STRESS WAVE PROPAGATION IN THE SITE 12
HYDRAULIC/EXPLOSIVE FRACTURING EXPERIMENT

MASTER

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ABSTRACT

The Site 12 experiment was a heavily instrumented field event performed to examine the hydraulic/explosive fracturing concept for preparing an underground oil shale bed for true in situ processing. One of the key phases of this fracturing concept is the blasting operation which involves the insertion and detonation of slurry explosive in a pre-formed system of hydrofractures. To obtain a sound understanding of the nature of the blasting operations, a rather extensive array of stress gages, accelerometers, and time-of-arrival gages was installed in the rock mass in the vicinity of the explosive to monitor the dynamic events initiated by the detonation. These gages provided considerable amounts of information which were useful in evaluating overall results of the experiment. Details of the gage array, of the data, of analysis methods, and of the results and conclusions are considered in the report.

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EXECUTIVE SUMMARY

On December 1, 1977, Sandia National Laboratories, in a cooperative venture with the Laramie Energy Technology Center (LETC), completed the explosive phase of a field experiment to examine the hydraulic/explosive fracturing concept for preparing an underground oil shale bed for true in situ processing. The experiment was performed at Site 12 of the LETC field laboratory west of Rock Springs, Wyoming.

As applied in this experiment, the hydraulic/explosive fracturing concept involves first the creation of three nominally equally spaced, sand-propped, horizontal hydrofractures in the shale bed, each from one of three wells drilled in a cluster near the center of the region under study. This operation is followed by the insertion of slurry explosive into the lower two hydrofractures, then by the simultaneous initiation of detonation in the two explosive layers at points lying close to a vertical line near the centers of the layers. With this concept, rock fracture would be expected to occur as detonation-induced compressive stress waves reflect as tensile waves from the surfaces of the uppermost hydrofracture (not explosive-filled) and of the lower two hydrofractures (explosive-filled) which, by the time of the reflection, would have been opened by the expanding explosive gases. One of the premises of this fracturing concept was that rock fracturing should be more prominent in the region between the two explosive layers than elsewhere because of the interactions between stress waves from the explosive layers. This premise depends on detonation of the two layers being simultaneous, or nearly simultaneous.

All phases of this highly instrumented experiment were designed so that sufficient information would be acquired before, during, and after each major event to characterize the nature of the event itself as well as the effects of the event on the oil shale bed. With regard to the blasting operation, which is the focus of this report, gages of several types (stress gages, time-of-arrival detectors, and accelerometers) were emplaced at selected downhole locations to monitor the dynamic processes induced by the detonation; of particular interest were data pertinent to the propagation of the stress waves which emanate from the explosive-filled hydrofractures.

There were two attempts to complete the explosive phase of the Site 12 experiment. The first attempt, which was made in August of 1977, was not successful because of a detonator failure. After this attempt, the explosive insertion and firing procedures were reevaluated and a new experiment plan was formulated and implemented. The new plan led to the successful completion of the explosive phase of the experiment in December.

The gage array that was in place for the final firing attempt consisted of 40 individual gages, many of which had been emplaced prior to the first firing attempt. The basic configuration of the gage array, in fact, was designed to be compatible with the explosive insertion and detonation procedures of the first firing attempt. In that case, explosive was introduced into each of the two lower hydrofractures by first loading explosive into the casing of the well used to create that hydrofracture, then forcing the explosive downward and into the hydrofracture with a head of pressurized water applied to a wiper placed above the explosive in the casing. The primary detonator/booster units in this case were at the levels of the two lower hydrofractures in the third well of the central cluster (the one used to create the uppermost hydrofracture).

As was mentioned, detonation was not achieved in the first firing attempt. The explosive in the insertion wells, however, was detonated in a follow-up, safety motivated operation. Explosive in the hydrofractures did not detonate during this operation. Formation damage in the vicinity of the central cluster of wells did occur, however, making it necessary to drill new explosive insertion and detonation wells for the final firing attempt. In keeping with the new experiment plan, two such wells were drilled and positioned so that the gages already in place could be used as effectively as possible.

The new explosive insertion/detonation system was similar to the old system except that the primary detonator/booster units for the final firing attempt were in the wipers used to push the explosive downward. This meant that instead of detonation being initiated directly in the explosive layers, as was the intent for the first firing attempt, it was initiated at the top of the explosive columns in the insertion wells; ignition of the explosive in the hydrofractures would occur only after detonation waves had traversed the columns.

Several factors were considered in the selection of the final insertion/detonation plan, including economics, scheduling and the probability for a successful detonation. It was also recognized that the new procedure would in effect alter the primary function of the gage array. Initially, the gages were to provide information primarily about the detonations in the hydrofracture. In the final firing attempt, however, most of the gages were positioned to experience the arrival of a stress wave from an explosive column prior to experiencing the arrival of a wave from a hydrofracture.

In retrospect, this change in function was valuable because it provided a reliable means to determine the configuration of the underground explosive assembly at shot time. In particular, it was possible to determine with precision the location of the primary detonator/booster units in the wipers at shot time; the alternate method to obtain this information; which was perfectly adequate for the first firing attempt where the detonator/booster units were at the levels of the explosive-filled hydrofractures, was to measure the quantity of water pumped into the casings during explosive insertion. Knowing the positions of the detonator/booster units implies knowledge of explosive column heights and hence also knowledge of ignition times for the explosive-filled hydrofractures.

Analysis of the stress wave propagation data, with emphasis on prominent pulses that could be attributed to detonation of the explosive columns, led to the development of a mathematical formulation for describing the propagation of stress waves from both the columns and the explosive-filled hydrofractures. This model made it possible to identify the less prominent pulses originating at the explosive-filled fractures. In some cases, the conspicuous absence of a pulse at a time when there should have been one was considered to be evidence that no stress wave emanating from the hydrofractures was present at that gage location. It was also possible to verify an observation made during the post-shot formation evaluation that over a large portion of the experiment area, explosive intended for insertion into the lowest hydrofracture had actually travelled by some unknown path to a natural fracture system lying a few feet below the hydrofracture.

The remaining major contribution of the stress wave propagation data was an assessment of the degree to which simultaneous detonation was achieved in the two explosive layers as a function of horizontal

position within the experiment area. This evaluation led to the conclusion that simultaneity adequate for interactions between stress waves to be effective in producing fractures was achieved only to the southeast of the explosive insertion wells. Cores extracted from this region did not show a distinct abundance of fractures, compared to other regions; however, in a follow-up retorting experiment, the burn front propagated preferentially to the southeast indicating greater permeability in that direction than in other directions.

In general, the data from the gage array for monitoring stress wave propagation were very useful in evaluating the nature of the blasting operation. Information deduced by analyzing the data were used in the overall evaluation of the experiment and of the hydraulic/explosive fracturing concept. Discussions of these latter studies are given in other documents identified in the body of this report.

