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OIL SHALE PROGRAMS
SIXTEENTH QUARTERLY REPORT
OCTOBER 1979 THROUGH DECEMBER 1979

EDITED BY A. L. STEVENS

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87185
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INTRODUCTION AND SUMMARY

This document is the sixteenth in a continuing series of quarterly reports, and describes the Sandia National Laboratories oil shale activities during the period between October 1, 1979 and December 31, 1979. Sandia's major responsibility to the DOE in situ oil shale program is to provide a quantitative evaluation to DOE of the various field projects being supported by DOE in the development of commercial in situ oil shale processes. This requires the deployment of instrumentation systems and analysis techniques to evaluate key procedures and operations. In order to fulfill this responsibility, it is necessary to develop new and advanced instrumentation systems and associated deployment, recording and analysis techniques that are unique to the field projects. In addition, a rock mechanics program provides material properties, material response models, and computational methods to support the design and evaluation functions. This report describes detailed activities in these project areas over the last quarter.

Six ytterbium stress gages were emplaced in the rock mass in the vicinity of the four borehole charges of a rubbling experiment conducted by LASL at the Colony Mine in the final days of last quarter. Good quality time-resolved stress measurements were obtained from the gages and are now being subjected to a detailed analysis in which emphasis is being given to the triaxial nature of the transient stress field. Understanding the nature of the stress field is important because the electrical response of ytterbium gages, like that of other free-field stress gages, is influenced by each component of stress. The gages in the recent experiment were oriented so the response is dominated by the component of stress lying parallel to the axes of the charge holes. The CSQ two-dimensional wave code is being used as an aid in analyzing the stress data, in part to gain information about the stress field at the gage locations.

Sandia is participating in the Geokinetics in situ oil shale project through the design and fielding of instrumentation, acquisition and interpretation of data, and the development of models for design predictions and evaluation of results. This quarter the explosive frac-

turing of Retort 24, a full scale module, was executed. Instrumentation was fielded to monitor the explosive detonation timing performance. Extensive measurements were also made of the dynamic response (heave) of (1) the ground surface of the retort, (2) the heave and expansion of the oberburden, and (3) the vertical and lateral motion within the blast zone in the oil shale. Preliminary field data indicate that the blast occurred as planned to produce a successfully rubbled retort. Analyses and interpretation of field data from Retorts 21, 22 and 23 were also completed during the quarter.

During the third quarter of calendar year 1979, the DOE requested that Sandia participate in Phase II of the cooperative oil shale project between the DOE and Occidental Oil Shale, Inc. (OOSI). Instrumentation will be fielded to measure physical parameters for use in monitoring and evaluating the shale oil recovery process steps. Measurements are planned in the areas of: (1) explosive systems performance, (2) rubble evaluation, (3) retort reaction front characterization and movement, and (4) stability and integrity of the retort and mine openings. The purpose of the Phase II project is to demonstrate the technology which is proposed for commercial development of the C-b tract. Two full scale retorts, 7 and 8, will be blasted separately, but retorted simultaneously. Two approximately quarter scale retorts will be rubbled and ignited to test blasting procedures and evaluate equipment and procedures for ignition of the full scale retorts.

During this quarter a proprietary information agreement was signed by Sandia and OOSI, a detailed instrumentation plan was developed, and instrumentation and recording equipment were moved to the Logan Wash site in preparation for rubbleing tests early next quarter.

A limited surface model which describes the failure of oil shale under multiaxial status of stress is being developed for use in modified in situ retort stability calculations. The model accounts for the transversely isotropic character of the bedded oil shale. Complete determination of all the parameters of the model for oil shale will require some additional data. A series of tests have been defined which will provide sufficient data to describe the failure surface as a function of kerogen content and temperature.

