THE ROCK SPRINGS SITE 12 HYDRAULIC/EXPLOSIVE
TRUE IN SITU OIL SHALE FRACTURING EXPERIMENT

MASTER

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ABSTRACT

Sandia National Laboratories, in support of the Department of Energy Laramie Energy Technology Center's (LETC) in situ oil shale program, conducted a true in situ hydraulic/explosive fracturing experiment at Site 12 of the LETC field laboratory near Rock Springs, Wyoming. The objective was to examine an oil shale rubblization concept which relies on stress pulses generated by the detonation of slurry explosive in previously formed hydraulic fractures to further fracture the shale so as to create sufficient porosity and permeability for retorting. The experiment plan involved the creation and characterization of three horizontal hydraulic fractures, followed by the insertion and simultaneous detonation of slurry explosive in the two lower fractures. Shale fracturing should result as tensile stress pulses reflect from the surfaces of the three fractures, with reinforced stresses and a greater degree of fracturing in the region between the two explosive-filled fractures.

Numerous diagnostic and evaluation measurements were made throughout the experiment; in some cases new techniques were developed and employed. Core analyses, wellbore logging, and airflow and ^{85}Kr tracer tests were used for site characterization and assessment of the hydraulic and explosive fracturing. Tiltmeters, wellhead pressure and flow gages, and in-formation pressure, flow and crack-opening sensors were used to monitor hydrofracture creation and explosive insertion. Explosive detonation diagnostic data were taken with stress and time-of-arrival gages and surface and in-formation accelerometers.

The post-fracturing assessments indicated that: 1) hydrofracture creation and explosive insertion and detonation were accomplished essentially as planned; 2) induced fractures were randomly distributed through the shale with no extensively fractured regions or dislocation of shale; and 3) enhancement of permeability was limited to enlargement of the explosive-filled fractures. Successful retorting would be contingent on the ability to retort shale layers with random fractures but no significant permeability between enhanced fracture horizons.

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EXECUTIVE SUMMARY

INTRODUCTION

In situ processing techniques for extracting oil from oil shale offer potential advantages over surface methods - the reduction or elimination of mining, hauling, and disposal of shale, and perhaps, the reduction of detrimental environmental effects. The true in situ process, in which both the bed preparation and retorting phases are conducted remotely through a series of wellbores linking the underground shale bed with the surface, may be the most attractive environmentally but has experienced development problems.

In the bed preparation for in situ processing, the naturally impermeable oil shale must be rubblized such that sufficient porosity and permeability are introduced to permit process gases to flow from injection wells to the flame front and product liquids and gases from the pyrolysis zone to production wells. Fracturing of the shale by the insertion and detonation of slurry explosive in previously formed hydraulic fractures offers the potential of achieving bed preparation over a large area with a minimum number of wells. This report describes a heavily instrumented hydraulic/explosive fracturing experiment conducted at Site 12 of the Laramie Energy Technology Center (LETC) field laboratory near Rock Springs, Wyoming in support of the LETC in situ oil shale program. The primary objective of the experiment was to examine a rubblization concept that involved the creation of three closely spaced, horizontal, sand-propped hydraulic fractures, followed by the insertion and simultaneous detonation of slurry explosive in the two lower hydrofractures. Secondary objectives were to evaluate each step in the sequence of operations through extensive diagnostic measurements and to compare experimental results with predictive models.

EXPERIMENT DESIGN

The Green River Formation's Tipton member has been shown to have a lateral uniformity, with essentially horizontal bedding planes which is conducive to the creation of horizontal hydraulic fractures. Computer-simulated analyses showed that fracturing of oil shale sufficient for retorting might be achieved by detonating slurry explosive in closely spaced parallel cracks of substantial [≈ 6 mm (1/4 in)] width. Compressive stress waves generated by the explosive detonation would reflect from the hydrofracture surfaces as tensile waves that would fracture the shale. Building on a like experiment at LETC Site 9, the Site 12 experiment was designed to separately form three closely spaced [≈ 1.5 m (5 ft) apart], sand-propped, horizontal hydraulic fractures in the upper 12 m (40 ft) of the Tipton member [about 55 m (180 ft) below the earth surface at this site], followed by the insertion and simultaneous detonation of slurry explosive in the lower two hydrofractures. In the region between the two explosive-filled fractures, the simultaneous detonation would result in reinforcement of the reflected tensile waves which, in turn, could produce a greater degree of fracturing. The experiment, in addition to creating fractures in the shale, would thus provide a comparison of the degree of fracturing between two explosive-filled cracks and between an explosive-filled and a sand-propped crack. Dynamic heaving of the shale by the explosive gases, in addition to trapping the shock waves, could provide space for movement of the shale fragments to provide the increased porosity and permeability.

Hydraulic fracturing and explosive insertion would be through wells open only to a particular fracture to ensure that the desired quantities of explosive were inserted and detonated in the appropriate crack. Instrumentation and observation wells would be drilled at

strategic locations so that diagnostic measurements taken before, during and after major events would permit evaluation and determination of cause-effect relationships. An overall evaluation would be used to compare experimental results with predictive models as well as to determine the degree of fracturing achieved.

EXPERIMENTAL RESULTS

A. Preparatory Activities

Cores were extracted from five wells; stratigraphic markers were located at essentially the same depths over the experiment site. Logs were obtained for determination of material properties. Observation and instrumentation wells were drilled and cased to the top of the Tipton member to seal off overburden aquifers, then drilled to total depth. The hydrofracturing wells, which were also used for explosive insertion and detonation, were drilled and cased to total depth so hydrofracturing could be done from cased wells to reduce chances of creating vertical fractures.

Air acceptance and ^{85}Kr tracer tests were conducted to establish the initial shale permeability. Pre-existing horizontal fractures were found at the 58.5 m (192 ft) and 65.5 m (215 ft) levels. Depths of 60 m (197 ft), 61.5 m (202 ft), and 63 m (207 ft) were selected for the hydrofractures based on the core analyses and the pre-existing fracture depths.

Explosive compatibility tests revealed that three candidate slurry explosives would neither detonate nor burn in sand-propped cracks up to 9.4 mm (3/8 in) wide or in open cracks up to 1.5 mm (1/16 in) wide. As a result of these tests, the hydrofracturing procedure was modified to provide only a partial monolayer of sand in the two lower fractures; the slurry explosive insertion process was then designed for widening of the cracks through an appropriate insertion rate.

B. Hydraulic Fracturing

The three horizontal hydraulic fractures were created by (1) cutting a horizontal notch in the casing, grout, and a portion of the rock formation with a hydrojet tool; (2) applying high pressure water to the wellbore and notch to obtain crack initiation (formation breakdown); and (3) pumping gelled water and proppant sand through the wellbore and notch to propagate the crack and create a sand-propped horizontal fracture at the desired level over the experimental area.

Diagnostic data from pumpline pressure gages and flow meters, wellhead pressure gages and in-well hydrophones were used for tracking hydrofracture growth. Contours of the fracture front at discrete times during creation of the first hydrofracture showed the growth pattern to be nearly circular, with a slight preference to the north. Communication between wells through the first hydrofracture prevented tracking of succedent hydrofractures with pressure data. Surface tiltmeters were used to measure tilt vectors during the third hydrofracture, from which surface lift and hydrofracture shape and extent were derived.

Air acceptance and ^{85}Kr tracer tests conducted after each hydrofracture showed that air would flow freely through the hydrofractures between all wells except in the southeast corner of the experiment area where nearly all the flow was through the 65.5 m (215 ft) level pre-existing fracture. TV and flow logs were used to determine the levels of intersection of the three hydrofractures with each well. The hydrofractures were found to be nearly horizontal with no significant branching.

C. Explosive Fracturing

Instruments for monitoring explosive insertion included surface tiltmeters for determination of surface lift and estimates of crack

opening, wellhead pressure gages to monitor insertion pressures, and pumpline flow meters to measure cumulative flows. Stress, time-of-arrival (TOA) and acceleration gages were emplaced in the outlying wells near the levels of the hydrofractures to detect the transient events associated with the explosive detonation. Earth motion sensors were placed on the surface, directly above the detonation initiation point and at a radius of 305 m (1000 ft).

The explosive emplacement/detonation sequence was to emplace 7500 lb. of slurry explosive in each of two emplacement wells (connected to a particular hydrofracture), then insert the explosive into the lower hydrofractures by pushing wipers down the well casings with a pressurized flow of water. On the basis of a pretest analysis, the insertion was prescribed to increase the hydrofracture width about 4 mm (from 0.10 to 0.26 in) during extrusion of the explosive through the hydrofractures. At this rate, the explosive layers were expected to be about 15 m (~50 ft) in radius. Simultaneous detonation was planned through use of exploding-bridge-wire (EBW) detonator/booster systems placed at the fracture levels in a center well. A backup system was added with detonator/booster systems atop the wipers in the emplacement wells.

The first explosive fracturing attempt was unsuccessful; no explosive detonation occurred. Post-mortem evaluation indicated that the failure was due to a detonator that would not function after submersion in fluid under pressure. Diagnostic data also revealed that no formation lift occurred during explosive insertion. The ground water level for this attempt had been held below the hydrofracture levels to enhance the impedance mismatch at the level of the uppermost hydrofracture; apparently this resulted in insufficient formation backpressure in the hydrofractures for crack width increase during insertion of the slurry explosive.

A recovery procedure which led to a successful detonation consisted of the drilling of two new explosive emplacement wells and confirmation of communication between each well and (only) one hydrofracture, use of a reliable (environmentally tested) EBW detonator, and filling the lower two hydrofractures with water prior to explosive insertion to increase formation back pressure. A special instrumentation well was added near the new emplacement wells; this well contained pressure and resistivity gages at each hydrofracture level to monitor formation back pressure and explosive arrival, newly developed crack-opening gages to measure crack width changes, and accelerometers to monitor detonation. The explosive insertion rate was increased from 0.5 to 1.75 bbl/min and detonation was executed immediately prior to completion of explosive insertion for maximum crack (explosive) width at detonation.

Visual evidence that most, if not all, of the explosive had been inserted into the hydrofractures and detonated included vigorous expulsion of explosive gases from the emplacement/detonation wells, expulsion of sand-stemming from outlying wells, extensive cracking of the earth surface throughout the experiment area, and residual well casing lift ranging from ≈ 102 mm (4 in) at 4.6 m (15 ft) from ground zero to ≈ 76 mm (3 in) 26 m (85 ft) away. Preliminary review of the accelerometer, stress, and TOA data indicated that the magnitude and extent of the detonation was about as planned.

D. Post-Shot Assessment

An extensive fracture evaluation was conducted through field physical measurements and rigorous analyses of the acceleration, stress and TOA data. The formation assessment was coordinated with site preparation for a retorting experiment; this increased the number of wellbores interrogated. Cores extracted from ten wells provided

fracture densities versus depth at various radial distances and directions from the detonation initiation point. Caliper, TV and flow logs obtained from 35 wells were used for determination of location, density, and relative widths of significant fractures. Air acceptance and ^{85}Kr tracer tests provided post-shot permeability data.

The fracture densities found through coring were random throughout the zone of interest at all spots cored, with the fractures primarily along the bedding planes at the edges of the explosive-filled fractures, at natural tuff lenses, and/or at regions of low kerogen content. Contrary to predictions, no difference in fracture density was found between the explosive-filled fractures or between the explosive-filled and sand-propped fractures. Very few of the fractures noted in the cores could be seen with the downhole TV. Thus, while the stress magnitudes induced caused fracturing, dislocations that would create open fractures, which would have increased porosity and permeability between the hydrofractures, did not occur. Air entry points found by flow logging were coincided with one or more of the explosive-filled fractures. Caliper logs indicated widening of explosive-filled fractures at most wells.

The coring and logging also revealed an anomalous extrusion and detonation of the slurry explosive. In the region to the west of a line running from south-southwest to north-northeast and passing through (or very near to) the emplacement wells, the explosive inserted in the lower hydrofracture traveled by some unknown path to the lower [65.5 m (215 ft.) level] pre-existing fracture and was extruded into this fracture and detonated.

The airflow logs and air acceptance and tracer tests showed that airflow was enhanced through the fractures in which the explosive detonated, but no airflow paths were established in other regions.

This suggests little increase in permeability between the explosive-filled hydrofractures. Data obtained from the underground array of gages to monitor the detonation and subsequent stress wave propagation processes were also used in the post-test evaluation. Analyses of these data led to a determination of the geometry of the underground explosive system at the time of detonation which made it possible to determine the degree to which the desired conditions of the experiment were actually realized. The results indicated that simultaneous detonation in the two explosive layers was most nearly achieved in a southeasterly direction from the emplacement/detonation wells. This was also the direction where the greatest degree of permeability was detected.

CONCLUSIONS

The results of the Site 12 hydraulic/explosive fracturing experiment indicate:

1. Three closely spaced sand-propped hydraulic fractures were created essentially horizontal along bedding planes of the oil shale strata.
2. Controlled insertion and simultaneous detonation of slurry explosive in the two lower hydrofractures was executed; however, in some regions the explosive intended for the lower hydrofracture traveled by an unknown path to a lower pre-existent fracture and detonated.
3. Fracturing of the shale was induced by the detonation; the fractures were randomly distributed with no regions of extensive fracturing.
4. Dislocation of shale sufficient to increase porosity and permeability did not occur. These results show that the

hydraulic/explosive fracturing sequence was not successful in creating a uniform shale bed satisfactory for retorting. Successful retorting would be contingent on the ability to retort layers of competent shale between the enhanced fracture horizons.

THE ROCK SPRINGS SITE 12 HYDRAULIC/EXPLOSIVE
TRUE IN SITU OIL SHALE FRACTURING EXPERIMENT

I. INTRODUCTION

Knowledge of the abundance of synthetic crude oil which can be formed from the kerogen in oil shale and the need for technically feasible and economically viable methods to utilize this energy resource are well documented.^{1,2} While oil shale deposits are known to exist in many regions of the United States, the highest interest has been in the Green River Formation which underlies portions of Colorado, Utah, and Wyoming--a region of approximately eleven million acres with an estimated total resource equivalent to nearly two trillion barrels of oil.²

The feasibility of extracting oil from shale in aboveground retorts has been demonstrated. Practically, however, since the organic portion of Green River oil shale represents only 5 to 25 percent of the total weight, large tonnages of material would be required for commercial processing. This would involve large mining and haulage operations plus operations to dispose of large quantities of spent shale in an economical and environmentally acceptable manner.

In situ processing of oil shale offers many potential advantages. The modified in situ technique reduces significantly, but does not totally eliminate, the mining, hauling, and spent shale disposal problems. On the other hand, the true in situ method, in which all bed preparation and product recovery operations are performed through wellbores, offers total elimination of the mining, haulage, and spent shale disposal requirements. Environmental concerns with in situ processing concepts consist primarily of possible contamination of subsurface water.

