing the depth and thickness of the coal and associated strata, 5) log analyses showing lithology, computer-generated average porosity, density and velocity, 6) composition diagrams of the geophysical logs run and the lithologic correlations picked from the logs, and 7) coal analysis from selected coal core obtained in the Felix Coal. Specifically, we found the Wyodak-Anderson coal ranged from 16 to 29 m thick at depths of 232 to 377 m from four holes drilled in the Powder River Basin. The Wall seam in one Montana drill hole was found at a depth of 156 m and was 15.8 m thick. The Felix coal at the preliminary gasification site was found in two seams of uniform thickness (3.4 and 7.6 m).

Rambo, J. T., TERHUNE, R. W., Glenn, H. D., Burton, D. E. and McKague, H. L., Calculation Examination of the Baneberry Event, to be presented at American Geophysical Union Spring Meeting (Miami, Florida, April 17-21, 1978). Lawrence Livermore Laboratory, Rept. UCRL-52365 (1977).

Rambo, J. T., TERHUNE, R. W., Glenn, H. D. and Burton, D. E., Containment Analysis for the Simultaneous Detonation of Two Nuclear Explosives, Lawrence Livermore Laboratory, Rept. UCRL-52268 (1977).

RAMSPOTT, L. D. and Ballou, L., Heater Experiments in the Climax Stock, Nevada Test Site, prepared for presentation at Waste Rock Interaction in the Immediate Vicinity Meeting (Penn State University, July 6-7, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79666 Abstract (Jun. 1977).

The Climax Stock is a composite granitic intrusive at the Nevada Test Site, with an existing shaft and an open drift about 1400 ft below the surface. In September, 1977, the Lawrence Livermore Laboratory plans to operate three in-situ heater experiments in this area.

The first experiment consists of a single heater surrounded by thermocouples at distances of from 1/10 to 5 meters. The close spacing will scale down the time required for useful thermal measurements. The heater, which is 3 meters long and capable of about 3 kW, will be energized for a month, turned off for a month, and the cycle repeated. The rock surface temperature in the heater hole is not expected to exceed 500 to 600°C, and the temperature beyond 0.1 m into the rock is not expected to exceed 400°C. Measurements will be taken during all four months. These measurements will be compared to numerical simulations to determine the thermal properties of the medium.

The second experiment, also involving only a single heater, will be more completely instrumented to include the measurement of permeability, rock displacement, stress/strain, and possibly acoustic emission measurements. The scale of the experiment will be larger, and the heater will be energized continuously for about 4 months.

The third test in the series is envisioned to be a scale-up of the second, except that multiple heaters will be used. These heaters will be energized for about a year. They will be arranged around a pillar structure left in the room to obtain information on mine stability in the presence of multiple heaters.

The experiments will be conducted in a quartz monzonite porphyry. It consists essentially of quartz and feldspar (about 90%) with minor amounts of other minerals, principally biotite (about 7-8%). Aside from chlorite (about 1-2%); all other minerals are present in amounts of less than 1%. Quartz ranges from 15-30 volume percent. The quartz monzonite is medium- to coarse-grained (1-4 mm in diameter), but contains large, pink, alkali feldspar crystals up to 5 cm in diameter. Approximately 1 weight percent of the rock is chemically combined water in biotite and other hydrous minerals. About 1-2 weight percent water is estimated to be localized in small-scale fractures and pores. The latter water is free to migrate under thermal or pressure gradients. The experiment level is about the regional water table. Except for small amounts from unconnected, scattered fractures, water inflow does not occur.

Although the stock is bounded on the east and west by active faults and contains numerous faults, joints, and fractures, relatively unfractured and

unfaulted areas suitable for a nuclear waste simulation thermal experiment are known. Some of the faults and joints are healed; that is, filled with secondary minerals. Apparently many of the numerous fractures are not interconnected, as measurements of background permeability in drill holes give values from a few millidarcies to tenths of millidarcies.

RAMSPOTT, L. D. and Borg, I. Y., Underground Nuclear Tests Below the Water Table as Waste Disposal Pilot Plants, Geological Society of America Annual Meeting, Symposium on Hydrogeology of Radioactive Waste Disposal (Seattle, Washington, Nov. 7-9, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79632 Abstract (1977).

Much of the radioactivity from nuclear tests is encapsulated in a glass originating from the vaporization and melting of the adjacent rock. Although the activity of fission products in the melt-glass is significantly less than that of either spent reactor-fuel or reprocessed waste, the concentrations of Pu and U are within a few orders of magnitude of reprocessed waste. Since 1962, there have been 94 tests below the water table at the Nevada Test Site. Thus, information obtained about the leaching and migration of radionuclides from these nuclear tests is relevant to modeling of migration from a nuclear waste repository.

The slow to moderate movement of the ground water in the aquifers within northern portions of NTS, 76 to 180 (maximum) meters/year depending on locale, has contributed to the slow movement of the tritium, the most mobile of the radionuclides. Sorptive processes are especially important in retarding nuclide movement at NTS. The altered tuffaceous rocks, which comprise a large portion of the rock in the saturated zone, are rich in zeolites (clinoptilolite) and clays (montmorillonite and illite), which effectively sorb many radionuclides moving through the formation.

In spite of the difficulties associated with a deep water table (about 600 meters), large volume water samples have been pumped within or near nuclear cavities in six instances. All data obtained have indicated that there has been minimal movement of radioactivity.

Ramspott, L. D., BORG, I. Y., Stone, R. and Levy, H. B., "Movement of Radioactivity Deposited at the U.S. ERDA Nevada Test Site," Transactions and Proceedings of Transfer of Nuclear Technology Conference (Atomic Energy Organization of Iran, Apr. 10-14, 1977). Lawrence Livermore Laboratory, Rept. UCRL-78670 Abstract (1977).

RODEAN, H. C., "Thermodynamic Relations for Shock Waves in Materials with a Linear Relation between Shock-Wave and Particle Velocities," in Journal of Applied Physics 48, (Jun. 1977). Lawrence Livermore Laboratory, Rept. UCRL-77441 (1977).

The Rankine-Hugoniot relations for shock waves and the empirical linear relation between the shock-wave and particle velocities define an incomplete thermodynamic description of the states along the Hugoniot curve. This incomplete description defines the following along the Hugoniot: (1) internal energy and pressure as functions of specific volume, (2) the ratio of enthalpy to internal energy, (3) the ratio of the changes in enthalpy and internal energy across a shock wave, and (4) the relation between the Gruneisen coefficient and the effective isentropic exponent. We use the Dugdale-MacDonald relation for the Gruneisen coefficient at low pressure, an assumed constant value for the specific heat at constant volume, and reasonable physical assumptions for extremely strong shock waves together with the incomplete thermodynamic state description to define the following along the Hugoniot: (5) the Gruneisen coefficient, (6) the effective isentropic exponent, (7) the ratio of specific heats, and (8) thermal and elastic components of pressure, temperature, and entropy. We present representative numerical values of these parameters as functions of reduced volumetric compression. We show how the solutions for these parameters, define tangent planes to the surfaces of the incomplete, E, P , and V and P, V , and T equations of state at each point along the Hugoniot curve.

PACS numbers: 62.50+p, 65.50+m, 65.40-f, 64.10+h.

Rodean, H. C., MARSHALL, P. D. and Springer, D. L., Magnitude Corrections for Attenuation in the Upper Mantle, submitted to Geophys. Jour. of the Royal Astron. Soc. Lawrence Livermore Laboratory, Rept. UCRL-80423 (1977).

ROTHMAN, A. J. and Lewis, A. E., Experimental Work on Oil Shale at LLL and Predictions of Retorting Characteristics of Oil Shales, presented at 11th Israel Conf. on Mechanical Engineering 1977 (Technion - Israel Instit. of Tech., Technion City, Haifa, Israel, Jul. 11-12). Lawrence Livermore Laboratory, Rept. UCRL-79630 Abstract (1977).

Oil shale technology in the United States is well enough developed to allow us to construct a predictive computer model of the retorting characteristics of oil shale based on knowledge of the composition and reactions. Agreement between predictions and experiments has been encouraging for the Green River formation in the United States.

By acquiring some specific information on other oil shales of the world, the model developed may be used to predict their retorting characteristics, thus saving significant development efforts otherwise required to establish operating conditions for application to these other oil shales. The paper includes a discussion of those properties of oil shale that have an important influence on the retorting process.

Analysis using the predictive computer model in this manner may be useful in estimating the feasibility of various oil shales for commercial production.

ROTHMAN, A. J. and Lewis, A. E., Lawrence Livermore Laboratory Oil Shale Project Quarterly Report, March-June 1977, Lawrence Livermore Laboratory, Rept. UCID-16986-77-2 (1977).

ROTHMAN, A. J., Oil Shale Project Quarterly Report July-September 1977, Lawrence Livermore Laboratory, Rept. UCID-16986-77-3 (Dec. 1977).

Rothman, A. J. and LEWIS, A. E., Modified In-Situ Technology--Experimental Results at Lawrence Livermore Laboratory and Present Status, presented at Amer. Nuclear Soc. Topical Meeting on Energy and Mineral Recovery Research (Golden, Colorado, Apr. 12-14). Lawrence Livermore Laboratory, Rept. UCRL-79149 Abstract (1977).