Problems associated with the explosive rubbleization of oil shale prior to in situ retorting are well known. In addition, these processes

have associated underground working so that safety of the underground openings and minimization of the attendant pillar and overburden deformation require long-term stability. Successful computational modeling of the long-term stability will require constitutive models that are accurate over long time spans, and may need to include time or rate of deformation explicitly. Such a constitutive model for oil shale is in development using existing data on unconfined, stress-relaxation tests of two different grades. The data are found to fit a linear viscoelastic constitutive law. As a result, the principle of superposition is valid, a wholly desirable result both from the standpoint of analysis (calculational) procedures and for ease of determination of the necessary complete set of material properties.

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OIL SHALE PROGRAMS
SIXTEENTH QUARTERLY REPORT

A. Analysis of Dynamic Stress Data from the September 1979 Colony Mine Rubbling Experiment (R. R. Boade, 4734; R. P. Reed, 1116)

On September 27, 1979, LASL conducted another of a series of explosive rubbling experiments in the Colony Oil Shale Mine. As has been the case in previous instrumented experiments of this series, Sandia was involved through the fielding of stress gages to monitor the detonation-induced stress wave propagation in the oil shale surrounding the explosive charges and through the reduction and evaluation of the resulting data. The latter portions of this work are currently in progress and form the primary thrust of the present discussion.

The configuration of the recent experiment is depicted in Figure I-1. Four blast holes are shown in the plan view along with six instrument holes. All holes were 0.11 m in diameter and were drilled vertically into the floor of the mine. Each blast hole was half-filled with ANFO, had a detonator/booster unit at the bottom, and was stemmed to the surface. Detonation was initiated simultaneously in all four charges.

The instrument holes each contained one ytterbium stress gage at the level indicated. Coupling of the gages to the formation was achieved by filling the instrument holes with a rock matching grout. Each gage was oriented with its planar surface normal to a radius vector extending from the axis of the closest shot hole to the gage.

Because of this orientation, the electrical response of a gage is controlled predominantly by the component of the transient stress field lying parallel to the axes of the shot holes, which is the Z, or vertical component, since the four shot holes were drilled vertically. Since the triaxial character of the stress field is rather complex and can influence the interpretation of the data, it is important that the analysis process include a detailed examination of the physical phenomena

FIGURE A 1. LAYOUT OF THE SEPTEMBER 1979 COLONY MINE EXPERIMENT.

involved. Some features of the evaluation in progress are discussed here.

The stress field induced in a rock mass by the detonation of an array of charges depends on position and time in a manner that is controlled by the performance properties of the explosive, the mechanical properties of the rock, and the geometrical configurations of the charge and detonation assemblies. The illustrations in Figure A-2 provide some information about the nature of stress wave propagation after initiation of detonation in a cylindrical explosive charge like those of the recent Colony Mine experiment.

FIGURE A-2. ILLUSTRATION DEPICTING INSTANTANEOUS POSITIONS OF A FEW OF THE INFINITUDE OF NOMINALLY SPHERICAL COMPRESSIVE STRESS PULSES THAT EMANATE FROM INCREMENTAL UNITS OF EXPLOSIVE ALONG A 1.58 m HIGH CHARGE COLUMN. THE ARROWS MATCH A PARTICULAR STRESS PULSE WITH ITS POINT OF ORIGIN. THE DASHED CURVES ALONG THE PERIPHERY MARK THE POSITION OF THE LEADING EDGE OF THE COMPOSITE WAVE FORMED BY THE COELESCEENCE OF ALL THE STRESS PULSES FROM THE INCREMENTAL SOURCES. THE ILLUSTRATION IS BASED ON THE GEOMETRY, EXPLOSIVE PERFORMANCE, AND ROCK PROPERTIES OF THE SEPTEMBER 1979 EXPERIMENT BY LASL IN THE COLONY MINE.