The bed preparation phase of true in situ oil shale processing requires the introduction of sufficient porosity and permeability into the naturally impermeable shale bed to permit process-support gases to flow from the injection wells to the combustion zone and product liquids and gases from the pyrolysis zone to the production wells. The primary problems associated with true in situ processing are the development of technically and economically feasible methods to rubble the shale, i.e., to fracture and fragment the shale so as to create a suitably porous and permeable retort bed with appropriately sized fragments. Two basic true in situ fracturing techniques have been investigated in prior experimentation.³⁻⁵ The borehole springing method⁴ in which explosives are detonated in boreholes shows promise where the shale is close to the surface, i.e., where void volume can be introduced by explosively lifting the overburden. The second method, herein called hydraulic/explosive fracturing, achieves fracturing by the detonation of slurry explosive in a previously formed system of hydrofractures. This latter method has more appeal for deeper lying shale beds⁵ than does the wellbore springing method.

This report describes a true in situ fracturing experiment conducted at Site 12 of the LETC field laboratory near Rock Springs, Wyoming. The primary objective of this heavily instrumented experiment was to examine the hydraulic/explosive fracturing concept for a specific configuration involving three closely spaced horizontal hydraulic fractures, with slurry explosive inserted into the lower two hydrofractures and subsequently detonated. Of interest was whether or not this procedure would produce sufficient fracturing and fragment motion to render the shale bed suitably porous and permeable for retorting. Secondary objectives included the characterization of each event to determine cause-effect relationships and the comparison of experimental results with numerical simulations. Thus, numerous

diagnostic and evaluation measurements were performed during the sequence of events. Details of the various events, of the instrumentation systems and analysis methods, and of the post-fracturing evaluation are presented in this report, together with conclusions regarding the degree of success of the experiment as well as the overall prognosis for the hydraulic/explosive fracturing concept.

II. EXPERIMENT DESCRIPTION

A. Background

The Laramie Energy Technology Center has been conducting research in true in situ processing of oil shale for more than a decade. Much of this work has been in the upper portion of the Tipton Member of the Green River Formation at the LETC field laboratory near Rock Springs, Wyoming, where the overburden thickness ranges from 15 to 122 m (50 to 400 ft.), or at a similar facility near Green River, Wyoming, where the overburden is about 120 m (400 ft) thick. The feasibility of creating horizontal hydraulic fractures was investigated and verified at Green River Site 2.⁶ A successive experiment, at Rock Springs Site 9,⁴ had as its conceptual plan the creation of three horizontal, sand-propped hydrofractures with subsequent insertion and detonation of slurry explosive in the middle hydrofracture. An attempt to follow this plan did not succeed. A follow-up attempt employed a different plan in which slurry explosive could enter one or both of the two lower hydrofractures. While difficulties were clearly encountered in the Site 9 experiment, it did indicate that the concept of combined hydraulic/explosive fracturing had potential for increasing permeability in tight rock formations. The results suggested that closer spacing of the hydrofractures and better control of the explosive insertion/detonation sequence should lead to improved fracturing of the shale bed.⁷

The Site 12 hydraulic/explosive fracturing experiment was planned to advance the fracturing concepts examined at Site 9. The design concept was to again create three horizontal hydraulic fractures, followed by the insertion and detonation of slurry explosive in one or more of the hydrofractures.⁸ Detailed design parameters would be established through analyses using characteristics of candidate explosives, as well as the physical properties of the geological medium.

B. Site Characterization

The LETC field laboratory is located along the eastern margin of the Green River Oil Shale Formation. Beds outcropping along the edge of the basin range upward from the Wasatch Formation to the Laney Member of the Green River Formation. The attitude of the beds is north striking with a gentle west dip of about 19 m/km (100 ft/mile). No major structures disrupt this trend in the vicinity of the test site.⁹ The basal part of the Wilkins Peak Member forms the cover from the ground surface down to the top of the oil shale and consists primarily of marlstone with thick tuff lenses. The lithology in the Tipton Member remains essentially the same--marlstone with occasional tuff lenses up to 0.15 m (0.5 ft) thick. The consistency of the tuff lenses throughout this general region provide an excellent identification by "marker" designation. This permits detailed structural mapping of experiment sites throughout the local region.

The oil shale zone selected for the Site 12 experiment was the upper 12 m (40 ft) of the Tipton Member, which at Site 12 is about 55 m (180 ft) below the surface. The lithology in this zone was expected to be nearly the same as at Site 9, with an increased overburden of about 15 m (50 ft) at Site 12.

Prior to selection of a final experiment design, a core was extracted from the center of the experiment site. The lithology

of this core was found to correlate with those taken at Site 9 when the increased overburden was taken into account; the depths and thicknesses of the "markers" were at the same location relative to each other and to the top of the Tipton Member.¹⁰ Four additional cores were extracted at 15 m (50 ft) distances to the north, east, south, and west for assays and for further confirmation of the uniformity of lithology. These cores exhibited "markers" at the same depths (accounting for slope) as on the first core. This provided one of the ingredients felt necessary for the creation of closely spaced horizontal hydrofractures.

C. Experiment Design

1. General Plan - The Site 12 experiment was selected to further investigate, through a heavily instrumented field laboratory test, the concept of hydraulic/explosive fracturing to produce a rubblized oil shale bed satisfactory for true in situ retorting.¹¹ As was previously stated, the general approach was to: (1) separately create three equally spaced, sand-propped, horizontal hydraulic fractures from three closely spaced wellbores in the upper portion of the Tipton shale member; (2) insert a pre-determined amount (~7500 lbs) of slurry explosive into each of the two lower fractures from the well used to create the respective hydrofracture; and (3) detonate the slurry explosive in the two fractures simultaneously from the third well of the center cluster. The detonation would produce compressive stress waves propagating away from the explosive layers; tensile stresses would develop as these waves reflect from the surfaces of adjacent hydrofractures. If the tensile stress amplitudes were sufficiently high, the shale would be fractured and rubblized zones might be formed. This rubbling concept was to be evaluated prior to the field experiment by simulation models and explosive compatibility tests; final design parameters, e.g., amount of explosive, crack spacing, etc. were to be contingent on the results of the preliminary analyses.

The original well layout, shown in Figure IIC-1, had at its center a cluster of three wells (A, B and C) that would be used for hydrofracture creation at the upper, lower, and center levels, respectively. Wells B and C would subsequently be used as explosive emplacement wells, Well A as the detonation well. The wells would be cased to total depth. Hydrofracturing would be accomplished by notching each well, through the casing, at the desired level. Well A would subsequently be notched at the levels of the two lower hydrofractures so that slurry explosive could enter the wellbore and surround the detonating system. This would provide the conditions needed for simultaneous detonation of the slurry explosive at the center of the pattern.

FIGURE IIC-1. ORIGINAL WELL LAYOUT - SITE 12 TRUE IN SITU FRACTURING EXPERIMENT

Observation wells (1-8) were located at 45° intervals at alternating radii of 7.6 and 15.2 m (25 and 50 ft.); the larger value is the expected radius of the explosive when extruded into the hydrofractures. An additional observation well (9) at a 3.0 m (10 ft) radius is also shown in the original plan. The observation wells were drilled and cased to the top of the Tipton Member to seal off overburden aquifers, then drilled to the bottom of the zone of interest [67 m (220 ft)]. They would be used for diagnostics during the hydrofracturing and explosive fracturing events and for formation characterization before and after each event.

Instrumentation wells (AA, BB, CC, and EE) were drilled and cased in the same manner and positioned along an east-west line through Well A at radii of 3.0, 5.3, and 7.6 m (10, 17.5 and 25 ft). Another instrumentation well (DD) was similarly drilled 5.3 m (17.5 ft) to the south of Well A. The instrumentation wells were to house gages to monitor the detonation-induced stress waves and were positioned to provide information pertinent to the asymmetry caused by the geometrical configuration of Wells A, B, and C. An elevation view of the well layout in the east-west direction, depicting the instrumentation, is provided in Figure IIC-2.

Important aspects of the overall experiment were the characterization of each hydraulic fracture during and subsequent to their creation, control of the placement of the explosive, and characterization of the explosively induced fractures. Table IIC-1 lists the instrumentation techniques included in the original plan and the purpose of each measurement. The diagnostic measurements made during the hydrofracturing (acoustic, resistivity, pressure and flow) were intended to provide information on fracture rate, fracture radius, and proppant placement.

FIGURE IIC-2. CROSS-SECTIONAL VIEW OF THE HYDROFRACTURE INITIATION AND EXPLOSIVE EMPLACEMENT AND DETONATION WELLS (A, B, AND C) AND OF THE INSTRUMENTATION WELLS (AA, BB, CC, AND EE) FOR THE ROCK SPRINGS SITE 12 EXPERIMENT. PLANNED LOCATIONS FOR GAGES ARE SHOWN. THE HEAVY VERTICAL LINES IDENTIFY CASSED PORTIONS OF WELLS.

The wellbore logging operations, together with airflow acceptance and tracer tests, were included to provide fracture locations and indications of permeability. The post-explosive fracture measurements, together with the stress gage data, were intended to provide information regarding explosive performance as well as the degree and extent (radial and vertical) of fracturing and/or rubblization of the shale bed.

2. Detonation/Stress Wave Simulation - During the planning phases of the Site 12 experiment, a computational study was undertaken to examine the dynamic processes that occur immediately after detonation

TABLE IIC-1
SITE 12 INSTRUMENTATION

<u>Technique</u>	
<u>HYDRAULIC FRACTURE</u>	
Hydrophones in observation wells	Passive acoustic mapping (20) of the fracture front
Current probes in observation wells	Time of arrival of the fracture fluid at the observation wells
Current probes on the surface	Resistivity mapping of the fracture front
Pressure measurements at the observation wellhead	Time of arrival of the fracture fluid at the observation wells
Pressure measurement at the frac well	Independent pressure profile of the fracture
Recording of the Halliburton pressure and flow	Correlation with Sandia data
<u>HYDRAULIC FRACTURE CHARACTERIZATION</u>	
Air flow and tracer injection	Permeability of the fracture
Flow Logging	Fracture location and permeability
TV Logging	Fracture location
Temperature Logging	Fracture location
Gamma Log	Fracture location if proppant sand is radioactively loaded
Impression Packer	Fracture location
<u>EXPLOSIVE CHARACTERIZATION</u>	
Pressure measurement at Holes B and C	Pressure profile on explosive emplacement holes
Time of Arrival	Verification of detonation quality and symmetry
Stress Measurements	Correlation with the theoretical model
	Verification of the slurry emplacement
Round Robin	Ground motion
<u>RUBBLE IDENTIFICATION</u>	
Core back, log and photograph	Rubble identification
Air flow and tracer injection	Permeability of the rubble area
Air flow logging	Location of the rubble area
TV Log	Location
Temperature Log	Location

of explosive in a system of hydrofractures. The results of the work, which have been previously reported,¹² were used to design certain geometrical and operational aspects of the hydrofracture creation, instrumentation deployment, and data acquisition portions of the experiment. Some of the salient results of the computational study will be reviewed in the following discussion.

The calculations were performed using the one-dimensional wave-code, CHART D.¹³ The configuration assumed in zoning the problem is depicted in Figure IIC-3. Nearly all calculations were made with

FIGURE IIC-3. PLANNED GEOMETRY OF THE SITE 12 EXPERIMENT AS INCORPORATED INTO THE WAVECODE CALCULATIONS.

a separation distance between hydrofractures of 1.5 m (~5 ft) because early in the work it was established that this distance was about the minimum that could be realized in actual practice, in view of the need to maintain the identity of each hydrofracture over a rather large portion of the shale bed. The primary variable in the calculations was crack thickness; three thicknesses, 0.15, 0.30, and 0.60 cm (~1/16, 1/8, and 1/4 in), were considered, which effectively span the range expected in the experiment. When the calculations were performed, the detonation properties of the explosive to be used in the experiment were not known, so those of a common liquid explosive, nitromethane, were assumed.¹⁴ The oil shale was taken to be homogeneous with a density of 2.27 g/cm³ and was treated in the calculations as an elastic, perfectly plastic material using parameters determined in a previous study.¹⁵ The sand-propped crack was assumed to be void in the calculations.

Use of a one-dimensional wave code for problems involving explosive-hydrofractures is tantamount to assuming that the explosive detonation is initiated simultaneously over the entire lateral extent of the explosive layer and that induced stress waves propagate perpendicularly away from the explosive layers as planar waves. The actual problem, of course, is two-dimensional since detonation in a given layer is initiated at a point; from there the detonation wave propagates radially outward in the layer, sending stress waves into the surrounding medium all the while. Use of a two-dimensional wave code for the study was not possible, however, because the fine zoning required to adequately represent the thin explosive layers would have led to an overwhelming requirement for computer storage to accommodate the inclusion of a suitably large region of oil shale in the problem.

An illustration of the physical events induced by detonations in a pair of explosive-filled hydrofractures is shown in Figure IIC-4.

FIGURE IIC-4. PLOT ILLUSTRATING POSITIONS OF THE DETONATION WAVES, COMPRESSIVE AND TENSILE STRESS REGIONS, AND CRACK SURFACES AT 0.8 ms AFTER THE START OF DETONATION.

The illustration here is based on one of the CHART D calculations and is in effect a "snap-shot" taken 0.8 ms after the start of detonation in the two explosive layers. In the figure, the instantaneous positions of the crack surfaces are shown by the solid lines and the positions of the stress wave fronts are shown by the dashed lines; the small arrows on the dashed lines indicate direction of propagation. At the time of the snap shot, the detonation waves have propagated radially outward 5 m (16 ft). As the detonation occurs, compressive stress waves are continually transmitted into the oil shale in both directions from each explosive layer. It is these waves, and the subsequent interactions with each other and with the physical discontinuities of the formation that provides the primary mechanisms for altering the conditions of the shale bed.

There are three regions of oil shale depicted in the figure which are of interest because of unique stress wave interactions. Of prime importance is the region between the explosive layers where two compressive pulses propagate. Assuming simultaneous initiation of detonation in the two explosive layers (the case considered in the calculation), the two compressive pulses initially propagate toward each other, then meet and reinforce each other at the center of the region between the explosive layers. After this interaction, the pulses continue to propagate as before but now each propagates in the tail of the other wave. When the waves reach the opposite explosive-filled cracks, which have been opened by the action of the expanding explosive gases, the compressive pulses reflect and, because of the impedance differences at the crack surfaces, propagate back into the oil shale as tensile pulses. If of sufficient amplitude, the tensile pulses will cause fracturing, or spallation, of the oil shale near the fracture. As is evident in Figure IIC-4, the interactions of the stress pulses with the surfaces of the explosive cracks reverse the directions of free surface motion. If fragments are formed as a result of the interactions at the surfaces, it is desired that they will move into the opened cracks, rotate as they move and come to rest with random or nearly random orientations, thereby providing a mechanism for permanently retaining the void volume created by the expanding explosive gases. Besides the fracturing that could occur as a direct result of the reflected tensile pulses, additional fracturing could occur when these pulses meet in the middle of the region between the two explosive cracks.

In the region between the upper explosive crack and the sand-propped crack, only a single compressive pulse propagates; when this pulse reaches the sand-propped crack, a reflection occurs that sends a tensile stress pulse back into the oil shale. Fracturing could result after this reflection, but because interactions with other stress pulses

are absent in this region, the degree of fracturing should be less than in the region between the two explosive cracks.