I. INTRODUCTION

On December 1, 1977, Sandia Laboratories, in cooperation with the Laramie Energy Technology Center (LETC), executed the explosive portion of a field experiment to examine the so-called hydraulic/explosive fracturing concept for preparing an underground oil shale bed for true in situ processing. This bed preparation technique involves the insertion and subsequent detonation of slurry explosive in a pre-formed system of hydrofractures and relies on interactions of detonation-induced stress waves with other such stress waves and with the surfaces of the hydrofractures to fragment the rock. The degree to which fragmentation occurs, together with the degree to which the fragments are displaced relative to each other, are the primary controlling factors in determining the effectiveness of this explosive treatment. Effectiveness is judged relative to the ultimate goal of transforming the initially very tight oil shale into a bed of rubble that is suitably porous and permeable for retorting, i.e., for underground extraction of hydrocarbons from the oil shale.

The experiment of interest here was performed at Site 12 of the LETC field laboratory west of Rock Springs, Wyoming. The total experiment involved both a bed preparation phase and a retorting phase. Throughout both phases, the guiding principle was "instrumentation". With regard to the bed preparation activities, the intent was to acquire sufficient information to make it possible to quantitatively correlate observed changes in formation conditions with detailed characterizations of the physical processes that produced the changes. In keeping with this philosophy, an extensive array of gages was emplaced in the rock formation to monitor the transient events initiated by the detonation. The primary purposes of this array were to provide information about the actual geometrical configuration of the underground explosive system at detonation time and about the nature of the transient stress field established by the detonation. This instrumentation activity forms the basic focus of the present report.

Background information relating to the general design and operational plan for the Site 12 experiment will be presented in the next section (Section II) of this report. This will be followed in Section III by

a description of the gage array used to monitor the blasting operations. Section IV will deal with the analysis methods that were used in interpreting the data. The results of the measurements and the conclusions drawn from these results will be considered in Section V. Finally, in Section VI, a summary of pertinent observations and conclusions will be given.

There are several other documents dealing with various aspects of the Site 12 experiment which have been published or are in the process of being published. Noteworthy is Reference 4, which is a complete review of all activities conducted as part of the bed preparation phase of the experiment. Much of the information discussed in the present report is also reviewed in Reference 4. Reference 5 deals with the retorting phase of the experiment, so is a natural continuation of Reference 4. References 1 through 3 deal with experiment plans and with intermediate or preliminary results, so are also reviewed in the later document.

II. OVERVIEW OF SITE 12 EXPERIMENT

A. General Description of Fracturing Concepts

There are a number of variations of the hydraulic/explosive fracturing concept; these differ from each other primarily with respect to the underground explosive and hydrofracture geometries and the explosive insertion and detonation procedures. The variation examined in the Site 12 experiment involved the following basic operations:

- (1) The creation of three equally-spaced, horizontal, sand-propped hydrofractures in the underground oil shale bed;
- (2) The insertion of slurry explosive into the lower two of the three hydrofractures; and
- (3) The simultaneous initiation of detonation in the two explosive layers.

The intent was to create an underground explosive/rock configuration consisting of two parallel explosive layers extending similar radial distances from a common vertical axis, and a nearby open (sand-propped) crack lying above and parallel to the explosive layers. By initiating detonation simultaneously in the two explosive layers at points near the center axis, detonation waves are intended to propagate radially outward at essentially equal rates. As they propagate, compressive stress pulses are continually transmitted into the rock from each

explosive layer. The stress waves formed by the coalescence of the pulses from the incremental units of explosive provide one of the essential ingredients needed for rock breakage with this fracturing concept.

There are two regions of rock that are particularly noteworthy. One lies between the two explosive layers and the other between the upper explosive layer and the open crack. In both regions tensile stress waves, which may cause dynamic fracturing, are formed as the compressive waves induced by the detonations reflect from the surfaces of neighboring hydrofractures. The region between the two explosive layers should experience greater damage because here two compressive waves propagate, one from each explosive layer. These waves interact during their compression phase and again after reflection, during the tension phase. The additional fracturing between the explosive layers would be due primarily to the interaction between tensile waves. Rock above and below these two regions would experience this type of tensile fracturing if natural formation discontinuities were present for wave reflection.

There are other fracturing mechanisms which may have contributions in this version of the hydraulic/explosive fracturing concept. First, the stress waves propagating in the rock will have an oblique character (the stress wave fronts are not parallel to the hydrofractures) because they are introduced by detonation waves that sweep radially outward in the explosive layers. This promotes the generation of shear stress, which could also cause fracturing. Second, the radially propagating detonation waves cause the rock formation to be flexed, which could lead to additional fracturing. Finally, the high detonation pressures may cause the rock directly adjacent to the explosive layers to yield, crush, or be pulverized. The thickness of the rock region affected by this high pressure would be small, probably a few centimeters.

It is evident that several mechanisms for fracture can be envisioned for the hydraulic/explosive fracturing concept. None of these mechanisms, however, will be effective in creating a uniformly permeable zone of oil shale unless rock fragments are formed and unless at least some limited amount of fragment motion is realized. The hope for meeting these requirements lies primarily with the events that occur near the hydrofractures which have been opened by the expanding explosive gases. Because of the radially propagating

detonation waves, the stress waves impinge on the crack surfaces at a non-normal angle. This should impart a rotational motion to the fragments that are formed and should also provide conditions that would promote the formation of fragments. At the uppermost hydrofracture, which is simply sand-propped, there is little hope for appreciable fragment motion. We see then that, besides the greater probability for fracturing, there is also a greater probability for fragment motion in the region between the two explosive layers in comparison with the region between the upper explosive layer and the uppermost hydrofracture. Realization of either of those factors, of course, is dependent on achieving simultaneous initiation of detonation in the two explosive layers.

B. Description of Site 12 Bed Preparation Procedure

The oil shale bed under examination in the Site 12 experiment was the upper portion of the Tipton Member of the Green River Formation. At the experiment location, this bed is about 200 ft (60 m) deep. Preliminary site evaluations and analyses led to a procedural plan for the experiment which, as a first step, involved the creation of the three hydrofractures, each from one of three cased wellbores (Wells A, B and C in the plan view of the site shown in Figure 1) that had been drilled in a rather tight cluster near the center of the experiment area. The vertical separation between hydrofractures was intended to be about 5 ft (1.5 m). In each case, the casing was cut with a hydro-jet tool at the elevation intended for the hydrofracture; this operation also introduced a horizontal slot a short distance into the formation. Hydrofracturing fluid was then forced into the casing, through the slot and into the formation. Near the end of the hydrofracture creation procedure, proppant sand was carried into the hydrofractures with the fluid. Measurements of various types in the outlying wellbores (see Figure 1) indicated the separation distance between hydrofractures ranged between about 2.6 and 8.5 ft (0.8 and 2.6 m) in the region containing the wellbores and that the hydrofractures followed the nominally horizontal bedding planes of the oil shale bed.