The figure depicts a few of the infinitude of nominally spherical compressive stress pulses that emanate from incremental units of explosive along the length of the column. These spherical pulses coalesce to form a composite stress wave with a leading edge that is shown by the dashed curves in the figure. Consistent with conditions in the Colony Mine experiment, the illustration is based on a detonation velocity of 3.5 km/s, which is slightly larger than the assumed stress wave velocity in the rock (3.4 km/s). These velocities lead to a composite stress

wave having a nearly spherical front except for the slight bulging at the top. Interactions between the stress pulses from the various portions of the column cause the composite stress wave to be higher in amplitude and shorter in duration in the upper portion of the rock mass than in the lower portion; this is evident in the figure from the observation that the circles representing the spherical waves tend to become concentrated in the upper portions of each illustration.

In general, the largest principle stress component is directed normal to the front of the composite wave. This means that near the axis of the explosive column, the Z component of stress (i.e., the component which dominates the measurement) is larger than the other two orthogonal components. Further from the axis of the charge, the radial component becomes dominant.

Quantitative information about the character of the triaxial stress field has been obtained from a series of calculations performed with the CSQ wavecode simulating the Colony Mine experiment. Some results of these calculations are shown in Figures A-3 and A-4. The graphs here show peak values for three components of compressive stress; radial (σ_{RR}), hoop ($\sigma_{\theta\theta}$) and axial (σ_{zz}); as functions of position relative to the explosive charge. For these calculations, the properties of the explosive were adjusted to be compatible with LASL's evaluation of ANFO in 0.1 m diameter boreholes. The oil shale was treated as an elastic perfectly plastic material using parameters deduced in prior studies. The trend evident in the two figures is consistent with the qualitative observations given above, namely that at small radial distances the axial component is largest and at large radial distances the radial component is largest. The hoop component is smallest for all positions considered.

Each of the gages in an experiment like the one of interest here will respond to each of the explosive charges in the array. Only one such charge is included in the computer simulations. For a given gage, direct consideration can be given only to the wave from the closest charge and then only until a subsequent wave arrives. Waves from more remote charges can also be considered, but it must be recognized that these waves traverse portions of rock that may have been altered by the action of preceding stress wave. Radial distances of the gages from the various shot holes are indicated in the lower portion of Figure A-4. Radial distances of the gages from the closest charge range from ~0.4

FIGURE A-3. RESULTS OF A COMPUTER (CSQ) SIMULATION OF LASL'S SEPTEMBER 1979 EXPLOSIVE RUBBLING EXPERIMENT IN THE COLONY MINE. THE GRAPHS SHOW PEAK STRESS AMPLITUDES AS A FUNCTION OF VERTICAL POSITION AT RADIAL DISTANCE OF 0.25, 1.0, AND 1.7 m FROM THE AXIS OF A 1.58 m HIGH, 0.1 m DIAMETER CHARGE OF ANFO.

to ~1.2 m. Measured peak stress amplitudes of the earliest arriving waves ranged from 1.8 to 0.3 kbar, which is in generally good agreement with computed results.

Current efforts are being given to the triaxial nature of the transient stress field and its effect on gage response. In addition, the response caused by the arrival of waves from remote charges is being examined.

1. GKI Explosive Fracturing (R. D. Jacobson, J. T. Schamaun, 4734; P. J. Langdon, 2514)

The explosive fracturing of Retort 24 was executed on November 15, 1979. Preliminary indications were that the blasting occurred essentially as planned. The residual surface uplift shape was about as expected. The magnitude of the surface heave was greater than analytical predictions; this was probably due to (a) more explosive was used than considered in the calculations; and (b) the numerical model used did not incorporate lateral motion of the shale.

Earth motion measurements made during the test included: (a) surface motion utilizing four camera locations recording the motion at 37 flag stations on and near the retort; (b) vertical displacement v.s. time of the earth surface and the top of the blast zone relative to the undisturbed shale at six locations via borehole extensometers utilizing specially designed potentiometric displacement transducers (PDT's); (c) vertical displacement v.s. time of the earth surface relative to the top of the blast zone with borehole extensometers; and (d) vertical and lateral motion within the blast zone with accelerometers.

