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ROCK SPRINGS OIL SHALE FRACTURIZATION EXPERIMENT:
EXPERIMENTAL RESULTS AND CONCEPT EVALUATION

A. L. Stevens, P. C. Lysne and G. B. Griswold

MASTER

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ROCK SPRINGS OIL SHALE FRACTURIZATION EXPERIMENT:
EXPERIMENTAL RESULTS AND CONCEPT EVALUATION

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ABSTRACT

Sandia Laboratories has participated with the Laramie Energy Research Center of the Bureau of Mines in the explosive-fracturing phase of an oil shale fracturization and retorting experiment conducted near Rock Springs, Wyoming. The concept of the explosive event is new and amenable to computer simulation. Specifically the oil shale formation was hydraulically fractured in three horizontal planes located at about 148, 160 and 172 feet (49, 52, and 56 m) below ground level. Ideally, the middle hydraulic fracture was to be filled with a slurry explosive, whereas the upper and lower fracture would constitute void space. Shock waves reflecting from these voids cause multiple fractures (spalls), thereby increasing the permeability of the formation.

Prior to the fracturization experiment conducted on May 31, 1974, stress gages and geophones were emplaced in or on the oil shale formation for the purpose of measuring the spatial and temporal variation of the shock wave generated by the detonation of approximately 7,000 pounds (3.2×10^3 kg) of explosive. The purpose of this instrumentation was to enable a correlation

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of observed and predicted fracturization. The observed stress pulse amplitudes were about an order of magnitude less than expected. This discrepancy could have been caused by an absence of explosive or a failure of detonation in the middle hydraulic fracture in the region just below the stress gages. Alternatively, lenses of porous material (tuff) were found in post-test coring, which could have seriously degraded the stress pulse. In any event, the stress pulses were insufficient to induce a significant number of fractures into the formation, and post-test coring verified that the induced fracturization was very low.

While the Rock Springs event was not as successful as one might have hoped from a fracturization standpoint, a great deal was learned concerning the details of the concept and computer simulations outlined in this report indicate that experiments like that of Rock Springs can induce significant fractures into nonporous rocks like oil shale. With this in mind, we make recommendations which should lead to an expeditious development of the fracturization concept.

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I. INTRODUCTION

The in situ processing of oil shale offers many advantages over conventional surface processing methods--large-scale mining operations may be reduced or eliminated, deposition of spent shale is not a serious problem, and the usage of water is minimized. Nevertheless, in situ processes have not advanced rapidly in view of difficult problems pertaining to the efficient usage of natural resources, process control, and bed preparation.

In regard to this latter problem, several approaches have been attempted. The Garrett Research and Development Company has used conventional mining and blasting techniques to induce permeability by rubbleizing large volumes of oil shale.¹ Such a technique is convenient when the formations are near the surface and in competent rock. However, as deeper formations are processed, the cost and difficulty will certainly increase. Another in situ retorting approach, largely due to efforts of the Laramie Energy Research Center of the Bureau of Mines, is based on permeability introduced into tight oil shale formations by hydraulic fracturing, electrolinking and explosive techniques.^{2,3} Should any of these latter approaches prove feasible, deep formations could be processed cheaply and without mining.

The Rock Springs event of May 31, 1974, was conducted by the Laramie Energy Research Center to prepare an oil shale formation for retorting. The bed-preparation phase of this event, to be discussed in detail below, consisted of first hydraulic fracturing the formation, then the injection and detonation of a slurry explosive. This concept is not new. Several patents⁴ have been issued on various techniques and numerous service companies⁵ use them to stimulate oil and gas wells.⁶ This does not mean the process, as applied to oil and gas well stimulation, is well understood.

Commonly, the evaluations of a treatment are simply related to the increase (or decrease) in production.⁷ Since the results can be negative, good wells have not been treated and a conclusive evaluation of the concept has not been achieved. Even less can be said concerning the application of these fracturization techniques to oil shale formations. Before the Rock Springs event, only limited attempts had been made to use them in oil shale.⁸ Thus, numerous uncertainties exist dealing with such nontrivial engineering considerations as hydraulic fracture spacing and desired explosive characteristics.

Several methods could be used to eliminate these uncertainties. Historically, blasting techniques have progressed on a trial and error basis. While such methods could be used here, their cost would be prohibitive since satisfactory evaluation of test results requires extensive drilling or even mining. A much more satisfactory method of development is centered about recent advancements in the calculation of the stress pulse generated by the detonation of an explosive and the response of materials to this pulse. Such calculations, as applied to events like the Rock Springs experiment, are contingent upon: (a) a knowledge of the composition and heat of formation of the explosive; (b) a laboratory rock mechanics program designed to determine mechanical response models for rocks and to collect appropriate materials data for specific sites; (c) extensive computer modeling and simulation as a means of testing the feasibility of various explosives and geometries proposed prior to undertaking costly field experiments; and (d) the measurement of various parameters during actual experiments to check laboratory determined material data against data collected in the field and to compare computer models and simulation results with field results. The participation of Sandia Laboratories in numerous field events has this

latter objective. The Rock Springs event was of particular interest in view of the amenability of the experiment to both computer simulation and field measurements.

Sandia Laboratories was invited by the Laramie Energy Research Center to instrument the explosive event as well as make pre- and post-test measurements on the oil shale formation. The purpose of this report is to detail those measurements and computer modeling studies that we have made that pertain to the fracturization experiment. (Other reports detailing ground motion measurements,⁹ the design of stress gages¹⁰ and a summary of the Rock Springs event, are being prepared by other investigators.) Specifically, herein we (1) detail pre- and post-test coring results as they pertain to fracturization evaluation, (2) detail stress and sonic (geophone) measurements made during the event, (3) draw conclusions concerning the effectiveness of the event from the modeling studies and from all available data, and (4) make suggestions in regard to future efforts concerning this technique. We specifically exclude a discussion of the suitability of the prepared bed for retorting operations, although calculations regarding this subject could be based on our post-test coring experiments.

In the next section we detail the measurements and calculations made to aid in our understanding of the Rock Springs event. In Section III the results of these measurements are presented along with the results of post-test geologic experiments. In Section IV we summarize our conclusions and make recommendations for future work concerning the concept of hydraulic fracturing with liquid or slurry explosives.

II. THE GENERAL EXPERIMENT

II.A. Background

The site selected by the Bureau of Mines for the in situ rubblization and retorting experiments is located approximately six miles west of Rock Springs, Wyoming, and is designated Site 9. The current experiment is one of a series on in situ processing of oil shale conducted in this vicinity over the last several years by the Laramie Energy Research Center of the U.S. Bureau of Mines.

Before Sandia's participation, the Bureau of Mines had drilled a well into the formation, hydraulically fractured and propped three horizontal cracks in the formation (see Fig. 1a for an idealized section view of the formation), and contracted with an explosive supplier, Teledyne-McCormick Selph,⁵ to provide, emplace and detonate approximately 7000 pounds (3.2×10^3 kg) of slurry explosive. For air injection, oil recovery and monitoring purposes during the retorting process, eight additional wells were also drilled around the initial well in the nine-spot pattern shown in Fig. 1b.