A third region of interest is below the lower explosive crack. Here, no free or nearly free surfaces exist, so no tensile pulses develop. The same is true of the region above the sand-propped crack. In the calculations, propagation into this uppermost region occurs after the closure of the crack.

The presumed mechanism for rock fracture in the one-dimensional analysis is clearly related to the development of tensile stress pulses, and because of interactions between stress waves from the two sources, the greatest degree of fracturing would be in the region between the two explosive layers. Next in order would be the region between the upper explosive crack and the sand-propped crack. No tensile fracturing would be expected in the oil shale above the sand-propped crack or below the lower explosive crack.

A one-dimensional treatment of the problem ignores the facts that the detonation waves propagate radially outward in the explosive layer with a finite speed and that the stress waves in the rock propagate obliquely with respect to the hydrofractures. These features will lead to flexure of the oil shale bed and to the development of shear stresses, both of which could cause fractures that would not be taken into account in a one-dimensional analysis. The oblique nature of the stress waves could provide a means to impart rotational motion to the oil shale fragments and, thus, enhance the probability for retaining the void volume in the explosive cracks.

Some quantitative results of the CHART D calculations are shown in Figures IIC-5 and IIC-6 to illustrate effects produced by varying initial explosive layer thicknesses. In Figure IIC-5, which depicts stress pulse amplitudes as functions of vertical position, we see

FIGURE IIC-5. CALCULATED PEAK STRESS AMPLITUDES IN THE OIL SHALE PLOTTED AS A FUNCTION OF VERTICAL POSITION. A SEPARATE GRAPH IS SHOWN FOR EACH OF THREE INITIAL CRACK WIDTHS INVESTIGATED.

that the attenuation of the compressive pulses which originate at the explosive cracks (Note--directions of arrows identify propagation directions) becomes more rapid as the explosive layers become thinner. While this is evident in all regions of the oil shale, it has its most important effects in the regions where tensile stress pulses develop and propagate. The increased energy in the stress pulses which emanate from the thicker explosive layers, together with the correspondingly broader pulses and slower attenuation, lead to higher amplitude tensile pulses and hence to a greater probability for fracture.

The results plotted in Figure IIC-5 were determined in calculations where material fracture was suppressed, so tensile pulse amplitudes plotted in the graphs are higher than would be expected in an actual situation. Other calculations, however, were performed in which fracture was allowed to occur when the tensile amplitude exceeded a prescribed threshold (taken as 40 MPa). While the calculations with fracture permitted are not considered to be quantitatively accurate because of the overly simplistic treatment of the fracture process, they do qualitatively illustrate a number of important features. First is that for each explosive layer thickness, considerably more fractures occur in the region between the two explosive layers than in the region between the sand-propped crack and the upper explosive layer. Secondly, the number of fractures occurring in the region between the sand-propped crack and upper explosive layer are very much less for the thinnest explosive layer than for the other two thicknesses. In all cases, tensile stress amplitudes steadily increase after a reflection until the threshold for fracture is reached. At that time, a crack is formed and the local stress is relieved. Continued propagation of the stress wave, however, leads again to a build-up of tension, at different locations, and to the formation of additional fractures if the threshold for fracture is exceeded. This process

can occur repeatedly, essentially as long as sufficient energy remains in the wave to produce conditions for fracture. For the thinnest explosive layer, only a single fracture was noted between the sand-propped crack and the upper explosive layer. This is in contrast to the calculation for the thickest explosive layer where fractures occurred at more than 20 locations in the same region. Results for the middle explosive layer thickness were not significantly different than those for the thickest layer. In the region between the two explosive layers, a rather large number of fractures was noted for each of the three explosive layer thicknesses, more than for any of the calculations for the region between the sand-propped crack and the upper explosive crack. The actual number of fractures in any case is not considered to be a physically correct quantity, in part because of the previously stated oversimplification of the fracturing process and also because of the strong influence of zoning on fracturing. It was not practical to reduce these uncertainties; however, the qualitative assessments discussed above are considered to be reliable.

While the success of the hydraulic/explosive fracturing concept depends strongly on the amount of fracturing that can be achieved, the ultimate criterion is the degree to which the permeability of the shale bed can be enhanced. The latter feature here is dependent in part upon the motion of rock fragments after fracturing occurs. To achieve uniform permeability throughout the shale bed, it is necessary that fragments of rock move into the expanded explosive cracks while they are open, that some fragment rotation occur during this time to prevent the formation from simply regaining its initial condition, and that these fragment motion characteristics exist to at least some degree over the entire vertical range of the shale bed intended for rubbleing. To maximize the probability for achieving these conditions, it is important to ensure that the explosive cracks are open to near

optimum states at the time fragment motion occurs. Clearly, the initial thickness of the explosive layer will have strong influence on the maximum crack opening, and hence on the maximum amount of void volume that can be permanently retained in the shale bed.

Crack openings predicted with the CHART D calculations are shown in Figure 11C-6 for the three explosive layer thicknesses considered in the calculations. As depicted in the graphs, the crack surface motion is initially very rapid, but then slows as the prompt shock stimulus of the explosive is reduced to a steady push induced by gas pressure. The arrival of the compressive stress pulse is evident at the time the lower crack surface stops its downward motion and moves upward. Fragment motion into the open cracks would follow this velocity reversal. Delay of this interaction to permit greater crack expansion can be achieved by increasing the separation distance between explosive layers. Such a move, however, would also result in lower tensile pulse amplitudes, and hence in a lower probability for fracture. The 1.5 m (≈ 5 ft) separation distance of the calculations was selected as a reasonable separation distance to attempt in creating the hydrofractures. It was, of course, recognized that in actual practice significant random departures from any selected separation distance would occur as a function of horizontal position.

For the hydraulic/explosive fracturing concept to be an effective method to rubble an oil shale bed, it is imperative that tensile fracturing occur. If amplitudes of tensile stress pulses are too low, such fracturing will not be evident in the manner described in the foregoing discussion. Other mechanisms for fracture do exist, however; but unfortunately these would not be expected to produce increased permeability. These other mechanisms would be activated by the flexing and shearing that would occur as the detonation waves sweep through the explosive layers. The resulting stresses would be continued as

FIGURE IIC-6. CRACK OPENINGS PREDICTED WITH CHART D CALCULATIONS FOR ASSUMED EXPLOSIVE LAYER THICKNESSES OF 0.15, 0.30, AND 0.60 cm.

the explosive gases expand, causing lifting of the portion of the formation directly over the explosive layers. This action could lead to failure of the rock in weak regions, but because of the absence of a mechanism for fragment motion, no enhanced permeability would be expected. Fractures of a similar nature could be produced in the region below the explosively-loaded hydrofractures.

3. Explosive Compatibility Tests - A series of tests were conducted on each of three candidate slurry explosives,¹⁶ TAL-1005-E, GOEX, and TELEDET, to evaluate their compatibility with the Site 12 experiment plans. Parameters investigated were (1) compatibility of the explosive with the Sandia detonator/booster system, (2) whether

the explosives could be forced into sand-propped hydrofractures and subsequently detonated, and (3) the minimum width such explosive-filled hydrofractures must have to ensure that detonation be initiated and sustained. The series of tests described below was conducted only on the TAL-1005-E slurry explosive which was the primary candidate from early in the planning activity; the other two candidates were subjected to similar but less comprehensive tests to determine if they would respond differently.

The chemical compatibility tests consisted of the firing of the detonator/booster assembly in a short section of steel pipe filled with slurry explosive; this simulated the cased well conditions planned for Site 12. These tests showed the detonator/booster assembly to be chemically compatible with the explosive; e.g., a normal detonation would be produced in a wellbore.

The next tests consisted of firing the detonator/booster system in a similar pipe that intercepted an explosive-filled crack (no sand), simulating the intersection of a wellbore with an explosive-filled hydrofracture. Explosive layers with thickness of 6.4 mm (1/4 in), 3.2 mm (1/8 in), and 1.6 mm (1/16 in) were examined. Successful explosions with consistent detonation velocities were obtained in the tests with 6.4 mm (1/4 in) and 3.2 mm (1/8 in) crack widths. No detonations were produced in two attempts with the 1.6 mm (1/16 in) crack width. Two attempts were also made to detonate 1.6 mm (1/16 in) thick explosive layers using fixtures which simulated only the explosive-filled hydrofractures (no wellbore); no detonations were realized in these cases either.

Tests were conducted to observe the migration of explosive pumped through empty simulated fractures ranging in width from 1.6 mm (1/16 in) to 9.5 mm (3/8 in) as well as through simulated fractures with widths between 3.2 mm (1/8 in) and 9.5 mm (3/8 in) which were

filled with 8-12, 10-20, or 20-40 mesh sand. The explosive was found to flow with comparative ease through the empty fractures but could not be forced through 10-20 mesh or smaller sand at reasonable pumping pressures (250 psi); the explosive did flow smoothly through packed 8-12 mesh sand at about 50 psi.

Attempts were made to detonate the explosive after it had been extruded into 8-12 mesh sand in fixtures with varying gap widths, simulating explosive-filled, sand-propped hydrofractures. In these tests, the detonator/booster was at one end of the fixture. Explosive was forced into the fixture from the detonator/booster end. No sand was in the region next to the detonator booster. Crack widths ranged from 3.2 mm (1/8 in) to 9.5 mm (3/8 in). In each case, the explosive detonated in the portion of the fixture which contained no sand, but did not detonate or burn in the sand-slurry mixture.

A test was also conducted wherein the crack width in the fixture was progressively stepped down from 6.4 mm (1/4 in) to 3.2 mm (1/8 in) to 1.6 mm (1/16 in). The explosive in this fixture, which contained no sand, did detonate.

The results of the explosive compatibility tests on TAL-1005-E showed that: (1) the Sandia designed detonator/booster was chemically compatible with the candidate explosive in a simulated borehole configuration, (2) detonation could not be consistently initiated or maintained in cracks of 1.6 mm (1/16 in) width or less, (3) slurry would not readily flow through propping sand with 10-20 mesh size or smaller, and (4) the explosive would not detonate or burn when forced into cracks up to 9.5 mm (3/8 in) thick that contained 8-12 mesh sand. The other two explosive candidates exhibited better flow properties in sand, but, like TAL-1005-E, failed to detonate when forced in sand-filled cracks.

As a result of the explosive compatibility tests, a decision to use TAL-1005-E was made, but plans for the Site 12 experiment were modified. During the hydrofracturing, only a partial monolayer of 8-12 mesh and 6-8 mesh sand would be inserted rather than a full layer or multiple layers of 10-20 mesh sand. The explosive insertion rate would be such that the cracks would be reopened to at least 6.4 mm (1/4 in) and the overburden supported by the explosive until detonation was accomplished.

III. SITE (BED) PREPARATION

A. Pre-fracturing Activities

The experiment wells were drilled and cased per the original plan (Figures IIC-1 and IIC-2). Density, gamma, gamma-density, electric, and 3-D velocity logs were obtained and formation materials properties (bulk modulus, Young's modulus, Poisson's ratio, etc.) were determined for use in data analyses. Surface surveys and wellbore directional surveys were obtained to provide a means for specifying underground instrumentation and hydrofracture locations (Figure IIIA-1).

Air acceptance and tracer flow tests were conducted to determine the initial porosity and permeability of the top 12 m (40 ft) of the Tipton Member. Air and ^{85}Kr tracer were injected at one wellhead and recovery rates measured at four other wellheads. By subtracting the estimated time for the tracer to travel through the well casing, the across-formation time could be deduced. The relative amounts of ^{85}Kr recovered at each well as a function of time provided indications of the relative void volumes in the flow paths between wells.

Two interesting observations were made during the airflow/tracer tests: (1) distinct communication paths existed between wells within the Site 12 layout and (2) air injected in Site 12 wells was found to

FIGURE IIIA-1. SURFACE AND DOWNHOLE LOCATIONS OF DETONATION AND INSTRUMENTATION WELLS.

be exiting from wellbores at sites of other experiments (LETC Sites 6, 9, and 10). Flow logging of the wells revealed existing horizontal fractures at approximately the 58.5 m (192 ft) and 65.6 m (215 ft) levels in the formation; the evidence was that at least one of these fractures reached the other experiment sites. Except for flow through the pre-existing fractures, the formation was found to be essentially impermeable.

B. Hydraulic Fracturing

The results of the core analyses, numerical calculations, explosive compatibility tests, and pre-fracture formation assessment were incorporated into the final plans for the hydraulic fracturing. Hydrofracture depths of 60 m (197 ft), 61.5 m (202 ft), and 63 m (207 ft) were established; this was consistent with the recommended 1.5 m (5 ft) spacing, located all hydrofractures between the pre-existent fractures, and placed them at levels where initiation and propagation of fractures could occur with comparative ease because of shale grade and/or the existence of a tuff lens.

The three horizontal hydraulic fractures were created¹⁷ using procedures developed in consultation with an oil field service company. The wellbore casings were notched with a 4.8 mm (3/16 in) diameter orifice hydrojet tool using high velocity gelled water and fine mesh sand. This procedure was to provide a horizontal cut about 6.3 mm (1/4 in) wide through the casing, grout, and for some distance into the formation. High pressure water was then pumped into the wellbore and through the notch to initiate crack propagation (formation breakdown). Gelled water carrying proppant sand was then pumped into the formation according to a predetermined procedure. A "pre-pad" of fine sand was inserted first and followed by coarser sand according to the hydrofracturing schedule established for the fracture in question. The upper fracture was totally propped with

sand and the two lower adjacent fractures were propped with a partial monolayer.

1. Hydrofracture No. 1 - The first (middle) hydrofracture was created from Well C at a depth of 61.5 m (202 ft). Formation breakdown parameters were not recorded but were estimated to have been ≈ 600 psi wellhead pressure and 0.5 bbl/min flow rate. The hydrofracturing continued (the following day) at a pumpline pressure of ≈ 520 psi resulting in a bottom hole pressure of ≈ 600 psi. The planned hydrofracturing schedule is shown in Table IIIB-1. Difficulties with the sand-gel blender caused several delays during the hydrofracturing, but the total volume and flow-rate schedules were kept.

Diagnostic instrumentation consisting of wellhead pressure gages, pressure gages and flow rate meters in the injection pump lines, in-well hydrophones, and resistivity networks were utilized to determine the growth rate and shape of the hydrofracture. The observation wells were maintained full of water, causing the pressure in each well to rise rapidly when the crack front intersected the well. The wellhead pressure histories, together with the flow rate data, permitted "tracking" the growth of the hydrofracture until all observation wells had been intersected. The fracture fluid flow rate and pumpline pressure are shown as functions of time in Figures IIIB-1 and IIIB-2. A composite plot showing the time at which the hydrofracture intersected the outlying wells is shown in Figure IIIB-3.

Contours of the fracture front at selected times (Figure IIIB-4) show that the growth pattern was nearly circular with a slight preference for more rapid growth to the north. Correlation between fracture extent and accumulative flow indicates that, at the time of intersection with the outer wells, the average fracture width was ≈ 0.86 mm (0.034 inches).