Detonation timing was measured with five break-wire time-of-detonation (TOD) gages, twelve time-of-arrival detectors (TOAD's), fifteen light-emitting time-of-detonation (LETOD) detectors, and five SLIFER strings. In addition to the actual measurements made, an evaluation of the different time-of-detonation detectors was made. The break-wire data were essentially the same as the more expensive TOAD data; the "Nonel" LETOD's provided optical timing information comparable to TOA data.

In some earlier retort blasts, delay sequencing problems had been experienced. It was subsequently determined that this was probably due to the delay time of the HD Nonel caps being deleteriously affected by age. Prior to the blasting of Retort 24, a small test program was conducted to determine the delay time tolerances on the blasting caps planned for use in this and future retorts. The test data showed that knowledge of the actual delay times and expected tolerances in delay times were valuable information for use in blast designs. It also indicated that each type of blasting cap planned for use should be periodically tested for timing information.

The final interpretation of test data from the blasting of Retorts 21 and 22 was completed and forwarded to GKI. Blasting test data from

Retort 23 was forwarded to GKI in a preliminary form. Final interpretation is presently being written. The data from Retort 21 indicated that an average of 20% void ratio was obtained. The optical data shows non-symmetric motion of the overburden. This non-symmetry was probably due to overloading of several blast holes near the south end of the retort. The data from the blasting of Retort 22 indicated a fairly uniform motion which probably resulted in a fairly uniform rubblization. The total lift and relatively low void ratio was expected. The data from Retort 23 blasting shows a fairly consistent behavior. The data shows that the "toe" charges did not detonate when planned. Other blast timing seemed excellent. Pre-blast predictions based on program JUMP showed good correlation with measured data.

C. Analytical Evaluation of Geokinetics Retort Blasting
(J. T. Schamaun, 4734)

Analysis based on lumped-mass methods has continued this quarter. The results of these analyses are necessary to provide a basis which can be used to predict future designs, to assess test data and instrumentation, and to assist in the layout of future experiments. The lumped-mass method is based on simulating the continuous rock by a series of discrete masses. The motion of these masses is then calculated with simple computer programs.

Analytical results from Program JUMP, which was completed last quarter, were used for comparisons with test data from retort blasts 17, 18, and 19. Very poor correlations could be made. In spite of these poor results, pre-test predictions for the response of Retort 24 were made. The predictions were less than actual measured results, as might be expected. Apparently, the horizontal motion of rubble oil shale is important in the behavior of these types of blasting patterns. Program JUMP does not include horizontal motion.

A modification was incorporated into Program JUMP which enables the explosive pressure to be a function of the overburden motion. This modification is based on a direct relationship between the pressure and the volume. This modification was named IJUMP and simple users instructions were written. IJUMP was then used to predict motion for blasting geometries similar to Retorts 20 to 23. The results seemed very reasonable.

The need for a lumped-mass model which could incorporate a more elaborate loading input in addition to lateral motion was obvious from

the results with blasts 17, 18, 19 and 24. The basic structure existing in Program JUMP was modified to incorporate these changes. Program LUMP was written. Considerable changes were necessary in the plotting routines. At present this program is being debugged.

D. Geokinetics Retort 22 (R. L. Parrish, 4734)

Two meetings were held with Geokinetics this quarter regarding the instrumentation and monitoring of the retorting phase of Geokinetics Retort 22. As presently envisioned, Sandia will (1) design and emplace all subsurface instrumentation; (2) design the surface instrumentation in conjunction with Geokinetics; (3) specify the process parameters (e.g., injection gas flow rates and composition); (4) monitor the process and reaction parameters; and (5) conduct real time data interpretation and retort evaluation. The final design of Geokinetics should be complete by February 1980. Ignition is scheduled for late May.

E. Occidental Oil Shale Project (R. R. Neel, 4734)

During the third quarter of calendar year 1979, the DOE requested that Sandia participate in Phase II of the cooperative oil shale project between the DOE and Occidental Oil Shale, Inc. (OOSI) by measuring physical parameters for use in the evaluation of the shale oil recovery processes. In addition, Sandia is expected to perform the analytical modeling necessary to enable appropriate measurements to be made and to evaluate the data recorded.