During the hydrofracture creation operation, only a minimal quantity of proppant sand was introduced into the lower two hydrofractures. (The ones that were to contain explosive.) In contrast, considerably more sand was introduced into the uppermost hydrofracture

so that in this case the crack width achieved would be as large as possible, hopefully 1/8 inch (5 mm) or more. The reason for the difference was that prior examinations of several slurry explosives had indicated that detonation could not be guaranteed for cases in which the slurry had been extruded through a sand-filled crack. Thus, an experiment plan was devised whereby the explosive would be forced into the hydrofractures at rates and pressures which were sufficiently high to cause the slurry itself to serve as the proppant, rather than the sand. Detonation was to be initiated immediately after completion of the insertion process, while the pressure on the explosive was still being maintained.

FIGURE 1. WELL LAYOUT FOR SITE 12 RUBBLING EXPERIMENT. THE WELLS IDENTIFIED WITH THE SOLID CIRCLES WERE DRILLED PRIOR TO THE FIRST FIRING ATTEMPT. THOSE IDENTIFIED WITH THE OPEN CIRCLES WERE DRILLED IN PREPARATION FOR THE FINAL FIRING ATTEMPT.

There were two explosive insertion and detonation procedures used at Site 12. The first did not result in a successful firing because of a detonator failure. Thus a second plan was devised; this plan lead to a successful execution of the explosive portion of the experiment. While the second plan is the one of ultimate interest, it is important to review the general features of the first plan because it served as a basis for the design of the gage array used to measure stress wave propagation.

Figure 2 schematically depicts the explosive insertion and detonation scheme used in the first firing attempt.

FIGURE 2. ILLUSTRATION OF EXPLOSIVE INSERTION AND DETONATION SYSTEMS USED IN THE FIRST FIRING ATTEMPT.

Explosive was introduced into the two lower hydrofractures through the wells that had been used to create these hydrofractures (Wells B and C). Well A housed the primary detonation systems which consisted of a detonator/booster unit at the level of each of the lower two hydrofractures. The intent was for slurry explosive to flow through the two hydrofractures, then into the Well A casing via slots that had been cut at the appropriate elevations with a hydrojet tool. Care was taken to maintain the isolation of the two lower hydrofractures from each other by means of a specially designed packer assembly which contained the detonator/booster units as well as sensors to detect if and when the slurry explosive arrived in Well A.

In preparing for explosive insertion, a packer (or retainer) with a one-way valve was set in each insertion well (Wells B and C), just above the appropriate hydrofracture. A wiper with a burst diaphragm was then placed in each casing, near the top, and a wellhead assembly equipped with special plumbing and containing another wiper (with a secondary detonation system) was installed on the top of each casing. Slurry explosive was then introduced into each casing on top of the wiper with the burst diaphragm, forcing this wiper downward in such a way that when the casing was full of explosive, the wiper would rest on the retainer. After loading the casing, the wiper in the wellhead was brought down to the top of the explosive column. Water was then pumped into the wellhead assembly above the top wiper. The water pressure and flow rate were sufficient first to break the burst diaphragm and then to force the explosive into the hydrofracture at the desired rate. The intent was to move the top wipers in the two insertion wells downward together. When both were near the bottom wipers, detonation would be initiated, first in Well A with the primary system, and then in Wells B and C with the secondary systems. The timing sequence was adjusted so that a detonation wave propagating from Well A, through, for example, the lower hydrofracture, would arrive at the intersection of this hydrofracture with Well B simultaneously with a detonation wave from the secondary detonation system in Well B. The same was true for the middle hydrofracture and Well C.

The configuration and operational plan of the explosive insertion and primary detonation system for the first firing attempt were designed to achieve simultaneous initiation of detonation in the two explosive layers at points along a common vertical axis, namely along Well A.

The secondary detonation system was designed so its effect would be unimportant if the primary system performed properly. In the case of a problem with the primary system, the secondary system was intended to provide simultaneous initiation of detonation over at least a portion of the shale bed.

At firing time, however, both detonation systems failed because of leakage of pressurized water into the detonators which had been selected for use. This led to an immediate recovery effort which, as a first step, required the elimination of the hazard presented by the undetonated explosive that remained underground, particularly that which was still in Wells B and C. To remove the hazard, additional explosive and detonators were introduced into Wells B and C, just above the top wipers. Firing of these added charges resulted in detonation of the explosive in Wells B and C but did not initiate detonation of the explosive that had been inserted into the hydrofracture. This initial cleanup operation resulted in formation damage in the vicinity of Wells A, B and C, but most of the rest of the experiment area was found to be suitable for continuing the experiment.

In designing another firing attempt, the decision was made to drill two new explosive insertion wells (Wells X and Y in Figure 1). A new detonation scheme was also devised. This new plan, which is illustrated in Figure 3, did not involve a separate detonation initiation well (analogous to Well A), but rather had three independent detonation systems in the insertion wells.

The new primary detonation system was similar to the secondary system of the first firing attempt; an important difference was that two independent detonator/booster units of a proven design were installed in each wiper. The new secondary system consisted of an explosive/detonator unit housed in a small metal enclosure that was welded to the exterior of the casing of each insertion well, just above the appropriate hydrofracture. Access to these enclosures for inserting the explosive and detonators was through metal pipes extending to the surface. It was expected that detonation of the explosive within the enclosure would initiate detonation of the explosive inside the casing. At the outset, this system was intended to be the primary detonation system because it provided an adequate method to achieve

simultaneity of detonation in the two explosive layers, at least along the midplane between the two insertion wells. Testing of the system, however, revealed that while detonation through casing could be readily achieved at temperatures near 25°C, there was only about a 50% probability for success at the downhole temperature of about 10°C. Thus, the system in the top wipers was designated as the primary system, and the system exterior to the casing was relegated to a backup role. To ensure that detonation was achieved, if both the primary and secondary systems failed, as before, a third system was provided. This tertiary system was incorporated into a middle wiper and was designed to be activated when the top wiper forced the middle wiper against the bottom wiper.

FIGURE 3. ILLUSTRATION OF EXPLOSIVE INSERTION AND DETONATION SYSTEMS USED DURING FINAL FIRING ATTEMPT.

III. DESCRIPTION OF GAGE ARRAY

The gage array that was in place during the final firing attempt consisted of two sets, with one set being those gages that remained operational after the first firing attempt and the other being those that had been installed specifically for the final attempt. Locations of some of these gages (those on an east-west line through the center of the experiment site) are shown in Figure 4. A few additional gages were located off the east-west line in Wells DD, 1, 2, 4 and 5.

FIGURE 4. ELEVATION VIEW DEPICTING LOCATIONS OF MOST GAGES THAT WERE IN PLACE AND FUNCTIONAL DURING THE FINAL FIRING ATTEMPT. THOSE SHOWN WERE IN WELLS DRILLED ON AN EAST-WEST LINE THROUGH THE CENTER OF THE EXPERIMENT AREA.