TABLE IIIB-1

FLUID-PROPPANT SAND SCHEDULE FOR
THE PARTIAL MONOLAYER TYPE HYDROFRACTUERS

VOLUME GAL.	DESCRIPTION	--PROPPANT--		--ADDITIVES--	
		SIZE	CONC. #/GAL.	TYPE	CONC. #/M GAL.
1,200	Pre-Pad @ 0.5 BPM	--	--	MYF-1 GBW-3	25 0.125
4,200	Pre-Pad @ 20BPM	--	--	MYF-1 GBW-3 70-170 Sand	25 0.125 2000
6,000	Pad (MY-T-GEL ^R I Fluid) @ 20 BPM	--	--	WAC-9 GBW-3	25 0.5
1,000	MY-T-GEL @ 20 BPM	8-12	1.0	WAC-9 GBW-3	25 0.5
2,000	MY-T-GEL @ 20 BPM	8-12	2.0	WAC-9 GBW-3	25 0.75
1,000	MY-T-GEL @ 20 BPM	6-8	1.0	WAC-9 GBW-3	25 1.0
2,000	MY-T-GEL @ 20 BPM	6-8	2.0	WAC-9 GBW-3	25 1.0
<u>800</u>	Flush	--	--	--	--
18,000

FIGURE IIIB-1. FRAC FLUID FLOW RATE VS TIME, DURING CREATION OF MIDDLE (202 ft) HYDROFRACTURE.
 $T_0 = 640$ MINUTES

FIGURE IIIB-2. PUMP LINE PRESSURE VS TIME DURING CREATION OF MIDDLE (202 ft) HYDROFRACTURE.
 $T_0 = 640$ MINUTES

FIGURE IIIB-3. COMPOSITE PLOT OF WELLHEAD PRESSURE VS TIME DURING CREATION OF MIDDLE (202 ft) HYDROFRACTURE. $T_0 = 640$ MINUTES

FIGURE IIIB-4. CONTOURS DEPICTING HYDROFRACTURE SHAPE AND EXTENT AT VARIOUS TIMES DURING THE CREATION PROCEDURE.

Hydrophones were placed in three of the observation wells to determine whether the propagating crack front would generate a unique sound. The data showed that the arrival of the crack front could be detected; the results were found to agree with the wellhead pressure data. The resistivity experiment, which has been successfully used in the past to observe hydrofracture growth, was not successful in the test. The well casings were electrically interconnected at the surface by metal plumbing, thus masking the changes in formation resistivity caused by the movement of a conductive fluid through the fracture.

2. Hydrofracture No. 2 - The second (lower) horizontal hydraulic fracture was made through Wellbore B at a depth of 63 m (206.5 ft). Difficulty was experienced in achieving an adequate notch in this casing because the crookedness of the wellbore caused the hydrojet

tool to be forced against one side of the casing. Initial attempts at hydrofracturing were unsuccessful because of the poor notch and because the bottom of the wellbore soon became filled with sand to a level above the notch as a result of a limited amount of "rathole". A successful hydrofracture was achieved in a subsequent attempt by (1) using a centralizer to hold the hydrojet tool in the center of the well, thereby obtaining a uniform cutting of the casing, grout, and shale; (2) extending the cutting period; and (3) flushing all sand from the wellbore, including that held in suspension, prior to the hydrofracturing process.

Formation breakdown pressure at the 63 m, (206.5 ft) level (Figure IIIB-5) was ≈ 1400 psi compared to the estimated 600 psi breakdown

FIGURE IIIB-5. PUMP LINE PRESSURE VS TIME DURING FORMATION BREAKDOWN - LOWER (206.5 ft) HYDROFRACTURE. START TIME AT T = 1200 MINUTES

pressure for the 61.5 m (202 ft) level hydrofracture. Communication with outlying wells was established during the prolonged formation breakdown operation; this communication resulted in essentially identical pressure-time responses at all wells (Figure IIIB-6),

Continuation of the hydrofracturing operation followed the same procedure as for the first hydrofracture (Table IIIB-1), except that the pumping pressure during the second fracture extension operation was greater (Figure IIIB-7).

Pressures in the observation wells were recorded during the hydrofracturing; the presence of the previously made fracture and the establishment of communication during formation breakdown masked the growth rate. Following creation of the hydrofracture, the formation was shut in overnight; leakage of fracture fluid from the immediate areas was shown to be negligible.

3. Hydrofracture No. 3 - The third (top) hydraulic fracture was formed and sand propped through Wellbore A at a level of 60 m (197.5 ft) according to the schedule shown in Table IIIB-2. A centralizer was again used while notching the well casing. Difficulty was again experienced in obtaining formation breakdown. A pressure considered to be adequate for breakdown was applied several times with no results. A slow crack growth was finally achieved by cycling the pressure from 400 to 1900 psi until a flow rate of 0.5 bbls/min could be achieved. The flow rate indicated in Table IIIB-2 was maintained until 1200 gallons of fluid had been displaced. Pressure cycling to 1800 psi was then required to attain the desired flow rate of 20 bbls/min. The scheduled fracturing procedure was then resumed and the hydrofracturing continued. The fracture fluid flow rate is shown in Figure IIIB-8. Pumpline pressure versus time is shown in Figure IIIB-9.

FIGURE IIIB-6. COMPOSITE PLOT OF WELLHEAD PRESSURES VS TIME DURING FORMATION BREAKDOWN-LOWER (206.5 FT) HYDROFRACTURE START TIME AT T = 1200 MINUTES.

FIGURE IIIB-7. PUMPLINE PRESSURE VS TIME DURING CREATION OF LOWER (206.5 FT) HYDROFRACTURE.
START TIME AT T = 500 MINUTES

Pressure sensors were again used at outlying wellheads in an attempt to monitor the areal extent of the fracture versus time. The presence of the two previous fractures with the resulting communication between fractures through the wellbores and the slow early crack growth rate again masked the crack growth measurements. Hydrophones were placed in Wells 1 and 9, and the travel of the crack front was monitored acoustically. The results of these hydrophone observations again demonstrated the viability of this measurement technique as a means of observing fracture arrival at outlying wells. Following completion of the hydrofracturing, wellhead pressures were again monitored at outlying wells; fracture fluid loss was again shown to be negligible. An experiment was conducted during the creation of the third hydrofracture to determine the effectiveness of surface

TABLE IIIB-2
FLUID-PROPPANT SCHEDULE FOR
THE SAND-PROPPED HYDROFRACTURE

VOLUME GAL.	DESCRIPTION	--PROPPANT--		--ADDITIVES--	
		SIZE	CONC. #/GAL	TYPE	CONC. #/M GAL
1,200	Pre-Pad @ 0.5 BPM	--	--	MYF-1 GBW-3	25 0.125
4,200	Pre-Pad @ 20 BPM	--	--	MYF-1 GBW-3 70-170 Sand	25 0.125 2000
5,200	Pad (MY-T-GEL ^R) @ 20 BPM	--	--	WAC-9 GBW-3	25 0.5
1,100	MY-T-GEL @ 20 BPM	10-20	1.0	WAC-9 GBW-3	25 0.5
1,100	MY-T-GEL @ 20 BPM	10-20	2.0	WAC-9 GBW-3	25 0.75
1,200	MY-T-GEL @ 20 BPM	10-20	3.0	WAC-9 GBW-3	25 0.75
1,200	MY-T-GEL @ 20 BPM	8-12	2.0	WAC-9 GBW-3	25 1.0
1,200	MY-T-GEL @ 20 BPM	8-12	3.0	WAC-9 GBW-3	25 1.0
1,000	MY-T-GEL @ 20 BPM	8-12	4.0	WAC-9 GBW-3	25 1.0
<u>500</u>	Flush	--	--	--	--
18,000

FIGURE IIIB-8. FRAC FLUID FLOW RATE VS TIME DURING
CREATION OF UPPER (197.5 FT) HYDROFRACTURE.
START TIME AT T = 740 MINUTES

FIGURE IIIB-9. PUMP LINE PRESSURE VS TIME DURING
CREATION OF UPPER (197.5 FT) HYDROFRACTURE.
START TIME AT T = 740 MINUTES

tiltmeters in tracking the crack propagation. An array of tiltmeters was placed around the site to measure surface tilt during the fracturing operation. The tilt measurements were used to deduce surface lift. The shape of the crack growth contours were deduced by the directional vectors of the tilt measurements. The crack propagation indicated by the tilt measurements was nearly circular with emphasis toward the north, similar to that shown in Figure IIIB-4 for the first hydrofracture.¹⁸

C. Hydraulic Fracture Characterization

Air acceptance and flow tests and tracer/flow tests were conducted following the creation of each hydrofracture to determine the change in airflow characteristics. Air was found to flow freely through the hydraulic fractures between all wells except Wells 5, 6, and 7, where nearly all the flow was through the pre-existing "natural" fracture at a depth of 65.5 m (215 ft). No evidence was noted of increased permeability between the horizontal fractures which would indicate the presence of branched and/or vertical fractures.

Airflow logging of the observation wells was performed following the first [61.5 m (202 ft) level] hydrofracture using an impeller type tool with a photo-optic sensor to measure the level at which air flowed into each wellbore from the fractures. Crack levels were poorly determined by these measurements because of leakage of air around the wiper system and slippage in the cable counter each time the tool was moved. Water flow logging of the wells was performed after creation of the second hydrofracture. More accurate determination of the fracture levels was achieved by measuring and mechanically marking the wireline and using a rubber wiper system. Crack locations were determined from the change in the accumulative flow rate. The presence of two hydraulic fractures plus the pre-existent fracture at a lower level led to the need for very large total flow rates in order to obtain a measureable differential flow at a given crack level. The depths of the first two hydraulic fractures were located with reasonable accuracy in all observation wells except Wells 5, 6, and 7, where again virtually all the flow was observed to be through the preexistent lower level fracture.

To overcome difficulties encountered in the early flow logging operations, the wiper system was again modified so that the flow

coming into the well between the two wipers could be measured directly, while the flow from lower cracks bypassed the sensor (Figure IIIC-1).

FIGURE IIIC-1. FLOW LOGGING TOOL SCHEMATIC ILLUSTRATING ACCUMULATIVE AND DIFFERENTIAL FLOW MEASUREMENT.

The flow from a particular entry point was thus isolated. This system was useful for identifying entry points with low flow. Absence of entry flow between the horizontal fracture locations indicated the absence of vertical fractures. Water flow logging using this differential flow wiper system was repeated following the creation of the third hydrofracture. The intersection of the three hydrofractures and the two pre-existent fractures were found in nearly all the wells and no evidence of vertical fractures were noted.

A television camera lowered into the wellbores was also used to locate the hydrofractures and to resolve ambiguous flow logging results. Forcing air through the formation from the hydrofracturing wells increased the visibility of the hydrofractures; the hydrofractures could be easily located with the TV by the bubbling of air and liquid from them into the well.

Impression packers were used in three wells to obtain a more accurate determination of the crack levels and widths. Multiple and low angle cracks noted during TV logging were confirmed by the impression packers.

An auxiliary experiment was conducted to determine whether the depth of the intersection of the lower two hydrofractures with Well A could be accurately located through the casing. A background gamma log was made of Well A prior to hydrofracturing. Near the end of the propping operations of the first two hydrofractures, a small amount of 8-12 mesh sand coated with Scandium 41 was inserted into the fractures. Post-fracture gamma logs clearly showed the presence of the radioactive sand outside the well casing (Figure IIIC-2). The fracture depths were determined within ± 19 mm (0.75 in).

The results of the several logging operations were examined collectively to establish the hydrofracture profiles through the test area. The three hydraulic fractures were found to be reasonably horizontal. No significant branching was noted. The hydrofractures did not intersect each other or the pre-existing horizontal cracks in the vicinity of the well pattern. A section view of the hydrofractures the east-west direction is shown in Figure IIIC-3.

FIGURE IIIC-2. FRACTURE LOCATION BY GAMMA LOGGING. HORIZONTAL FRACTURES CREATED FROM WELLS B AND C DETECTED THROUGH CASING AND COLLAR IN WELL A.

FIGURE IIIC-3. HYDRAULIC FRACTURE ELEVATIONS IN EAST-WEST DIRECTION DERIVED FROM WELLBORE LOGGING DATA.

IV. EXPLOSIVE FRACTURING

A. Preparation For Explosive Fracturing

In preparation for explosive fracturing, various gages and measurement or detection devices were put in place, data acquisition equipment was installed, the hardware and electronic gear associated with the explosive emplacement and firing systems were installed and/or made ready, and the explosive insertion rates that should provide crack widening through formation lift were determined. Brief

descriptions of specific activities and/or hardware are provided in the following.

1. Explosive Emplacement/Insertion Procedure - A schematic illustration of the downhole gear used for the explosive emplacement insertion and detonation operatives is shown in Figure IVA-1.

FIGURE IVA-1. SKTECH DEPICTING EXPLOSIVE INSERTION AND DETONATION TECHNIQUES. FIRST DETONATION ATTEMPT.

A Baker Model K retainer with a one-way valve was first set in each emplacement well about 0.3 m (1 ft) above the casing notch cut during hydrofracture creation. The one-way valve permits flow from the well casing into the formation, but no reverse flow. A "bottom wiper" with a burst diaphragm was placed in the well casing, near the top, after which a specially designed wellhead adapter housing a "top wiper" was installed on the top of the casing. Slurry would then be emplaced between the top and bottom wipers; during emplacement the bottom wiper would be moved downward until it rested on the retainer. The final step in the insertion operation involves forcing the top wiper downward with a pressurized head of water; the downward motion of the wiper first causes the burst diaphragm to break, thereby permitting the slurry explosive to flow through the one-way valve and into the hydrofracture.

2. Arming and Firing (A & F) Procedure - The primary detonation scheme involved two detonator/booster systems in Well A (located five feet away from emplacement/insertion wells B and C), one at the level of each explosive-filled fracture. Four-inch wide notches were cut in the casing of Well A at the levels of the two lower hydrofractures as determined by the gamma logs taken following hydrofracture creation; communication between each emplacement well and Well A was confirmed. It was planned that during the insertion process, slurry explosive would be extruded through the two lower hydrofractures into Well A and would then surround the detonator/booster systems. A special packer assembly was designed that would hold the detonator/booster charges at each hydrofracture level and at the same time provide a "pocket" for holding the slurry explosive that was extruded into the detonation well. The packers were designed to hold a pressure differential of 500 psi between the two hydrofractures. The assembly was installed in Well A and the well stemmed with sand (Figure IVA-1).

Concern that sufficient slurry explosive might not be extruded into the cavities surrounding the detonator/booster assemblies to sustain detonation led to the incorporation of an active backup detonation system in the explosive emplacement wells (Wells B and C). The technique included the fastening of a detonator/booster unit to the top of the wiper that would be used to push the explosive down the emplacement well. A detonator cable was pre-twisted and wound on a double canister spool which was also fastened to the wiper; this system was designed and fabricated to allow the cable to trail off the spool in an untwisted fashion as the wiper moved down the well during the explosive insertion. The detonation systems were designed so that if both the primary and backup systems functioned properly, the detonation fronts from the two units for each explosive layer would arrive at the juncture between the hydrofracture and the insertion well simultaneously. If detonation were achieved in only one of the hydrofractures from the primary system, addition of the backup system should provide detonation in the other hydrofracture; the nonsimultaneity of the detonation waves in the two explosive-filled cracks would range from no time differential in the direction from Well A to the emplacement well (B or C) feeding the explosive layer not detonated by the primary system to ≈ 0.5 ms in the opposite direction. If detonation were not achieved in either hydrofracture from Well A, the backup system should provide detonation in both hydrofractures; the timing between the two detonation fronts would vary from ≈ 0.3 ms in the direction through the emplacement wells, to no time differential at right angles to that direction (through the instrument wells containing the stress gages).