SANDHOLTZ, W. A. and Ackerman, F. J., Operating Laboratory Oil Shale Reports in an In-Situ Mode, prepared for Soc. of Petroleum Engineers 52nd Annual Meeting (Denver, Colorado, Oct. 9-12). Lawrence Livermore Laboratory, Rept. UCRL-79035 Preprint (Aug. 1977).

To study and develop the modified in situ oil-shale retorting process, LLL operates two laboratory oil-shale retorts. Experiments explore retorting parameters. Some results are compared with those of a predictive computer model. Some features of in situ processing are simulated in the laboratory by controlling heat losses and void fraction in the shale bed. A single computer system provides data acquisition and process controls for both retorts. Control methods and algorithms are discussed. Experimental results with and without control of heat losses are compared. Reasonable agreement exists in retorting rates, temperature profiles, and yields between the experimental measurements and the computer model. These, as far as we know, are the first retorting data taken under heat-loss and void-fraction conditions similar to those expected in situ. Retorting experiments on oil shale of uniform particle size have given yields of 99% of Fischer assay for inert gas, and of more than 90% for combustion retorting. Yield is decreased in packed beds with a wide range of particle sizes, similar to beds expected in situ.

SCHATZ, J. F., Effect of Porosity on the Mechanical Behavior of Rocks, presented at NSF Workshop on Mechanics Problems Associated with the Mining and Processing of Energy Related Minerals (Asilomar, California, Sept. 1977). Lawrence Livermore Laboratory, Rept. UCRL-79810 (1977).

All crustal rocks, in their natural state, contain pore space. The fraction of pore volume may be as little as tenths of a percent in some fine-grained igneous rocks, or as much as several tens of percent in other igneous rocks, poorly consolidated sedimentary rocks, and fractured rock. Pore space may contain water or other fluid. Pore geometry may vary from small, more-or-less spherical inclusions which are not interconnected, to long, tortuous, interconnected crack systems. With respect to energy-related resource recovery, porosity has three dominant effects. They are: (1) The pores contain fluids and allow the flow of fluids. Therefore, changes in porosity, or pore geometry, as caused either intentionally or not, can have considerable effect on resource recovery. (2) Inelastic deformation of the void system in a rock is the major cause of weakening, failure, and mechanical wave attenuation. Therefore, the intensity and range of effect of such operations as explosive-induced fracture for

permeability enhancement are dominated by porosity and pore geometry changes. (3) Porosity provides internal surface area in a rock. Therefore, the success and efficiency of in situ processing schemes also depends on porosity and pore geometry.

To predict porosity effects for the benefit of resource recovery planning, it is desirable to have models of behavior that are simple as possible in concept and in their mathematical expression, but that nevertheless represent as closely as possible the true physical mechanisms involved, rather than pure "curve fitting" to general expressions. In this way, extrapolations to regimes of behavior in which one cannot obtain direct measurements for confirmation are more reliably made. From a modeling viewpoint, void space in rocks can be described either as space between objects or holes in an otherwise continuous solid. These two viewpoints, although both in principle valid, have led to rather different models with different areas of application.

The modeling of pore behavior as changes in the geometry of objects in contact seems to have the most chance of success where the movement of the objects, and possibly their breakage, plays a dominant role in the behavior of interest. Such modeling has been used for the deformation of sand and the compaction of metal powders, but not extensively for rocks. New developments in computer techniques make the modeling of "rubble", or other masses of rock that may be described as "blocky" as objects in contact promising for application to resource recovery problems. The technique consists of actually building a model of rock blocks on the computer, with simplifying assumptions made to allow the efficient computation of block motion and interaction due to external forces, body forces and contact forces. Of particular hope is that the interconnection of pore space to allow fluid flow, and geometry changes as a result of processing, can be modeled by this technique.

In problems where elastic or inelastic compaction phenomena are of dominant interest, the modeling of porosity as holes in a continuous solid has had considerable success, particularly where the interconnection and/or interaction of holes is sufficiently unimportant that it can be ignored or approximated to a suitable degree. The effect of pore geometry and density on elastic behavior is fairly well known. Inelastic effects, as accounted

for by treating the solid rock as a Mohr-Coulomb solid, and treating the porosity as equivalent spherical pores, can do a very good job of modeling irreversible compaction and cycling effects. Therefore, wave propagation and attenuation are successfully attacked by these kinds of models. With the addition of statistical concepts and the use of fracture mechanics, it is possible that rock breakage and the associated changes in porosity and pore geometry can be accounted for, and some steps have been made in this direction, but it is still uncertain as to whether the fluid flow problem can be approached from this viewpoint.

In addition to modeling, measurement techniques must be invented or modified to be used for porosity effects. To determine the effect of pore geometry on the properties of interest, not only must "standard" stress-strain measurements be made, but we must directly observe the changes in pore geometry to determine the physical realism of a model, and, if possible, make coincident fluid flow measurements. Perhaps the most important problem left for the future is to account for the changes in the scale of pore geometry as one goes from a laboratory measured and modeled phenomena to one that occurs in the field. It is doubtful that one can ever have a fully satisfactory rock model that accounts for porosity effects in a particular recovery process without the input of at least one full-scale field test.

SCHATZ, J. F., Effect of Porosity on the Mechanical Behavior of Rocks, presented at NSF Workshop on Mechanics Problems Associated with the Mining and Processing of Energy Related Minerals (Asilomar, California, Sept. 1977). Lawrence Livermore Laboratory, Rept. UCRL-79810 (1977).

All crustal rocks, in their natural state, contain pore space. The fraction of pore volume may be as little as tenths of a percent in some fine-grained igneous rocks, or as much as several tens of percent in other igneous rocks, poorly consolidated sedimentary rocks, and fractured rock. Pore space may contain water or other fluid. Pore geometry may vary from small, more-or-less spherical inclusions which are not interconnected, to long, tortuous, interconnected crack systems. With respect to energy-related resource recovery, porosity has three dominant effects. They are:

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To predict porosity effects for the benefit of resource recovery planning, it is desirable to have models of behavior that are as simple as possible in concept and in their mathematical expression, but that nevertheless represent as closely as possible the true physical mechanisms involved, rather than pure "curve fitting" to general expressions. In this way, extrapolations to regimes of behavior in which one cannot obtain direct measurements for confirmation are more reliably made. From a modeling viewpoint, void space in rocks can be described either as space between objects or holes in an otherwise continuous solid. These two viewpoints, although both in principle valid, have led to rather different models with different areas of application.

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SCHATZ, J. F., Kusubov, A., Hearst, J. R., Abey, A. E., Snell, C. M. and Thigpen, L., Rock Mechanics Project Progress and Results: Rock Fracture and Pore Collapse, Lawrence Livermore Laboratory, Rept. UCID-17527 (May 1977).

We of the Rock Mechanics Project are studying problems in rock fracture and pore collapse with the intent of understanding mechanisms of and developing models for rubble formation, permeability enhancement, and wave

propagation. The progress and results of this project are outlined for the following studies:

1. Explosive-induced fracture and fluid flow in a gas-bearing sandstone at confining pressures to simulate in situ conditions,
2. Explosive-induced fracture in a brittle plastic with multiple charges fired both simultaneously and sequentially,
3. The effect of several intermediate-strain rates on strength and fracture in limestone, and
4. Development and testing of a theoretical model for yielding and pore collapse in porous rocks.

Schatz, J. F., BROWN, P. S., Burton, D. E., Butkovich, T. R. and Snell, C. M., Calculational Modeling of Explosive Fracture in Natural Resource Formations, presented at Amer. Assoc. Advanc. Sci. Annual Mtg., (Washington, D.C., Feb. 12-17, 1978). Lawrence Livermore Laboratory, Rept. UCRL-80212 Abstract (Oct. 1977).

Schatz, J. F. and KASAMEYER, P. W., "Well-Log Resistivity Evaluation," in The LLL Geothermal Energy Program Status Report January 1976-January 1977, Lawrence Livermore Laboratory, Rept. UCRL-50046-76, Section 5.3.2, A. L. Austin, A. W. Lunberg, L. B. Owen, G. E. Tardiff (Apr. 1977), p. 136.

SCHOCK, R. N., Generalized Models for Rock Response to Stress, presented at Amer. Assoc. Advanc. Sci., Annual Mtg. (Washington, D.C., Feb. 12-17, 1978). Lawrence Livermore Laboratory, Rept. UCRL-80216 Abstract (Oct. 1977).

It is commonly necessary to fracture a resource for purposes of economically feasible extraction or in situ processing. Laboratory experimental data of three-dimensional stress-strain behavior can be used to predict the response of rock to explosive or impact loading by identifying the important parameters which determine that response. These data have demonstrated the importance of shear stress, mean pressure, and strain rate in defining explicit regions of behavior. Brittle rocks exhibit a characteristic strength followed by rupture and a pronounced inelastic volume dilatancy before they fail. Some rocks fail in a ductile-like manner, and confining pressure is known to enhance this effect. However, increasing strain rate has the effect of enhancing brittle behavior.

Porosity has a strong effect on the response of rocks to stress, the pore fluid and shape, as well as the matrix serving to control the observed behavior. Observations such as these serve as a guide in the development of models for use in predicting the effects of stress on rock.

SCHOCK, R. N., Inelastic Response of Rock to Stress, presented at Workshop on Mechanics Problems Associated with the Mining and Processing of Energy Related Minerals (Asilomar Conference Grounds, Sept. 14-16, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79799 Abstract (1977).