The gage array for the first firing attempt was designed with a primary objective of obtaining information pertinent to the detonations in the hydrofractures. Most of these gages were in Wells AA, BB and CC which, relative to the detonation initiation points in Well A, were located in the opposite direction from the explosive insertion wells. This configuration ensured that the stress waves from the hydrofractures would arrive at the gage locations well before any waves from the explosive columns in the insertion wells. A few gages were emplaced in Wells DD and EE to obtain information pertinent to the asymmetry that resulted from having the explosive insertion wells off the axis of the detonation initiation points in Well A.

The objective of the instrumentation effort for the final firing attempt was the same as for the first attempt; however, because of the modified detonation initiation system, it was not possible to take advantage of an ensured delay between the arrivals of the waves from the explosive columns and those from the hydrofractures. The effects of this will be considered in more detail later in this report.

Gages of four different types were installed: lithium niobate stress gages, ytterbium stress gages, lead-zirconate-titanate time-of-arrival (TOA) detectors, and acceleration gages. The ytterbium and lithium niobate stress gages are capable of providing time resolved measurements of the stress induced by the detonations, while the TOA gages simply provide indications of when disturbances arrive. The acceleration gages, of course, sense material motion. Descriptions of the gages are given elsewhere⁷⁻⁹, so no discussion will be presented here.

The wells which housed the gages were all uncased in the regions there the gages were located. Gages in Wells AA, BB, CC, DD, EE and 3 were all firmly coupled to the formation with rock-matching grout. Gages in Wells 1, 2, 4, and 5, which were TOA gages, were coupled with water-saturated sand. In Well 2, the two TOA gages were epoxied in place along with several other instruments which were installed to detect the arrival of explosive and to measure the expansion of the crack during explosive insertion.

Electrical data from the gages were recorded on frequency modulated magnetic analog tape units with frequency response of 20 kHz. Sub-

sequently, the recorded information was reduced to voltage versus time plots, stress versus time plots, or acceleration versus time plots. In the final analysis, all of the gages were useful primarily as TOA gages because of the complexity introduced by the need to initiate detonation at the top of the explosive columns.

IV. ANALYSIS METHODS

In analyzing the data, then, it is important at the outset to establish a clear picture of the dynamic processes induced by detonation. An illustration of the manner in which stress waves develop and propagate after initiation of detonation in an explosive column linked to an explosive-filled hydrofracture is shown in Figure 5.

FIGURE 5. ILLUSTRATION OF HOW STRESS WAVES DEVELOP IN A ROCK MASS AFTER INITIATION OF DETONATION AT THE TOP OF AN EXPLOSIVE COLUMN THAT IS LINKED TO AN EXPLOSIVE-FILLED HYDROFRACTURE.

In Figure 5 the configuration is like that of the primary detonation system used in the final firing attempt (shown in Figure 3). Detonation is initiated at the top of the explosive column and the hydrofracture explosive is initiated by a detonation wave that propagates down the explosive column, then into the hydrofracture. During the entire detonation process, nominally spherical stress waves are continually transmitted into the rock. These spherical pulses coalesce to form the transient stress fields depicted in Figure 5. In each illustration of the figure, a few of the infinitude of spherical pulses are shown (solid circles); these pulses have propagated to their designated locations by times t_1 , t_2 , and t_3 and collectively form the stress waves whose fronts, or leading edges, are represented by the dashed lines. The geometrical representations here are based on an assumption that the detonation wave in the explosive travels twice as fast as the stress wave in the rock, which is similar to the conditions of the Site 12 experiment.

At time t_0 , detonation has just been initiated and no stress wave propagation has occurred. At time t_1 , the detonation wave has just reached the level of the hydrofracture. The stress wave in the rock at this time consists of a spherical upper portion and a conical lower portion. At time t_2 , the detonation wave has entered the hydrofracture and there now are two distinct stress waves in the rock, one induced by detonation of the explosive column and the other induced by detonation of the explosive in the hydrofracture. The stress wave produced by detonation of the explosive column is now, and continues to be, characterized by spherical portions at the top and bottom, with a conical section in between. The stress wave produced by detonation of the hydrofracture explosive has two parts, one above the hydrofracture and one below. Both have conical wavefronts, except in the region near the axis of the explosive column where the shapes are spherical. The illustration at time t_3 is similar to that at time t_2 except for additional propagation of both stress and detonation waves.

In the field experiment, two superposed sets of transient waves like those depicted in Figure 5 exist, one for each explosive-filled hydrofracture and associated explosive column. That the situation is complex can be visualized by mentally overlaying the illustration at time t_3 in Figure 5 upon another such illustration which has been displaced slightly, both in time and space. As was previously mentioned, the

complexity of the transient stress field was quite pronounced for the final firing attempt and measurement was complicated because most of the gages were part of the deployment scheme that had been designed to be compatible with the primary detonation system of the first firing attempt. The difficulty is that, in the final firing attempt, most gages experienced the arrival of a stress wave from one or both explosive columns prior to experiencing the arrival of a pulse from either explosive-filled hydrofracture.

The difference between the two firing attempts is depicted in the two illustrations in Figure 6. The upper illustration is based on the configuration of the final firing attempt, with the detonator at the top of the explosive column; the lower one is based on the configuration of the first firing attempt, with the detonator at the level of the explosive-filled hydrofracture, a short distance from the explosive column. Three sets of wave fronts are shown for each configuration. Those labelled "C" originate in the explosive column and those labelled "H" originate in the hydrofracture. The subscripts (1, 2, and 3) identify time in much the same way as in Figure 5. In the upper portion of Figure 6, it is clear that the stress waves from the explosive column dominate the scene. Dashed lines have been drawn to separate the regions where the first arriving stress wave originates at the hydrofracture detonation (Region A) from the regions where the first arrival originates at the explosive column (Region B). These regions have also been identified in the lower portion of the figure. In the lower illustration, Region A dominates, at least to the right of the explosive column, which is the region where the bulk of the stress and TOA gages were emplaced (Wells AA, BB, and CC) for the first firing attempt. It should be noted here that the portion of the illustration to the left of the explosive column in the lower illustration represents the situation that would exist when the detonation initiation point is located on the axis of the explosive column, at the level of the hydrofracture; i.e., it is representative of the secondary detonation system on the final firing attempt.

The detonation system for the first firing attempt made it possible to emplace gages over a rather large vertical range in Wells AA, BB, and CC and expect these gages to provide unambiguous data about the hydrofracture explosions; this remained true even when considering the fact that the detonation would involve two explosive columns and two

FIGURE 6. ILLUSTRATIONS DEPICTING SOME OF THE KEY DIFFERENCES BETWEEN THE FIRST AND FINAL FIRING ATTEMPTS. IN BOTH ILLUSTRATIONS, REGION A IS WHERE THE FIRST STRESS WAVE ARRIVAL IS FROM THE HYDROFRACTURE DETONATION. REGION B IS WHERE THE FIRST ARRIVAL IS FROM THE EXPLOSIVE COLUMN.

explosive filled hydrofractures. As was mentioned previously, this experiment design goal was not possible on the final firing attempt where many of the gages experienced arrival from the explosive columns before experiencing arrivals from the hydrofractures.