The booster charges were 2.32 lbs. of Composition B-3 machined in three inch diameter by six inch long cylinders and housed in a canister which allowed two SEI/31 exploding-bridgewire (EBW) detonators

to be placed in contact with the booster. The EBW detonators consisted of a bridgewire resting in a 50% density PETN explosive. Detonation was to be accomplished by discharging a capacitor to explode the bridge-wire with sufficient shock to detonate the PETN explosive, which in turn would detonate the composition B-3 booster.

3. Explosive Insertion Modeling - As previously noted, modification of the experiment plan to emplace only a partial monolayer of 8-12 mesh and 6-8 mesh sand in the middle and lowest hydraulic fractures was in part predicated on the expectation that when the slurry explosive was inserted under pressure, the hydrofractures would be reopened and the overburden supported by the explosive until detonation was accomplished.

A finite element fluid flow model was developed and implemented¹⁹ to predict the amount of crack deformation that should occur during the explosive insertion. The model consisted of two parts: (1) the fluid flow from the wellbore into the fracture at the wellbore-hydrofracture juncture and (2) the flow of explosive through the crack. The crack was modeled with an initial width of 2.54 mm (0.10 in) and filled with water at overburden pressure to create a back pressure acting against the explosive being extruded through the fracture. Assuming an explosive viscosity of 25 centipoise, deformations of 3.0 mm (0.12 in) were predicted for an insertion rate of 0.5 bbl/min. This was expected to require an insertion pressure of ~ 4 MPa (600 psi) at the wellhead and would cause the explosive to be extruded a radial distance of ~ 15 m (50 ft). A plot of the predicted crack deformation for the 0.5 bbl/min flow rate is given in Figure IVA-2.

The back pressure assumed in the modeling was an approximation of conditions expected in the experiment. The operational plan called for the reduction of the water level in the formation to below the

FIGURE IVA-2. PREDICTED CRACK OPENING DURING SLURRY EXPLOSIVE INSERTION AT A FLOW RATE OF 0.5 BBL/MIN.

uppermost (sand-propped) hydrofracture to enhance the impedance discontinuity at that hydrofracture; a pronounced impedance mismatch is needed for development of significant tensile stresses. The back pressure required for overburden lift was expected to be provided by an explosive/sand interaction; i.e., the explosive slurry moving through the hydrofracture was expected to sweep sand at its front, causing a buildup of sand and slurry which would retard the flow.

4. Instrumentation - Instrument strings which contained lithium niobate and ytterbium stress gages, lead-zirconate-titanate time-of-arrival (TOA) gages, and triaxial accelerometers were installed in instrument wells AA, BB, CC, DD, and EE (Figure IIC-2); these gages were oriented toward the detonation point (Well A) and grouted in place with rockmatching grout. Time-of-arrival gages were installed in observation wells 1-9 at the depths of the two hydrofractures that would be filled with explosive; these wells were then sandstemmed to the surface. Earth motion sensors were placed on the earth surface

at ground zero and at a radial distance of ≈ 300 m (1000 ft) from ground zero.

B. First Explosive Fracturing Attempts

Approximately 4000 kg (9000 lbs) of TAL-1005-E slurry explosive was emplaced in Wells B and C according to plan. After instrumentation checkout, the slurry explosive was inserted simultaneously into the lower two hydrofractures. The insertion rates were essentially as predicted, with the insertion time for 21 bbls being about 41 minutes. The wellhead pressures were essentially constant throughout the process at 3.9 MPa (570 psi) and 4.3 MPa (620 psi) in Wells B and C, respectively. A standard firing procedure with a 30 second countdown was initiated immediately upon the completion of the explosive insertion. Detonation was not accomplished.

Initial diagnostic attempts revealed that all bridgewires in the detonators had burst, so further efforts to achieve detonation with the original firing system would be futile. It was considered, however, that another attempt to detonate the explosive already in place must occur without delay. Two basic reasons exist for this attempt: (1) to try to detonate the explosive in the hydrofractures and thus bring the experiment to fruition and (2) to detonate the live boosters and explosive remaining in the wellbores as an initial cleanup effort if explosive detonation was not achieved in the hydrofractures. For this attempt, additional detonator/booster units were lowered into the emplacement wells, covered with about 2.5m (8 ft) of slurry explosive, and fired. Only the wellbore detonation was achieved; little or no detonation of the slurry explosive in the hydrofractures was accomplished.

C. Detonation Failure Diagnosis

Post shot diagnostics¹⁹ of the first detonation attempt resulted in three important observations:

(1) The failure to achieve detonation was due to the use of an EBW detonator that would not function properly in the use environment; i.e., after submersion in water under pressure. Introduction of water into the 50% density PETN explosive surrounding the bridge-wires raised the effective density of the PETN and, in turn, the energy required to detonate the PETN beyond that supplied by the exploding bridgewire.

(2) Formation tilt, which would provide a measure of formation lift and evidence of the fractures being widened during the explosive insertion, did not occur. This indicated that, even if the detonators had functioned properly, detonation of the explosive in the hydrofractures still would likely not have been achieved. It was suspected that lift did not occur because the sand-slurry mixture at the front of the moving explosive layer did not provide the required back pressure. To evaluate this conjecture, a large amount of water was pumped into the formation the day after the detonation attempts and tilt measurements were again taken, this time showing that formation lift could readily be detected with pressures considerably less than those used during explosive insertion.

(3) An assessment of the condition of the formation and a review of the records from the stress and TOA gages indicated that (a) no detonation occurred during the first attempt and (b) formation damage from the second attempt occurred out to about 4 m (13 ft) from emplacement/detonation wells B and C (the degree of damage that would be expected by the detonation of 2.5 m (8 ft) columns of explosive in the wellbores).

An assessment of these three observations led to the conclusion that, while the malfunctioning of the EBW detonator was the primary failure mode, detonation of the explosive in the hydrofractures necessary for a successful experiment would likely not have occurred

anyway because the cracks, and hence the explosive layer, were too thin. Thus, a successful recovery plan for the experiment would require both the use of a reliable detonator and an explosive insertion procedure that would ensure adequate reopening of the explosive-filled hydrofractures.

Many of the gages that had been installed and grouted in the instrumentation wells were found to be undamaged by the wellbore explosion and would be satisfactory for use in a subsequent explosive fracturing event. The emplacement/detonation wells had been damaged to the extent that they were unsatisfactory for reuse. Detonation Well A had also been damaged by the wellbore explosion making it impossible to remove the packer containing the primary detonator/booster system from the well. A subsequent explosive fracturing attempt would thus require new wells in an undamaged portion of the formation.

D. Site 12 Experiment Recovery Plan

1. Well Layout - The results of the post-shot diagnostics provided guidance for establishing a recovery plan for a subsequent explosive fracturing event that was expected to satisfy most of the major objectives of the experiment. This included the drilling of two new explosive emplacement/insertion wells (designated Wells X and Y) between Well CC and Well 3 (Figure IVD-1), and conversion of Well 3 from an observation well to an instrumentation well.

No separate detonation well to replace Well A was included in the recovery plan. The new layout was such that the positioning and direction of instrument wells with respect to the explosive emplacement/insertion wells would be nearly identical to the original layout (e.g., Well 3 replaced Well EE, Wells CC and AA interchanged roles, and Well BB is unchanged; the stress gages remained oriented nominally toward the detonation point). The symmetry of the observation wells

was not retained; this led to drilling of evaluation wells after the successful explosive fracturing event.

FIGURE IVD-1. SITE 12 WELL LAYOUT SHOWING WELLS X, Y, AND Z ADDED TO FACILITATE EXECUTION OF THE SECOND DETONATION ATTEMPT

The recovery plan included the addition of a special instrumentation well (Well Z) west of the midpoint between Wells X and Y (Figure IVD-1). This well was added for placement of instruments at each of the two lower hydrofracture levels to monitor events associated with the insertion and detonation of the slurry explosive in the hydrofrac-

ures; these included a pressure gage to monitor in-crack pressure, an explosive-arrival detector, and a newly developed crack-opening gage.²⁰

Wells X and Y were first drilled to a depth one foot above the lower and middle hydrofractures, respectively, then cased, and finally drilled to one foot below the respective hydrofracture; the uncased portion of each well intersected only one hydrofracture. Water flow tests were conducted to demonstrate that a flow path existed from these wells into the hydrofractures and that each well intersected only one hydrofracture. Airflow/tracer tests were then conducted to re-define the pre-fracturing formation permeability.

2. Instrumentation - Instrumentation for the recovery plan (Figure IVD-2) was essentially the same as for the original attempt except for the addition of the instruments in Well Z and Well 3.

FIGURE IVD-2. CROSS-SECTIONAL VIEW OF MODIFIED WELL PATTERN FOR SECOND EXPLOSIVE FRACTURING ATTEMPT. GAGE LOCATIONS IN THE INSTRUMENT WELLS ARE SHOWN.

The gages for monitoring the explosive insertion process included a total of eight tiltmeters placed at 90° intervals at radial distances of 68 m (225 ft) and 98 m (325 ft) from the midpoint between Wells X and Y to provide surface tilt and evidence of crack opening, pressure and resistivity gages at the depths of the two lower hydrofractures in Well Z to detect explosive arrival and the in-crack formation pressure, and newly developed crack opening gages which utilize linear variable differential transformers (LVDT's) to measure the amount each hydrofracture was reopened.²⁰ (The instruments in Well Z were installed as part of a specially constructed nonmetallic packer system which was secured with epoxy to facilitate removal after the explosive event so this well could be used for formation evaluation.) Wellhead pressure gages at Wells X and Y and flow meters in the pump lines were installed to provide explosive insertion pressures and rates. Stress gages and accelerometers in the instrument wells and TOA gages in the observation wells would again be used to provide records of the transient events associated with the explosion detonation.

A low-frequency recording system consisting of a PDP-11 computer, a Visicorder, and strip charts was prepared to record data during the explosive insertion phase. A high-frequency system utilizing high speed tape drives was prepared to record data pertinent to the transient events during the several millisecond period following the explosive detonation.

3. Explosive Handling Systems - The explosive emplacement/insertion method (see Figure IVD-3) for the recovery plan was similar to that used in the first detonation attempt. The only significant difference was that a "middle wiper" was used in the recovery detonation attempt. This wiper contained a backup detonation system which would be activated when the top wiper bottomed out, i.e., when it forced the middle wiper against the bottom wiper.

FIGURE IVD-3. SKETCH DEPICTING EXPLOSIVE INSERTION AND DETONATION TECHNIQUES - SECOND (SUCCESSFUL) DETONATION ATTEMPT

4. Detonation Systems - The primary detonation system for the initial fracturing attempt (see Section IVA-2) was designed to provide simultaneous detonation of the explosive in both hydrofractures from the center of the experiment site, i.e., at Well A. Questions about whether or not the slurry explosive from the emplacement wells would reach and surround the detonator/booster systems in the detonation well (Well A) to make this concept viable had led to the incorporation of the active backup systems atop the wipers in the emplacement wells. Concern about use of a detonation system in a well remote from the emplacement

wells, together with the failure to achieve detonation on the first attempt, led to an extensive effort to establish an arming and firing system for the recovery procedure which would be as positive and fail-safe as possible, while retaining the overall objectives of the experiment--(1) explosive fracturing via simultaneous detonation of slurry explosive in the two hydrofractures so that reinforced stress pulses would be induced and (2) timing of the firing procedure so that the numerous diagnostic measurements associated with the transient events would be recorded.

As previously noted, the failure mode of the arming and firing (A&F) system had been isolated to the use of a detonator that would not function after submersion in a pressurized water environment. Equally important to the recovery plan was the observation that the remainder of the A & F system functioned as predicted in the initial detonation attempt. Thus, a reliable A & F system was obtained by the selection of an EBW detonator that had been shown to work in the environment. The "proof" test involved submersion of the detonators in water for 24 hours, followed by subjecting them to a hydrostatic pressure of 1000 psi for 60 minutes, and finally detonating them under the 1000 psi hydrostatic pressure.

As has been mentioned, placement of the primary detonation system in a center well was not included in the recovery plan. Instead, the primary detonation system for the recovery plan had the detonator/booster units mounted on the upper wiper of the emplacement/detonation wells, much like the secondary system of the initial firing attempt. To enhance reliability, two detonators were installed in each booster; a separate cable was used to activate each detonator. The cables were pre-twisted and wound as a pair onto a spool attached to the upper wiper in a manner similar to that employed previously. Because of the pre-twisting, the cable pair would uncoil off the end of the spool with no twists as the wiper moved down the well.

A secondary detonation system consisted of detonator/booster units located in "doghouses" welded to the outside of the emplacement well casings just below the levels of the retainers (Figure IVD-3). Two pipes were placed alongside the casing of each well for insertion of the detonators and booster explosive immediately prior to emplacement of explosive into the wells. The intent was that detonation of the booster explosive would initiate detonation of the explosive in the well. The merit of this system was the fixed position; if for any reason it were deemed necessary to activate the firing mechanism while the slurry explosive was only partially inserted in the formation, the detonation points would be precisely known and would be set distances above the corresponding fractures. This would ensure the desired simultaneity of detonation. Initially, this system was to serve as the primary detonation system and early tests suggested that this would be feasible. However, additional tests at the 54°F downhole temperature environment indicated there was about a 50% chance of initiating only a burn in the explosive in the emplacement wells. This detonation system was, therefore, relegated to a backup role with the timing adjusted so the detonation fronts from the detonator/booster systems atop the wipers would pass the doghouses prior to the activation of the secondary detonation system. This would imply that the secondary system would have utility only if needed, since successful detonation with the primary system would no doubt destroy the means to initiate the secondary system (by severing cables outside the casing) as well as the doghouse assembly itself.

A tertiary system was also added that consisted of a mechanically activated detonator/booster assembly contained in the middle wiper and designed to be operative at the completion of the explosive insertion sequence. At that time, a foot extending downward from the detonator would engage the bottom wiper; when (or if) a differential pressure of

320 psi was induced, a shear pin would be severed and detonation would be initiated. Since simultaneous detonations could be achieved with this system only in the unlikely event that the 320 psi pressure differential in each of the two wells was reached simultaneously, the tertiary system was regarded as a means to detonate the explosive if the other systems failed, and not as a means to maintain the major objectives of the experiment.

The timing sequence for the three detonation systems was set up so the primary systems would be triggered when the top wipers were within 11 ft of their lowest positions, but before they bottomed out on the retainers; the latter event would of course detonate the tertiary system. The secondary system was set to trigger 1 ms after the primary system. This delay would ensure that the detonation wave in the column had passed the doghouse before the secondary system was activated. The positions of the top wipers were to be deduced from the quantity of water pumped into the upper portion of the casing during insertion.