The purpose of Phase II of the Occidental Program is to demonstrate the technology which is proposed for commercial development of the C-b tract during Phase III. Specifically, two full scale retorts will be blasted and retorted in Occidental's development mine. The two retorts, Retort 7 and Retort 8, are to be blasted separately, but retorted simultaneously. Two approximately quarter scale rubble beds will be ignited as retort start-up tests to evaluate the basic equipment and procedures planned for the full scale systems. The measurements which are planned by Sandia during the project are of four general classes:

1. Explosive Systems Performance
2. Mine Stability and Integrity
3. Rubble Evaluation
4. Retort Front Characterization and Movement

A detailed instrumentation plan was developed during this quarter:

Explosive Systems Performance Measurements - The fact of detonation, time of detonation, and detonation velocity are the parameters which will be measured to evaluate the explosive and explosive initiation systems. This information coupled with the rubble evaluation data will provide a measure of the rubblization system. Time-of-detonation gages (PZT, breakwire, resistive change, etc.) will indicate booster detonation and detonation timing. Detonation velocity in the explosive column will be measured by SLIFER cables.

Mine Stability and Integrity Measurements - In situ rock mass stresses and strains during mining, blasting, retorting and cooldown will be made to evaluate the integrity of pillars surrounding the retorts. Borehole inclusion stressmeters with strain gage sensing elements will be used to measure stress perpendicular to the test boreholes. Cable and rod extensometers will be used to measure strains between the drill hole and wellhead and the extensometer anchors. The stressmeters and extensometers will be placed at critical areas in and around the retort roofs (back) and supporting pillars.

Rubble Evaluation Measurements - After the rubble beds have been blasted, a series of measurements will be made to evaluate the permeability variations throughout the retort. Air flow tests, tracer gas flow tests, gamma-gamma density logs, measurement of high frequency electromagnetic (HFEM) characteristics, neutron porosity measurements will all be performed to evaluate the permeability under pre-retort (cold) and retorting (hot) conditions. A special tracer gas system will be designed based upon a mass spectrometer gas identification system for use with a tracer gas, such as helium, to be used during retorting.

Density loss will be used to evaluate the void fraction variation along various boreholes. Similar void fraction variation is expected to be measured using a standard neutron porosity logging tool.

The changes in the electromagnetic characteristics of the shale brought about by the rubbling processes and hence the void fraction and/or particle size will be inferred by measuring the changes in an HFEM signal as it is passed through a portion of the rubble bed.

Retort Front Characterization - A large array of thermocouples embedded at known locations in the retort rubble beds will be used to describe the retort front profile and movement as it passes through the rubble bed. Gas sampling ports throughout the retort will be used to recover gas samples for retort analysis, and to evaluate permeability during the retort. The HFEM technique will be tested for feasibility as a remote monitoring method.

Data Recording System - Three types of recording systems will be used on the Occidental program.

A system of fast tape recorders in Trailer B-74 will be used to monitor early program fast measurements primarily associated with the blasting activity. A Mod Comp classic mini computer in Trailer B-61 will be used to record, store, and analyze large quantities of low sample rate digital data primarily associated with retort front characterization. An HP9845T microcomputer will be used to record low sample rate data on early tests involving a relatively small number of data channels.

A special portable, downhole digital recording system will be used to record detonation times during the rubblization activities.

Administrative Activities - A proprietary information agreement between Occidental and Sandia was signed late in the quarter. This proprietary information agreement is intended to define and provide safeguards for proprietary information which Occidental must eventually share with Sandia in order that appropriate measurements systems can be designed and fielded. The fact that the agreement was not signed until late November has had the effect of delaying Sandia's participation on the program. Instrumentation and recording equipment were moved to the Logan Wash site in early December in preparation for rubbling tests early next quarter.

