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PERMEABILITY ENHANCEMENT USING EXPLOSIVE TECHNIQUES

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ABSTRACT

A problem common to all *in situ* georesource recovery techniques is creation or enhancement of permeability within the bed to allow a uniform and predictable flow of fluid. A new branch of rock mechanics, devoted to computer prediction of fracture patterns, void distributions, particle size distributions, and path permeabilities resulting from explosive loading, has developed in response to these needs. The method requires step-wise solution of the non-linear equations of compressible flow, with the initial and boundary conditions defined by the detonation properties of the explosive, and the material wave propagation and dynamic fracture constitutive relations determined by high strain rate mechanical tests of the resource bed material. Large-scale field tests are necessary to establish confidence in the results, but once this has been attained the codes may be used as a predictive tool on a production basis. This new branch of rock mechanics is developing and expending rapidly, and is proving a useful tool as guidance for technical end economic optimization of explosive technology.

EXPLOSIVES HAVE PLAYED A ROLE IN GEORESOURCE recovery since at least 1705 in this country, and since the early 1600's in Europe (1*). However, until recently it has not generally been necessary to exercise great control over [illegible] explosive events in rocks since processing [illegible] always been done above ground, although in practice a considerable expertise has evolved. With the emergence of *in situ* processes for extraction of energy and mineral resources, this picture has changed. There is now a need for a predictive dynamic fragmentation or fracture capability that can optimize both technically and economically the preparation of *in situ* coal or oil shale retort beds, *in situ* leach or solution mines for copper, uranium, or other materials, and stimulation from a well-bore of oil, gas or geothermal resources in low-permeability reservoirs. Although the processing requirements for each of these diverse operations are quite different, the underlying theory and approach for preparation of the resource bed is basically the same for each operation. As an example of such requirements, an explosively-prepared *in situ* oil shale retort should have the following characteristics:

a) A particle size distribution throughout the retort volume which peaks in the range of that required for maximum extraction efficiency. Current chemical kinetics and process studies place this range at roughly 5-50 cm, with the peak around 10 cm.
b) Uniform void distributions in both the horizontal and vertical sense in order to achieve a stable flame front and avoid channeling.
c) Permeability of the resultant rubble pile which is sufficient to support pyrolysis and allow removal of retorted products without excessive compressor costs.
d) Fines produced in the rubblization process which are minimal in order to avoid plugging the paths through which the gases and other products must move. This is probably the most important single factor to control.
e) A rubblized volume which is 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, prevention of water influx, and maximum utilization of the resource.

Similar criteria apply to successful explosive stimulation of oil, gas or geothermal reservoirs in tight formations, particularly if the explosive exercise is performed in conjunction with chemical treatment or other completion technology. Clearly a generalized approach to the prediction of blast effects in rocks is required, one which can be applied on a site-specific basis to any geologic formation, geometry, and need. The development of large digital computers over the past few years has made such an approach possible. Use of such a sophisticated tool for this purpose is actively being studied at LASL and other laboratories in this country, including particularly SRI International, Sandia and Science Applications, Inc.

THEORY

The propagation of a stress wave through a solid medium, such as might be generated by an explosive event in rock, is governed by the Euler equations of compressible flow (2), which express conservation of mass, momentum, and energy respectively:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho\bar{u} = 0 \qquad (1)$$

$$\frac{\partial \bar{u}}{\partial t} + \bar{u} \cdot \nabla\bar{u} = \frac{1}{\rho} \nabla P \qquad (2)$$

$$\frac{\partial}{\partial t} \left[\rho E + \rho\frac{u^2}{2}\right] = - \nabla \cdot \left[\rho\bar{u}\left(E + \frac{u^2}{2}\right) + P\bar{u}\right] \qquad (3)$$

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*Numbers in parentheses designate references at end of paper.

This is a coupled, non-linear system of partial differential equations that cannot be solved analytically except under the simplest of conditions. It is the complexity of these equations which has provided much of the impetus for development of larger and faster computers by the scientific community over the past several decades. In these equations, ρ is the density, U the particle or mass velocity, t the time, and E and P the internal energy and pressure, respectively. Under the assumption of a given set of initial and boundary conditions, these equations can be solved by a bootstrap method, in which the state variables at any time are obtained from those at the previous timestep through the difference forms of Eqns. 1-3. Since the number of time and space meshes required for solution of a realistic field-size event must be quite large, the need for a large computing facility is apparent.

