Explosive Rubblization of *In Situ* Oil Shale Retort Beds

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Introduction:

A number of technical, environmental, economic and political problems remain to be solved before *in situ* extraction of hydrocarbons from oil shale deposits becomes a practical reality (1). Of all the technical problems, perhaps the most challenging is that of preparing the resource bed on the massive scale and with the control and precision required for commercial exploitation. Although the requirements are not yet fully defined, it is generally agreed that a properly-prepared *in situ* oil shale retort would have the following characteristics:

a) The particle size distribution achieved by the process should peak in the range of that required for maximum extraction efficiency. Current chemical kinetics and process studies places this range as roughly 5-50 cm, with the peak around 10 cm.

b) Void distributions in both the horizontal and vertical sense must be uniform in order to achieve a stable flame front and avoid channeling.

c) The permeability of the resultant rubble pile must be sufficient to support pyrolysis and allow removal of retorted products.

d) Fines produced in the rubblization process must be minimal, both to avoid plugging the pores through which the gases and other products must move and to maximize the efficiency of the rubblization event.

e) The rubblized volume must be well defined, with maximum residual wall and roof integrity in order to provide retort stability, containment of combustion products, safety for workers in adjacent areas, and maximum utilization of the resource.

f) The economics of the process must be favorable.

Obviously, the final result must be a compromise between the ideal and that which is achievable. At present, chemical explosives appear to be the most feasible method for achieving these goals, but present blasting technology is certainly not sufficiently well-advanced to guarantee any success of the event, much less technical and economic optimization.

For this reason, the Los Alamos Scientific Laboratory and Sandia Laboratories have jointly undertaken a basic research program, under the auspices of the Energy Research and Development Administration, aimed at producing a controlled, predictable, and optimized breakage pattern in western, or Green River, oil shale. The work of Los Alamos is presently directed primarily toward the modified *in situ* technology, in which void space and free faces can be created by conventional mining operations, although the results will be applicable to design of true *in situ* operations as well. This is a long-term and continuing program which will involve a considerable effort both in the laboratory and the field. This report is therefore intended only to indicate the direction of the program and the long-term goals. However, the importance of the program to the eventual success of *in situ* technology makes it desirable for chemical and process engineers to be aware of the difficulties, possibilities, and achievements of research on the bed preparation problem.

Program Outline:

The laboratory phase of the program falls into three clearly defined but closely related categories:

a) Measurement of material properties of oil shale. The Los Alamos effort is concentrated on measurement of properties of the shale subjected to high strain rate loading such as is encountered in an explosive event. Wave propagation characteristics, such as Hugoniots and wave profiles on shock and release, are measured in order to determine the stress field. This stress field must then be related to the dynamic failure surfaces and the kinetics of the fracture process. Measurement of these dynamic materials properties is a program which is well advanced.

b) Measurement of non-ideal explosive behavior. Detailed knowledge of the detonation characteristics of ANFO and other commercial explosives is required in order to define the initial conditions of the expanding stress waves into the oil shale. Tailoring of the explosive impulse to the response of the rock is also an eventual goal which should result in reduced fines around the borehole and enhanced energy transfer to the far-field region. The effect of expanding explosive gases in propagating radial cracks is also a subject of interest. This work is presently underway.

c) Computer modeling. Lagrangian and Eulerian hydrodynamic computer codes are being used to synthesize the materials and explosive properties into a coherent picture of the event. Ideally, the codes could be used both as a design tool for shot layout and as a predictive tool for shot optimization. A series of field tests specifically designed for testing the predictive capability of the codes are required before the codes can be used with confidence. These tests constitute a major part of the latter stages of the program.