F. Static Failure Model for Oil Shale (L. S. Costin, 5532)

A limit surface model which describes the failure of oil shale under multiaxial states of stress is being developed for use in modified in situ retort stability calculations. The failure surface has a functional form similar to that given by Priddy (5522) for an orthotropic brittle material. Complete determination of all the parameters of the model for oil shale is not yet possible because there is insufficient

data. However, there is enough data on Westerly granite to evaluate the model's material parameters. In addition to uniaxial data, biaxial and triaxial data are available for Westerly granite and this information is sufficient to explore some of the consequences of the model. An important observation (see Fig. F-1) is that the failure surface predicted by the original model does not compare favorably with the experimental data on Westerly granite under conditions of biaxial compression. A slight modification of the model, however, resulted in a failure surface that is in good agreement with existing data (see Fig. F-1). In the next quarter, experimental work will concentrate on determining the material parameters for the modified model which will be sufficient to describe the failure surface of oil shale as a function of kerogen content and temperature.

G. Fracture Mechanics of Oil Shale (L. S. Costin, A. K. Jones, 5532)

The optimization of in situ bed preparation techniques relies heavily on determining the requirements for crack propagation in oil shale and how these requirements depend on the kerogen content, the in situ stress state, the direction of crack propagation with respect to the bedding planes, and the local rate of loading.

In this quarter, small three-point bend specimens of 200 ml/kg oil shale were tested using an instrumented Charpy pendulum impact machine. Specimens of all three orientations (divider, arrester, and short-transverse) were tested at a loading rate of $\dot{K} = 10^4 \text{ MPa-m}^{1/2}/\text{s}$. The results were compared to test results from previous quarters which included quasistatic tests ($\dot{K} = 10^{-2} \text{ MPa-m}^{1/2}/\text{s}$) as well as dynamic tests conducted at a slower rate ($\dot{K} = 10^0 \text{ to } 10^3 \text{ MPa-m}^{1/2}/\text{s}$). The results of the previous quasistatic tests showed a clear effect of both specimen size and crack orientation on the measured value of fracture toughness. The results obtained this quarter show some evidence of a rate effect on the fracture toughness as well as the same orientation dependence. However, no specimen size dependence was evident.

A summary of the results of all the fracture toughness tests conducted for the present study is given in Figure G-1. Each histogram in Figure G-1 represents the average value of fracture toughness derived from each test technique at a given crack orientation and loading rate. From the data displayed in Figure G-1, it can be concluded that:

FIGURE F-1. A COMPARISON OF THE ORIGINAL PRIDDY MODEL AND THE REVISED VERSION OF THE MODEL WITH BIAXIAL DATA FROM SWENSON, 1972.

FIGURE G-1. A SUMMARY OF THE RESULTS FROM EACH TYPE OF FRACTURE TOUGHNESS TEST. EACH HISTOGRAM REPRESENTS THE AVERAGE VALUE OF K_Q DETERMINED FROM THE TEST METHOD INDICATED. THE CODE IN EACH HISTOGRAM IS AS FOLLOWS: SPECIMEN TYPE, RATE (STATIC OR DYNAMIC), ORIENTATION OF THE CRACK WITH RESPECT TO THE BEDDING (D, A, OR ST). NOTE THAT FOR THE STATIC THREE-POINT BEND TESTS, BOTH K_Q AND K_{Jc} VALUES ARE GIVEN. ALSO FOR THE SHORT ROD TESTS (SR), BOTH THE UNCORRECTED (UC) AND PLASTICITY CORRECTED (C) RESULTS ARE GIVEN.

1) The static fracture toughness measured by the A.S.T.M. fracture toughness test method and the equivalent toughness derived from the J-resistance curve method (K_{Jc}) are in agreement, however, both sets of data are specimen size dependent.

2) The effect of material anisotropy on the calculation of K_Q from the standard formulas is negligible.

3) The short rod method yielded toughness values that are 20 to 40% below the toughness measured with comparably sized three point bend specimens. If the plasticity correction method is used, the toughness values are in reasonably good agreement with the three point bend results. However, it is doubtful whether the plasticity correction method is valid at $P = 0.5$.