To be able to identify the various pulses evident on the gage records, it is necessary to develop a method to mathematically predict when these pulses should arrive. In particular, it is necessary to have some reliable method to identify the pulses from the explosive columns in the two explosive insertion wells (Wells X and Y) as well as those from the two explosive-filled hydrofractures. This was done by considering each wave separately.

In developing the mathematical formulation, some features of the underground geometry and of the materials involved (explosive and oil shale) were considered to be fixed, i.e., known from pre- or post-test measurements; these include, as examples, the locations of the gages, the hydrofractures, and the explosive insertion wells. Other features, while approximately known, were considered to be variable parameters; these include detonator locations, stress wave velocity in the rock, and detonation wave velocities in the explosive column and in the hydrofracture (these latter two velocities need not be identical). Detonator locations were considered to be variables because these positions were determined only in an approximate way by measuring the quantity of water introduced into the explosive insertion wells during the operation that forced the top wipers, which carried the detonator/booster units, down the wellbores. In the analyses, the oil shale was assumed to be homogeneous and isotropic; by so doing, the stress wave velocity used represents a mean value, averaged over deviations caused by variations in kerogen content in the vertical direction, as well as directional variations related to the non-isotropic nature of oil shale. These variations are comparatively small in relation to other uncertainties in the experiment. Detonation velocities in the explosive column and hydrofracture were treated independently to allow for the possible dependence of this quantity on explosive layer thickness. While both detonation velocities were varied, no improvement in interpretation was observed when using values different than those deduced in prior studies.

The geometry that was used in determining arrival times at gage locations for waves from the explosive columns is shown in Figure 7.

FIGURE 7. GEOMETRY ASSUMED IN DETERMINING WAVE ARRIVAL TIMES AT GAGES G1, G2, AND G3 FOR THE WAVE ORIGINATING AT THE EXPLOSIVE COLUMN.

The explosive column was assumed to be detonated at the top (Point D). Three gages are shown, at points G1, G2, and G3. Gage G1 is located in the region of spherical stress wave propagation center at Point D. The arrival of a stress wave at G1 is given by

$$t_{G1} = \frac{c}{U_{os}} \left[(X_{G1} - X_D)^2 + (Y_{G1} - Y_D)^2 + (Z_{G1} - Z_D)^2 \right]^{1/2}$$

where U_{os} is the stress velocity in oil shale, the X_i , Y_i , and Z_i are rectilinear coordinates of the two points in question, and time zero has been taken as the time of detonation initiation. Vertical (Z) co-

ordinates represent depths below ground surfaces, so the positive z direction is downward.

Gage G2 is located in the region where the wavefront is conical. The arrival time here is given by

$$t_{G2}^C = (z_{G2} - z_D)/U_{ex} + [(x_{G2} - x_D)^2 + (y_{G2} - y_D)^2]^{1/2} (\cos \theta) / U_{os} ,$$

where U_{ex} is the detonation velocity and the angle θ is defined by

$$\sin \theta = U_{os} / U_{ex} .$$

The arrival time at point G2 is equivalent to the time required for a conical wavefront, with cone angle θ , to propagate from Point B to point G2 with velocity U_{os} .

Gage G3 is located in the spherical stress wave propagation region centered at the bottom of the explosive column, point C. The arrival time in this case is given by

$$t_{G3}^C = (z_C - z_D)/U_{ex} + [(x_{G3} - x_C)^2 + (y_{G3} - y_C)^2 + (z_{G3} - z_C)^2]^{1/2} / U_{os} .$$

Arrival times for stress waves originating at the explosive-filled hydrofractures were calculated using the illustration depicted in Figure 8. In this case the arrival time at the gage is given by

$$t_G^H = (z_{F1} - z_D)/U_{ex} + [(x_{G1} - x_{F1})^2 + (y_{G1} - y_{F1})^2]^{1/2} / U_{ex} +$$

$$|z_{F2} - z_{G1}| (\cos \theta) / U_{ex} ,$$

where points F1 and F2 respectively represent the points of intersection of the hydrofracture with the explosive insertion well and with a vertical line drawn through the gage. The absolute value signs in the last term make the relation valid for gages located both above and below the hydrofracture. It has been assumed here that the hydrofracture is horizontal and planar; this, of course, is not strictly true, but the error introduced is not significant.

FIGURE 8. GEOMETRY USED TO CALCULATE THE ARRIVAL TIME OF A STRESS WAVE FROM THE HYDROFRACTURE AT GAGE G1.

In analyzing the dynamic data from the Site 12 experiment, consideration was also given to the possibility that one, or both, of the explosive columns had been initiated by the secondary detonation system, namely, the detonator/explosive unit exterior to the casing in the explosive insertion well, just above the hydrofracture. It was established in the early stages of analysis that measured arrival times were not consistent with this option for detonation; thus, no discussion of computational methods for the secondary detonation system will be given.

Having established that detonation of both explosive columns was initiated by the primary detonation system, four calculated arrival times were determined for each gage location in each computational run. Each run was based on specific set of detonation and stress wave velocities and detonator locations. Since the detonators were assumed to be located at the tops of the explosive columns, changing detonator location is equivalent to varying the length of the column. Once determined, the calculated arrival times were compared with measurements for the entire gage array. The comparison provided the basis of altering variable values for the next run. Ultimately, it was possible to establish best values, for the various parameters, which will be given in the next section.

As was mentioned previously, most of the gages experienced the arrival of a stress pulse from an explosive column prior to the arrival of a pulse from a hydrofracture. A feel for the extent to which this occurred can be obtained from Figure 9. This figure, which is based on a computational run using the final, or best, values for the variables, pictures each explosive column and adjoining hydrofracture separately. Well Y and the upper hydrofracture are shown in the upper portion of the figure and Well X and the lower hydrofracture in the lower portion. The stress, TOA, and acceleration gages in place during the final detonation effort are shown in each portion of the figure at appropriate radial distances from the explosive column and at vertical positions established according to distances above or below the hydrofracture. The same gages are, of course, depicted in both portions of the figure, but positions are different because of different reference points.