5. Explosive Emplacement/Insertion Procedures - To correct deficiencies in the initial detonation attempt, the explosive emplacement/insertion procedure was modified to increase the water back pressure and thus enhance the probability of significant reopening of the hydrofractures during explosive insertion. Water was pumped into the formation on the two days prior to and in the early morning on shot day through the emplacement wells while formation back pressure, crack opening, and formation tilt were monitored by the in-formation pressure and crack-opening gages in Well Z and by the surface tiltmeters. The planned explosive insertion rate was increased from the 0.5 bbl/min used in the first attempt to between 1.5 and 2 bbls/min, provided the higher rate could be achieved without exceeding the 1000 psi pressure to which the detonators had been tested. In filling the two lower hydrofractures with water, it was of course recognized

that the uppermost hydrofracture might also be filled with water; the impedance mismatch at that discontinuity in the oil shale could thus be reduced, which in turn could reduce the magnitude of the reflected tensile pulse and hence the probability for tensile fracture. This compromise was felt necessary to maximize the chance for detonation.

E. Explosive Emplacement and Detonation

The explosive fracturing event of the Site 12 recovery procedure was executed on December 1, 1977. Activities on that day prior to detonation included flexing of the formation in the morning by pumping water into the insertion wells, installation of the special wellhead adapters and wipers, assembly of pump lines and other miscellaneous gear, extensive checking of instrumentation and recording equipment, installation of the detonation systems, and of course, emplacement and insertion of the explosive slurry. Extremely adverse weather conditions hindered field operations. Pressure checks of the water lines and dry runs to establish coordinated explosive insertion rates could not be made because the water would have frozen in the lines before the actual explosive insertion. The shot did not occur until just after dark; no photographic coverage was obtained.

Approximately 15,000 lbs (7500 lbs in each well) of explosive was emplaced in Wells X and Y. Insertion of the explosive into the formation was followed by pumping water into the casing above the top wipers. The insertion rates varied somewhat but averaged about 1.75 bbls/min, the mean of the desired range. The cumulative water flow (equal to the cumulative amount of explosive inserted) versus time during the insertion period is shown in Figure IVE-1.

The wellhead pressures (Figure IVE-1) varied with the pumping rate variation, but ranged between 300 and 500 psi. The in-crack pressure, as measured in Well Z, is also shown in Figure IVE-1. The pressure in the lower hydrofracture increased to 200 psi after 1.6 minutes. The

FIGURE IVE-1. GRAPHS OF EXPLOSIVE INSERTION HISTORY (UPPER GRAPH) AND PRESSURE HISTORIES (LOWER TWO GRAPHS) AT THE EMPLACEMENT WELL WELLHEADS AND AT THE POSITIONS OF THE LOWER TWO HYDROFRACTURES IN WELL Z.

pressure in the middle hydrofracture, however, did not increase until halfway through the insertion process. This was probably due to loss of water from the formation during the day which required the insertion of a significant amount of slurry explosive before back pressure was obtained. Crack opening data were obtained with the LVDT gages in Well Z. These data indicated that the crack opening also occurred at this late time.

The detonation sequence was successfully initiated just before the explosive insertion would have been completed (in Well Y). Detonation was achieved in both wells by the primary detonation/booster system atop the wipers. Just after detonation, a very vigorous expulsion of explosive gases from both emplacement wells was noted; the expulsion continued for a comparatively long period of time, obviously longer than if only the wellbore explosive had detonated. The instrument string and sand stemming in Well 2 [7.6 m (25 ft) from Wells X and Y] were expelled to the level of the lower hydrofracture. A portion of the sand stemming was also expelled from Well 5 [18.5 (61 ft) away]. The wellhead flanges on Wells B and C [10.7 (35 ft) away] were blown free of the uppermost casing collar and the sand stemming was expelled. Visual examinations of the ground surface revealed extensive surface cracks and disruptions out to about 18.3 (60 ft) with some cracks extending beyond 30 m (100 ft). Residual lift of each well casing, shown in Figure IVE-2, varied from over 10 cm (4 in) near the emplacement/detonation wells to 7.5 cm (3 in) at Well 7, 26 m (85 ft) away. Cursory examinations of the measured stress amplitudes, pulse arrival times and accelerations provided indications that the areal extent of the explosive detonation was rather large. The implications of the preliminary observations was that much, if not all, of the explosive inserted into the formation had detonated.

FIGURE IVE-2. RESIDUAL LIFT OF WELL CASINGS RESULTING FROM EXPLOSIVE DETONATION.

V. FORMATION ASSESSMENT

Assessment of the type and amount of fracturing of the oil shale formation resulting from the explosive detonation was made by physical interrogation of the experiment site, as discussed in this section, and by reduction and interpretation of the stress, time-of-arrival and acceleration gage data (see Section VI). Specific goals were to ascertain both the vertical and areal extent of fracturing as well as the degree of rubblization in the zone of interest.

Physical interrogation methods consisted of coring, visual logging via downhole TV, caliper logging, flow logging and air acceptance, and ^{85}Kr tracer tests. Wells interrogated included the observation wells, the special instrumentation well (Well Z), and additional wells drilled after the detonation, some especially for fracture assessment and some primarily for the planned retort. The locations of all wells interrogated are given in Figure V-1.

FIGURE V-1. LOCATION OF WELLS INTERROGATED DURING POST-SHOT FORMATION ASSESSMENT.

A. Fracture Density Evaluation

Because of the decision to center the recovery detonation plan near the west side of the original well pattern, it was necessary to drill additional wells for fracture assessment in a westerly direction from the detonation initiation locale. These wells (E2, E4, E5, and E6) were positioned so that they could be used for determination of the variation in fracture density (if any) as a function of location and for possible use in a follow-on retort.

Plans for a follow-on retorting experiment were formulated during the initial formation assessment. The well layout for the retorting, shown in Figure V-1, included two center production wells and four injection wells. The production wells (Wells V and W) were located as closely as possible to the emplacement/detonation wells. The injection wells (Wells 2, 4, E2 and E4) were spaced at 90° intervals along the circumference of a 7.62 m (25 ft) circle centered midway between the production wells. Sixteen instrument wells were placed at strategic locations, as shown. Four additional instrument wells were later added in the region between Observation Wells 5 and 6 for a preliminary retorting experiment. The formation assessment was expanded to provide additional information about fracture densities in the vicinity of the proposed retort sites.

Evaluation Well E6 was cored from the ground surface to a depth of 73 m (240 ft) to determine (1) if explosive-induced fracturing that would be significant during a retorting operation had occurred in the shale above the Tipton Member, (2) the fracture density versus depth in the zone of interest, and (3) the presence of significant aquifers. The core would also be used for additional lithology studies by LETC. Subsequently, Well E6 was reamed and cased to a depth of 55 m (180 ft), then drilled to a depth of 73 m (240 ft) for use as a pump well and for hydrology studies. Evaluation Wells E2 and E4 were drilled to the top of the Tipton zone [55 m (180 ft)], then cored to the 70 m (230 ft) level.

The cores taken from Wells E2, E4, and E6 provided initial information regarding fracture patterns in the western region of the site. These cores were compared with one another and with the cores taken prior to the hydraulic/explosive fracturing sequence. Comparative results are shown in Figures VA-1 and VA-2. The major difference between pre- and post-experiment cores was an increase in the number of cracks throughout the entire length examined. No rubblized zone of any significance was found; further, there was no increase in the density of fractures seen in the region between the two explosive-filled fractures or between the explosive-filled and sand-propped fractures. Diagonal cracks were apparent between the 61 m (200 ft) and 65 m (214 ft) levels. The majority of the cracks were "tight"; i.e., no evidence of movement or dislocation could be noted. The core from Well E6, 17 m (56 ft) from the center of the explosive initiation, contained about the same number of cracks (77) as core from Well E4, 7.6 m (25 ft) away (82); the core from Well E6 contained more cracks than the core from Well E2 (49), which also was 7.6 m (25 ft) away. A gap of about 0.24 m (0.8 ft) was found at the 61.6 m (202 ft) level in the core in Well E4, indicating a wide crack in the formation. A similar gap of about 0.2 m (0.6 ft) was found at the 66 m (217 ft) level in the core of Well E2, also indicating a wide crack in the formation, but in this case at a low level. (The presence of these gaps was confirmed by caliper logging and by visual observation via downhole TV.)

Wells V and W were drilled 1 m (3 ft) west and east of the center of the emplacement/detonation wells (X and Y) and cased to 55 m (180 ft) depth, then cored (and subsequently drilled) to 73 m (240 ft) depth to determine if fracture densities in the close-in region had been affected by the explosive detonations in Wells X and Y as well as by the detonations in the hydrofractures. The cores for Wells V and W had greater fracture densities between the 55 m (180 ft) and 63 m (207

FIGURE VA-1. FRACTURE DENSITY VS DEPTH IN DETONATION WELL A AND OBSERVATION WELLS 1, 3, 5 AND 7 PRIOR TO HYDRAULIC/EXPLOSIVE FRACTURING DENOTES A SEGMENT OF RUBBLED CORE

ft) depths than did cores at this depth from other wells. This indicated that the fractures in Wells V and W were primarily from the wellbore detonations. Fracture densities between the 63 m (207 ft) and 70 m (230 ft) were about the same for cores from Wells V and W as cores from Wells E2, E4, and E6. The fracture density versus depth for cores from Wells V and W are also shown in Figure VA-2.

Seven cores were extracted from selected retort instrument wells. The fracture densities of these cores (Figure VA-3) were also random through the 55 m (180 ft) to 70 m (230 ft) region, with the exception

FIGURE VA-2. FRACTURE DENSITY V.S. DEPTH IN POST-SHOT EVALUATION WELLS. DENOTES SEGMENT OF RUBBLED CORE.

of core T0 which had a larger number of fractures in the 55 m (180 ft) to 58 m (190 ft) region. The number of fractures in core TU, which was outside the area thought to have been reached by the slurry explosive, was as great as in cores taken from within the area reached by the explosive (e.g., those from Wells TA, and TI).

In general, the fractures in the cores were random in nature with fracture densities at the 70 m (230 ft) level as great as in the regions between the explosive-loaded fractures and between the explosive-loaded and sand-propped fractures. No correlation could be established between fracture density and core location. As will

FIGURE VA-3. FRACTURE DENSITY VS. DEPTH IN RETORT INSTRUMENT WELLS
 HATCHED DENOTES SEGMENT OF RUBBLED CORE.

be discussed later, few of the cracks noted in the cores could be seen with a downhole TV. This suggests that the cracks may have been generated, but there was no accompanying dislocation. This would, in turn, suggest that stresses sufficient to break the interlaminar bonds were generated by the explosive detonation, but no lateral or rotational dislocations occurred. It is also possible that some of the fractures were created by the coring operation.

B. Wellbore Logging

Several types of logs (TV, caliper, airflow) were obtained from the wells at the experiment site. Composite examples of these logs

are shown in Figures VB-1 through VB-5. A complete set of logs is included in Appendix A.

Video logging of all open wells was conducted with a forward-looking downhole TV camera. Observation Wells 1-9 (except Well 3) were also logged with a special camera with a side-viewing capability which provided a close view of and into fractures, resulting in more quantitative information regarding fracture width and extent.

As previously mentioned, very few of the cracks noted in the cores could be seen in the cored wells with the downhole TV. Additional logging of these same wells was performed after the wells were reamed in preparation for flow logging. Like results were obtained. The type and density of horizontal fractures versus depth seen in the observation wells were, in general, much the same as the cored wells. No correlation was found between fracture density and radial distance from the detonation wells; e.g., Wells 2 and 4 at a radius of 7.6 m (25 ft) revealed no more cracks via TV than Wells 6 and 8 at a distance of 17 m (56 ft) or Wells 1 and 5 at 186 m (61 ft). In Well 4, the formation between the two explosive-filled fractures had been shifted laterally, but no significant increase in fracturing was noted. The 61.5 m (202 ft) hydraulic/explosive fracture was found to be about 10 cm (4 in) wide. Apparently the crack was held open by fragments not visible from the wellbore with the TV camera; alternatively, fragments from near the intersection of the hydrofracture and the well could have been ejected into the wellbore, giving the appearance of a wide crack.

In general, the TV logging revealed that the explosive detonation had caused damage in or near the explosively loaded hydrofractures, but provided little evidence of additional fracturing elsewhere. Evidence of damage was detected near the upper explosive hydrofracture [at

about 61.5 m (202 ft) depth] out past the 17 m (56 ft) radius wells. Near the lower explosive hydrofracture [at about 63 m (207 ft) depth] evidence of damage was observed southeast of a line running approximately southwest to northeast through the midpoint of the emplacement/detonation (X and Y) wells. Northwest of this line, no evidence of damage was detected near the hydrofracture. Rather, damage was observed near the preexistent horizontal fracture at about 65.5 m (215 ft). This provided evidence that the slurry explosive inserted into the lower hydrofracture had traveled through some (unknown) path to the pre-existent fracture, was extruded through this fracture, and detonated.

Extensive air flow logging was conducted in the evaluation and observation wells in an effort to ascertain airflow patterns that could be expected during a retort operation, as well as determine the degree of permeability of the formation. Two injection flow logs (with inlet airflow down the well being logged and outlet airflow up a selected companion well) and two production flow logs (with inlet airflow down a selected companion well and outlet airflow up the well being logged) were obtained for each well, using Well 9 as the corresponding inlet or outlet well. The procedure was repeated using Well Z as the corresponding inlet or outlet well. (Wells 9 and Z were used since they were near the proposed location of the production process wells for two alternate retort layouts.) The logs were taken using the single wiper arrangement on the flow logging tool; hence accumulative (or total) flow versus depth was obtained. A special strip chart recording device was used so that small increments of flow could be noted. The tool was calibrated so the recorded flow could be compared to the inlet airflow. Following this logging procedure, the wiper arrangement on the flow logging tool was set to obtain differential (or entry point) flow, and the flow logging was repeated to determine if small increments of flow could be detected in one-foot increments between the large entry flow locations.

The results of the flow logging indicated that the airflow through the formation was not diffused through a fractured zone, but rather, all the flow was through fractures where explosive detonations had occurred. In Wells 2, 4, 7, 8, 9, E4, and E6, the entire flow was through the middle [61.5 m (202 ft)] hydrofracture. In Well 2, 20 percent of the airflow entered through the middle hydrofracture; the remaining 80 percent entered through the lower [63 m (207 ft)] hydrofracture. In Well 6, 20 percent of the airflow entered through the middle hydrofracture; the remaining 80 percent entered through a pre-existing fracture at the 65 m (215 ft) level. The total airflow into Well 5 was through the lower hydrofracture. In Wells 1 and E2, the total flow was through the pre-existing crack at the 65 m (215 ft) level in Well 1 and at the 66.1 m (217 ft) level in Well E2.