It is commonly necessary to fracture a resource as part of economically feasible extraction or in situ processing. To predict the effect on a material of a stress wave driven by an explosive or other impacting source, knowledge of the relation between stress and mechanical response is crucial. The proportions of work done by the stress wave in the form of heat, elastic or inelastic deformation, fracture, or compaction, are directly dependent on the response (strain) for a given stress state. Laboratory experimental data shed light on the response of rocks to stress waves, and analyses of these data, collectively with that obtained in the field, can lead to generalizations which are useful in modeling rock behavior. As part of this scheme, a basic understanding of the physical processes responsible for observed behavior is necessary so that models developed can be applicable to a broad range of stress and strain conditions and rock types.

All rocks or mineral resources may be classified according to the manner in which they fail by one or more of the terms: brittle, ductile, and porous. Brittle rocks exhibit a characteristic strength followed by rupture. One of the most striking characteristics of low-porosity brittle rocks is a pronounced inelastic volume dilatancy before they fail in compression. At constant strain rate, both the onset of this behavior and ultimate strength are independent of loading path used to achieve a given stress condition, suggesting a uniqueness in strain with respect to total stress state even in this inelastic regime. This hypothesis has been verified and used to develop a constitutive relation that expresses inelastic dilatant strain ϵ_d as

$$\epsilon_d(\bar{\sigma}, \tau) = b_0(\bar{\sigma}) \exp b_1(\bar{\sigma})$$

where b_0 and b_1 are material constants and σ and τ are the mean stress and shear stress, respectively. Although the physical meaning of the exponential form is not yet clear, the relation expresses rock behavior in terms of a small number of experimentally measurable and thermodynamically meaningful parameters and can predict failure stress accurately. When one or more of the principal stresses are tensile, dilatancy has also been observed and is a simple function of the principal tensile stress-principal compression stress ratio. Brittle fracture strength is a strong function of strain rate and increases at about five percent per ten-fold increase in strain rate. There is evidence that the dilatant strain is reduced as strain rate increases but that there is ultimately an increasing amount of pulverized rock, rather than a few through-going fractures.

Some rocks contain minerals that are ductile at normal pressures. With increasing confining pressure, many of the mineral constituents in a rock that behave in a brittle manner at low confining pressure undergo a transition from brittle to ductile behavior. In addition, many rocks whose individual minerals are still brittle will, because of their polycrystalline nature, exhibit increased frictional forces across grain boundaries followed by intergranular sliding. The net effect of any one or all of these processes is reflected in a response which can be described as ductile; that is a maximum shear stress is not associated with a fixed strain but rather both stress and strain continue to increase usually in a highly non-linear relation. Dilatancy is an inherent property of brittle rocks and diminishes as ductile flow becomes predominant, whether the macroscopic principle stresses are compressive or tensile. Increasing strain rate in ductile rocks has the effect of stiffening the stress-strain relation and of enhancing brittle behavior at fixed confining pressure by raising the brittle-ductile transition pressure. Thus, brittle deformation is enhanced during explosive deformation over that observed during experiments at normal laboratory strain rates.

Porosity has a strong effect on the mechanical response of rocks to stress. Pore deformation is controlled by both the response of the rock

matrix and the pore fluid. When the pore fluid is a gas, catastrophic pore collapse rather than fracture of flow becomes the dominant failure mechanism. Pressure-volume response, and therefore energy absorption, during pore collapse is a function of the shear stress and is therefore stress path dependent, unlike the dilatant region previously discussed. Simplified constitutive relations which describe the pore-collapse process itself have been developed.

Water or other liquids confined in the pores strongly influence behavior, with the collapse of porosity being controlled primarily by the liquid compressibility. Pressure on the liquid affects failure stress by relieving some or all of the applied differential stress. Fully saturated rocks are weaker than when dry. Dilatant behavior in liquid saturated rocks has the effect of decreasing the liquid pressure and may even result in an undersaturated condition. Movement of fluid through interconnections between pore space now becomes the controlling factor to the equilibration of stress and hence to observed behavior. This movement is a strong function of viscosity and therefore of strain rate.

When taken collectively, observations such as these can be used to develop simplified constitutive models which can then be used to predict the response of rock to explosive or impact loading by identifying the important parameters which determine that response. The importance of shear stress, mean pressure, and strain rate, in defining explicit regions of behavior is now clear. Simple constitutive relations which describe behavior within specific regions seem warranted. However, care must be taken when extrapolating the generalizations beyond the conditions under which the observations were made. More work is needed to quantify the influence of other variables which may influence rock response but which have not been well studied. Cyclic loading is known to affect strength, dilatant behavior, and compaction. The effect of intermediate principal stresses also appears to affect rock response. Sample size certainly limits the usefulness of detailed laboratory data by precluding the effects of flaws whose dimensions exceed the sample (joints, bedding and fissile planes, cleats, faults, boundaries of blocks in rubble). Attention should be paid to the interpretation of low stress-high frequency acoustic velocity and attenuation data for inelastic materials such as rocks, as these hold

promise of yielding much information about how rock responds to high stress-low frequency stress waves.

SCHOCK, R. N., Duba, A. G., Heard, H. C. and Stromberg, H. D., "The Electrical Conductivity of Polycrystalline Olivine and Pyroxene Under Pressure", in High-Pressure Research, Applications in Geophysics, eds. M. M. Manghnani, and S. Akimoto (Academic Press, New York, pp. 39-51 (1977)).
Lawrence Livermore Laboratory, Rept. UCRL-78048 Preprint (1977) .

Electrical conductivity (σ) measurements on polycrystalline olivine and pyroxene were made at pressures up to 5.0 GPa and at temperatures up to 1200°C to examine the effect of grain boundaries on conduction. Values of σ were observed within one-half order of magnitude of those for single crystals at lower pressures and under controlled oxygen fugacity (f_{O_2}). If this difference prevails over the entire temperature range, these values result in temperature profiles for the earth and moon that are lower than profiles from single-crystal data by no more than 200°C. However the small σ differences between single and polycrystals most probably are due to a higher f_{O_2} in the experimental apparatus rather than the presence of grain boundaries. The data indicate pressure has a small effect on conductivity and activation enthalpies associated with conduction.

SCHOCK, R. N. and Louis, H., Strain Behavior of a Granite and a Graywacke Sandstone in Tension, presented at Annual American Geophysics Union Fall Meeting (San Francisco, California, Dec. 5-9, 1977). Lawrence Livermore Laboratory, Rept. UCRL-80051 Abstract (1977).

Ten samples of Westerly granite and six of Lance graywacke (8.5% porosity) were deformed in extension with the axial stress ($\sigma_3 < \sigma_2 = \sigma_1$) tensile. Both of these rocks fail in a brittle manner in compression at low confining pressure. The apparatus used was that developed for fluid end-loading of cylindrical samples. The tensile stress is directly proportional to the confining pressure ($\sigma_2 = \sigma_1$), the ratio σ_3/σ_1 being determined by the ratio of sample throat to end diameters. In all tests, both axial and circumferential strain was continuously measured with foil strain-gages. Stress paths with σ_3/σ_1 as low as -2.0 were achieved. In granite, dilatant behavior

(negative effective bulk modulus) precedes failure when σ_3 is tensile. The amount of dilatancy before brittle failure is observed to be a strong function of σ_3/σ_1 , varying between two extremes. Only compression and no dilatant behavior is observed when $\sigma_3/\sigma_1 > 0$ (simple extension). No compression and only dilatant behavior is observed when $\sigma_3/\sigma_1 < 1.5$. It appears that preferentially oriented cracks are pulled open by the tensile stress when compressive stress is lowest. In contrast the graywacke sandstone loaded in a similar manner exhibits little tendency to dilate prior to failure. The explanation of this behavior must lie in the nature of the predominant cracks in the two rocks. In order for tensile stresses of the order of megapascals (tens of bars) to open cracks in granite, aspect ratios must be very small ($< 10^{-5}$). Thus the average aspect ratio of preferentially oriented cracks present in this sandstone must be large enough to preclude appreciable opening, before the stress at the crack tip is such that the crack propagates.

Schock, R. N. and COSTANTINO, M. S., An Empirical Relation for Dilatant Behavior in Brittle Rocks, Sixth Intl. High Pressure Conf. (AIRET, Boulder, Colorado, Jul. 1977). Lawrence Livermore Laboratory, Rept. UCRL-79011 Preprint (1977).

Schock, R. N. and COSTANTINO, M. S., An Empirical Relation for Dilatant Strain in Low Porosity Rock, Am. Nucl. Soc., Topical Mtg. (Golden, Colorado, Apr. 1977). Lawrence Livermore Laboratory, Rept. UCRL-79355 Abstract (1977).

Schock, R. N., DUBA, A. G., Heard, H. C. and Chakrabarty, M. R., The Electrical Conductivity Tensor of Olivine Under Controlled Oxygen Fugacity, Trans. Am. Geophys. Union 58 (1977), pp. 1235-1236. Lawrence Livermore Laboratory, Rept. UCRL-80023 Abstract (1977).