The dashed lines in Figure 9, which are similar to those in Figure 6, permit a quick determination of which stress pulse arrived at each gage first. In Region B, the first arrival is from the explosive column and in Region A, the first arrival is from the hydrofracture. In the upper portion of the figure, most of the gages are in Region A, as would be desired. However, the lower figure indicates that most of these same gages are in Region B. Gages in the upper portion of the figure which are blackened were impacted first by a stress wave from either the explosive column from Well X (simply blackened) or a stress wave from the lower hydrofracture (blackened and marked with an "h"). Gages which experienced a first arrival from either the Well Y column or upper hydrofracture are similarly identified in the lower portion of

FIGURE 9. GAGE LOCATIONS DEPICTED RELATIVE TO EXPLOSIVE COLUMN/HYDRO-FRACTURE PAIRS. ALL GAGES ARE PORTRAYED IN EACH PORTION OF THE FIGURE. THOSE IN REGION A IN EACH CASE EXPERIENCE AN ARRIVAL FROM THE CORRESPONDING COLUMN. THE OPPOSITE IS TRUE FOR REGION B. THE BLACKENED CIRCLES IN EACH CASE IDENTIFY GAGES THAT EXPERIENCED ARRIVAL FROM THE OPPOSITE COLUMN/HYDROFRACTURE PAIR FIRST; THE "h" MEANS IT WAS FROM THE HYDROFRACTURE.

the figure. It should be noted that on the basis of the illustration in Figure 9, the gage array in place for the final rubbing effort was best suited to detect stress waves arriving from the explosive column in Well X; twenty-three gages should experience stress pulse from this source first. Several of the gages were suitably positioned to detect the arrival of stress pulses from the explosive-filled hydrofractures as well; in particular, a total of eleven gages should have experienced the arrival of pulses from the lower hydrofracture first and five should have experienced an arrival from the upper hydrofracture first. In no case should an arrival from the explosive column in Well Y be the first experienced. As will be shown, however, the distinctive character of the pulses from the explosive columns as well as their comparatively high amplitude, makes the pulses from both explosive columns more readily identifiable than the lower amplitude and often characterless pulses from the hydrofractures.

V. EXPERIMENTAL DATA AND EVALUATION

Examples of data obtained from stress gages in the final rubbing effort are shown in Figure 10. These examples, which were obtained at three elevations in Well BB, illustrate several aspects of the measurements themselves, as well as the comparisons that were made between calculated and measured arrival times. Results of detailed examinations of all gage records are given in Table I, along with results of calculations made using the finalized set of parameter values. The nomenclature for gage identification in Table I, and elsewhere in this report, has the following meaning: the first two numbers or letters represent the well in which the gage was located, the next two numbers indicate the approximate distance of the gage in decimeters from the lower explosive-filled hydrofracture, and the last two letters identify gage type. TA identifies time-of-arrival gages; AR, AT, and AV identify accelerometers; LR and LT identify lithium niobate stress gages; and YR and YT identify ytterbium stress gages (the suffixes, R, T, and V, respectively, indicate radial, transverse, or vertical orientations for accelerometers and stress gages).

The stress histories in Figure 10 show clear indications of pulses which can be identified as originating at the explosive columns. Not so clearly identified are pulses which can be attributed to detonations in explosive-filled hydrofractures. In general evidence for detonations

in the hydrofractures was limited to the presence of a series of low-amplitude pulses much like those for gages BB21YB and BB17YB in Figure 10; thus interpretation is not necessarily straightforward. In some cases, the distinct absence of a pulse at a time when the gage appeared to be

FIGURE 10. EXAMPLE OF STRESS RECORDS OBTAINED IN THE FINAL FIRING ATTEMPT AT SITE 12.

operative (e.g., the pulse from the lower explosive layer for gage BB06YB in Figure 10) was interpreted as an indication that no stress wave from the source in question was detected. Such cases are identified in Table I with a dash, rather than a number, a superscript "d", or simply a blank space; the blank space implies that no pulse was observed, but the reason could have been a faulty gage, electrical noise or some other deleterious phenomenon.

Each of the records in Figure 10 indicates the arrival of a pulse with distinctive characteristics at about 3.5 ms. This time is too late to be associated with a column or hydrofracture detonation. Late arriving pulses, such as these, were common and some, in fact, suggest that the underground explosive configuration was somewhat different than planned. Particularly noteworthy are the gages in Wells AA, BB, and CC, where, with one exception (CC14TA), late arrivals were observed for every gage that had not failed prior to about 3 ms. These late arrivals suggest the presence of an accumulation of explosive in some section of the formation that was open or void prior to the explosive insertion operation. Judging from arrival times of the late pulses, this accumulation was likely in the vicinity of Wells AA and BB. Such a void region could have been created during the first firing attempt, or it could be a natural system.

Previous mention has been made of the prominence of the pulses from the explosive columns on the gage records. This is evident on Table I by the large number of data entries for the columns in comparison to the number of entries for the hydrofractures. Because of the quantity of reliable measurements, arrival time data for the column detonations were used to determine just where the detonators were located at shot time and to determine suitable values for the stress wave velocity in the rock and detonation velocity in the explosive column.

Referring back to Figure 7, it is possible to visualize how changes in detonator location, detonation velocity, and stress wave velocity will alter arrival times at various gage locations. For gages located in the upper spherical region and in the upper portion of the conical region, changes in detonation velocity will have little or no effect on arrival time; for lower gage locations, however, arrival times become strongly dependent on detonation velocity because the cone angle

TABLE I. SUMMARY OF STRESS WAVE ARRIVAL TIME MEASUREMENTS MADE DURING THE EXPLOSIVE FRAGMENTATION EVENT AT SITE I2.