4) The results from the dynamic tests on small specimens are in agreement with the results from static tests on the largest specimen size, indicating that the manner in which the crack-tip process zone develops is dependent on strain rate.

5) The instrumented Charpy test yields results which are consistent with the other test methods even though the specimens were not pre-cracked. Because of the low cost per specimen and the ease with which the test can be conducted, the Charpy test seems most suited for such tasks as the collection of sight-specific field data where many specimens may be required.

In summary, it was found that the fracture toughness test methods used here are probably adequate for determining the fracture behavior of rock material such as oil shale, provided proper specimen size requirements can be determined. In oil shale, our results suggest that the imposed strain rate in the near crack-tip region affects the development of the process zone leading to an apparent rate sensitivity of fracture toughness in finite specimens.

Future work will concentrate on the development of a model which will describe the failure of oil shale under static compressive stresses. Since fracture nucleation and growth is one of the primary failure mechanisms, the fracture toughness is an important parameter in the model. In addition, new experimental work will be directed towards the detection of the nucleation and the growth of cracks in deforming rock through acoustic emission methods.

H. Stress-Relaxation in Oil Shale (W. A. Olsson, 5532)

Oil shale is an energy resource of vast potential, and because of the relative difficulty of extracting the kerogen from the rock, it is essential to optimize the production process. Most proposed schemes

employ explosive rubblization of the rock prior to retorting in situ or in above ground retorts. In addition, most processes have some associated underground workings so that safety of these underground openings, and minimization of the attendant surface subsidence, require a certain long-term stability. Clearly then, oil shale will be subjected to varied loading histories lasting from fractions of seconds during blasting, to years or tens of years during sustained gravitational loading of pillars and other support structures. Successful computational modeling of the diverse process of fragmentation and long-term stability will require constitutive models that are accurate over long time spans, and may need to include time or rate of deformation explicitly.

Some contribution to the development of a constitutive model for oil shale from the Piceance Basin, Colorado, has been gained from an analysis of Bureau of Mines data on unconfined, stress-relaxation tests on material of grades 31 and 71 gallons per ton. Approximate step function strain-histories of various strain magnitudes (0.4 to 1.0%) were applied to the specimens by a servocontrolled testing machine and the engineering stress was monitored as a function of time up to 2.5×10^5 s.

Two examples of the stress-relaxation curves are displayed in Figure H-1. These curves exhibit rapid stress drops within times of about 5000 to 10,000 s, followed by very slow decreases thereafter. The form of the curves is typical for many materials including other rocks. A simple power law gives the best broad band representation of the stress-relaxation curves: the equation fit to the data is $\sigma(t) = \sigma(0)t^{-n}$, which is of course not strictly valid for very short times (<1 s.), but is sufficiently accurate for present purposes.

The stress at a given time (and grade) is higher for larger strain steps and, in fact, is a linear function of the strain. This result implies that a linear constitutive law--in this instance the linear viscoelastic law--is appropriate for oil shale. Moreover, the principle of superposition is valid, a wholly desirable result from the viewpoint of boundary value problems. The one-dimensional viscoelastic constitutive equation can be written,

$$\sigma(t) = E_{\infty}\epsilon(t) + \int_{-\infty}^t E(t - \tau) \dot{\epsilon}(\tau) d\tau \quad (1)$$

FIGURE H-1.

where $E(t - \tau)$ is known as the relaxation modulus, t is current time, τ is variable time, and E_∞ is the equilibrium elastic modulus. If $E_\infty = 0$, the equation describes a viscoelastic liquid. The tests reported here did not last long enough to establish a non-zero value for E_∞ directly but an indirect method gives an upper bound.

Once linearity has been established, the problem is one of the experimental determination of $E(t - \tau)$. Because for the Heaviside strain histories used here $\epsilon(t) = \epsilon^* H(t)$, where ϵ^* is a constant, the integral in (1) can be explicitly evaluated and thus the relaxation modulus is given by $E(t) = E(0)t^{-m}$. A very small difference in grade seems to have a measurable effect on the values of $E(0)$ but m , on the other hand, is independent of grade.