Results to Date:

In the first few months of the program, attention has been directed primarily toward propagation characteristics of the stress waves rather than the dynamic fracture properties of the material. At low pressures, this is a particularly complex problem because of the anisotropic nature of the material and its non-linear response to dynamic stresses. Figure 1 shows the u_s-u_p Hugoniots in the pressure region of 50-200 kb of oil shales of varying density obtained from explosive experiments on small samples. This pressure range is that which would be experienced in the near-field region around a borehole, and lies just below the sluggish but large-volume phase transformation identified in dolomite. The Hugoniot of a material is the locus of thermodynamic equilibrium states attainable by a single shock along which the energy is known, although not constant, and is fundamental to the science of shock wave physics (2). Here, u_s is the velocity of propagation of the shock front, and u_p is the associated material, or particle, velocity. The shock velocities were measured by high-speed smear cameras which recorded the transit times through small samples, and the particle velocities were determined by impedance matching against an aluminum alloy standard. The family of Hugoniots shows a well-defined sequence from the low density, or high kerogen content, samples to the high density samples. Figure 2 shows these kinematic data transformed from the shock velocity-particle velocity plane to the pressure-relative volume plane by use of the Rankine-Hugoniot conservation relations, which require equilibrium for their validity. The solid lines on these plots are not fits to the data, but rather calculations based on a simple mixing theory known to be generally valid for mixtures of non-reacting components. The Hugoniots and thermodynamic parameters for the end members of pure kerogen and the lean rock matrix must be known. These have been obtained from the work on dolomite by Grady, *et al.* (3) and from extensive shock wave work on rocks and minerals and on polymers performed at Los Alamos in the past (4,5). It is

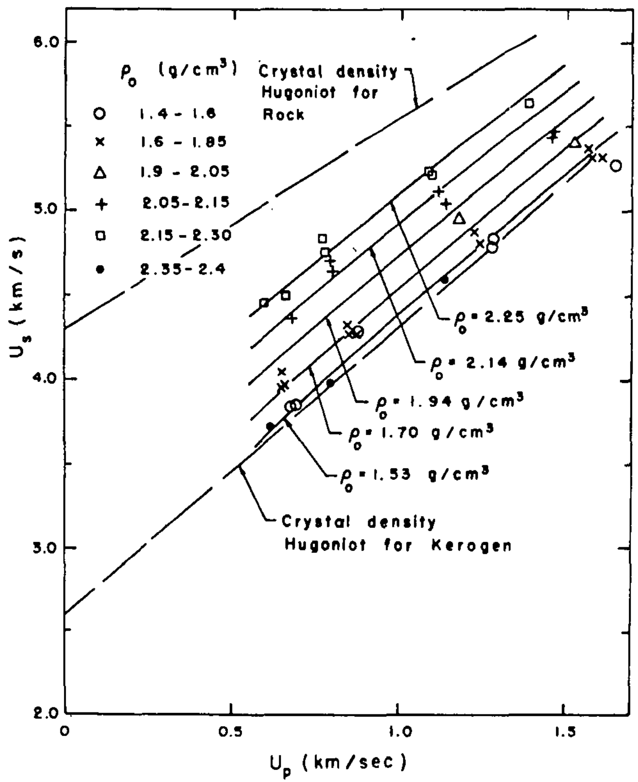

Figure 1. High pressure u_s-u_p Hugoniot data for oil shales of varying densities. The solid lines are theoretical calculations.