Gage Identification	Gage Location ^a		Pulse Arrival Times ^b (ms)					General Comments
	A	B	From X Column	From Y Column	From Lower Exp. Layer	From Upper Exp. Layer	Late Arrivals	
ZL02TA	X							No detectable pulses.
ZM14TA		X	1.60(1.52)	1.70(1.69)	- (2.32)	1.83(1.71)		
0302TA	X		2.37(2.38)	2.72(2.58)	- (2.00)	2.61(2.47)	3.05(3.05) ^c	
0311TA	X		^d (2.15)	^d (2.35)	^d (2.36)	^d (2.11)	3.41(3.41) ^c	Several distinct but not identifiable pulses between 2.4 and 3.2 ms.
0314YB		X	1.94(2.02)	2.25(2.22)	^d (2.60)	(2.07)		Small pulses at 2.62, 2.93, and 3.18 ms.
0314LH		X	1.94(2.02)	2.22(2.22)	(2.60)	2.14(2.07)		Gage failure 2.32 ms.
0317AR		X	1.87(1.97)	(2.17)	(2.68)	(2.15)		
0317AT		X	1.89(1.97)	(2.17)	(2.68)	(2.15)		
0317AV		X	1.91(1.97)	(2.17)	(2.68)	(2.15)		
0321LH		X	1.92(1.91)	2.23 ^e (2.11)	- (2.78)	2.00 ^e (2.25)		Gage failure at 2.34 ms.
0321YB		X	1.90(1.91)	2.25 ^e (2.11)	^d (2.78)	2.10 ^e (2.25)		Small pulses at 2.52, 2.78, and 2.85 ms.
0327LH		X	1.76(1.82)	2.02(2.02)	(2.94)	(2.41)		Small pulse at 1.92 ms. Gage failure at 2.11 ms.
CC14TA		X	1.61(1.61)	2.16(2.29)	^d (1.94)	^d (2.01)		Sharp pulses at 1.80, 1.88, 1.93, and 2.03 ms.
CC17YB		X	1.57(1.56)	2.21(2.24)	(2.02)	1.95(2.09)		Gage failure at 3.1 ms.
CC21LH		X	1.45(1.40)	(2.08)	(2.25)	(2.32)		Gage failure at 1.55 ms.
CC27TA		X	1.34(1.33)	2.11(2.01)	^d (2.38)	2.44(2.45)	4.00	Small, sharp pulses at 1.68, 1.82, 1.94, and 2.35 ms.
BB02TA	X		2.51(2.50)	(3.21)	- (2.11)	2.72(2.73)	3.52	
BB06LH	X		2.41(2.42)	(3.12)	- (2.24)	2.55(2.60)	3.38	Questionable gage response between 2.7 and 3.2 ms.
BB06YB	X		2.43(2.42)	3.17(3.12)	- (2.24)	2.57(2.60)	3.35	
BB11TA	X		(2.34)	(3.05)	(2.36)	(2.47)		No detectable pulses.
BB14TA		X	- (2.29)	(3.00)	- (2.44)	- (2.42)	3.31	No detectable pulses except late arrival
BB17YB		X	2.90(2.24)	2.95(2.95)	^d (2.52)	^d (2.50)	3.35	Small pulses at 2.28, 2.41, 2.50, and 2.61 ms.
BB21LH		X	2.10(2.09)	(2.79)	(2.75)	(2.73)		Gage failure at 2.25 ms.
BB21YB		X	2.12(2.09)	2.92(2.79)	(2.75)	(2.73)	3.56	Several very weak pulses between 1.4 and 1.9 ms.
BB27LH		X	2.06(2.02)	(2.72)	(2.86)	(2.85)		Gage failure at 2.30 ms.
BB34TA		X	1.94(1.89)	2.37(2.60)	^d (3.05)	^d (3.05)	3.90	Small pulses at 3.01, 3.13, 3.33, and 3.52 ms.
AA14TA		X	- (2.88)	(3.57)	- (2.87)	- (2.78)	3.32	Late arrival here not particularly late but profile similar to other late arrivals.
AA21YB		X	2.74(2.67)	3.40(3.37)	(3.18)	3.08(3.08)	3.55	Late arrival possibly extension of Y column pulse.
AA34TA		X	(2.51)	(3.19)	(3.47)	(3.36)	3.75, 3.90, 4.35	
EE17YT		X	4.94(5.00)	(5.61)	- (4.13)	- (4.17)	6.26	Arrival times of pulses at ~5 ms in agreement with predictions, but amplitudes larger than expected.
EE21LT		X	4.92(4.90)	(5.48)	- (4.35)	- (4.39)		
0202TA	X		3.10(3.13)	4.10(3.96)	- (2.55)	3.32(3.35)	4.68	Y column pulse barely detectable.
0214TA		X	(2.76)	(3.59)	(3.14)	2.95(2.96)		Only single pulse observed.
0102TA	X		- (5.75)	- (6.52)	- (4.21)	- (5.12)	-	No detectable pulses.
0114TA		X	- (5.47)	- (6.14)	- (4.99)	- (4.63)	-	No detectable pulses.
0402TA	X		- (3.51)	- (3.96)	- (2.77)	- (3.29)	-	No detectable pulses.
0414TA	X		- (3.22)	- (3.67)	- (2.98)	- (2.84)	-	No detectable pulses.
DD14TA	X		4.10(4.15)	4.62(4.68)	- (3.29)	- (3.39)	4.33	Late arrival here not particularly late but profile similar to other late arrivals.
0502TA	X		- (6.47)	- (6.79)	- (4.46)	- (5.20)	-	No detectable pulses.
0514TA	X		- (6.17)	- (6.38)	- (5.00)	- (4.50)	-	No detectable pulses.

- a. "A" location is below the middle hydrofracture. "B" location is above the middle hydrofracture.
b. The first number listed is an observed arrival time; the second number (in parentheses) is a predicted arrival time based on $Z^X = 182.4$ ft., $Z^Y = 173.0$ ft., $U_{ex} = 20.5$ ft/ms, and $U_{os} = 10.9$ ft/ms.
c. Predicted arrival time from lower explosive layer if this layer is assumed to be at depth of 215.7 ft.
d. See comment column.
e. Identification of these pulses as originating at the Y explosive column and upper explosive layer as shown was based largely on pulse profiles; comparisons of observed and predicted arrival times, however, suggest that interchanges could be appropriate.

θ will change. Arrival times at all gage locations are dependent upon detonator location and stress wave velocity, but the effects of these two variables can be separated. In fact, the validity of a given set of parameter values can be assessed by plotting the effective distance the wave had propagated (herein called slant range) versus arrival time. For gages in the upper spherical region, the definition of slant range is simply the straight-line distance from the gage to the detonation initiation point. For gages in the conical region, slant range is the distance from the gage to the point B in Figure 7. Since no gages were located below the conical region, it is not necessary to define a slant range for the lower spherical region.

Figure 11 shows a plot of slant range versus arrival time for the parameter values which are listed on the figure. For the upper portion of the figure, the parameter values are the ones that produced the best fit of the data on a slant range, arrival time plot. Note that the points fall reasonably on a straight line and that the line intersects the origin. The fact that the straight line fit to the data intersects the origin indicates that the correct detonation initiation points have been used. The good quality of the linear fit indicates that the correct stress wave velocity has been used. The stress wave velocity found appropriate for an adequate representation of the data is consistent with information previously acquired in both laboratory and field studies.

Another plot, using different detonator locations, is shown in the lower portion of Figure 11 to illustrate an improper selection of parameter values. The detonator locations in this case are those estimated in the field by measuring the quantity of water pumped into the explosive insertion wells as the explosive was being forced into the hydrofractures. The line drawn in this portion of the figure is identical to the one in the upper portion. Clearly, the fit to the data in the lower graph is poor; the fact that the data generally track parallel to the line suggests that no change in stress wave velocity is appropriate, only a change in detonation location.

While it is not illustrated, the effect of changing the detonation velocity is to alter the apparent slope of individual sets of data, i.e., data from gages in a specific instrumentation well. This effect results because a change in detonation velocity produces a change in

FIGURE 11. GRAPHS OF SLANT RANGE VERSUS ARRIVAL TIMES FOR THE SITE 12 STRESS WAVE DATA. THE UPPER GRAPH WAS PLOTTED USING PARAMETER VALUES DEDUCED IN THIS STUDY. THE LOWER GRAPH WAS SIMILARLY PLOTTED BUT WITH DETONATOR LOCATIONS DEDUCED FROM MEASUREMENTS OF WATER FLOW INTO THE INSERTION WELL CASINGS.

slant range that is pronounced for gages in the lower portion of the conical region (see Figure 7), but negligible in the upper portion of this region. The detonation velocity shown in Figure 11 is very close to that determined in other experiments and tests. The evaluation of the stress records, including examinations of pulses from explosive columns as well as from hydrofractures, indicated the explosive performed as expected and that there was no support for a possible conjecture that the detonation velocity in the hydrofracture was different than that in the columns.