II.B. Geologic Information

Site No. 9 is located along the eastern margin of the Green River Basin. Beds outcropping along the escarpment marking the edge of the basin range upward from the Wasatch Formation to the Laney Member of the Green River Formation. The attitude of these beds is north striking with a gentle west dip of about 100 feet per mile (19 m per km). No major structures disrupt this trend in the vicinity of the test site.

The oil shale zone used for the test lies in the upper part of the Tipton Member of the Green River Formation. An idealized section showing the significant features of lithology is given in Figure 2. The basal

part of the Wilkins peak member forms the cover from the ground surface down to the top of the oil shale. This cover is approximately 125 feet (38 m) thick at the site and consists of marlstone with thin lenses of tuff. Phosphatic beds containing minor amounts of uranium are present as well as a few thin (less than 5 feet (1.5 m)) lenses of low grade oil shale. The transition from the Wilkins Peak down into the Tipton is marked by a sudden increase in oil shale content. The lithology remains essentially the same; i.e.,

Figure 1a. Idealized East-West section view of the formation showing the instrument holes, wells and hydraulic fractures. This geometry was used in the computer prediction of stress-wave propagation, cf. Section II.E. A more realistic view of the formation is given in Figures 10 and 11.

Figure 1b. Surface location of all wells. Wells 0-2, -3, -4, and -5 were drilled after the explosive event. They were used for fracturization evaluation and are planned for thermocouples and gas analysis instrumentation.

Figure 2. Lithology of Site 9

marlstone with occasional tuff lenses up to 0.5 feet (0.15 m) thick. Differential compaction during lithification has caused several zones to have wavy bedding in contrast to the typical platy layering present in most of the section. The Tipton Member is approximately 130 feet (40 m) thick here, but drilling has only penetrated the upper 65 feet (20 m).

Site No. 9 was deliberately selected so that the oil shale section would lie under sufficient cover so as to eliminate alteration effects due to surface weathering. This being the case, the evaluation of the characteristics of the formation had to be done either by examination of the core or by borehole geophysical methods. Table 1 summarizes the techniques used. Excellent hole-to-hole correlations were attainable using these techniques which was to be expected because the oil shale beds are very uniform and the holes were closely spaced.

The changes in lithology provided a good number of "picks" for horizon markers. The natural gamma ray logs alone provided nine high emission markers, the sonar scanner provided 10 distinctive layers (normally tuff beds), and the resistivity log provided four contrasting layers which correlate with oil shale richness. For sake of simplicity, only four of these horizons will be described. They are used here because they represent markers at the top, bottom and middle parts of the formation.

Top Marker Bed. This marker consists of a barren, wavy-bedded unit of marlstone and compacted tuffs 3.2 feet (0.98 m) thick. The unit is sandwiched between two rich lenses of oil shale. The wavy bedding makes it easily identifiable in core and on the sonar scanner.

Middle Marker. This marker consists of two tuff beds 1.5 feet (0.45 m) apart. These show well on the sonar scanner and in the core.

TABLE 1

SUMMARY OF TECHNIQUES USED BY SANDIA TO EVALUATE FORMATION CHARACTERISTICS

Evaluation Technique	Information Sought	Holes Used In																
		<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>S-1</u>	<u>S-2</u>	<u>S-3</u>	<u>S-4</u>	<u>O-2</u>	<u>O-3</u>	<u>O-4</u>	<u>O-5</u>
Core	Lithology Fractures										x		x		o	o	o	o
Caliper	Fractures	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	x	x		x				
Resistivity	Lithology	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	x	x		x				
Self-Potential	Lithology	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	x	x		x				
Gamma Ray	Lithology	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	x	x		x				
Sonar-Scan	Fractures	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	x	x		x				
Sonic Velocities	Physical Properties	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	x	x		x				
Down Hole TV	Lithology, Fractures	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	x	x		x	o	o	o	o
Gamma-Gamma	Density	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	x	x		x				
Survey	Location	x			x	x				x	x	x		x				

x Pre-shot Survey Only

o Post-Shot Survey Only

⊗ Pre-and Post-Shot Survey

Lower Marker. This marker is a zone 2.6 feet (0.79 m) thick containing numerous tuff lenses, three of which consistently reveal themselves on the sonar scanner.

M1 Bed. This is a thick tuff (up to 0.4 feet (0.12 m) thick) that has traditionally been used in the Green River Basin as a horizon marker. The unit is easily identified in core. A subsidiary tuff unit lying 1.8 feet (0.54 m) above the M1 bed was more distinct on the sonar scanner. This unit was designated the M1 bed and used as an auxiliary marker.

Detailed structural mapping of the formation under the diamond-shaped drill pattern was possible. Structural contours of the middle marker and M1 bed are given in Figures 3 and 4. In general, the markers conform with the regional trend, i.e., north striking with gentle western dip. In detail, however, local warping is obvious. This can be explained by differential compaction, minor tectonic forces subsequent to lithification, or minor vertical faulting. If the latter is the case then the smooth contouring is not a true portrait of the surfaces.

Figure 3. Contours of the base of middle marker.

Figure 4. Contours of the M1 Bed.

II.C. Fracture Evaluation (Pre-Shot)

Four methods were available to examine the state of natural fractures existing in the original pattern of nine boreholes before the shot: sonar scan, caliper, seismic wave velocity, and down-hole TV. No core was available on these holes so fracture analysis had to be done by the above techniques. Core was taken on instrument holes S-1 and S-3, but since these holes terminated short of the middle fracture, no correlation could be made below that point with the other records.

The output from the sonar scanning tool was recorded photographically from an oscilloscope display. The orientation of the tool is also monitored, thus the film record was oriented which allowed an easy calculation of the attitude of inclined fractures. A limitation was that in order for fractures to be identified there had to be a significant impedance contrast and the feature must have a width of at least a few millimeters. Hairline cracks were seldom recorded.

It was hoped that the sonar scans would pinpoint the location of the hydraulic fractures. While partially successful, several factors prevented detection of these artificial fractures in many instances. The most

significant factor was the abundance of thin horizontal features (impedance contrasts) caused by tuff lenses, rich oil shale, or formation partings. Another factor was that the hydraulic fractures probably are very thin, less than a centimeter. These same problems relate to the capability of detecting small fractures with the other tools leaving only the down-hole TV. Even this method had problems resolving small features, and good fracture identification was possible only at those points where formation water was seeping back into the hole. The problem here was that formation partings and tuff lenses also were found to be very permeable, and inconclusive results were common. For this reason, it was decided to rely on the locations of the artificial fractures as derived from the Bureau of Mines air injection and impression packer measurements.