Schock, R. N., DUBA, A. G., Heard, H. C., and Piwinski, A. J., Geothermal Prospecting and the Electrical Conductivity Changes Associated With Melting, Panel Mtg. Expl. Meth. of Dry Hot Rock (Los Alamos, Jun. 1976) Los Alamos Scientific Laboratory, Rept. LA-6659-MS (1977), pp. 35-37. Lawrence Livermore Laboratory, Rept. UCRL-78261 Abstract (1977).

SCHWARTZ, L. L., Emerson, D. O., Tewhey, J. D. and Beiriger, W. J., The Importance of Geosciences in Developing In Situ Technologies for Energy Resource Recovery, presented at Amer. Assoc. Advanc. Sci. Annual Mtg. (Washington, D.C., Feb. 12-17, 1978). Lawrence Livermore Laboratory, Rept. UCRL-80218 Abstract (Oct. 1977).

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

Springer, D. L., MARSHALL, P. D. and Rodean, H. C., Magnitude Corrections for Attenuation in the Upper Mantle, submitted to Geophys. Jour. of the Royal Astron. Soc. Lawrence Livermore Laboratory, Rept. UCRL-80423 (1977).

It was first noted in 1969 that the $m_b:M_s$ relation for explosions at NTS is different from the $m_b:M_s$ relations for explosions in other parts of the world. One possible reason for the different relation for NTS explosions is relatively high body-wave attenuation in the upper mantle beneath the NTS. We have developed a correction for this attenuation based on the hypothesis that there is a relation between the P_n -wave velocity and the effective Q_α for the upper mantle. We have defined a new body-wave magnitude called m_Q which includes a correction for attenuation at both the receiver and the source ends of the teleseismic body-wave path. We show that use of m_Q instead of the usual m_b results in a common

$m_q M_s$ relation for a world-wide set of explosions and common m_q yield relations for explosions with similar seismic coupling.

Shaffer, R. J., HANSON, M. E., Anderson, G. D., Heard, H. C., Emerson, D. O., Knutson, C. and Haimson, B., LLL Gas Stimulation Program, Quarterly Progress Report, July through September 1977, Lawrence Livermore Laboratory, Rept. UCRL-50036-77-3 (Oct. 1977).

Shaffer, R. J., HANSON, M. E., Anderson, G. D., Heard, H. C. and Montan, D. N., LLL Gas Stimulation Program, Quarterly Progress Report, January through March 1977, Lawrence Livermore Laboratory, Rept. UCRL-50036-77-1 (May 1977).

Shaffer, R. J., HANSON, M. E., Anderson, G. D., Heard, H. C., Tonnessen, K. A., Montan, D. N. and Knutson, C. F., LLL Gas Stimulation Program, Quarterly Progress Report, April through June 1977, Lawrence Livermore Laboratory, Rept. UCRL-50036-77-2 (Aug. 1977).

Shaffer, R. J., HANSON, M. E., Heard, H. C. and Hearst, J. R., LLL Gas Stimulation Program, Quarterly Progress Report, October through December 1976, Lawrence Livermore Laboratory, Rept. UCRL-50036-76-4 (Feb. 1977).

Shaffer, R. J., HANSON, M. E., Hearst, J. R., Anderson, G. D., Montan, D. N., Heard, H. C. and Emerson, D. O., Update on the LLL Gas Stimulation Program, submitted to 3rd Ann. ERDA Symp. on Enhanced Oil and Gas Recovery (Tulsa, Oklahoma, Aug. 30-Sept. 1, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79587 Preprint (Jul. 1977).

Snell, C. M., BROWN, P. S., Burton, D. E., Butkovich, T. R., and Schatz, J. F., Calculational Modeling of Explosive Fracture in Natural Resource Formations, presented at Amer. Assoc. Advanc. Sci. Annual Mtg. (Washington, D.C., Feb. 12-17, 1978). Lawrence Livermore Laboratory, Rept. UCRL-80212 Abstract (Oct. 1977).

Snell, C. M., BRYAN, J. B., Heusinkveld, M., Burton, D. E., Bruce, A. L., Lettis, Jr., L. A. and Butkovich, T. R., Controlled Blasting Calculations and Experiments, ANS Topical Meeting, Energy and Mineral Resource Recovery (Colorado School of Mines, Golden, Colorado, Apr. 12-14, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79109 Preprint (1977).

Snell, C. M., SCHATZ, J. F., Kusubov, A., Hearst, J. R., Abey, A. E. and Thigpen, L., Rock Mechanics Project Progress and Results: Rock Fracture and Pore Collapse, Lawrence Livermore Laboratory, Rept. UCID-17527 (May 1977).

Snell, C. M., WALTON, O. R., Bryan, J. B., Thomsen, J. M. and Goodrich, M., Effects of Porosity, Strength and Water Content on Attenuation of Stresses Generated by Subsurface Explosions in Soils, ANS Topical Meeting, Energy and Mineral Resource Recovery (Colorado School of Mines, Golden, Colorado, April 12-14, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79113 (1977).

STONE, R., Measurement of the Spatial Variation of Hydraulic Characteristics of an Explosion-Fractured Coal Seam, Lawrence Livermore Laboratory, Rept. UCRL-52298 (1977).

A series of preliminary incremental slug-withdrawal tests were conducted in the Felix No. 2 coal seam to determine how the hydraulic properties of the coal were affected by the detonation of two, 340-kg explosive charges near its base. For the tests, three wells completed in the seam at various distances from the explosive emplacements were used. The wells were constructed and tested in a manner that allowed estimation of the hydraulic conductivity of the upper, middle, and lower parts of the seam. Test results showed some increased permeability 12.6 m from the nearest explosion and greatly increased permeability in the lower third of the seam between 5.8 and 7.6 m from the nearest explosion site. The results also indicated that hydraulic conductivity is proportionate to the degree of coal fracturing. The incremental slug-withdrawal tests provided a simple, relatively rapid, and economical measure of the vertical and areal variation of local hydraulic conductivity in the explosion-fractured coal seam.

Stone, R. and HOFFMAN, D. C., Radioactivity Deposited Underground by the Cambrian Nuclear Explosion at the Nevada Test Site, presented at 1977 Annual Mtg., Geol. Soc. Am. (Seattle, Washington, Nov. 7-9, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79631 Abstract (1977).

The first investigation to successfully characterize the radionuclide distribution in both ground water and rock in the environment around the detonation point of an underground nuclear test was carried out at the site

of the 0.75-kt Cambric test at the Nevada Test Site ten years after its detonation. The Cambric test took place in tuffaceous alluvium, 300 m below the surface of Frenchman Flat, in 1965. In the course of constructing a well through the explosion zone, an extensive suite of samples of alluvium and debris was obtained from near ground level to below the original explosion cavity. Five different zones in the well were isolated and representative water samples were pumped from each zone in succession. No activity above the natural background was observed in water from a region 50 m below the original explosion cavity. Water from the region of highest radioactivity at the bottom of the cavity contained tritium, ^{85}Kr , ^{90}Sr , ^{106}Ru , ^{125}Sb , ^{137}Cs , and negligible amounts of ^{144}Ce and ^{239}Pu . Of these, only tritium and ^{90}Sr were presented at levels higher than the recommended concentration guides for drinking water. The level of ^{106}Ru was two times lower, that of ^{125}Sb and ^{137}Cs were 20 or more times lower, ^{144}Ce was more than 100 times lower, and the level of ^{239}Pu was 600 times lower than the recommended concentration guides. After ten years, most of the radioactivity is still retained in vitrified or fused debris within the region of the original cavity created by the explosion.

STONE, R. and Snoeberger, D. F., "Cleat Orientation and Areal Hydraulic Anisotropy of a Wyoming Coal Aquifer," Ground Water 15, 6, (Nov.-Dec. 1977), pp. 434-438. Lawrence Livermore Laboratory, Rept. UCRL-79045 Preprint (1977) .

The anisotropic, areal hydraulic conductivity of the Felix No. 2 coal (Eocene, Wasatch Formation) has been defined in a four-well pump test at a site in the Powder River Basin of northeastern Wyoming. The direction of maximum draulic conductivity of the subbituminous coal bed bears N59°E and is associated with a horizontal hydraulic conductivity of 0.27 m/day. The direction of minimum hydraulic conductivity bears N31°W and is associated with a horizontal hydraulic conductivity of 0.15 m/day. The direction of maximum hydraulic conductivity approximately corresponds to the trend of the prominent face cleat in the coal, while the direction of minimum hydraulic conductivity corresponds to the trend of the butt cleat. The cleat orientation appears related to the alignment of major structural features of the region. Prediction of the direction of both maximum and minimum

horizontal hydraulic conductivity in near-horizontal coal beds appears possible. However, either the cleat orientation of the bed or the alignment of the controlling fold structure must be known or obtainable.

Stone, R., BORG, I. Y., Levy, H. B. and Ramspott, L. D., Movement of Radioactivity Deposited at the U.S. ERDA Nevada Test Site, Transactions and Proceedings of Transfer of Nuclear Technology Conference (Atomic Energy Organization of Iran, Apr. 10-14, 1977). Lawrence Livermore Laboratory, Rept. UCRL-78670 Abstract (1977) .

TERHUNE, R. W. and Carlson, R. C., Site Characterization Requirements for Nuclear-Cratering Design, Lawrence Livermore Laboratory, Rept. UCRL-52253 (Mar. 1977).