The flow logging results were found to be repeatable, with varying amounts of total airflow, for both injection and production logging, and independent of companion well. No airflow could be detected at levels between large fractures with either accumulative flow or differential (entry point) flow methods. While attempting to detect alternate flow paths, the airflow was increased to the maximum capability of the compressor. This flow was achieved at essentially zero gage pressure, as compared to a pressure of ~30 psi during pre-detonation tests. The accumulated data indicates that the flow properties of the formation as a whole had been enhanced significantly by the explosive detonation but the flow was entirely through the large fissures.

Airflow logs were also obtained from Wells V, W, E5, and the 20 retort instrument wells (TA, TB---TU). Only injection flow logs were obtained. The retort instrument wells were not cased; thus the formation was open to the surface through these wells, making production

flow logging impossible. The results reinforced the previous findings, namely, that airflow was entirely through the hydraulic or pre-existing fractures which had experienced detonation.

Caliper logs were obtained in the 35 open wells. The enhanced horizontal fractures were easily observed on these logs; some additional fractures or wellbore irregularities were also noted. Evidence of formation effects other than fracture enhancement near explosively loaded hydrofractures were noted only in Wells V, W, and Z which were "close in" to the detonation of the explosive columns in Wells X and Y. Composite plots (shown in Figures VB-1 through VB-5 and in Appendix A) depicting synthesized results of the interrogation of each well were made for use in overall formation assessment. For comparison, the results of the pre-shot flow and TV logging are included on the plots of the observation wells. Similarly, fracture locations determined from the core taken from Well A before the explosive shot are shown on the composite plot for each well cored after the shot. For all wells, zones where several horizontal cracks were noted with the TV are depicted by hatched regions; vertical cracks are shown as vertical lines.

Analyses of the composite plots permitted an assessment to be made of the general conditions of the underground formation after the shot and of the nature of the explosive event. For example, the elevation views in the southwest-northeast and northwest-southeast directions passing through the midpoint of the emplacement/detonation wells (X and Y), shown in Figures VB-6 and VB-7, provide synthesized results from the composite logs of the wells along those lines. Parallel lines are drawn between the wells at the depths where airflow was found to enter fractures from the wells and/or where significant enhanced fracturing was indicated by TV and caliper logging. Assuming that the airflow entry points and/or fractures of significant width

SITE 12 - WELL 2

FIGURE VB-1. COMPOSITE POST-SHOT LOG OF WELL 2.

SITE 12 - WELL 4

FIGURE VB-2. COMPOSITE POST-SHOT LOG OF WELL 4.

SITE 12-WELL E-2

POST FRAC LOG

FIGURE VB-3. COMPOSITE POST-SHOT LOG OF WELL E-2.

SITE 12 - WELL E-4

FIGURE VB-4. COMPOSITE POST-SHOT LOG OF WELL E-4.

FIGURE VB-5. COMPOSITE LOG OF TYPICAL INSTRUMENT WELL, WELL TG.

are coincident with the location where the explosive detonation enhanced the horizontal fracture, the following conclusions can be derived. The explosive inserted in the upper explosive hydrofracture [61.5 m (202 ft)] was extruded through this fracture in all directions and was detonated. The explosive inserted into the lower explosive hydrofracture [63 m (207 ft)] extruded through the hydrofracture in the southeasterly region and detonated; however, in the opposite (northwesterly) region, the explosive apparently traveled through some unknown path to the pre-existing fracture at the 65.5 m (215 ft) level, extruded through this fracture and detonated. The areal boundaries of the different levels were estimated using composite logs of wells lying between the orthogonal directions shown. A plan view depicting the probable region in which the explosive detonation occurred at the 61.5 m (202 ft), 63 m (207 ft) and 65.5 (215 ft) levels is shown in Figure VB-8.

C. Air Acceptance and Tracer Tests

Air acceptance and tracer tests were conducted at two intervals during the post-shot assessment. ^{85}Kr tracer tests were conducted through the observation wells soon after the explosive fracturing event using a wellhead-to-wellhead measurement system. With this technique, a steady state-flow of air is first established between two wells. Then a pulse of the radioactive gas, ^{85}Kr , is injected into the air stream at the wellhead of the injection well. Subsequently, the ^{85}Kr pulse is detected at the wellhead of the production well. Information about the flow properties of the formation can, in principle, be deduced from the time-resolved measurement of krypton concentration at the detector. These tests indicated very short across-formation times, with the air flowing at essentially zero gage pressure. The data were of limited value; in some cases the calculated transit times between wells were less than the uncertainties in up-and-down wellbore times.

FIGURE VB-6. ELEVATION VIEW IN THE NORTHWEST-SOUTHEAST DIRECTION. ----- INDICATES WHERE THE SLURRY EXPLOSIVE DETONATED. DENOTES FRACTURES DETECTABLE FROM POST-SHOT WELLBORE LOGGING.

FIGURE VB-7. ELEVATION VIEW IN THE SOUTHWEST-NORTHEAST DIRECTION. ----- INDICATES WHERE SLURRY EXPLOSIVE DETONATED. ---- DENOTES FRACTURES DETECTABLE FROM POST-SHOT WELLBORE LOGGING.

FIGURE VB-8. PLAN VIEW OF EXPERIMENT AREA DEPICTING PROBABLY REGIONS IN WHICH EXPLOSIVE DETONATION OCCURRED IN (1) THE MIDDLE (202 FT) HYDROFRAC, (2) THE LOWER (207 FT) HYDROFRAC AND (3) A LOWER PRE-EXISTING FRACTURE.

The ^{85}Kr tracer tests were repeated following the drilling and casing of the evaluation wells, which extended the region that could be evaluated westerly from the detonation point. In these tests, air hoses, extending from the tracer system hardware to the top of the Tipton zone, were used, thereby significantly reducing the "well time" and the uncertainty of "in well" time. The results of these tests showed that the increase in permeability and porosity was entirely due to enhancement of the horizontal fractures by the explosive detonation, with no evidence of any permeability in the zones between the horizontal fractures.

D. Evaluation of Formation Interrogation

The results of the wellbore interrogations provided evidence that the hydraulic/explosive fracturing sequence did not fracture or rubblize the formation in the manner or degree expected. On the basis of the pre-test analysis in which dynamic tensile fracturing was the primary mechanism for rock failure, the predicted pattern was for the greatest intensity of fracturing to be between the two explosively loaded hydrofractures, with a lesser intensity of fracturing between the middle hydrofracture and the uppermost (sand-propped) hydrofracture and with no significant fracturing outside this zone. The oblique direction of stress waves relative to the hydrofractures was expected to create rotation and/or dislocation of the shale which would in turn provide a means to retain the permeability and porosity of the fractured zone created as the explosive gases expanded the hydrofractures. These expected results were not observed. Instead, fractures induced by the explosive detonation were at random locations throughout the Tipton Member, with no concentrations of fractures between or near the hydraulic/explosive fractures. The fractures, in general, were in regions where the kerogen content was low and/or in regions of tuff lens. No dislocation of fragments was apparent, except immediately adjacent to the horizontal fractures where explosive detonation occurred. The damage near the explosively loaded fractures effectively widened the fractures, causing the total airflow between pairs of wellbores to be through one or more of these fractures, with no airflow or other evidence of increased permeability or porosity at other levels. Possible flow paths included the two lower hydrofractures, which were intended for explosive loading, as well as the pre-existing fracture. The observation that explosive had entered the pre-existing fracture indicates that control of the explosive insertion/detonation sequence is not easy. In

this case, most, if not all, of the explosive inserted into the lower hydrofracture in a northwesterly direction traveled through an uncharted path to the preexistent lower horizontal fracture, was extruded through this fracture, and detonated.

VI. TRANSIENT STRESS FIELDS

A. Geometry Considerations

The stress, TOA, and acceleration gages used in the Site 12 experiment were emplaced primarily to provide information about the detonation of the explosive in the two hydrofractures. Because of the presence of significant quantities of explosive in the insertion wells, as well as in the hydrofractures, the evaluation of the data recorded during the first few milliseconds after the detonation is a rather complex matter. This is particularly true for the final explosive rubbing effort where it was necessary to use a detonation initiation system that was not optimally matched to the design of the gage deployment scheme. In analyzing the data, then, it is important at the outset to establish a clear picture of the dynamic processes induced by the 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 VIA-1. In this case, the configuration represents that of the primary detonation system used in the final rubbing effort (Figure IVD-3). With that system, detonation is initiated at the top of each 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, stress waves radiating from each increment of explosive are transmitted into the rock. These spherical stress pulses combine to form the transient stress fields depicted in Figure VIA-1. In each illustration of the

FIGURE VIA-1. ILLUSTRATION OF HOW TRANSIENT STRESS FIELDS EVOLVE AFTER INITIATION OF DETONATION AT THE TOP OF AN EXPLOSIVE COLUMN THAT INTERSECTS AN EXPLOSIVE-FILLED HYDROFRACTURE.

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 front 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 disk-shaped 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, and 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 shapes, except in the region near the axis of the explosive column where the wave-front 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 VIA-1 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 VIA-1 upon another such illustration that is displaced slightly, both in time and in space.

With regard to the Site 12 experiment, the complexity of the transient stress field was quite pronounced for the final detonation effort. The difficulty is that, in the final detonation effort, most gages and cables experienced the arrival of a strong stress wave from one explosive column prior to experiencing the arrival of a pulse from an explosive-filled hydrofracture. Since the detonation of the explosive in the hydrofracture was of primary interest, the opposite situation would have been more desirable. This would have been the case for the first rubbing attempt. Recall that the primary detonation system for the initial explosive rubbing attempt involved two detonator-booster units, one at the elevation of each explosive-filled hydrofracture⁸ in a separate well located a few feet from the explosive insertion wells. Recall also that the back-up system in the final rubbing effort consisted of a detonator/explosive unit on the exterior of the casing of the explosive insertion well, just above the hydrofracture. Both of these initiation schemes have features which would have eliminated much of the ambiguity in the data analysis, but unfortunately, circumstances precluded their use.

To explain the difference between the various detonation options in questions, consider the two illustrations in Figure VIA-2. The upper illustration is based on the configuration of the final rubbing effort, with the detonator at the top of the explosive column; the lower one is based on the configuration of the initial rubbing effort, with the detonator at the level of the explosive-filled hydrofracture, a short distance from the explosive column. Two 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 times in

REGION A: WAVE FROM HYDROFRACTURE ARRIVES FIRST.

REGION B: WAVE FROM COLUMN ARRIVES FIRST.

FIGURE VIA-2. STRESS WAVE FRONTS AT THREE TIMES (DESIGNATED BY SUBSCRIPTS 1, 2 and 3) AFTER INITIATION OF DETONATION. WAVE FRONTS MARKED WITH AN "H" ORIGINATE IN THE HYDROFRACTURE; THOSE MARKED WITH A "C" ORIGINATE IN THE COLUMN.

much the same way as in Figure VIA-1. In the upper portion of Figure VIA-2, it is clear that the stress waves from the explosive column dominate. Dashed lines have been drawn to separate the regions where the first arriving stress wave originates at the hydrofracture (Region A) from the region 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 initial explosive rubbing attempt. Some gages were also emplaced to the left of the explosive column (Well EE) to examine the effect of the asymmetry caused by initiating the detonation at a location other than on the axis of the explosive column. 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 exists when the detonation initiation point is located on the axis of the explosive column, at the level of the hydrofracture; i.e., it is similar to the backup system on the final rubbing effort.

The detonation system for the initial rubbing attempt made it possible to position 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 explosive filled hydrofractures. As was mentioned previously, most of the gages in the final rubbing effort did not experience stress waves from the hydrofractures until after being subjected to waves from the explosive columns. Thus, the data of primary interest were in many cases obscured by data of lesser importance. We will return to this subject, giving specific con-

sideration to each gage, after discussing the data analysis methods that were developed.

B. Data Analysis Methods

To understand the nature of the underground transient stress field from the data acquired with the stress, TOA, and acceleration gages, it is necessary to develop a method to mathematically predict the arrival times of the various stress waves; namely, the waves from the explosive columns in the two explosive insertion wells (Wells X and Y) and the waves from the two explosive-filled hydrofractures. This was done by considering waves from each source 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 measured down-hole locations of the gages, the hydrofractures, and the explosive insertion wells. Other features, while approximately known, were considered to be variables; these include detonator locations, stress wave velocity in rock, and detonation wave velocities in the explosive column and in the hydrofracture (these latter two velocities need not be equal). Detonator locations were considered to be variables because they 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 over a rather large range to study the sensitivity of results to this variable, no justification was found to use values different than those deduced in prior studies.

The geometry that was used in determining arrival times at gage locations due to the detonation of explosive columns is shown in Figure VIB-1. 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 centered at point D. The arrival time of a stress wave at G1 is given by

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

where U_{OS} is the stress wave 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 detonator ignition. Vertical (Z) coordinates represent depths below ground surfaces, so the positive Z direction is downward.

Gage G2 is located in the region of conical wave propagation. The arrival time here is given by

$$t_{G2}^C = (Z_{G2} - Z_D) / U_{ex} + \left[(X_{G2} - X_D)^2 + (Y_{G2} - Y_D)^2 \right]^{1/2} (\cos \theta) / U_{OS} ,$$

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

FIGURE VIB-1. ILLUSTRATION OF GEOMETRY ASSUMED IN CALCULATING ARRIVAL TIMES AT GAGES G1, G2, AND G3 FOR STRESS WAVES THAT ORIGINATE IN AN EXPLOSIVE COLUMN.

conical wave, 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

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

Arrival times for stress waves originating at the explosive-filled hydrofractures were calculated using the illustration depicted in Figure VIB-2. In this case the arrival time at the gage is given by

$$t_G^H = (z_{F1} - z_D)/U_{ex} + \left[(x_G - x_{F1})^2 + (y_G - y_{F1})^2 \right]^{1/2} / U_{ex} + |z_{F2} - z_G| (\cot \theta) / U_{ex} ,$$

where the 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 precisely true, but the error introduced is not significant, as will be shown later.

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 back-up detonation system, namely, the detonator/explosive unit exterior to the casing in the explosive insertion well and 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

FIGURE VIB-2. ILLUSTRATION OF GEOMETRY ASSUMED IN CALCULATING THE ARRIVAL TIME OF A STRESS WAVE FROM AN EXPLOSIVE-FILLED HYDROFRACTURE.

times were determined for each gage location in each computational run. Each run was based on a trial 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 parameter values for the next run. By iteration, it was possible to establish best values for the various parameters; these values will be given in the next subsection.

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. The extent to which this occurred can be seen in Figure VIB-3. This figure, which is based on a computational run using the final, or best, values for 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 and functional during the final detonation experiment 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 VIB-3, which are similar to those in Figure VIA-2, permit a quick determination of which stress pulse arrives 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 the figure. It should be noted that, on the basis of the illustration in Figure VIB-3, the gage array in place for the final rubbing effort was best suited

FIGURE VIB-3. ILLUSTRATION OF GAGE LOCATIONS RELATIVE TO WELL Y AND THE UPPER EXPLOSIVE-FILLED HYDROFRACTURE AND WELL X AND THE LOWER EXPLOSIVE-FILLED HYDROFRACTURE. IN REGION A, THE FIRST ARRIVAL IS FROM THE HYDROFRACTURE; IN REGION B, THE FIRST ARRIVAL IS FROM THE EXPLOSIVE COLUMN.

to detect stress waves arriving from the explosive column in Well X; twenty-three gages should experience stress pulses 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 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 amplitudes, makes the pulses from both explosive columns more readily identifiable than the lower amplitude and often indistinct pulses from the hydrofractures.