The tools were successful, however, in defining any major discontinuity in the holes. All evidence pointed to these conclusions:

- No significant pre-shot fracture pattern was present in the formation. Essentially all flat-lying features were attributable to formation partings or tuff lenses.
- Inclined fractures, i.e., fractures oblique to the bedding, were rare, with frequency probably less than one fracture per 50 vertical feet (16 m).
- Some identifiable horizontal feature was always present near where the Bureau of Mines reported an artificial fracture.
- No zones of degraded physical properties were detected on the sonic velocity logs that could not be accounted for by the presence of tuff beds. In other sections the properties agree well with laboratory measurements of solid oil shale specimens.
- Permeable zones other than the three artificial fractures do exist. These were commonly from the thicker tuff beds.

II.D. Relationship Between Hydraulic Fractures and the Structure of the Formation

Graphic presentation of the surfaces of the three hydraulic fractures are presented in Figures 5-9, along with the isopach of the intervening thickness between them. From these drawings it is obvious that, while in a general sense the fractures are horizontal, they certainly do not follow any particular bed within the formation. In addition, there seems to be no correlation with any of the variations in physical properties measured, e.g., Young's Modulus, Poisson's Ratio, etc. The structural contours of the M1 bed and the Middle Marker have a common feature--a rise, or dome, in the southeast part of the drilled area--yet this feature appears to have had no effect on the fractures.

The upper and middle fracture surfaces do have a feature in common. Both have distinct gradient contrasts along a westerly direction from well 1 to well 9. The surface of the bottom fracture has an anomalous zone extending south from well 1 to well 8. The reader is to be cautioned in interpreting the shapes of these surfaces because smooth contours were assumed. It could be that the actual fracture has cleaved surfaces representing abrupt changes in attitude. Another factor is that it is conceivable that the location of the true hydraulic fracture was mistaken for tuff lenses in several holes which would completely destroy the confidence of the plots.

A pictorial summary of the pertinent geologic information is given in Figs. 10 and 11. Shown are the formation markers, the hydraulic fractures and some post-shot fracture information (wells 0-2, -3, -4 and -5). This latter information will be discussed in detail in Section III.D.

Figure 5. Contours of upper fracture.

Figure 6. Contours of middle fracture.

Figure 7. Contours of lower fracture.

Figure 8. Isopach of thickness between upper and middle fractures.

Figure 9. Isopach of thickness between middle and lower fractures

Figure 10.

Cross section of the formation looking northeast. Wells 0-3 and 0-5 were drilled after the explosive event.

Figure 11.

Cross section of the formation looking northwest. Wells 0-2 and 0-4 were drilled after the explosive event.

II.E. Simulation Calculations

One- and two-dimensional simulation calculations using wave propagation codes were used extensively in this fracturization experiment for designing the placement of the stress gages, for predicting the stress histories to be recorded, and for predicting the extent of the spallation-induced fracturization. At the time these calculations were made, all of the geologic information given in Sections II.B and II.C had not been digested. Hence, the idealized geometry given in Figure 1a was used in the calculations.

Material properties data used in these calculations were determined from information on oil shales available in the literature,¹¹ from limited laboratory tests on core samples from the Rock Springs site,¹² cf. Table II, and from in situ measurements. These data were insufficient to establish a sophisticated model for the shock and release wave response for oil shale. Nevertheless, they were used for lack of any other data available in the time frame imposed on these calculations. The limitations of these calculations are discussed below. Note, in particular, that the presence of the middle marker, located between the center crack and the stress gages, was unsuspected at the time these calculations were made.

TABLE II
ACOUSTIC PROPERTIES OF MATERIALS OF THE ROCK SPRINGS EXPERIMENT

Property \ Material		Rock Springs Oil Shale	Alumina Filled Epoxy	Cement Grout
Density, ρ gm/cc	Range	2.0 - 2.3	2.35 - 2.36	2.1 - 2.2
	Median	2.2	2.35	2.2
Sound Speed, C_L mm/ μ sec	Range	3.0 - 3.6	3.22 - 3.25	2.9 - 3.1
	Median	3.3	3.23	3.0
Impedance, ρC_L	Median	7.3	7.6	6.6

The oil shale formation was modeled as a homogeneous, isotropic, void-free material. An examination of any oil shale core indicates that this is not true. However, we were primarily interested in shocks propagating in directions nearly normal to the formation layers, and these layers were closely spaced (≈ 0.1 inch or 0.3 cm). Thus the dispersion of the shock by the layers was small and could be reasonably neglected. The presence of voids in a material can cause mitigation as well as dispersion of a shock. However, the core obtained from wells S-1 and S-3 indicated the formation above the gage locations was competent and nearly void-free. Thus it was decided to model the oil shale as a hydrodynamic medium with an equation of state of the Mie-Grüneisen form commonly used in shock wave calculations. The parameters chosen for this equation of state are $\Gamma = 1.14$, $\rho_0 = 2.2$ to 2.7 gm/cm^3 , and $U = [3.3 \text{ to } 3.7 + (1.1) \text{ to } (3.3)u] [\text{mm}/\mu\text{sec}]$ where Γ is the Grüneisen parameter, ρ_0 is the initial density, U is the shock velocity and u is the particle velocity.

The detonation characteristics of the explosive and the release adiabats of the product gases were also needed for the simulation calculations. Such information could be measured or it can be calculated if the major constituents of the explosive are known. Unfortunately, the constituent information is proprietary and the time available did not allow for the necessary measurements. Thus, the explosive was modeled using parameters applicable to TNT and nitromethane.

Since some ambiguity exists in the parameters chosen to represent the oil shale and the explosive, studies were made, using one-dimensional stress wave calculations,¹³ to examine the effects of varying the material parameters, explosive properties and quantities (center crack thickness), and fracture strengths of the shale. Figure 12 shows the range of peak stress amplitude

as a function of distance from the explosive-filled center crack. These calculations were used as guides in setting the dynamic range of the recording equipment for the experiment. They also gave some indication of the extent of the shock-wave-induced fracturization.

Figure 12. Range of peak stress values obtained in one-dimensional computer calculations.

This fracturization can occur when a finite-duration shock pulse, such as that obtained from an explosive, interacts with a free surface. The leading compressive portion of the shock pulse reflects from the free surface as a release wave, i.e., the stress behind the reflected wave front is zero. The interaction of this release wave with the release waves which are trailing the shock produces tensile stress states which may exceed the

dynamic failure strength of the material. Whenever this happens, fracturization, commonly referred to as spallation, occurs and a new free surface is generated. Numerous fractures can result from the triangular-shaped stress wave produced by explosive loading.¹⁴

An estimate of the spall-induced fracture density obtained from the one-dimensional stress wave calculations is given in Figure 13. This estimate may be high for several reasons. As mentioned above, the dispersive effects of the bedding layers and the tuff layers were not accounted for in the calculations.

Figure 13. Estimate of shock-induced fracturization. As discussed in the text, this estimate may be high for several reasons.

In addition, the one-dimensional calculations assumed a normal incidence of the compressive wave upon the free surface at the upper (or lower) crack, whereas the actual angle of incidence is approximately 30 degrees. Diffraction of the incident compressive wave into two reflected waves, rarefaction and shear, results in lower tensile stresses than are predicted by the one-

dimensional calculations. Finally, the present calculations assumed the top and bottom cracks to be open, when in fact they contained the sand proppant and, very likely in the actual experiment, water. Taken individually or together, these effects all tend to reduce the spall fracture from the level predicted by the one-dimensional calculations.