This paper presents a material properties measurement program for the design of large engineering, nuclear-excavation projects by computer calculation. Material properties of the site and their relative effect on crater size are analyzed and ordered in relation to their importance in determining the overall cratering efficiency. The measurement program includes both in situ logging and laboratory measurement of core samples, together with the reason for each measurement and its use in the calculations.

TERHUNE, R. W. and Glenn, H. D., Estimate of Earth Media Shear Strength at the Nevada Test Site, Lawrence Livermore Laboratory, Rept. UCRL-52358 (Nov. 1977).

We present a method of estimating the effective shear strength of the fractured rock that surrounds a nuclear detonation. To do this, we measure the cavity radii from previous detonations. We also use numerical computer codes to model the explosion phenomenology and develop the functional relationship between the normalized cavity displacement and the normalized shear strength of the rock. In this sense, the computer codes serve as replica models that are dimensionally analyzed to interpret the field experience. We separate the effects of gravity and overburden pressure from the effects of the material properties and give scaling laws for each. We have analyzed approximately 300 nuclear detonations at the Nevada Test Site (NTS) and have found that the most frequent shear strengths are between 0.20

and 0.60 kbars. They are also essentially independent of the depth-of-burial ranges considered. We obtained good agreement between predicted shear strengths and those measured from core samples for different areas at the Nevada Test Site.

TERHUNE, R. W. and Glenn, H. D., Estimate of Residual Shear Strength Around Explosive Sources in Earth Media, to be presented at 19th Symposium on Rock Mechanics (Mackay School of Mines, University of Nevada, State-line, Nevada, May 1-3, 1978). Lawrence Livermore Laboratory, Rept. UCRL-80393 Abstract (1977).

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

Numerical computer codes that model the explosion phenomenology are utilized to develop the function relationship between the normalized cavity displacement and the normalized shear strength of the rock. In this sense, the computer models serve the role of a replica model to which dimensional analysis is applied to interpret the field experience. The effects of gravity and overburden pressure are separated from the effects of the material properties and scaling laws for each are given. The analysis is applied to approximately 300 nuclear detonations at the Nevada Test Site for a variety of rock types. Good agreement was obtained between the predicted shear strengths and those from numerous laboratory measurements on core samples.

TERHUNE, R. W., Glenn, H. D., Burton, D. E., McKague, H. L. and Rambo, J. T., Calculational Examination of the Baneberry Event, Lawrence Livermore Laboratory, Rept. UCRL-52365 (Dec. 1977).

On December 18, 1970, Baneberry, a 10-kt nuclear device, was detonated at a depth of 278 m in hole U8d at the Nevada Test Site. A shock-induced fissure near ground zero opened and vented radioactive gases and debris into the atmosphere. This report presents the calculational results describing the sequence of dynamic phenomena that produced the vent. The calculations predict the long positive velocity pulse and the surface motion that were

observed experimentally. The surface fissure through which the material vented is the same radial distance from ground zero as the maximum horizontal displacement is calculated to be. The calculations predict a final cavity radius that is very close to the measured Baneberry radius. Finally, the calculations indicate that an open fracture path runs from the cavity to the Baneberry Fault, up the fault to the spall region, and then vertically to the surface. This was the vent path predicted by calculations and is consistent with the vent path found from the radioactivity in postshot drill holes. Because of our extensions in computational capabilities, we believe this report advances the state of the art for numerical simulation of the containment problems associated with underground nuclear tests.

TERHUNE, R. W., Glenn, H. D., Burton, D. E., McKague, H. L. and Rambo, J. T., Calculational Examination of the Baneberry Event, to be presented at American Geophysical Union Spring Meeting (Miami, Florida, Apr. 17-21, 1978). Lawrence Livermore Laboratory, Rept. UCRL-80600 Abstract (1977).

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

TERHUNE, R. W., Glenn, H. D., Burton, D. E. and Rambo, J. T., Containment Analysis for the Simultaneous Detonation of Two Nuclear Explosives, Lawrence Livermore Laboratory, Rept. UCRL-52268 (1977).

In this report, we examine the explosive phenomenology associated with the simultaneous detonation of two 2.2-kt nuclear explosives and present a comprehensive spatial-time pictorial of the resultant shock-wave phenomenology. The explosives were buried at depths of 200 m and 280 m, corresponding to a separation of approximately 4 final cavity radii. Constitutive relations for the surrounding medium were derived from the geophysical logs and core samples taken from an actual emplacement configuration at the Nevada Test Site. Past calculational studies indicate that successful containment may depend upon the development of a strong tangential-stress field (or "containment cage") surrounding the cavity at late times. We present a series of conditions that must be met to insure formation of this cage. Our calculational results, based on one- and two-dimensional finite-difference codes of continuum mechanics, describe how each condition has been fulfilled and illustrate the dynamic sequence of events important to the formation of the containment cage. They also indicate, at least for the geological site chosen, that two nuclear explosives do not combine to threaten containment.

Terhune, R. W., HANSON, M. E. and McKee, C. R., Explosive Enhancement of Permeability, presented at Sixth AIRAPT Intl. High Pressure Conf. (Univ. of Colorado, Boulder, Colorado, Jul. 25-29, 1977). Lawrence Livermore Laboratory, Rept. UCRL-78207, Rev. 1 (May 1977).

TEWHEY, J. D., Geological Characteristics of a Portion of the Salton Sea Geothermal Field, Geothermal Resources Council, Transactions, vol. 1, May 1977 - presented at Annual Meeting (San Diego, May 9-11, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79352 Abstract Apr. (1977).

Petrographic analysis of drill cutting samples from the Magmamax Nos. 2 and 3 and Woolsey No. 1 well in the Salton Sea Geothermal Field has resulted in the categorization of the sedimentary sequence. The cap rock extends to 325 m and unaltered reservoir rocks occur to approximately 900 m. The lowermost sequence is hydrothermally altered reservoir rocks. Laboratory measurements of core samples indicate a reduction in porosity with depth and

fracture porosity appears to contribute to the total porosity of the system. The geologic picture that emerges from SP log correlation is that of a structural basin whose axis lies to the northwest of Magmamax No. 2.

TEWHEY, J. D., Geologic Characteristics of a Portion of the Salton Sea Geothermal Field, Lawrence Livermore Laboratory, Rept. UCRL-52267 (Apr. 1977).

The examination of drill cuttings and core samples from the Magmamax Nos. 2 and 3 and Woolsey No. 1 wells indicate that the sequence of sedimentary rocks in the Salton Sea geothermal field from the surface to below 4000 ft (1200 m) can be divided into three categories: (1) cap rock, (2) unaltered reservoir rocks, and (3) hydrothermally altered reservoir rocks. The cap rock extends from the surface to a depth of approximately 1100 ft (350 m) in all three wells. The uppermost 600 ft (200 m) of the cap rock consists of unconsolidated silt, sand, and gravel. The interval from 600 to 1100 ft (200 to 350 m) consists of anhydrite-rich evaporites in a carbonate-clay matrix and has low permeability. There is evidence to suggest that the cap rock has undergone self-sealing through time as a result of the circulation of hot brine through the rocks. Essentially unaltered reservoir rocks extend from a depth of 1100 ft (350 m) to approximately 3000 ft (900 m). The sequence consists principally of well-indurated shales, siltstones, and sandstones consisting of clastic quartz and feldspar grains cemented with calcite and/or silica. The mineralogical and textural changes that occur at depth can be attributed to the process of hydrothermal alteration. Alteration has occurred in a chemically open system and the important variables in the alteration scheme have been temperature, permeability, brine composition, and rock composition. The transition from unaltered to altered reservoir rocks is marked by the replacement of calcite by epidote. The first appearance of epidote correlates reasonably well with the top of the alteration zone as determined in other studies by electric log analysis. Biotite and chlorite, potential indicators of alteration zones, are considered to be of detrital origin rather than hydrothermal origin. The primary effect of hydrothermal alteration on the reservoir rocks in the Salton Sea geothermal field has been the reduction of porosity and permeability with depth. Petrographic

analysis indicates that porosity and permeability in the field is enhanced by the presence of fractures in shales. Spontaneous potential (SP) log correlation is possible for the wells studied, and the geologic picture that emerges from the correlation scheme is that of a structural basin whose axis lies to the northwest of Magmamax No. 2. Geothermal production characteristics vary with depth and position in the field as a result of temperature, salinity, and porosity/permeability gradients in the reservoir. The data suggests that unaltered reservoir rocks on the periphery of the field offer good production possibilities.

TEWHEY, J. D., The Distribution of Uranium in Sediment Samples as Determined by Multi-Element Analysis, presented at USGS Uranium-Thorium Symp. (Colorado School of Mines, Golden, Colorado, Apr. 27-28, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79274 (1977).

A number of sediment samples collected from the Walker River, Winnemucca, and Smoke Creek Basins, Nevada, as part of a National Uranium Resource Evaluation (NURE) program orientation study, was selected for detailed analysis in order to determine the nature of the uranium distribution in sediments from a semiarid environment. The results of this study suggest that an estimate of the leachable versus nonleachable uranium in samples studied can be made on the basis of certain geochemical indicators that are obtainable by means of multielement instrumental neutron activation analysis (INAA).