The equations 1-3 represent primarily kinematic relations of space and time. Real material properties enter only through the stress terms in the momentum and energy relations, eqns. 2-3. The time dependence of the pressure, or stress, must be independently specified in order to reproduce the response of a given rock. This time-resolved pressure dependence, loosely referred to as the "constitutive relation", is subject to experimental determination using modern dynamic rock mechanics techniques; this behavior depends on inherent mechanical and equation of state properties of the rock governing the shock response, such as the shock and release wave profiles, visco-elasticity and visco-plasticity, phase transformations, anisotropy, and fracture mechanisms. Since these properties are often dependent on stress levels and strain rate, and in fact are closely inter-related, a large number of experiments are required to characterize the rock fully. If other variables are present, such as bedding, variable kerogen content, or substantial changes in mineral composition, these must be studied as well. Only when the constitutive relations are determined will the calculations using the Euler equations faithfully reproduce the flow and breakage in the rock.

As for all such systems of partial differential equation, the Euler equation.must be solved subject to specified initial and boundary conditions. Hence, the detonation properties of the explosives must be specified in order to determine the initial stress distrubution and the time-resolved energy depositions resulting from the explosion. Until recently, these properties have not been known for commercial non-ideal explosives commonly used for blasting purposes, that is, those explosives whose properties depend on geometry, confinement, and boostering. During the past several years significant progress in our understanding of non-ideal explosive behavior has been achieved.

CONSTITUTIVE RELATIONS

No geologic material has yet been studied sufficiently to allow unambiguous calculation of the breakage pattern resulting from a given explosive loading. However, much work has been done on a number of materials of interest, including Green River oil shale (3), Antrim shales (4), and Devonian gas shales (5), and calculations with these materials can proceed with some confidence. Experiments are most conveniently done in plane geometry, and for strain rates above 10^4/s are most often performed on a gas-driven gun. A schematic drawing of such a laboratory-scale gun is shown in Figure 1. The instrumentation used to determine

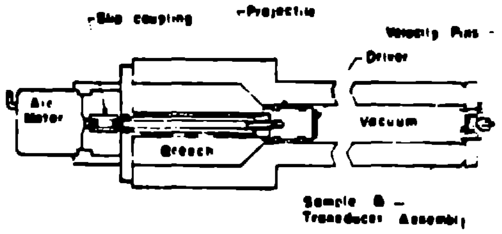

Fig. 1-Schematic of gas-driven gun used for dynamic rock mechanics experiment. The projectile/driver assembly strikes the sample at a carefully controlled velocity to achieve a controlled stress level in the sample.

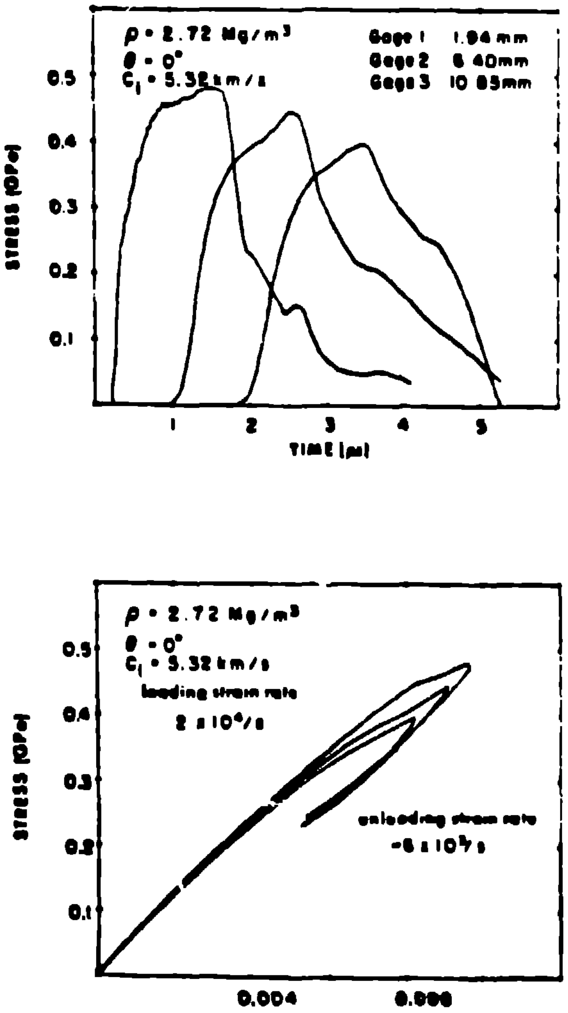

Fig. 2-Stress-time and stress-strain profiles obtained from samples of Devonian shales. Three manganin gauges were embedded at different levels within the target; the effects of bedding and attenuation on the profiles is evident.