Typical two-dimensional stress wave propagation¹⁵ results are indicated in Figure 14 where a section through the conoidal wave front is shown in the form of stress isobars at 1.4 msec after detonation of the explosive at the intersection of the center borehole and center crack. These calculations were made using median values of the material parameters for the oil shale ($\rho_o = 2.2 \text{ gm/cm}^2$ and $C_L = 3.3 \text{ mm/\mu sec}$), and the assumption of a perfect impedance match of the gage assembly and cement grout to that of the oil shale. The results indicated the proper angle for mounting the stress gage elements, expected values of stress amplitude at the gage locations in this cylindrically symmetric geometry, and expected stress histories throughout the oil shale formation.

Figure 14.

Predicted stress isobars 1.4 msec after detonation. The results shown were obtained from a two-dimensional calculation.

In regard to the simulation calculations we have reached the following conclusions:

- Stress amplitudes on the order of a few tenths of a gigapascal (1 GPa = 10 kbar) may be expected between the middle and upper hydraulic fractures. These amplitudes are in a convenient range for existing instrumentation.
- Significant shock-wave-induced fracturization would occur in the vicinity of the upper and lower hydraulic fractures according to our preliminary modeling of the Rock Springs event. Post-test evaluation of this event indicated that such fracturization was not achieved (see Section III.D). Although our calculations support the concept of Rock Springs-like events, details such as bedding layers, tuff lenses, water and proppant in the cracks, etc., should be accounted for in detail to determine the degree of their influence on fracturization.

II.F. Stress Gage Placement and Design

The locations, in plan view, of the four wells for the stress gages are shown in Fig. 1b. These locations were selected on the basis of pre-shot test data which showed a high degree of communication along the hydraulically fractured cracks between well 1 and wells 5 and 9. This suggested that stress gages placed in this region would have the highest probability of having a propagating detonation in the center crack near the gages. A somewhat idealized sectional view showing the radial positions of the three gage sets S₂, S₃, and S₄ relative to the bore holes 1 and 9 and their vertical positions relative to the middle and upper cracks is given in Fig. 1b. The radial distance from well 1 to the nearest gage was selected to minimize

the effect on the stress measurements of a large mass of explosive in the center well. The positioning of gages S2, S3, and S4 along the same radial was designed to map the stress history in this axially-symmetric problem. All of the gage holes were drilled down through the upper crack to a depth near but not entering the center crack. In this manner it was hoped that competent oil shale separated the gage assemblies from the center crack which was to contain the explosive. That this was not the case became apparent only after the explosive event, when the m_1 marker was located, cf. Section II.B.

Two different types of gage elements were used in the stress gages fielded in this experiment. Gage set S1 was fabricated using ytterbium foil gage elements which are piezoresistive units. The remaining three gage sets, S2, S3, and S4, employed piezoelectric lithium niobate gage elements. A detailed description of the construction and operating characteristics of the ytterbium gage may be found in Reference 16, and a similar description of the lithium niobate gages, together with details of signal conditioning and recording, during the experiment, is given in Reference 10. Thus, only the assembly of these elements into the field gage configuration will be discussed here.

By operating these gages in the hydrostatic sensing mode for stress pulses with at least many tens of microseconds risetime and at least many hundreds of microseconds duration, it is not normally necessary to orient the gage elements in relation to the direction of stress wave propagation. However, prediction of the stress waveform was uncertain for the Rock Springs experiments. Pre-test shock-propagation (projectile-impact) experiments on representative core samples indicated that risetimes as short as 10 microseconds might be expected.¹⁷ This possibility dictated

that the lithium niobate gage disks be oriented with their axes normal to the local wavefront. In this way the risetime of the sensor was made to be less than 3 microseconds. This orientational requirement suggested that the gage elements for each borehole (S2, S3, and S4) be packaged as an assembly to simplify down-hole alignment in the field.

The ytterbium gages, by comparison, are very thin foils, but the only available units had a 2.25 inch (5.7 cm) dimension across the grid diagonal and could only be installed with their grid plane horizontal. Consequently, the inclination of the wavefront to the grid plane resulted in a risetime of as much as 14 microseconds for these gages. This does not include the ring-up time of the wave in the sizable gage body which was not impedance-matched to the oil shale. The ytterbium gages were also packaged in an assembly to simplify field installation.

Each of the four gage assemblies consisted of three gage elements with 24 inches (0.61 m) between each element (see Figure 13 and Reference 14). Each gage assembly was fabricated in canister form by molding an epoxy resin around the gage elements. This epoxy was selected to match the density and sonic velocity of the oil shale.¹⁸ In turn, the 4-inch diameter 6-foot long gage canisters (10 cm dia. x 1.8 m) were grouted into their respective 6.25-inch diameter (15.8 cm) boreholes, to a level just below the upper crack, with a cement grout which was also chosen to match the oil shale, both in density and sonic velocity.¹⁹ Acoustic properties of the oil shale, epoxy and cement grout are compared in Table II (page 20).

For the lithium niobate gages, the signals were transmitted to a signal conditioning package at the surface by miniature 50-ohm coaxial cables, RG122. For protection in the shock-loaded environment, these cables were run from each gage canister to the surface in a thick-walled aluminum

conduit. The signal conductors for the ytterbium gages were RG213 cables, which were emplaced without additional shielding. In all cases the signal cables traversed the upper crack a short distance above the gage canisters. Each gage hole was filled with sand stemming to the ground surface.

The signal conductors were run about 500 feet (150 m) from the well pattern to Sandia recording trailer B22 where the output was recorded on magnetic tape together with appropriate fiducial, calibration and timing signals.¹⁰ Because of uncertainties in the experiment, primarily having to do with the quantity of explosive expected in the vicinity of the stress gages, the output from each gage element was recorded at three sensitivities. Selection of these recording levels was guided by the stress levels predicted by the computer calculations discussed above. The complete stress measuring and recording system was capable of measuring stress waves of up to 1.2 GPa (1 GPa = 10 kbar) peak amplitude with risetimes as rapid as 10 microseconds and durations as long as a few seconds.

II.G. Geophones

In general, explosives all have critical dimensions below which the propagation of an induced detonation becomes unstable and eventually ceases. These dimensions are dependent upon the composition of the explosive and, for a given explosive, are dependent on the geometry (e.g., a tube versus a sheet) the characteristics of the surrounding media, and thermodynamic parameters such as temperature and pressure. While Teledet,¹⁷ the explosive used in the Rock Springs event, had demonstrated thin layer propagating qualities in laboratory experiments (detonation was stable for thicknesses on the order of 0.015 inches (0.4 mm) when surrounded by aluminum), the adverse conditions occurring in the field could cause a failure of detonation.