C. Experimental Data and Evaluation

Examples of data obtained from stress gages in the final rubbing effort are shown in Figure VIC-1. 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. Interpreted results of detailed examinations of all gage records are given in Table VIC-1, along with results of calculations made using the finalized set of parameter values. The gages included in the table are those that were installed specifically for the final rubbing effort as well as those that had been installed prior to the initial rubbing effort and appeared to have survived the bore-hole detonations in Wells B and C. The nomenclature for gage identification in Table VIC-1, 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 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 (R's, T's, and V's indicate radial, transverse, or vertical orientations for accelerometers and stress gages).

FIGURE VIC-1. EXAMPLES OF RECORDED STRESS HISTORIES ALONG WITH INDICATIONS OF WHEN PULSES WERE EXPECTED ON THE BASIS OF NUMERICAL CALCULATIONS.

The stress histories in Figure VIC-1 show clear indications of pulses which can be identified as originating at the explosive columns. Less definitely identified are pulses which are 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 BB21YR and BB17YR in Figure VIC-1; thus interpretation is not necessarily direct. In some cases, the definite absence of a pulse at a time when the gage appeared to be operative (e.g., the pulse from the lower explosive layer for gage BB06YR in Figure VIC-1) was interpreted as an indication that no stress wave from the source in question was present, implying that the detonation did not occur as expected or that the propagation path of the pulse contained an obstruction, like a void. Such cases are identified in Table VIC-1 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 adverse occurrence.

The records in Figure VIC-1 indicated the arrival of distinctive pulses at times between about 3.4 and about 3.6 ms. These pulses are not simultaneous; thus, they cannot be attributed to electrical noise. Additionally, they arrive too late to be associated with a column or hydrofracture detonation. Well defined and late arriving pulses, such as these, were common and some, in fact, demonstrate that the underground explosive configuration was somewhat different than planned. Particularly noteworthy are the records from 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 indicate the presence of an accumulation of explosive in some section of the formation that was open or void prior to the

TABLE VIC-1. SUMMARY OF STRESS WAVE ARRIVAL TIME MEASUREMENTS MADE DURING THE EXPLOSIVE FRAGMENTATION EVENT AT SITE 12.

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.

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 initial detonation 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 in Table VIC-1 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 actually located at shot time and to determine accurate effective values for stress wave velocity in the rock and detonation velocity in the explosive columns.

Referring back to Figure VIB-1, 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, 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 VIB-1. Since no gages were located

below the conical region, it is not necessary to define a slant range for the lower spherical region.

Figure VIC-2 shows a plot of slant range versus arrival time for the parameter values which are listed in the figure. These values are the ones that produced the best fit of the data on a slant range, arrival time plot. Note that the points fall near 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 locations 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.

In contrast, another plot using slightly different detonator locations is shown in Figure VIC-3 to illustrate an improper selection of parameter values. The detonator locations in this alternate case are those deduced 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 figure is identical to the one in Figure VIC-2. Clearly, the fit to the data is poor in Figure VIC-3; the fact that the data generally track parallel to the line suggests that no change in stress wave velocity is required, 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 slant range that is pronounced for gages in the lower portion

FIGURE VIC-2. GRAPH SHOWING LINEAR FIT OF ARRIVAL TIME-SLANT RANGE DATA BASED ON FINAL PARAMETER VALUES.

of the conical region (see Fig. VIC-1), but negligible in the upper portion of this region. The detonation velocity shown in Figure VIC-2 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 from prior tests 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 location deduced from the stress wave data (182.4 ft in Well X, 173.0 ft in Well Y) indicate that the explosive column in Well X extended 28.0 ft above the lower hydrofracture (201.0 ft) and in Well Y the column extended 25.0 ft above the middle

FIGURE VIC-3. GRAPH SHOWING INFERIOR FIT OF ARRIVAL TIME-SLANT RANGE DATA FOR CASE WHERE PARAMETER VALUES WERE DEDUCED FROM WATER FLOW INFORMATION.

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 spacial separation of the initiation points for the hydrofractures imply that the detonation waves in the hydrofractures will not be propagating radially outward together. This could 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 VIC-4. The downhole loca-

Contours Depicting Lag
of Upper Explosive Layer
Relative to Lower Layer.
Times in Milliseconds.

FIGURE VIC-4. CONTOUR PLOT SHOWING DEGREE TO WHICH THE DETONATION WAVE IN THE UPPER EXPLOSIVE LAYER LAGS THE DETONATION WAVE IN THE LOWER EXPLOSIVE LAYER.

tions 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 (a desirable condition) occur only in the southwest half of the figure. Lag times toward the northeast are large enough to negate much of the advantage that would be expected from the interactions between stress waves from the two explosive layers. Thus, the test of the effect of stress wave interactions on fracture 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 Fig. VB-8), the explosive intended for insertion into the bottom hydrofracture actually entered a natural fracture system several feet below this 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.

The identification and evaluation of stress pulses from the explosive columns provided considerable insight about the underground explosive configuration, 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 VIC-1) 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. To the southeast, there is no specific evidence from the stress records that detonation did occur in the upper explosive layer; however, the flow and caliper logs indicate that detonation definitely did occur. The enhancement in flow was, in fact, greater to the southeast than in other directions, which is what would be expected in a region of near simultaneous detonation of the two explosive layers.

Regarding the lower explosive-filled hydrofracture, clear evidence for detonation, based on the stress data, is questionable at nearly all locations. In some cases, however, there does appear to be evidence for the absence of a detonation. For example, gages BB02TA, BB06LB, and BB06YR, 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 VIC-1 measured and calculated late arrivals are shown for gages 0302TA and 031TA. The calculations here are based on an assumption that the lower explosive layer was 215.7 ft deep. This is about the level of the natural fracture system.

It should be noted that stress pulses from the lower explosive layer may not be observed, even if this layer detonated on schedule. Reasons for this are that the crack expansion produced by detonation of the upper explosive layer can impede 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.

The overall analysis of the stress wave propagation data provided useful information about the underground conditions at shot time, particularly about the explosive columns. The data further suggests that detonation of the upper explosive layer occurred at the horizontal positions of most of the gages except those at rather large distances. Evidence for the planned detonation in the lower explosive layer is not present, although the absence of such data does not prove that the detonation did not occur. In fact, evidence from other sources indicates that a disturbance did occur in the hydrofracture. Data obtained in one of the wells provide support for a conclusion that explosive intended for the lowest hydraulic fracture actually entered a natural fracture system at greater depth.

VII. SUMMARY OF RESULTS AND CONCLUSIONS

The Site 12 experiment provided a realistic examination of the hydraulic/explosive fracturing concept for producing a fractured network within an oil shale bed. Real time measurement made during each step in the sequence of operations, along with formation interrogation throughout the course of the experiment, provided data for a reliable assessment of this fracturing method. Insight relating to an overall evaluation of bed preparation methods for true in situ oil shale processing was also acquired.

The hydraulic fracturing sequence was executed essentially as planned. Three closely spaced, sand-propped hydrofractures were created approximately horizontally along the bedding planes of the oil shale strata. The distance between the fractures varied somewhat over the experiment area, but no significant branching was discovered. The depths at which the hydrofractures intercepted the outlying wells were determined by combining the results of borehole TV and flow logging; the intercept with the center well, which was cased, was determined by gamma logs.

Explosive fracturing via insertion and detonation of slurry explosive through two wells, each intersecting one of the two lower hydraulic fractures, was accomplished during a second attempt on this operation. The successful second detonation attempt demonstrates that emplacement and detonation of slurry explosive in relatively thin hydrofractures can be achieved by utilizing formation back pressure to induce formation lift and accompanying crack expansion during the explosive insertion.

The execution of the hydraulic and explosive fracturing events showed that the techniques and procedures for conducting these operations are well within the state of the art. This is not to say

that use of the hydraulic/explosive fractures concept will result in an oil shale bed that is suitable for retorting. In fact, the test data indicate that flow paths through the affected portion of the formation were confined only to narrow zones near the explosive layers. A detailed evaluation of the experimental data and of the hydraulic/explosive fracturing concept in general indicates that this fracturing concept will not be viable for commercial operations.

Reduction and interpretation of diagnostic data acquired during the explosive fracturing event, together with interrogation of the formation through wellbore logging, air acceptance and tracer tests, provided evidence of the degree of success of the experiment in light of the stated objectives. To some degree, the negative prognosis for the hydraulic/explosive concept stated above is attributable to lack of control over particular events. Specifically, it was found that slurry explosive had entered a natural fracture system during insertion through a path that was not identified prior to the shot. In addition, while the hydraulic fractures were nominally horizontal, uniformity of separation distance does not ensure uniform rubbing. Furthermore, uniform propagation of slurry into the hydrofractures cannot be expected in all directions nor can one explosive layer be expected to lie directly over the other layer. The features mentioned here are controlled by in situ properties of the oil shale which cannot necessarily be specified prior to the shot.

Certain other operations of the experiment were not executed in an optimal manner, but the consequences did not significantly affect the final conclusions. For example, the flooding of the hydrofractures to create back pressure for crack expansion during explosive insertion may have reduced the impedance mismatch at the upper sand-propped hydrofracture and hence also the probabilities for tensile fracturing in that region. Additionally, the unequal explosive column heights

at shot time caused the detonations in the two explosive layers to be non-simultaneous in certain regions of the shale bed.

The results of the coring, together with the analysis of dynamic stress, indicate that tensile stresses of sufficient magnitude to generate fracturing of the shale were obtained. These fractures were primarily along the bedding planes; some localized rubble areas were noted, either immediately adjacent to the explosive-filled fractures or in tuff lenses. Material dislocation and/or rotation, which would have led to increased porosity and permeability, apparently did not occur, except in the region immediately adjacent to explosive-filled fractures. As a result, enhancement of airflow was entirely along these fractures.

The successful retorting of the oil shale bed produced in the Site 12 bed preparation experiment is dependent on being able to process large blocks (~1 m thick) of material. Process support gases and product fluids must flow through the permeable regions where the explosive layers were detonated. The probability of such an operation being successful is small enough to indicate that the hydraulic/explosive fracturing concept holds little, if any, promise for ever becoming feasible.

APPENDIX A

Assessment of the type and amount of fracturing of the oil shale formation resulting from the explosive detonation was made, in part, by physical interrogation of the experiment site as discussed in Section V of this report. Specific goals were to ascertain both the vertical and areal extent of fracturing as well as the degree of rubblization in the zone of interest (the upper 12 m (40 ft.) of the Tipton member).

Physical interrogation methods consisted of coring, visual logging via downhole TV, caliper logging, flow logging, and air acceptance and tracer tests. Wells interrogated included the original observation wells, the special instrumentation well, and additional wells drilled after the detonation. These included four wells drilled to the west of the emplacement/detonation wells, especially for fracture assessment in this region, and 22 wells to be used both for fracture assessment and as process and instrument wells for a planned follow-on retort.

Composite plots depicting the results of the interrogation of each well were made. For the observation wells, this consisted of the results of the post-shot TV, caliper, and flow logging. The results of the pre-shot TV and flow logging were also included for comparative purposes. The composite logs of the evaluation and retort instrument wells include results of the coring and TV, caliper, and flow logging. Data from the pre-shot coring of Well A is also included for comparison of pre- and post-shot fracture density v.s. depth.

The locations of all wells interrogated was provided in Figure V-1. The composite data plots for each well are provided herein. As previously noted, these data were used in the fracture evaluation as discussed in Sections V and VI of the body of the report.

SITE 12-WELL 1

SITE 12 - WELL 2

SITE 12-WELL Z

SITE 12-WELL 4

SITE 12-WELL 5

SITE 12-WELL 6

SITE 12-WELL 7

SITE 12-WELL 8

SITE 12-WELL 9

SITE 12-WELL E-2

POST FRAC LOG

SITE 12 - WELL E-4

POSTFRAC LOG

SITE 12-WELL E5

POST FRAC LOG

PREFRAC
REFERENCE
CORE

TV

CALIPER

ACCUMULATIVE FLOW

SITE 12-WELL E-6

POST FRAC LOG

SITE 12-WELL V

POST FRAC LOG

SITE 12-WELL W

Post Frac Log

SITE 12-WELL TA

POST FRAC LOG

PREFRAC
REFERENCE
CORE

CORE

TV

CALIPER

ACCUMULATIVE FLOW

SITE 12-WELL T.B

SITE 12-WELL T.C

POST FRAC LOG

PREFRAC
REFERENCE
CORE

TV

CALIPER

ACCUMULATIVE FLOW

SITE 12-WELL TD

PREFRAC
REFERENCE
CORE

TV

POST FRAC LOG

CALIPER

ACCUMULATIVE FLOW

SITE 12-WELL TE

PREFRAC
REFERENCE
CORE

TV

POST FRAC LOG

CALIPER

ACCUMULATIVE FLOW

SITE 12-WELL T F

SITE 12-WELL TG

POST FRAC LOG

SITE 12-WELL TH

PREFRAC
REFERENCE
CORE

TV

POST FRAC LOG

CALIPER

ACCUMULATIVE FLOW

SITE 12-WELL T1

POST FRAC LOG

PREFRAC
REFERENCE
CORE

TV

CALIPER

ACCUMULATIVE FLOW

SITE 12-WELL TJ

POST FRAC LOG

PREFRAC
REFERENCE
CORE

CORE

TV

CALIPER

ACCUMULATIVE FLOW

SITE 12-WELL T K

POST FRAC LOG

PREFRAC
REFERENCE
CORE

TV

CALIPER

ACCUMULATIVE FLOW

SITE 12-WELL TL

POST FRAC LOG

PREFRAC
REFERENCE
CORE

TV

CALIPER

ACCUMULATIVE FLOW

SITE 12-WELL TM

POST FRAC LOG

PREFRAC
REFERENCE
CORE

TV

CALIPER

ACCUMULATIVE FLOW

SITE 12-WELL TN

PREFRAC
REFERENCE
CORE

TV

POST FRAC LOG

CALIPER

ACCUMULATIVE FLOW

SITE 12-WELL TO

POST FRAC LOG

PREFRAC
REFERENCE
CORE

CORE

TV

CALIPER

ACCUMULATIVE FLOW

SITE 12-WELL TP

SITE 12-WELL TR

POST FRAC LOG

PREFRAC
REFERENCE
CORE

TV

CALIPER

ACCUMULATIVE FLOW

SITE 12-WELL TS

POST FRAC LOG

PREFRAC
REFERENCE
CORE

TV

CALIPER

ACCUMULATIVE FLOW

SITE 12-WELL T.T

PREFRAC
REFERENCE
CORE

TV

POST FRAC LOG

CALIPER

ACCUMULATIVE FLOW

SITE 12-WELL TU

POST FRAC LOG

PREFRAC
REFERENCE
CORE

TV

CALIPER

ACCUMULATIVE FLOW

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