The presence of $\dot{\epsilon}(\tau)$ in equation (1) suggests that a series of constant strain-rate compression tests might be of some value in the determination of $E(t - \tau)$. Indeed this has been found to be the case. In Figure H-1, $\sigma(t)$ computed from (1) using $E(t - \tau)$ obtained from two series of constant strain-rate tests is compared to two directly measured

stress-relaxation curves. The stress response to a step-function strain input is seen to compare quite favorably with that predicted by a strain history corresponding to a constant strain-rate test. This result suggests that a small expansion in the typical testing program to include several different strain-rates would be very useful.

I. Minimum Bed Parameters for In Situ Processing of Oil Shale (C. E. Tyner, 4731)

A laboratory retort vessel to allow combustion retorting of 7.6-cm diameter by 36-cm long cylinders of shale in various configurations has been designed and fabricated (see Fig. I-1). The retort consists of the oil shale sample sealed in a low-thermal-conductivity castable ceramic inside a thin-walled stainless steel inner liner (10 cm diameter). This assembly is sealed to the retort bottom plate (to assure that all gas flow is through the sample) and then insulated inside a steel outer vessel. The bottom plate contains ports for gas and product collection as well as for instrumentation (thermocouples). The retort top plate seals the vessel and contains ports for inlet gas flow and electric heaters. The retort can be ignited either with these electric heaters on top of the shale or with hot gas.

Two basic sample geometries will be used in this vessel. One consists of a solid cylinder of shale with one or more axial holes to provide the flow paths (see Fig. I-2). Seven holes (between 0.6 and 1.2 cm in diameter) will provide an overall void of 5 to 20%. The inner hole in this geometry is somewhat additionally insulated by the symmetry of the pattern. The second geometry (Fig. I-3) consists of competent sections of an axially-sectioned cylinder of shale spaced to the original cylinder diameter with thin zones of rubble. Three rubble sections (~50% void) with thickness varying from 0.3 to 0.6 cm will provide an overall void range of 7 to 15%.

Figure I-4 shows the retort system schematically. Flow into the retort of the inlet gases (air, N_2 , and CO_2) is individually controlled. A series of cooled condenser/demisters and filters are used to remove condensibles from the product gas stream, which is then routed through a flow meter, an O_2 analyzer, and a gas sampling manifold (for grab samples). Thermal data from the retort as well as flow, pressure, and O_2 data are processed, stored, and plotted by the data acquisition system.

FIGURE I-1.

BOREHOLE GEOMETRY

FIGURE I-2.

SLICED-CYLINDER GEOMETRY

FIGURE I-3.

FIGURE I-4.

The first sample prepared for retorting was a multiple borehole geometry, with seven .95 cm holes drilled in a hexagonal pattern through a solid core of 100 l/tonne shale. A number of retort model calculations were done to help define appropriate operating conditions for the experiment. As a result of these calculations, undiluted air was selected as the inlet gas, at a total flow rate of between 1 and 2 slm (.006 to .012 kg_{air}/m_{sh}²·sec). The calculated yield at these conditions was around 90% FA, with most of the loss due to oil combustion.

After completion of the retort assembly, air flow was established through the retort and ignition attempted with 310 SS-sheathed electric heaters lying directly on top of the shale cylinder. Although this ignition procedure has worked satisfactorily on previous smaller samples, this ignition attempt was not successful. Apparently, by heating the shale (and not the inlet gas), the primary source of fuel for the process, oil, was depleted in the heated region before gas-phase temperatures were high enough to ignite the oil. (Because of the competent nature of the sample, too little char is available for combustion to sustain the burn.) It is felt that an ignition procedure heating the inlet gas, rather than the shale, will eliminate this problem. Since the ignition attempt described above was stopped before the bottom half of the sample was heated, another attempt to ignite the same sample will be made as soon as possible using a hot gas ignition system.

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