In the Rock Springs event, the propagation of a detonation in a westerly direction would be monitored by the stress gages, cf. Figure 1a. Evidence of detonation would be related to the magnitude of the stress pulse as well as its time of arrival. These measurements would not yield information regarding the distribution of a detonation front in nonwesterly directions. Hence, to monitor the symmetry of the detonation, an array of twelve geophones was placed in and about the well patterns to monitor the arrival time of the stress pulse. It should be noted that, unlike the measurement of stress with lithium niobate and ytterbium, the geophones had not been used in this application before and certain aspects of this work are developmental.

Geophones were placed on well heads 2 through 9 as well as in cardinal directions approximately 500 feet (150 m) from well 1, cf. Table III. The same fiducial was placed on both the geophone and stress gage records so that these records were time-tied. The resolution of the geophones was about 0.5 msec. This did not represent a state-of-the-art system, but time limitations dictated its usage.

TABLE III
LOCATIONS AND CALIBRATION OF OUTLYING GEOPHONES

Station	Elevation (Feet)	Coordinates (Feet)	Velocity (Feet/sec)
Well #1	6340	1000 N, 1000 E	-
N	6365	1558.6 N, 992.4 E	7220
E	6347	1002.2 N, 1506.1 E	7610
S	6314	494.6 N, 1028.5 E	9320
W	6333	1026.4 N, 469.9 E	7480

Unfortunately, pre-test time schedules precluded a mapping of the virgin formation sonic velocities between wells and to outlying geophone stations. Pre- and post-test acoustic logging of the wells indicated nearly identical sonic velocities for the formation. Thus we assume that the calibration of the geophone is valid even though it occurred after the event. These calibration measurements were made using small changes of explosive placed at 160 feet (49 m) in the central well. The results of these measurements are also listed in Table III.

III. THE ROCK SPRINGS EVENT AND POST-TEST ACTIVITIES

III.A. Pre-Detonation Activity

All Sandia instrumentation was in place by 4:00 PM, May 29, 1974. A final check of the instrumentation trailer was achieved by 5:30 PM, and, according to the Sandia Operations Procedure, all Sandia personnel retreated from the site. Earlier the Teledyne personnel and Harold Owen (representative of the subcontractor, Gearhart-Owen Industries, in charge of the detonator, booster charge and wiper⁵) decided that a small amount of explosive would be emplaced that evening and operations would begin in earnest the next morning. Pursuant to this emplacement, air injection into the formation was terminated at about 3:00 PM, thereby allowing water to enter the previously air-filled hydraulic fracture.

Emplacement of the explosive began early in the morning of May 30. The procedure initially followed was to partially fill the center well, cap this well and force the explosive into the formation with compressed air. Initially, the injection proceeded well. However, as the formation filled, the viscous and thixotropic properties of Teledet¹⁹ required

greater and greater injection pressures. By early afternoon bottled nitrogen regulated to about 700 psi was in use. Personnel not involved in emplacement retreated an additional 2000 feet (600 m) from the well site. Injection continued until all the planned 7000 pounds (3.2×10^3 kg) was either in the formation or could be contained in the central well casing. A wiper was then placed in the well casing and a gas/water column was used to transmit the gas pressure to the explosive.

At about 12:30 AM, May 31, the level of the water column suddenly dropped and pressure could no longer be maintained on the system. The location and condition of the water, explosive, and detonator-booster assembly was uncertain at this time. Post-shot logging indicates that the wiper had likely jammed at a constriction in the well at the bottom of the casing (138 feet or 42 m) and some component ruptured allowing loss of pressure.

Previous to this, Teledet²⁰ had been observed in wells 2-5, although the path followed by the explosive from well 1 to these wells was not known. Stemming had commenced on all wells, and by 1:00 AM Sandia personnel had returned to the instrumentation trailer. A fire pulse was placed on the detonator line at about 2:00 AM; however the detonator did not fire. The detonator line had not been checked prior to this firing pulse.

The next morning an interrogation of the detonator line by Harold Owen indicated an abnormally high resistance, abnormal polarity effects (diodes were incorporated in the detonator system) and polarization effects typical of lines placed in an electrolyte such as dirty water. The situation was obviously uncertain, although a second fire pulse delivered at about 10:45 AM, May 31, did initiate a detonation.

In the remainder of this section we detail the results of those measurements that were made before, during and after the detonation pertaining to fracturization evaluation.

III.B. Stress Gage Results

The results recorded for the three gages in instrument hole S2 are shown in Figure 15. These may be compared with the expected results predicted by computer calculations as shown in Figure 16. The disparity between prediction and results is readily observed. The predicted results show the sequence in time of arrival and the stress wave profiles as the expected stress wave propagates past the three gage elements in instrument hole S2 (see Figure 13). In comparison, the recorded results show all three signals deviated simultaneously in a negative direction from the base line at approximately 27.6 msec after the fiducial. (The fiducial signal was recorded at the same time the firing voltage was transmitted to the detonator.) Superimposed on this negative signal (on all three gage records) is a short-duration, apparently compressive pulse, which arrived at the top gage first. That is, the arrival of this compressive pulse at the three gages is opposite in time sequence to that of the compressive stress pulse that would be produced by detonating explosive in the center hydraulic fracture below the gages.

The onset of high amplitude noise, at approximately 28.7 msec after the fiducial, occurred simultaneously on all nine of the lithium niobate signal channels in this experiment. This 60 Hz noise, which swamped the stress information from these gages, is attributable to a ground loop in this system that would result if any one of the lithium niobate signal cables were shorted to ground.

The records for the three gages in set S-3 also deviated simultaneously in the negative direction from the base line at approximately 28.4 msec after the fiducial, similar to but later in time than for the S2 gages. The

Figure 15. Observed results of lithium niobate gages in hole S-2.

Figure 16. Predicted results for lithium niobate gages in hole S-2.

records for the S4 gages show no deviation from the base line prior to the onset of the high amplitude noise at 28.7 msec after the fiducial.

The results recorded from the bottom and middle ytterbium gages in set S-1 are shown in Figure 17. (The top gage element had opened during the final temperature curing cycle in fabrication of the gage canister; the canister was fielded with this gage inoperative.) Signal arrival was simultaneous at these two gages and the major peaks and troughs also occurred simultaneously. In addition, the indicated stress amplitude was very low compared to the range of predicted amplitudes.

Figure 17. Observed results of ytterbium gages in hole S-1.

Finally, comparison of the abscissa of Figure 13 with those of Figures 15 and 17 indicates that approximately 25 msec are unaccounted for in the interval between the transmittal of the detonating signal to the detonator and the arrival of the signals at the respective gages. No clear explanation

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for this delay is available, although a similar discrepancy is noted in the geophone records and is discussed in Section III.C.