Sediment samples were split into seven size fractions ranging from 63 μ to 2000 μ and each fraction was subjected to a 30-element INAA (including uranium) to determine its bulk chemical characteristics. Each split was then subjected to a heavy-liquid separation to facilitate optical mineralogical analysis. Light fractions (3.19 g/cm^3) consisted primarily of quartz, feldspar and mica; heavy fractions (3.19 g/cm^3) commonly consisted of sphene, zircon, magnetite, hematite, epidote, augite, and hornblende. The contribution that each mineral made towards the total uranium content of the split was determined by using the average abundance of uranium in the mineral, or by analyzing representative mineral fragments from one of the larger size fractions by INAA. In the latter case, the contribution from leachable uranium was minimized by (1) keeping a small

ratio of surface areas to mass by choosing several large grains for analysis rather than many small ones, and (2) by washing the grains prior to analysis. For each size fraction, the difference between the total uranium in the sample and the sum of the contributions of the individual minerals was considered to represent the leachable uranium. The amount of leachable uranium in the various size fractions determined by the procedure described above correlates reasonably well with the amount determined by acid-leaching experiments. The absolute amount of leachable uranium as analyzed by leaching experiments is always less than the amount calculated on the basis of INAA, but the relative amounts in the various size fractions and in different samples as determined by the two methods are correlative.

Through analysis of the INAA data for eight samples, it has been found that the amount of leachable uranium in samples from the area studied can be correlated with certain geochemical parameters, such as Th/U ratios and Zr and La values. Sediment samples containing heavy resistate minerals often exhibit moderately high uranium concentrations and concomitant low values of leachable uranium. In general, heavy resistate minerals are characterized by having high Th/U ratios. The resistates from the area studied are also characterized by moderately high concentrations of Zr and the rare earth elements. Weighted Zr-La values (ppm Zr + 10 ppm La) are plotted against the Th/U ratio of fine- and coarse-grained size fractions of eight sediment samples. An indication of the percentage of leachable uranium with respect to the total uranium concentration, as determined by acid leaching experiments, is given for each sample. Note that samples with high percentages of leachable uranium (solid circles) tend to be characterized by low Th/U ratios and low Zr-La values, and those exhibiting low values of leachable uranium (open circles) tend to have higher Th/U ratios and Zr-La values. It is suggested that the data derived from multielement INAA can be used to estimate the amount of leachable uranium in a sample without having to conduct costly and time-consuming acid-leaching experiments.

TEWHEY, J. D., The Effect of Hydrothermal Alteration on Porosity and Permeability in the Salton Sea Geothermal Field, California, presented at Ann. Mtg. of the GSA and Associated Societies (Seattle, Washington, Nov. 7-9, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79623 (1977).

On the basis of studies of drill cuttings, core samples, and geophysical logs from geothermal wells, the sequence of sedimentary rocks in the Salton Sea geothermal field can be divided into three categories: cap rock, reservoir rock and hydrothermally altered reservoir rock. The cap rock is a zone of low porosity and permeability consisting of anhydrite-rich evaporite deposits in a carbonate-clay matrix. Permeable reservoir rocks have been subjected to hydrothermal alteration as a result of their interaction with hot, saline brine. The principal effect of alteration, in particular the epidote-producing reaction, has been the reduction of porosity and permeability with depth. The porosity of westward-dipping sandstone aquifers is $\geq 20\%$ above the eastward-dipping epidote isograd and $< 10\%$ below the isograd. The isograd corresponds approximately to the 285°C isotherm. Intergranular porosity in reservoir rocks is subject to irreversible self-sealing due to alteration, whereas fractures can be considered as "renewable porosity" in that they can be reactivated subsequent to being sealed. Fractures are common in shales with fracture porosity estimated as $< 10\%$. Cathodoluminescence of calcite-filled fractures commonly reveal two or more episodes of fracturing and sealing. This suggests that the seismicity in the Salton Trough may play a role in maintaining fracture permeability in the reservoir.

Tewhey, J. D. and CHAN, M. A., Subsurface Structure of the Southern Portion of the Salton Sea Geothermal Field, Lawrence Livermore Laboratory, Rept. UCRL-52354 (Nov. 1977).

Tewhey, J. D., SCHWARTZ, L. L., Emerson, D. O. and Beiriger, W. J., The Importance of Geosciences in Developing In Situ Technologies for Energy Resource Recovery, presented at Amer. Assoc. Advanc. Sci. Annual Mtg. (Washington, D.C., Feb. 12-17, 1978). Lawrence Livermore Laboratory, Rept. UCRL-80218 Abstract (Oct. 1977).

Tewhey, J. D. and YOUNKER, L. W., The Influence of Magmatic Convection on the Development of Contact Metamorphic Aureoles, presented at Ann. Mtg. of the GSA and Associated Societies (Seattle, Washington, Nov. 7-9, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79622 (1977).

THIGPEN, L. and Heard, H. C., Vertical Stress Distribution in Oil-Shale Aggregate Columns During Retorting, submitted to Soc. of Petrol. Engineers Jour. Lawrence Livermore Laboratory, Rept. UCRL-79978 Preprint (Aug. 1977).

This paper considers the stresses developed in an oil-shale rubble column during in-situ retorting and assesses the change of the mechanical properties of this rubble mass as a result of the retorting process. New data on the variation of the frictional properties of a 103-1/t grade oil shale with temperature are also presented.

Solutions of the stress distributions within the column are developed in terms of the ratio of column cross-sectional area to perimeter, height, the solid density of shale particles, the coefficient of friction between rubble column and wall rock, and the porosity of the rubble. Through the use of experimentally determined relations for porosity as a function of temperature and stress, the solution implicitly accounts for the effect of material strength and bulk compressibility.

Example solutions show that the vertical-stress distribution is a strong function of both the area-to-perimeter ratio and the coefficient of friction between rubble column and wall rock. Finally, the analyses of this paper may be used to give bounds on the dimensions of rubble columns for efficient in-situ retorting operations.

Thigpen, L. and CARLEY, J. F., Modeling of Vertical Pressure Distribution in Large In Situ Retorts, presented at 10th Oil Shale Symp. (Colorado School of Mines, Golden, Colorado). Lawrence Livermore Laboratory, Rept. UCRL-79039 (1977).

Thigpen, L. and CHIN, R. C. Y., Waves in Linear Viscoelastic Medium - Asymptotic Theory, submitted to Geophysical Journal. Lawrence Livermore Laboratory, Rept. UCRL-79234 (1977).

Thigpen, L., SCHATZ, J. F., Kusubov, A., Hearst, J. R., Abey, A. E. and Snell, C. M., Rock Mechanics Project Progress and Results: Rock Fracture and Pore Collapse, Lawrence Livermore Laboratory, Rept. UCID-17527 (May 1977).

Thomsen, J. M., WALTON, O. R., Bryan, J. B., Snell, C. M. and Goodrich, M., Effects of Porosity, Strength and Water Content on Attenuation of Stresses Generated by Subsurface Explosions in Soils, ANS Topical Meeting, Energy and Mineral Resource Recovery (Colorado School of Mines, Golden, Colorado, Apr. 12-14, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79113 (1977).

TONNESSEN, K. A., Environmental Impact Assessment: Chemical Explosive Fracturing Project, Petroleum Technology Corporation/Columbia Gas Transmission Corporation, Lincoln County, West Virginia, Lawrence Livermore Laboratory, Rept. UCID-17374 (Jan. 1977).

The Devonian shales of the eastern United States will be the target for this natural gas stimulation project by an innovative chemical explosive fracturing technology (CEF). The program will be carried out in the southern region of the West Virginia, Lincoln County, Sheridan District, in a region of low productivity natural gas wells. This joint/industry government project will be undertaken by the Petroleum Technology Corporation (PTC) of Redmond, Washington, a subsidiary of Rocket Research Inc., and by the Energy Research and Development Administration (ERDA). To date PTC has spent \$3 million developing chemical explosive technology and has tested a downhole explosive mixing technique in the lab and in the field at Kanawha County, West Virginia. The program is to be carried out in conjunction with other chemical explosive fracturing experiments to be performed in the Devonian shales of eastern Kentucky and the Canyon sands of central Texas.

The program proposed by PTC, to be performed in conjunction with the Columbia Gas Transmission Corporation, will include the drilling and stimulation treatment of between three and five wells, to be located on a 1,258 acre farmout leased to PTC by Columbia. The number of wells ultimately drilled and tested will be dependent on the progress of the project and on information obtained from each successive well. Although precise locations for the wells have not been selected, the spacing will be such that a total of up to five wells may be drilled on this farmout acreage.

Chemical explosive fracturing might be considered to be the optimal technique for stimulation of natural gas reservoirs in the Devonian shale from the point of view of possible formation contamination by a hydraulic fracturing technique--or the possibility of contaminating another level of the formation which might contain another economically recoverable resource, i.e. coal.

TONNESSEN, K. A., Environmental Impact Assessment: Chemical Explosive Fracturing Project, Petroleum Technology Corporation, Letcher and Perry Counties, Kentucky, Lawrence Livermore Laboratory, Rept. UCID-17475 (May 1977).

Dwindling natural gas reserves make it expedient that a technology be developed to allow for gas stimulation in tight formations. The Energy Research and Development Administration (ERDA) has sponsored a number of government/industry projects designed to further the development of such technology. Currently ERDA is involved in projects concerned with foam fracturing, massive hydraulic fracturing, cryogenic fracturing and chemical explosive fracturing of natural gas deposits located in the tight western gas sands and the Devonian shales which characterize the Appalachian Basin region of the eastern United States.