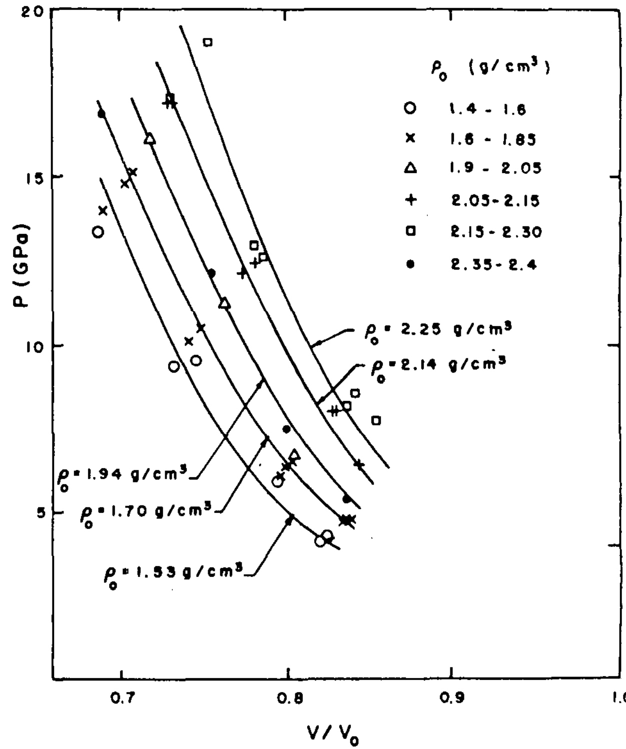

Figure 2. P-V/V_o Hugoniot data and calculations for oil shale. The Rankine-Hugoniot conservation relations were used to transform these data from Figure 1.

evident that the theoretical Hugoniots are quite adequate to reproduce the data, and that Hugoniots of oil shale with arbitrary kerogen content can now be calculated with confidence. These Hugoniots include the effect of shock heating, and theories such as that of Mie-Grüneisen must be used to calculate the equation of state E(P,V) off the Hugoniot, such as along an isentrope or isotherm. Samples were also fired with varying orientation of the shock wave to the bedding planes, and no significant orientation effects have been found at these high pressures. Experiments are underway to determine wave anisotropy at lower pressures, where those effects should be larger.

In order to establish the initial low pressure response of oil shale to both static and dynamic stresses, a program to determine the elastic constants at zero pressure as a function of kerogen content has been undertaken (6). The shale has been treated with the model of a transversely isotropic material, a reasonable assumption in view of the bedded nature of the material. Pulse-echo techniques were used to determine transverse and longitudinal sound velocities as functions of orientation in small, carefully prepared samples. The results are shown in Figure 3, where V_1, V_3, and V_5 are longitudinal velocities parallel, perpendicular, and 45^o to the bedding planes and V_4 and V_6 are shear velocities parallel to the bedding with particle motions perpendicular and parallel to the bedding respectively. From these five quantities, the various mechanical properties of oil shale such as elastic moduli, bulk modulus, and Poisson's ratio are readily obtainable as functions of density or kerogen content. The discontinuity in slope observed for all the sound velocities at a density slightly above 2.0 g/cm^3 is tentatively attributed to the fact that below this density the rock particles float more or less discretely in a matrix of kerogen and the properties of the kerogen largely determine the elastic properties of the shale. At higher densities, the rock properties play a more important role. We intend to continue such measurements under a hydrostatic environment up to pressures of about 10 kb.

Gas guns, with bores ranging in diameter from 2" to 6", are being used for detailed study of low-pressure wave profiles both on loading and release with the expectation that these profiles will have an important effect on fracture kinetics. There is good reason to believe that the high explosive properties can be tuned to take advantage of the dynamic response of the shale in this pressure range, as evidenced by these profiles, and thereby promote desirable fracture characteristics (7). Pressure gages, magnetic probes, pins, and free-surface capacitor gages are typical diagnostics used in these experiments. Other quantities amenable to measurement using these techniques include attenuation parameters, low pressure Hugoniots and dynamic spall strengths. Many of these experiments have already been performed, although discussion of them is as yet premature. As an example of the kind of experiment which can be useful in defining the fracture characteristics of oil shale, Figure 4 shows the velocity of the free surface of an oil shale sample as a function of time when the material is subjected to a plane impact stress of about 5 kb. This record was obtained using the dc capacitor technique, in which a thin metallic coating is placed on the free surface and the time rate of change of capacitance between the free surface and a charged parallel plate is monitored. Internal tension due to the rarefactions sends a signal which will decrease the free surface velocity and which can be directly related to the tensile stress necessary to cause spall fracture. In this experiment, the bedding planes were aligned along the direction of shock propagation. Other experiments include detonation of spherical charges in meter-size blocks of oil shale with pressure and particle velocity gages to monitor wave propagation and flash x radiography to view cavity formation and near-field behavior. The logical extension of these experiments, of course, is to small-scale field events which will test our ability to predict the breakage pattern resulting from any given explosive configuration, a prerequisite to optimization.