It is important to examine the local situation in the vicinity of the four Sandia instrument holes. The decision to place these instruments along radii westward out from hole 1 was based on evidence that the pre-shot permeability was greatest in that direction. Thus, it was felt it was the more likely area in which a sheet of explosive implaced into the middle fracture would detonate. After the instrument holes were drilled and geologic information could be correlated (i.e., after the explosive event) it was found that locating the instruments in this area was not necessarily optimum. This may be seen from Figures 5, 6 and 8. We note that the slopes of the middle and upper hydraulic fractures have steep gradients in the vicinity of the instrument holes. Of more significance is evidence that an atypical stratigraphic sequence passes directly between the middle hydraulic fracture and the bottoms of the instrument holes. This is the middle marker which contains two prominent tuff beds up to 0.4 feet (0.12 m) thick each plus numerous thinner lenses of the same material.

The manifestation of these tuff layers on the propagation of the shock wave and the spallation at the upper hydrafracture can be significant. In our simulation calculations, Section II.D., a hydrodynamic equation of state was used to represent the oil shale. In such calculations, the hysteretic energy imparted to the oil shale in the shock loading-stress release cycle is low. Thus, the shock is not attenuated rapidly as it propagates through the media. If a significant amount of void volume is present, such as in the case of a partially saturated tuff layer, the energy imparted in this layer is large and the shock is mitigated rapidly.²⁰ For the present case

we did not know the void volume at the time of the shot. We do recognize that the shock amplitude could be mitigated by the presence of voids. However, we note that the tuff layers cannot account for the anomalous arrival times of the shock (upper gages first) or the negative-tending signals from the lithium niobate gages.

An explanation for the arrival anomaly and the negative-tending records observed from the lithium niobate gages is that the explosive was pumped into and detonated for some distance in the top crack. If this detonation propagated as far as the gage cables, they would have been cut and the stress pulse would not have been recorded. However, partial detonation would increase the pressure within the fracture without cutting the cables. This pressure would result in a compression of the signal cables in the aluminum conduit as they passed through the top crack above the gage canisters. In other events such compressions have produced negative-going signals similar to those observed here. The short compressive pulses on the records of gage set 2 may have resulted when the stress pulse, which compressed the conduit, traveled down through the canister. Measured time intervals between the onset of the negative deviation and the arrival of the short compressive pulses agree with calculated values for stress pulse propagation down the conduit from the top crack to the gage position.

Considering the evidence in hand, these conclusions are drawn from the gage records:

- Stress pulses arrived at the upper gages first. This is opposite to the arrival sequence if a detonation occurred in the middle hydraulic fracture. This is evidence that a detonation was present in the upper fracture.

- The detonation in the upper fracture did not propagate as far as the instrument wells.
- The shock arrival was about 25 msec later than expected.

III.C. Geophone Results

The arrival times of the detonation signal at the various geophone locations are given in Table IV. These times are referenced to the fiducial and they are about 25 msec later than what was expected on the basis of acoustic logging of the wells before the event. A similar delay was observed in the stress gage measurements and is examined further here.

TABLE IV
GEOPHONE RESULTS

Station	Shot (msec) ^a	Calib. (msec) ^b	Station	Shot (msec) ^a	Calib. (msec) ^b
Well 1	-	18.0	Well 8	41.5	19.0
Well 2	42.5	-	Well 9	41.0	poor
Well 3	42.0	poor ^c	N	102.0	78.5
Well 4	42.5	poor	E	93.0	69.0
Well 5	42.5	poor	S	80.5	55.0
Well 6	42.5	19.0	W	89.5	66.5
Well 7	42.5	poor			

^aTime difference between fiducial and pulse arrival.

^bTime difference between detonator and pulse arrival.

^cPoor records resulted from a small explosive charge, poor coupling between the geophones and well head and an insensitive setting of the recorder.

Due to the geometry of the system and the resolution capabilities of the geophones, it is impossible to differentiate between a point and a disk-shaped detonation using only the geophones placed on wells 2-9. This is evidenced by the nearly identical 19 msec records obtained from a point source in the calibration experiment and the nearly-identical 42 msec records obtained at the Rock Springs event. However, the information from these geophones can be used to time-tie the fiducial and the firing of the detonators on the Rock Springs event.

Pre- and post-event acoustic logging of the wells indicated nearly identical sonic velocities for the formation. Thus we assume that the calibration of the geophones is valid even though it was accomplished after the event. In this event the top of the explosive was at the 138 foot level (42 m) in the central well whereas for the calibration shot the charge was at 160 feet (49 m). The time delay between the fiducial and initiation of the explosive is then $(42 - 19 \cdot 138 \cdot 160^{-1})$ msec ≈ 26 msec. This time is in good accord with the 25 msec discrepancy noted between calculated and observed pulse arrivals at the stress gages. It suggests that the detonation system was not operating properly in that the detonators did not fire immediately after receiving the fire pulse, cf. Section III.A. Furthermore, it suggests that the geophone records are useful for other calculations even though this system was not optimal.

When the far-field geophones are used in conjunction with the phones on the well heads, indications of the extent of the detonation can be made. First, note that the detonation velocity of Teledet is about 2.5 times the sonic velocity in the formation. Further, we assume that the velocity of a pulse in the formation is stress independent. (For a large portion of the 500 foot (150 m) transit distance to the far-field geophones the stress

pulse is so small as to make this assumption reasonable.) Then, if all of the shot explosive were concentrated at a point, the time difference between arrival of the pulse at in-line geophones, e.g., $(t_N - t_6)$, would be identical to the same differences obtained for the calibration shot; whereas, if a detonation occurred toward a far-field geophone, corresponding time differences would be smaller for the shot than observed on calibration. In this latter case, the distance of propagation from the central well is, e.g., $((t_N - t_6)_{\text{cal}} - (t_N - t_6)_{\text{shot}})/(U_D - U_S)$, where $U_D = 6.5$ km/sec is the detonation velocity and $U_S \cong 2.5$ km/sec is the average sonic velocity in the formation. The results of these calculations are given in Table V. Reasonable estimates of error are included here.

TABLE V
CALCULATED PROPAGATION DISTANCES

Stations	Δt_{shot} (msec)	$\Delta t_{\text{calib.}}$ (msec)	Distances (m)
N and 6	59.5	59.5	0 to 7 ^b
E and 7	50.5	50.0 ^a	0 to 7 ^b
S and 8	39.0	36.0	0 to 7 ^b
W and 9	48.5	47.5 ^a	0 to 7 ^b

^aCalculated using a value of 19 msec for the calibration shot.

^bCalculated from the r.m.s. error accumulated in differencing the times (error = $\sqrt{5(0.5 \text{ msec})^2}$), the detonation velocity of Teledet (6.5 km/sec), and an average sonic velocity for formation material (2.5 km/sec).

From the above information, we draw the following conclusions.

- A 25 to 26 msec delay occurred between the fire signal and detonator actuation. This is consistent with the stress gage measurements and it indicates the stress gages were operating properly at shot time.
- The detonation propagated at most 20 feet (7 m) from well 1.
- Geophones can provide useful information on events like Rock Springs. However, better systems and calibration techniques are needed.