The program being assessed in this report was submitted in response to RFP 261-76-6 by Petroleum Technology Corporation (PTC) of Redmond, Washington and the Kentucky-West Virginia Gas Corporation (KWV). Since the original contracts were negotiated with ERDA, KWV has withdrawn from the proposed experimental chemical explosive fracturing program. KWV will send a completed gas well (designated as #6810) located in Perry Co., Kentucky, to PTC for use in the project. Subsequent wells will be drilled and stimulated using the chemical explosive fracturing (CEF) technology in the Perry, Leslie, and Letcher County area of Kentucky. Involvement by KWV in these additional well stimulation attempts is questionable at this point.

The PTC chemical explosive fracturing program will be carried out in this tri-county area of Kentucky in a region of low productivity natural gas reservoirs. This program will be performed in conjunction with similar PTC projects in this Devonian shales of West Virginia and the Canyon Sands of central Texas.

This program, as proposed by PTC, calls for the fracturing of an already existing well (#6810) and two-four additional wells to be drilled within the tri-county area. The precise location of the additional wells is not known at present.

This chemical explosive fracturing technique will make use of the patented Astro-Flow II method to stimulate the shales at 3000 - 3500 ft. The selected location would appear to be optimal in that it is located near the site of demonstration projects for other gas stimulation techniques, including foam fracturing and massive hydraulic fracturing.

TONNESSEN, K. A., Environmental Assessment Report: Joint ERDA/GPE Massive Hydraulic Fracturing Experiment, Natural Buttes Unit, Uintah Co., Utah, Lawrence Livermore Laboratory, Rept. UCID-17358 (Jan. 1977).

This environmental assessment was prepared as a negative declaration regarding the environmental impacts associated with the joint Gas Producing Enterprises (GPE) and the Energy Research and Development Administration (ERDA) project to stimulate six natural gas wells by massive hydraulic fracturing in the Uinta Basin of Utah. The results of this program could prove valuable in the exploitation of those potentially recoverable gas reserves in low permeability reservoirs as identified in the National Gas Survey by the Federal Power Commission. The purpose of this assessment is to present a brief description of activities proposed by GPE and to evaluate possible environmental disruption which might result from such a project. This assessment was prepared in accordance with the requirements of Title 10, Part II of the Code of Federal Regulations which outlines procedures to be followed by ERDA for the implementation of the National Environmental Policy Act of 1969 (NEPA).

TONNESSEN, K. A. and Cohen, J. J., Survey of Naturally Occurring Hazardous Materials in Deep Geologic Formations: A Perspective on the Relative Hazard of Deep Burial of Nuclear Wastes, Lawrence Livermore Laboratory, Rept. UCRL-52199 (Jan. 1977).

Hazards associated with deep burial of solidified nuclear waste are considered with reference to toxic elements in naturally occurring ore deposits. This problem is put into perspective by relating the hazard of a radioactive waste repository to that of naturally occurring geologic formations. The basis for comparison derives from a consideration of safe drinking water levels. Calculations for relative toxicity of fast breeder reactor (FBR) waste and light water reactor (LWR) waste in an underground repository are compared with the relative toxicity indices obtained for average concentration ore deposits. Results indicate that, over time, nuclear waste toxicity decreases to levels below those of naturally occurring hazardous materials.

Tonnessen, K. A., HANSON, M. E., Shaffer, R. J., Anderson, G. D., Heard, H. C., Montan, D. N. and Knutson, C. F., LLL Gas Stimulation Program, Quarterly Progress Report, April through June 1977, Lawrence Livermore Laboratory, Rept. UCRL-50036-77-2 (Aug. 1977).

TOWSE, D., A Computer Simulation Model of a Nuclear Waste Facility, presented at Annual Meeting of GSA and Assoc. Societies (Seattle, Washington, Nov. 7-9, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79579 (1977).

A model of the geology, radiochemistry, food chain, and future geologic events at a nuclear waste facility incorporates data on site geometry, lithology, hydrology, and geochemistry in order to study the phenomena of waste transport and to develop technical criteria for waste disposal. Input can simulate any type of nuclear or non-nuclear waste, and quantitative results are stated as concentrations or radiation dose vs. time.

Analysis of parameter sensitivity evaluate the waste dispersion processes and the relative importance of factors in the geologic environment. These have shown the importance of hydrologic factors and the need for study of the geochemistry of the radionuclides, their solubility and complexes, and absorption in the natural environment.

The effects of future geologic events are calculated either deterministically, or probabilistically, using a Markov chain to determine future states of the geologic system.

This waste management model differs from others in that: (1) many geologic environments can be simulated; (2) any type of nuclear or non-nuclear waste can be modelled; (3) the effects of a number of future geologic events can be analyzed. Novel features include a simple one-dimensional hydrology approximation calibrated against more sophisticated calculations. Estimates of future geologic events are a unique application of predictive geology.

Towse, D. and HOWARD, J. H., History of Exploitation at Salton Sea Geothermal Field, California, presented at Amer. Assoc. of Petroleum Geologists Annual Meeting (Washington, D.C., Jun. 1977). Lawrence Livermore Laboratory, Rept. UCRL-78862 (1977).

TRIMMER, D. A. and Heard, H. C., Compaction and Permeability Behavior of Oil Shale Aggregates at Elevated Temperatures, Lawrence Livermore Laboratory, Rept. UCRL-80144 Preprint (1977).

Results of 20 new tests are reported which evaluate the change in the bulk volume and permeability of an oil shale aggregate of 103 μ /T particles resulting from an imposed axial stress and temperature in one-dimensional strain loading configuration. Particle sizes were in the range from 0.002 to 2 cm. At stresses of 0.69-6.2 MPa and temperatures ranging to 700°C, the 6 μ sample may compact by one-third and permeability may decrease by factors of 10 to 100. No simple relationship exists between strain or porosity and permeability that may be used for extrapolation purposes. In particular, attempts to analyze the data in terms of a Kozeny-type equation were unsuccessful.

Trimmer, D. A., DENGLER, L. A., Bonner, B. P., Netherton, R. and Piwinski, A. J., "Laboratory Investigations of Permeability Loss in Sedimentary Rocks," Trans. Am. Geophys. Union 58, 539 (1977). Lawrence Livermore Laboratory, Rept. UCRL-79197 Abstract (1977) .

Trimmer, D. A., PIWINSKII, A. J., Dengler, L., and Netherton, R., "Injection Studies: Section 5.5.1 Results; Section 5.5.2 Failure Modes; Section 5.5.3 Field Experiments," in The LLL Geothermal Energy Program Status Report January 1976-January 1977, Lawrence Livermore Laboratory, Rept. UCRL-50046-76, A. L. Austin, A. W. Lundberg, L. B. Owen, G. E. Tardiff, Eds. (Apr. 1977), p. 167-169.

WALTON, O. R., Bryan, J. B., Snell, C. M., Thomsen, J. M. and Goodrich, M., Effects of Porosity, Strength and Water Content on Attenuation of Stresses Generated by Subsurface Explosions in Soils, ANS Topical Meeting, Energy and Mineral Resource Recovery (Colorado School of Mines, Golden, Colorado, Apr. 12-14, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79113 (1977).

As part of the calculational and experimental study on the Effects of Subsurface Explosions (ESSEX) conducted jointly by the U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, and Lawrence Livermore Laboratory (LLL), Livermore, CA, a calculational parameter study was performed to determine the effects of various soil parameters on the ground motion resulting from high explosive (HE) and/or nuclear detonations.

Rapid attenuation of stress and particle velocity levels with distance from an underground explosion can significantly affect the range where failure of the material will occur. The effect of various parameters such as available air filled porosity, strength, water content, and initial bulk modulus of the material was studied via the one-dimensional finite difference computer code, SOC. A porous material model was developed in order to vary these parameters consistently. The model agreed well with laboratory test-generated compression and strength data for the types of soils found at the Ft. Polk, LA, test site. Air filled porosity and material strength were found to have large effects on the resulting ground motion. Ten percent air filled porosity leads to an order of magnitude reduction in peak stress, compared to that generated in fully saturated soils, at a distance of 10 metres from a 10-ton high-explosive detonation. The predicted stress and particle velocity levels compare favorably with measurements obtained on HE experiments conducted at the site.

Walton, O. R. and GATHERS, G. R., High-Temperature Yield-Strength Measurement of Porous Tantalum, submitted to the Jour. of Applied Physics, Lawrence Livermore Laboratory, Rept. UCRL-80378 Preprint (Nov. 1977).

The collapse of porous tantalum under pressure was studied by simulating porous material with hollow sealed tantalum tubes. Ambient pressure was established with inert gas, collapse was then initiated by softening the material with a heating current pulse. Streak-camera diagnostics recorded the dynamics of the collapse. Elliptic buckling was almost always the observed mode of collapse. The results are consistent with a model for the shear modulus proposed by Guinan and Steinberg.

WALTON, O., Holt, A. and Hanner, D., Some Calculations of Stress Wave Propagation and Attenuation in Porous Tantalum, Lawrence Livermore Laboratory, Rept. UCRL-52361 (1977).

We have added to the Carroll-Holt spherical-pore-collapse model an empirical modification that is easily adapted to materials with different initial porosities. The predicted static-compaction curve agrees well with hydrostatic data. Hydrocore predictions including a rate-dependent term

show reasonable agreement with gas-gun wave-profile experiments. A sample energy-deposition calculation shows that the dynamic-collapse term significantly affects the shape of the transmitted stress wave but has little effect on the total impulse produced.