the response of the target material to plane wave impact by the projectile includes both free surface (laser interferometry, parallel plate capacitors, magnetic probes, quartz or lithium niobate crystals) and in-material (manganin or ytterbium, magnetic probes) gauges. An example of such an experiment is shown in Fig. 2. Here, manganin gauges were inbedded within a sample of Devonian shale and the stress-time profile monitored. These profiles are transformed to the more usual stress-strain contours in Fig. 2-b. Such wave propagation data are relatively straightforward, although tedious, to obtain. Much more difficult are the dynamic fracture properties. Guns are again useful in some cases, in particular for dynamic spall strengths at strain rates in excess of 10^4/s. Split Hopkinson bars or torsion bars can yield data on fracture strength up to about 10^3/s, although interpretation of results from these devices is still open to question. These data are essential for determination of far field behavior, several borehole diameters removed from the explosion, where much of the damage occurs in the sub-kilobar pressure range and 10^2-10^3/s strain rate regime. Much experimental work remains on this problem, as well as that of the importance of gas fracture from the late-time explosive products.

EXPLOSIVE CHARACTERIZATION

Quantitative characterization of the performance of commercial blasting agents (non-ideal explosives) is crucial for success of a computer-designed fragmentation or permeability enhancement scheme, since these data provide the initial and boundary conditions for solution of the Euler equations. If the rock response characteristics are sufficiently well known, these calculations also provide guidance for tailoring, or chemical modification, of the explosive for optimum breakage efficiency. Such tailoring can include modifications of the detonation velocity, total energy, or peak (C-J) pressure, control of the pulse duration, or modification of the pulse rise time in order to prevent formation of fines in the vicinity of the borehole. Obviously, coupling of the detonation energy to the rock and the dynamic mechanical response of the rock itself are important considerations in explosive tailoring, and the choice of explosives must be specific to the reservoir bed. The explosive characterization experiments are designed to determine the importance of diameter, confinement, and the booster system, and to measure the time history of energy release (3). A typical experiment is the aquarium design, in which the test explosive induces a shock into water or a similar transparent material. The explosive, confined in a material of interest, is centered in a large water tank and detonated from one end. A measurement of shock position and bubble radius in the water as a function of time allows calculation of detonation pressure and late energy release. A record of such an event is shown in Fig. 3, where experimental shock and bubble contours in water resulting from detonation of ammonium nitrate-fuel oil are matched by a two-dimensional hydrocode computer calculation. Such analysis shows that less than half the energy of the ANFO detonation is released at the detonation front, the remainder being released a few ten of microseconds later. Such experiments have been performed on a large number of commercial explosives, and a consistent theory is beginning to emerge. This theory is based on a non-ideal BKW model (6), in which the components of the explosives are allowed to react according to the kinetics of the individual reactions to form all possible final products. Such an approach has proven very successful for calculation of ideal explosives properties in the past; development of such a tool for non-ideal explosives will reduce the necessity for extensive experimental work in the future.

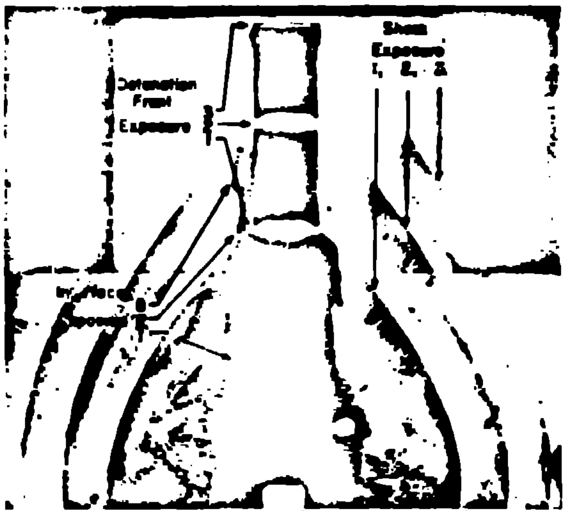

Fig. 3-An image-intensifier record of the detonation of ANFO confined in Plexiglas and immersed in water. The shock and bubble positions are clearly evident at all three times.