III.D. Fracture Evaluation (Post-Test)

The post-shot analysis of fracturing consisted of rerunning the complete set of borehole geophysical logs and TV scans back in the original 9 wells. In addition, four core holes (0-2, -3, -4, and -5) were drilled in the center part of the array (see Figure 1b). No geophysical logs were run on these core wells nor were the four Sandia instrument holes reentered. The latter had been partially cemented back and then sand-filled to the surface with the conduit containing the signal cables running to the surface.

Well 1, the emplacement well, was significantly altered. The zone from the bottom of the casing down to the middle fracture was enlarged from 8 inches to about 15 inches. The TV scan indicated that the walls were very irregular. This enlargement prevented obtaining good records on the sonic velocity and sonar scanner logs. Cross correlation of the pre- and post-shot geophysical logs in wells 2 through 9, the perimeter wells, showed no detectable change. The sonar scans of the walls of the wells revealed no change. If dilation had occurred at any fracture filled with explosive, then that dilation was below the resolving power of the scanner, which is the order of a few millimeters or less. Similar negative results apply to the acoustic velocity

measurements. The TV observations also indicated no change. In that some surface heave had occurred,⁹ and there was the possibility that multiple but tight fracturing had occurred which would go undetected by the observation techniques used, a measurement was made to determine if that fracturing had caused significant bulking over the zones between the three hydraulic fractures. This was done by careful measurement in each hole of the pre- and post-shot distances between three horizons in the general area of the three fractures. The lower interval represented the distance between the top of the m_1 tuff and the base of the Middle Marker, and then a second zone was measured an arbitrary distance upward from the Middle Marker to any horizon marker easily identifiable on the pre- and post-shot records. For this type of measurement the sonar scanner records were used because they were the most discriminating. The results are given in Table VI.

TABLE VI

Well	M_1 to Middle Marker (Feet)				Middle Marker to Arbitrary Marker (Feet)			
	Pre-test	Post-test	Diff.	B.F. ^a	Pre-test	Post-test	Diff.	B.F. ^a
1	-----HOLE DESTROYED BY EXPLOSION				-----			
2	14.2	14.4	+0.2	+1.41	10.4	10.3	-0.1	0.96
3	14.9	15.0	+0.1	+0.67	7.9	8.0	+0.1	1.26
4	N/A	14.8	-	-	12.4	12.3	-0.1	0.81
5	14.6	14.6	0	0.0	8.1	8.1	0	0
6	15.1	15.0	-0.1	-0.66	13.5	13.4	-0.1	0.74
7	14.3	14.3	0	0	9.5	9.5	0	0
8	14.8	14.7	-0.1	-0.68	10.5	10.6	+0.1	0.95
9	14.3	14.2	-0.1	-0.70	11.7	11.7	0	0

^aB.F. = Bulking factor defined as Diff/Pre distance x 100. Plus if expansion, minus if compaction.

It is sufficient to simply state that the data show that the degree of dilation or compaction is below the statistically significant detectable limits of the measurement technique. It does show that no significant bulking occurred.

The four post-shot core wells designated by 0-2, -3, -4, and -5, were located equidistant between the center well and wells 2, 3, 4, and 5 (see Figure 1b). The distance then between the core holes and the center well was approximately 18 feet. These post-shot wells were not surveyed. The procedure in drilling these wells was to rotary drill down from the surface to 125 feet (37 m), then core drill to a depth of 175 to 185 feet (53 to 56 m). Thus, cores were taken through the entire interval from above the upper to below the lower fractures. Fractures were carefully noted as each core run was withdrawn. In noting fractures, care was taken to differentiate between fresh, sharp breaks and smoothed breaks. The latter are probably natural partings in the formation while the former could have only two causes: mechanical breakage during the drilling or those induced by explosive shock. It is realized that there is no direct method to differentiate between explosion-induced fractures and those caused by the drilling. The only method was to correlate the fracture frequency of the two pre-shot instrument wells (S-1 and S-3) and the four post-shot wells. This comparison was hindered for two reasons. First, the instrument hole cores were only taken to 150 feet (46 m) depths while the post-shot holes went to at least 175 feet (53 m); hence, no information was known about the pre-shot "coreability" between 150 and 175 feet (45 to 53 m) into the formation. Secondly, it became necessary to change types of core bits during the post-shot drilling which in turn changed the coring rate which similarly changed the likelihood for mechanically induced breakage. That this second factor may be valid is exemplified

by the fracture frequency being highest in wells 0-2 and 0-3 which are the two wells drilled with a bit that had a lower cutting rate.

Realizing the shortcomings described above, a comparison is presented in Table VII. See also Figures 10 and 11 which are cross-sectional representations of the holes showing location and inclination of fractures.

These conclusions are drawn in relation to the fracture frequencies (the number of breaks per 2 foot (0.7 m) interval):

- A direct comparison of the frequency of fractures between pre- and post-shot conditions can be made only over the depth interval from 125 to 148 feet (38 to 45 m). This is the only interval for which pre- and post-shot cores existed. In hole S-1, the overall frequency was 0.9 (with a jump to 4.0 immediately around the upper fracture). In the post-shot holes, the fracture frequency was higher for the same interval, ranging from 1.0 in hole 0-5 to 3.4 in hole 0-2.
- An increase in fracture frequency is commonly present in and around the suspected position of the three hydraulic fractures. These fractures may have resulted from stresses developed during the hydraulic fracturing because a similar condition existed around the upper fracture before the explosion.
- There is an apparent increase in the number of inclined (typically 45° dipping) fractures. Such fractures were quite rare in the pre-shot drilling but have a frequency of 0.5 in the four post-shot core holes.
- No great void area was found by drilling. The core recovery (length of sample retrieved versus depth drilled) was essentially 100%. This indicates that the fractures are very tight. An exception is the cracked zone in hole 0-5 at 146.5 feet (44.6 m). It may contain a void, but certainly only a fraction of a foot, based on core recovery.

TABLE VII

FRACTURE FREQUENCY (BREAKS PER TWO FOOT INTERVAL)
AS REVEALED BY POST-SHOT DRILLING

Depth	Hole				
	<u>0.2</u>	<u>0.3</u>	<u>0.4</u>	<u>0.5</u>	<u>S-1</u>
125	0	0	1	0	1
	0	0	2	0	0
130	0	0	2	0	0
	2	0	3	0	1
	3	2	0	0	0
	3	4	2	0	1
	5	1	1	1	0
140	4	1	7	2	4 ^(U)
	7	0	1	2 ^(U)	2
	6	6 ^(W)	0	1	0
	3 ^(U)	8	0	5 ^(W)	2
	5	7 ^(U)	4 ^(U)	1	0
150	1	1	2	2	
	1	0	1	0	
	1	3	1	0	
	2	4	1 ^(M)	1 ^(M)	
	1	1	3	0	
160	3 ^(M)	7 ^(M)	1	0	
	1 ^(W)	2	0 ^(W)	0	
	1	0	0	2	
	1	1	0	2	
	2	0	3	0	
170	1	1	1 ^(L)	0	
	2 ^(L)	3 ^(L)	2	1	
	0	3	4	2 ^(L)	
175	1	1	1	-	

(U) Upper fracture
(M) Middle fracture
(L) Lower fracture
(W) Water level

- Drill water circulation was lost in three of the post-shot holes (0-2, -3, and -5). This loss always occurred near the position of the upper fracture horizon. A similar condition occurred in drilling the pre-shot instrument holes.