The detonator locations deduced from the stress wave data [182.4 ft (55.6 m) in Well X, 173.0 ft (52.7 m) in Well Y] indicate that the explosive column in Well X extended 28.0 (8.5 m) above the lower hydrofracture [201.0 ft (61.3 m)] and in Well Y the column extended 25.0 ft (7.6 m) above the middle hydrofracture. Not only does this observation indicate that the borehole blasts were definitely significant, but the difference in column heights indicates that the detonation waves did not reach the two hydrofractures simultaneously. The non-simultaneous initiation, together with the spatial separation of the initiation points for the hydrofractures, imply that the detonation waves in the hydrofractures did not propagate radially outward together. This would reduce the fracturing effectiveness of the stress waves in the region between the two explosive layers. Contours illustrating the lag of the detonation wave in the upper explosive layer relative to the wave in the lower layer are depicted in Figure 12.

The downhole locations of the two explosive insertion wells (Wells X and Y) and of Well A are shown for orientation purposes. It is seen that comparatively small deviations from simultaneity occurred only in the southwest half of the figure (the top of the figure is north).

Lag times toward the northeast are nearly as large as the transit time of a stress wave across the region between the two explosive layers (~0.4 ms). This means that little advantage from interactions between stress waves from the two explosive layers was gained. Thus, the test of the effect of stress wave interactions is not possible to the north and east of Wells X and Y. To the west and south, problems also exist. It has been noted in prior discussions that to the west-southwest of Wells X and Y (see Figure 1), the explosive intended for insertion into the bottom hydrofracture actually entered a natural

FIGURE 12. CONTOUR PLOT SHOWING LAG IN MILLISECONDS OF DETONATION WAVE IN UPPER EXPLOSIVE LAYER RELATIVE TO DETONATION WAVE IN LOWER LAYER.

fracture system several feet below the bottom hydrofracture. This observation is supported by the stress wave data, as will be shown a few paragraphs below. On the basis of simultaneity of detonation, the only region of the formation where a test of the effects of stress interactions can reasonably be made is in a south-southeast direction from Wells X and Y. Cores extracted after the explosive event did not indicate that there was an exceptional abundance of induced fractures in this region⁴, however, the reaction front during a retort attempt did propagate preferentially to the south-southeast from Wells X and Y.

The identification and evaluation of stress pulses from the explosive columns provided considerable insight about the actual underground explosive configuration at shot time, but unfortunately, as has been

previously mentioned, these pulses made evaluation of the stress pulses from the explosive-filled hydrofractures rather difficult. Nevertheless, some useful information can be derived.

Regarding detonation in the upper explosive-filled hydrofracture, there appears (see Table I) to be evidence of a detonation both to the east and west of the explosive wells as well as to the northeast, at least as far as Well 2. Evidence for detonation in the upper explosive layer to the southeast is not present, at least in the vicinity of Wells DD, 4 and 5. Flow logs and other measurements made after the shot, however, indicate that there was a significant increase in permeability near the elevation of this hydrofracture in the southerly direction.

Regarding the lower explosive-filled hydrofracture, evidence for detonation is questionable at nearly all locations. In some cases, however, there does appear to be evidence for the lack of a detonation. For example, gages BB02TA, BB06LH, and BB06YB, which were located between the two explosive layers and should have experienced a stress pulse from the lower layer first, all showed no such arrival at the appropriate time. In fact, no pulses that could definitely be attributed to a detonation in the lower explosive layer were observed in any of the gages located to the east, northeast, and southeast of Wells X and Y. Actually, the same is true to the west as well, except that here there are two "late arrivals" which support the contention that in this region the explosive entered a natural fracture system at a deeper level. Note that in Table I measured and calculated late arrivals are shown for gages 0302TA and 0311TA. The calculations here are based on an assumption that the lower explosive layer was 215.7 ft (43.2 m) deep. This is about the level of the natural fracture system. A significant detonation-induced enhancement of flow was detected at this level.

It should be noted that failure to observe stress pulses from the lower explosive layer may occur in some situations, even if this layer detonates on schedule. Reasons for this are that the crack expansion produced by detonation of the upper explosive layer can prevent propagation of the pulse from the lower layer to a gage located above the upper layer, or damage the signal cables from a gage located below the upper layer.

VI. SUMMARY AND CONCLUSIONS

The analysis of the stress wave propagation data from the Site 12 experiment provided much useful information about the actual configuration of the underground explosive assembly at shot time and about the nature of the detonations that occurred. This was in spite of the need to modify the explosive insertion and detonation schemes for a final firing attempt; this modification was necessary because of a detonator failure in the initial firing attempt. With the modified plan, the underground gage array was more sensitive to stress waves induced by detonation of the explosive that remained in the insertion wells than to the explosive in the hydrofractures, in contrast to the opposite situation which had been the intent for the initial firing attempt. Nonetheless, the measurements were very useful and provided a means for correlating observations from various post-shot evaluation activities with a description of the physical events that occurred during the blast.

The stress wave propagation data made it possible to confirm that detonation had been initiated in the two explosive insertion wells by the primary detonation systems which were located atop the explosive columns in these two wells. In addition, accurate locations of the detonator/booster units at shot time were determined, and hence so also were the heights of the explosive column at shot time. This information led to a quantitative determination of the times at which detonation was initiated in the two explosive-filled hydrofractures. While stress pulses which could be unambiguously identified with detonation in the two explosive-filled hydrofractures were few, those that were observed had arrival times that were consistent with the overall detonation sequence that was deduced from the assessment of the explosive column configurations.

The gages also indicated that some of the explosive inserted into the formation was not in the hydrofractures at shot time. Of particular interest is the observation that to the west of the insertion wells, explosive intended for the lowest hydrofracture had actually entered a natural fracture system located a few feet deeper; this observation was initially made during post-shot formation evaluations but was substantiated by the stress wave propagation data. The stress wave

propagation data also indicated that to the east of the insertion wells, explosive had collected in voids of the formation, possibly in cavities formed during cleanup operations which followed the first firing attempt.

It was concluded from the determinations of explosive column heights that the detonation waves in the wellbores did not arrive at the levels of the two explosive-filled hydrofractures simultaneously. Considering the departures from simultaneous initiation, along with the spacial separations between the two insertion wells and between the explosive layers (in the region where the explosive was in the designated hydrofracture as well as in the region where it was in the natural fracture system), it was further concluded that dynamic fracturing caused by interactions between stress waves should be prominent only in a southeasterly direction from the explosive insertion wells. Cores extracted after the shot did not reveal a distinct abundance of induced fractures in this region; however, it was observed that a retort burn front initiated near the insertion wells propagated preferentially toward the southeast, indicating greater permeability in that direction.

In analyzing the stress wave propagation data from the Site 12 experiment, it was observed that a large amount of useful information could be deduced, even under the conditions where the pattern of the gage array was not optimized for the modified explosive insertion and detonation plan. One of the major reasons for instrumentation is evident in this observation, namely, that a credible picture of the events which occurred can be pieced together from the data, even after a malfunction.

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