FRACTURE MODELS

A number of candidate models for the theoretical description of fracture under dynamic loading exist and await experimental verification in large-scale field tests. Most such descriptions are homogeneous, since they utilize parameters representing average properties associated with each computation cell and do not attempt to follow the propagation of individual fractures. They may range in complexity from calculation of a scalar, such as generalized strain, plastic work, or maximum tensile stress, that can be tested against a threshold value (7), to much more subtle models which predict the nucleation and growth of initial flaws and their coelescence into fractures that intersect to form particles (8). Problems associated with all such constitutive models of rock breakage are inclusion of the non-zero inelastic volume strain (dilatancy) and the loss of shear strength associated with brittle fracture. The scalar approach does not predict degree of rubblization, particle size, or porosity unless empirical correlations between these quantities and the theoretical parameters are found. A continuum model which overcomes some of these difficulties is to characterize fracture in the form of a single parameter that is equal to zero for intact rock and approaches unity for complete pulverization. The shear yield surface can then be written as functions of this parameter and material constants which can be determined directly from laboratory measurements of shear and yielding on prefractured rock. This damage parameter must also depend on the inelastic strain rate. Calculations based on this model (9) are shown in Fig. 5 for two explosives, low-density TNT and ANFO, 0.12 M in diameter and one meter long, and buried at a depth of 0.4 m. The contours in Fig. 5 represent different values of the damage parameter D; the region defined by D ≥ 0.5 is arbitrarily chosen to represent the crater volume.

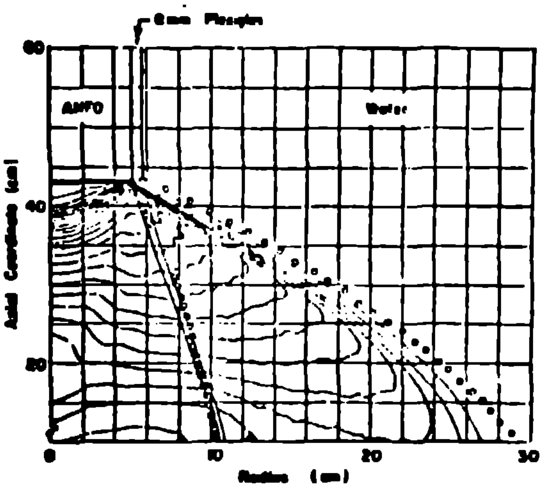

Fig. 4-Comparison of measured shock front and Plexiglas/water interface positions (circles) obtained from Fig. 3 with computer calculations using a non-ideal BKW explosive equation of state.

Other effects, such as anisotropy, inhomogeneities, natural fractures and joints, density variations or stratigraphy and the effects of gas fracture also must be included in these calculations on a site-specific basis. Because of these complexities and uncertainties, computer design is more useful as guidance for optimizing explosive technology rather than detailed prediction of fracture.

FIELD TESTS

In order to establish confidence in the codes and material properties determinations, large-scale, heavily instrumented explosive field tests are required. Parameters necessary for direct comparison with the calculations are stress wave profiles, particle velocity and acceleration, free surface motion, and post-shot damage determination. Very few such quantitative tests have been performed. Examples of such quantitative experiments on large scale blasting effects are the bed preparation studies soon to be conducted by Los Alamos under DOE auspices in close collaboration with the Colony Development Operation in Green River oil shale. The geometry for one of these experiments, a single explosive hole parallel to the bedding planes, is indicated in Fig. 6. The experiments must be sufficiently simple that unambiguous interpretation of the data is possible. They are not, therefore, designed to optimize the loading, but rather to yield understanding which can be used to optimize the fragmentation process.

These tests will combine extensive pre-shot diagnostics, including coring, acoustic mapping, photography, and permeability measurements, with