Walton, O., ISBELL, W. and Ree, F., Behavior of Porous Beryllium Under Thermomechanical Loading, Part 1: Summary of Results, Lawrence Livermore Laboratory, Rept. UCRL-51682 (1977).

The complex mechanical response of plasma-sprayed beryllium with 10-15% initial porosity to various static and dynamic loading conditions was studied. This combined experimental-theoretical program resulted in a calculational model capable of accurately predicting the propagation and attenuation of stress waves in porous beryllium. The program also included development of improved measuring techniques for both gas-gun and electron-beam experiments involving porous materials. Porous beryllium samples in the as-sprayed condition and after sintering were used in a comprehensive set of static (0 - 4 GPa) and dynamic (0 - 33 GPa) mechanical loading experiments. Microstructural analyses of the effects of pressure and specimen preparation on grain size, grain morphology, and void distribution were performed. Both types of porous beryllium were also exposed to high-energy, pulsed electron beams to determine the effects of rapid heating. The results of the experiments guided a modeling effort which added several new features to previous porous-material models, including deviatoric stresses, porosity-dependent pore closure relaxation time, elastic-plastic reopening of pores, and improved compaction functions. Wave profiles generated in plate-impact experiments were used to test the accuracy of the calculational model whose input parameters were determined from other experimental conditions. Excellent agreement was achieved between the predicted and experimental wave profiles. The use of thin layers of porous materials as protection against high-intensity short-duration shock waves arising from either mechanical impact or sudden heating are discussed.

Walton, O. R., ISBELL, W. and Ree, F., "Response of Porous Beryllium to Static and Dynamic Loading," submitted to Jour. of Proc. Sixth AIRAPT and the Intl. High Pressure Conf. (Univ. of Colorado, Boulder, Jul. 25-26, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79712, Rev. 1 Abstract (1977).

Previous investigations of the mechanical response of porous materials to dynamic loading have been extended to include the shock wave response of brittle metal. The complex response of berylliums of 10-15% porosity in two initial conditions has been examined in a theoretical and experimental program to be described. The study has resulted in the development of constitutive relations placed in hydrocodes which are capable of accurately predicting wave propagation in the berylliums. A comprehensive set of static (0 to 4 Gpa) and dynamic (0 to 44 Gpa) experiments was performed to measure the behavior of these brittle, porous materials to imposed loads. The results of the experiments guided a modeling effort which added several new features to previous models, including deviatoric stresses, porosity-dependent relaxation time of pore closure, elastic-plastic reopening of pores, and improved compaction functions.

Walton, O., REE, F. and Lacey, C. S., "EOS of Mixtures," in H-Division Quarterly Report, January through March 1977, Lawrence Livermore Laboratory, Rept. UCRL-50028-77-1 (1977).

The fast-response EOS generation code (MIX) for mixtures has been tested by using a system containing 10 wt% H_2O + 90 wt% SiO_2 . A scheme to correct a deficiency in MIX within a phase transition region is proposed.

WEED, H. C., Physico-Chemical Properties of Rocks and Earth Materials: A Chemist's Viewpoint, Invited lecture, Chemistry Dept., California State Univ. (Hayward, Apr. 8, 1977) Lawrence Livermore Laboratory, Rept. UCRL-79330 Summary (1977).

These investigations of the time dependence of physico-chemical properties of rocks and earth materials include measurements on the electrical conductivity (σ) of water-saturated sandstone, and on the sorption of several dissolved radionuclides by debris recovered from underground nuclear events.

The conductivity studies were undertaken to provide laboratory data to aid in the interpretation of field results and to explore the range of validity of Archie's Law, $\sigma_S/\sigma_R = \phi^m$. Here, σ_S (σ_R) are the solution (rock) conductivities, ϕ is the porosity of the rock, and m is a parameter. When dry Pictured Cliffs sandstone is immersed continuously in water, the rock shows a conductivity change with a maximum at 20 to 40 hours and approximately constant conductivity after 1000 hours. The conductivity of the water in which the sandstone is immersed increases monotonically, presumably because the water dissolves conductive materials out of the pores of the rock. The results suggest that time dependent conductivity may be quite common for rocks as they become saturated with low conductivity water. Such time dependence may limit the applicability of Archie's Law.

The purpose of the sorption studies on dissolved radionuclides is to provide information on calculated migration rates for radionuclides in underground cavities produced by nuclear events at Nevada Test Site (NTS). The extent of sorption of radionuclides can be expressed as a distribution coefficient $K_d = (A_s m/A_l S)$, where A_s (A_l) is the radionuclide activity in the solid (liquid), S is the surface area of the solid, and m is the mass of the liquid. Generally, sorptive behavior depends on the time, the solution composition, and the type of surface exposed. K_d is initially zero and has been found to increase with time for mixtures of natural water with finely-divided debris which was recovered from underground cavities. At 400 days, K_d ranges from 10^{-3} kg/m² to 12 kg/m² and increases in the order Sr-85, Co-60, Cs-134, and Eu-152. Surface effects are evident for chimney debris from the upper part of the cavity: K_d is larger for chimney debris produced from tuff. The calculated migration rate relative to ground water increases in reverse order to K_d , so that a lower migration rate is calculated for Eu-152 than for Sr-85.

WEED, H. C., Piwinski, A. J. and Keller, P., Time Dependent Electrical Parameters of Rock-Solution Systems: Part I, Int. Sympos. Soc. Pet. Eng. Am. AIME (San Diego, Jun. 1977) Lawrence Livermore Laboratory, Rept. UCRL-79013 Preprint (1977); SPE Rept. 6609, pp. 213-220.

The electrical conductivity of 25.4-mm diameter cylindrical cores of sedimentary and igneous rocks was measured at a frequency of 1 kHz under ambient conditions after saturation in tap water and in 0.1 M NaCl solution. Between measurements, each rock was stored in contact with its own separate solution that at the start of the experiment was either tap water or 0.1 M NaCl solution. Eighteen rocks have porosities between 0.7 and 42 percent were investigated; ten were sedimentary, eight were igneous. All solution conductivities were measured employing a dip cell. The time dependence of the conductivity was investigated as well as the range of validity of Archie's law. The formation factor and conductivity of rock specimens and their reacting solutions display time-dependent behavior up to 8,000 hours. The formation factor and electrical conductivity depend on the salinity of the pore fluid, the rock porosity and permeability, and the clay minerals present in the rock.

Weed, H. C., DUBA, A., Piwinskii, A. J. and Santor, M., The Electrical Conductivity of Sandstone, Limestone, and Granite, Lawrence Livermore Laboratory, Rept. UCRL-77314 Preprint (1977).

YOUNKER, L. W. and Tewhey, J. D., The Influence of Magmatic Convection on the Development of Contact Metamorphic Aureoles, presented at Ann. Mtg. of the GSA and Associated Societies (Seattle, Washington, Nov. 7-9, 1977). Lawrence Livermore Laboratory, Rept. UCRL-79622 (1977).

The dimensions and thermal history of a contact aureole are controlled by the size of the intrusive pluton and the maximum temperature developed at the contact. Basic intrusions typically are characterized by smaller contact aureoles than those surrounding more acidic intrusions of similar size. This is paradoxical in the light of the higher temperatures of the basic intrusions. To test the assertion that this difference is due to intensity of convection in the magma chambers, simple analytical solutions to heat transport equations have been used. Heat transfer from a 1 km thick gabbroic body with initial temperature 1000°C and viscosity 10^2 poise has been compared to heat transfer from a 1 km thick granitic magma body with initial temperature 800°C and viscosity 10^8 poise. Calculations indicate that both chambers will undergo convection, however, the gabbroic body has a much higher rate of vertical transport of heat (5.0×10^{-3}

cal/cm² sec) than the granitic chamber (1.6×10^{-4} cal/cm² sec). This high rate of heat transfer produced extremely high contact temperatures above the gabbroic intrusion. Heat lost at the upper and lower contacts is in the ratio 995:622. With less intensive convection in the granitic chamber heat loss is roughly uniform. These results are consistent with field observations: (1) Erosional slices through granitic and diapiroically-emplaced ultramafic intrusions exhibit wide, uniform contact aureoles. (2) Erosional slices through gabbroic intrusions typically reveal narrow, baked aureoles with evidence of fusion in roof rocks. The assimilation of fused roof rock can account for the greater than expected granophyre abundances that have been reported for some gabbroic intrusions. These diverse thermal effects can be attributed to differences in convection intensity within magma bodies of varying composition.

Younker, L. W. and KASAMEYER, P. W., Temperature-Gradient Analysis, in The LLL Geothermal Energy Program Status Report January 1976-January 1977, Lawrence Livermore Laboratory, Rept. UCRL-50046-76, Section 5.3.4, A. L. Austin, A. W. Lundberg, L. B. Owen, G. E. Tardiff, Eds. (Apr. 1977), p. 139.

CLASSIFICATION BY SUBJECT

ENERGY AND RESOURCES

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MEAD, S. W., Campbell, J. H. and Stephens, D. R.

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Viscosity of brine from the Salton Sea Geothermal Field, California, from
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Progress report on computer model for in situ oil shale retorting,

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