Down-hole observation via television of the post-shot holes was restricted because the formation was only partially drained of water when the runs were made. The water levels were: 0-2, 162 feet (49 m); 0-3, 143 feet (44 m); 0-4, 162 feet (49 m); and 0-5, 147 feet (45 m). In that the fractures were all tight, they rarely could be observed unless formation water was leaking back into the holes. As with observations in the original nine wells (No. 1 through 9), it was common to discover significant entry points in tuff beds and formation partings, and these flows were often greater than those in zones that were fractured. The camera did verify, in a qualitative way, that most of the heavily fractured zones present in the core were also present in the walls of the holes.

IV. SUMMARY OF MAJOR CONCLUSIONS, OBSERVATIONS, AND RECOMMENDATIONS

In this section the major conclusions that relate to the fracturization effort at Rock Springs are summarized and observations made during the event are presented. Recommendations for future work are then made which address the specific problem areas that became apparent during the Rock Springs experiment.

IV.A. Summary of Major Conclusions

- Extensive pre- and post-shot geophysical logging of the original nine holes (1 through 9) indicated that no extensive fracture system was created by the explosion, cf. Sections II.C and III.D. (The formation may be adequately prepared for retorting operations.)

- Comparison of the fracture frequency in the post-shot core holes versus two pre-shot instrument holes indicated that some explosive-induced fractures are probably present. The frequency increased from 0.9 per two foot (0.7 m) interval pre-shot to a high of 3.4 in well 0-2 post-shot. Lack of detection of post-shot fractures in wells 2 through 8 indicated that explosive effects were restricted to distances near well 1, cf. Section III.D.
- Logging in wells 2 through 9 indicated no springing occurred along any of the three artificial fractures. If a horizontal sheet of explosive was indeed detonated in any one of these holes then a dilation in the amount of a centimeter or so would be a reasonable expectation. The sonar scanner and caliper surveys eliminated this as having occurred in wells 2 through 8. Excellent core recovery in the post-shot holes (0-2, -3, and -4) indicated the same condition. A possible open fracture may exist at 146.5 feet (44.6 m) in hole 0-5. This depth is in the vicinity of the predicted depth for the upper hydraulic fracture in this well, cf. Sections II.C and III.D.
- As indicated by careful measurement of selected depth intervals in holes 2 through 8, no bulking effect by the explosion was detected, cf. Section III.D.
- The observed stress pulse amplitudes were about an order of magnitude less than that expected. The evidence strongly suggests that this was caused by the absence of a detonation in the middle fracture below the gages. An alternative explanation is that the middle marker, which lies between the gages and the middle fracture, could have caused a severe degradation of the stress amplitudes. Whatever the case, stress amplitudes were less than required to induce significant fractures with the formation, cf. Sections II.E and III.B.

- The results of the geophone measurements indicate that the detonation propagated on the order of 20 feet (7 m) from the central well, cf.

Section III.C.

IV.B. Observations

In addition to the above conclusions, the following observations are made:

- A significant amount of water could have intruded into the upper and lower hydraulic fractures during the approximate 30 hour period between shut-down of air injection and detonation. Even if all other systems worked perfectly, this would essentially eliminate spallation as a fracture mechanism.
- The rheological properties of the explosive required excessive pressures for injection. This caused a detrimental delay in the shot and the pressure may have caused a misfiring of the detonator system. Furthermore the injection pressures were sufficient to break down the formation. Thus, it is possible that the explosive was not in the prepared hydraulic fractures but went in uncontrolled directions and exterior to the formation of interest.

IV.C. Recommendations

We believe that concepts of combined hydraulic fracture and explosive treatments are valid and they should prove useful in inducing permeability into tight rock formations. Such induced permeability is of interest in the in situ retorting of shale as well as in the leaching of minerals, in oil and gas well stimulations, and in the preparation of rock for easy mining and drilling.

While the Rock Springs event was not as successful as one might have hoped from a fracturization standpoint, a great deal was learned concerning the specific details of the concept. In the following paragraphs we list several problems which must be solved before the benefits of the concept are realized. It is only through study of these problems that one can make judgments concerning the cost-effectiveness of the method, as used in various applications.

- General Concept -- The results of the computer simulation calculations indicate that reasonable fracturization could be expected for the explosive configuration used at Rock Springs. Extensions of these calculations indicate that a closer spacing of the hydrofractures would result in more fracturization of the formation. Many other variations which could lead to improved fracturization are possible, and computer simulation of these variations is straight-forward and should be done.
- Field Instrumentation -- Field instrumentation providing adequate feedback information needs to be an integral part of any development procedure. Such information allows a correlation of computer simulation with post-test analysis. For example, the stress measuring equipment and geophones used at Rock Springs were necessary in our assessment of the experiment, although insufficient data were obtained for complete interpretation of the results. Thus, some improvements in readily available systems such as geophones seem necessary. Generally, since unforeseen problems are likely to arise in the development of the fracturization concept, the liberal and redundant use of active field instrumentation is strongly recommended in future work.
- Geologic Assessment -- The presence of porous rocks in otherwise non-porous formations causes a severe degradation of short-duration stress

pulses such as are obtained from explosives. A case in point is the tuff layer (middle marker) which was not located until after the Rock Springs Event. Thus, we recommend that an extensive pre-test evaluation of a formation of interest is in order. With such an evaluation, computer modeling can be used to better advantage in designing the experiment.

- Explosive Characteristics -- Advantages may result from hydraulic fracturing with the explosive. This requires stability of the explosive at high pressures as well as suitable and adjustable rheological characteristics for appropriate flow in the newly forming fracture system. Some developmental work is required here, but this should be quite routine. The explosive must be sensitive enough for the detonation to propagate in thin layers but sufficiently insensitive for safe handling and pumping. In the past these characteristics have been somewhat exclusive. Although recent developments have produced several explosives which appear to have desirable characteristics, further developmental and testing work is recommended. Other considerations are the adjustment of the Chapman-Jouguet state and the release adiabats to maximize fracturization of a given formation. This work can be done by computer modeling of candidate explosives and formations although Laboratory and field verification will be required.

Finally, from our experience with this event, we are led to recommend that additional effort be expended in several general areas such as:

- Hydraulic Fracturing Technology -- As currently practiced, this is more an art than a science. Advances need to be sought that will allow prediction, control, and mapping of the fracture propagation. The extensive logging data obtained at Rock Springs may be used as a beginning point for such a study.
- Material Behavior -- Better equations of state for geologic materials and explosives, and better rock fracture models are needed for accurate computer simulation of experiments such as that conducted at Rock Springs. This program could reasonably begin with material from the Rock Springs cores. From data obtained in this study, one could re-examine the Rock Springs event and quantitatively answer questions that are addressed only qualitatively at present.

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