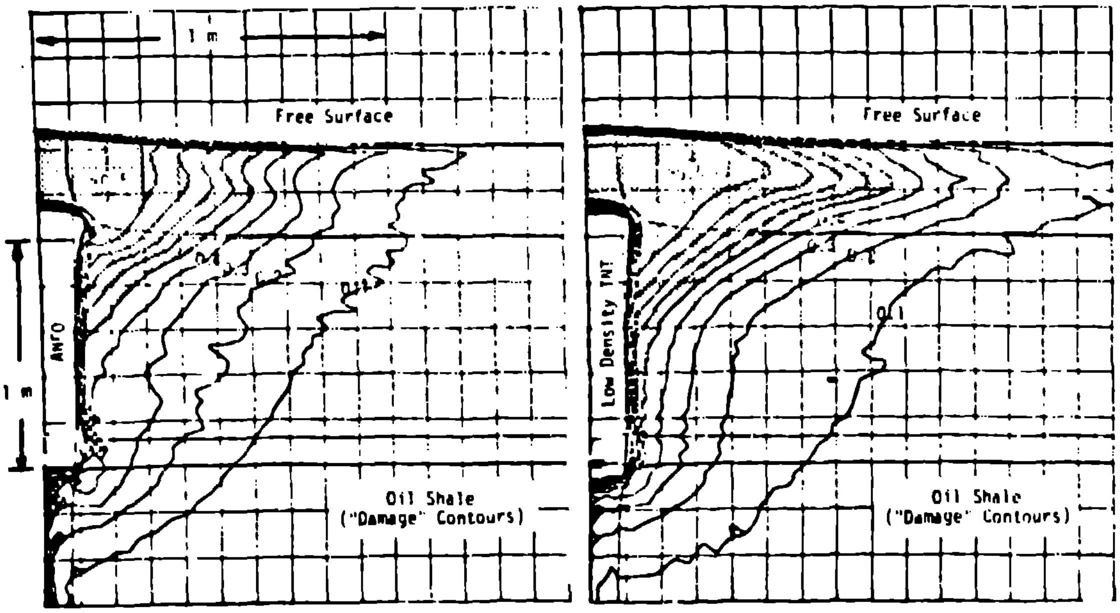

Fig. 5-Hydrocode prediction of damage contours for 12 cm dia charges of ANFO and TNT, 1 m long and 0.4 m below the free surface. The region defined by D ≥0.5 is arbitrarily chosen to represent the crater volume.

shot-time diagnostics, including stress gauge measurements, acceleration and velocity gauge measurements, and high-speed photography, and post-shot diagnostics including acoustic mapping, sieve analysis, permeability measurements, photography, coring, and mineback. Effects of bedding orientation, kerogen content, explosive type, size, and depth of burial, and constrained free volume will also be investigated. These experiments are difficult and costly. However, the potential payoff for improved blast control and increase in our understanding of basic explosive processes is so great as to fully warrent this extra effort.

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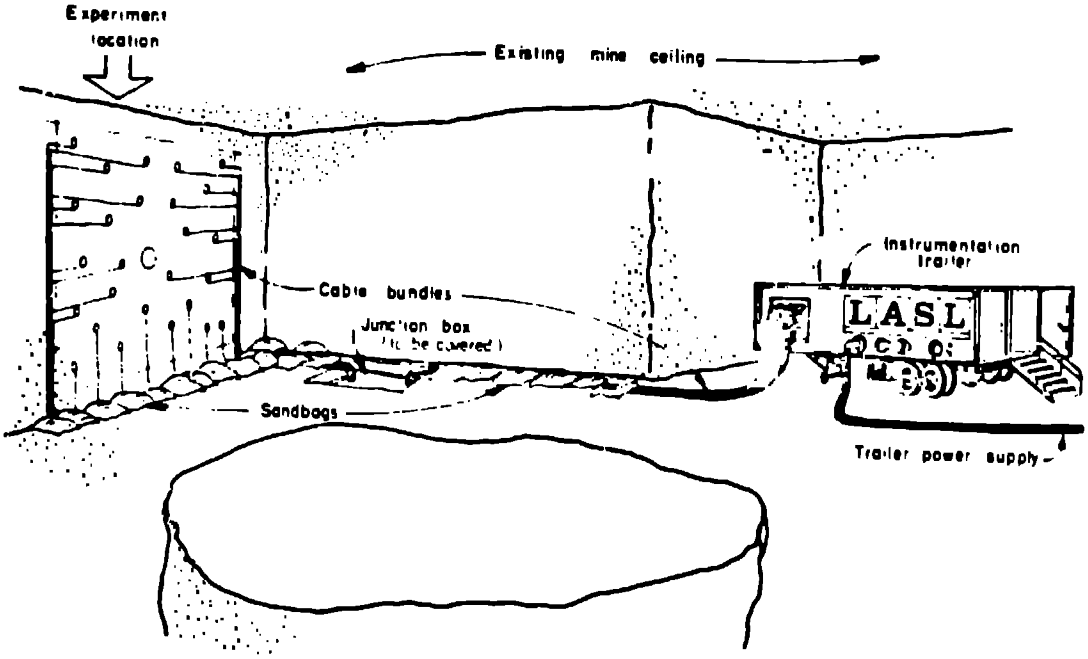

Fig. 6-Schematic of field experiments as performed in oil shale. The column of explosive is at the center, and the surrounding boreholes contain instrumentation designed to provide wave propagation and fracture data.