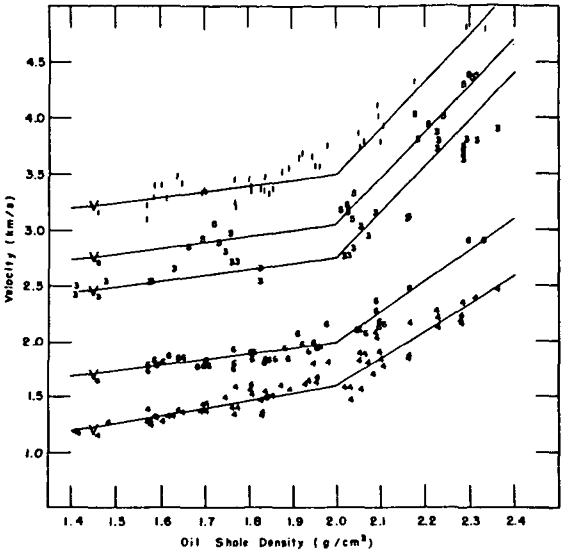

Figure 3. Zero-pressure sound velocities for oil shale as a function of density, or kerogen content. These data allow calculation of zero-pressure elastic moduli, assuming transverse isotropy.

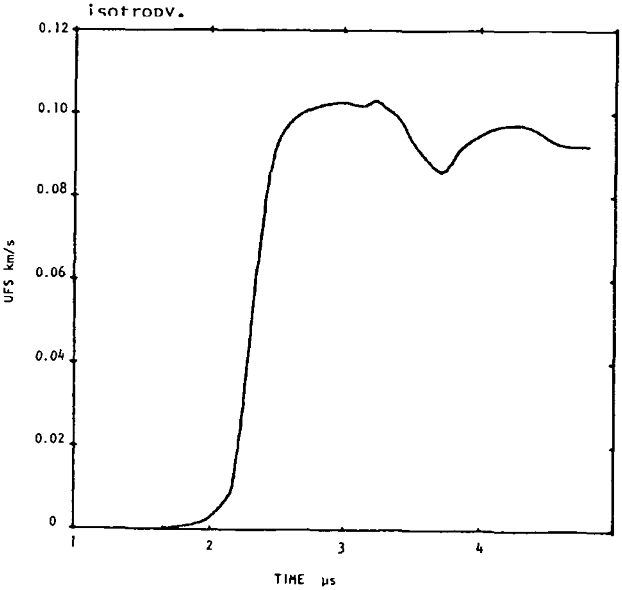

Figure 4. Typical capacitor free-surface record showing spallation of oil shale subjected to a 5-kb shock.

In order to demonstrate a quantitative understanding of the material response obtained by experiment, efforts are underway to model the results of the one-dimensional experiments described above. Large-two dimensional Lagrangian and Eulerian hydrodynamic codes originally used for weapons effects calculations have been modified to allow for plastic anisotropy, again assuming transverse isotropy. These codes are also being used for design and analysis of the large-block experiments mentioned earlier. This work is well underway, but detailed discussion of the results would be premature. Success of the codes in predicting the results of a large-scale rubblization effort in the field will be the test of our quantitative understanding of the physical processes involved in blasting.

Summary:

Since the program is still in its infancy, useful results to date are very preliminary and this paper is intended only as a program review. Eventually, there must be closer collaboration between those concerned with extraction efficiency and those who can set the attainable limits on the properties of the retort bed. It is hoped that the results of this study will have a favorable influence on decisions affecting the future utilization of the oil shale resource.

References:

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