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POSTHYDRAULIC FRACTURE REPORT

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DOE Contract No. ~~ET 77-C-03-1791~~
TALLEY ENERGY SYSTEMS, INC.

MASTER

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1. ABSTRACT

Talley Energy Systems, Inc., as a part of Phase I of their DOE contract No. ET-77-C-03-1791, created a series of four, parallel, hydraulically induced hydrofractures. The hydrofractures will be used later in Phase I as the loading fractures for slurried explosives.

An evaluation of the aerial extent, thickness, and resistance to air flow of each of these four fractures is reported. Downhole pressure, well-head pressure, surface resistivity, tiltmeter, hydrophone response, and crack opening measurements were used as dynamic tests to monitor and to later describe the hydrofracture. Downhole television, high-resolution seismic reflection survey (HRSRS), cross-hole seismic survey (CHSS), pressurized air-flow, tracer-gas flows, gamma-ray logging, and hydrogeologic monitoring were all used as post-hydrofracture tests. Of all of these tests, tiltmeter, well-head pressure, downhole television, pressurized air flows, and hydrogeologic monitoring were the most useful. Down-hole pressure, crack opening, hydrophone response, tracer gas flow, and gamma-ray logging were less useful and provided only supportive data. HRSRS and CHSS provided no useful evaluation data.

These evaluation tests showed the four hydrofractures to be narrow (≤ 0.01 inches) and horizontal; to extend out at least to the outer ring of production wells in a southeasterly direction; to extend beyond the outer ring of production wells in a northwesterly direction; to have some degree of vertical communication; to have had a minor impact upon the naturally fractured aquifer lying above the desired production zone; and to have had no impact on the naturally fractured aquifer lying below the desired production zone.

2. INTRODUCTION

This report is submitted as the "Posthydraulic Fracturing Report" for Contract No. ET-77-C-03-1791 between the U.S. Department of Energy and Talley Energy Systems, Inc. (TALLEY ENERGY). This report satisfies the requirements of the contract Statement of Work Item II.E.3. Additional copies are being sent in accordance with Contract Article XI.A. (Item No. 5) and B.1., 2., and 4.

Contained herein is a comprehensive report of the Posthydraulic Fracturing formation evaluation. In addition, an overall review of the project history is presented for TALLEY ENERGY Site, Section 17, Township 18 North, Range 106 West, Sweetwater County, Wyoming. This report also includes a summary of the baseline data up through the implementation of hydraulic fracturing, a section on the summary of the results of the fracturing, and the recommendations concerning the explosive fracturing phases and future testing.

3. PROJECT HISTORY

The TALLEY ENERGY true in-situ oil shale research and development contract effectively began in August 1977 with the on-site arrival of TALLEY ENERGY personnel. Planning, site selection, and site survey were completed by October. Exploratory drilling and coring was accomplished in November and December. The cores were used to prepare a lithology of the site and for Fischer assay of the Upper Tipton Member. Drilling of the explosive-loading wells (S1 thru S4), the hydrofracture well (S5), and the production wells (P1 thru P16) was completed during February 1978.

The drilling plan for the wells was based on experience from several sources; notably: LETC's experience at its Vernal tar-sands site and their Rock Springs true in-situ oil shale Sites 4, 6, 9, and 12. The drilling plan, coupled with the proposed shale-oil recovery system, was designed to be an environmentally acceptable system and to provide for multiple usage of the wells.

The drilling plan for the hydrogeological observation wells was in accordance with the approved Environmental Research Plan (ERP) (Ref. 33) and was based on the identified need for three strategically located wells for each identified aquifer. As will be noted in Section 4.1, two aquifers were identified; thus, a total of six wells were dedicated to this use. Two of these wells were those used in the earlier exploratory drilling and coring phase (01 and 02) and four of these wells were drilled specifically to be used as environmental observation wells (03 thru 06).

From January through March 1978, formation evaluation measurements were conducted to establish the prehydrofracture data baseline. The actual hydraulic fractures were created from mid-April through mid-May.

4. PREHYDRAULIC-FRACTURE BASELINE DATA

Figure 4.1 is the drilling plan for the wells and Figure 4.2 shows the well-completion details for the loading (S), production (P), and hydrogeological observation (O) wells. All depth figures in Figure 4.2 are referenced to a scribe mark on the casing of well S5. All other depths either in the body of this report or in other figures will be similarly referenced (See Table 4.1, Well Elevation), unless otherwise noted.

The dotted portion below well S4 indicates that this well was completed to 430 feet. The well was plugged back with sand as shown. The sand will be washed out after explosive fracturing and well S4 will be used as the air injection well for retorting.

To characterize the oil-shale formation prior to hydraulic fracturing and subsequent operations, a number of formation characterization tests were conducted. These tests were:

1. Exploratory Coring
2. Downhole TV Logging
3. High-Resolution Seismic Reflection Survey (HRSRS)
4. Cross-Hole Seismic Survey (CHSS)
5. Flow Testing
6. Gamma-Ray Logging
7. Hydrogeological Testing
8. Computer Modeling

4.1 Exploratory Coring

Core was taken from wells 01 and 02. Well 01 was cored from 370 feet to 443 feet. The top of the Tipton Member of the Green River formation was identified at about 375 feet. Assays and lithographic descriptions indicated that the Upper Tipton Member extended down to approximately 430 feet.

The oil shale interval between 377 feet and 417 feet was chosen as the 40 foot interval for the shale-oil production. The Fischer assay on this interval averaged 22.4 gallons per ton. As shown in Figure 4.2, well 01 was later completed to 565 feet, cased to 470 feet, and is being used as one of the dedicated hydrogeological wells.

Figure 4.1 Phase I Drilling Pattern

Details	Wells		
	S1 thru S5	P1 thru P16	O1 thru O6
Drilled Diameter (in.)	15	9-7/8	9-7/8
Cased Diameter (in.)	10-3/4	7	7

Figure 4.2 Phase I Well Completion Detail

Table 4.1 Well Elevations⁽¹⁾

WELL #	ELEVATION (FT ABOVE MSL)	REFERENCE POINT
P1	6354.28	Bracket Top ↓
P2	6351.76	
P3	6351.71	
P4	6354.20	
P5	6357.07	
P6	6358.37	
P7	6357.29	
P8	6355.13	
P9	6354.12	
P10	6352.76	
P11	6351.61	
P12	6353.16	
P13	6356.51	
P14	6354.18	
P15	6356.93	
P16	6355.35	
O1	6353.45	Bracket Top Collar Top ↓
O2	6357.00	
O3	6351.61	
O4	6354.73	
O5	6351.47	
O6	6354.55	
S1	6354.98	
S2	6355.96	
S3	6356.10	
S4	6356.15	
S5	6355.10	Collar Top Scribe Mark Collar Top ↓
U	6356.76	
V	6355.53	
W	6353.99	
X	6355.61	
Y	6355.04	Collar Top ↓
Z	6354.49	

⁽¹⁾Per Bennett-Carder Survey, dated 8/15/78

Well 02 was cored from approximately 25 feet to 545 feet. A lithologic description of the entire core was prepared (Ref. 72). This description indicated the Green River Formation base at about 515 feet. It also indicated a fracture-network aquifer in the Wilkins Peak Member in the interval between 300 feet and 361 feet and another such aquifer beneath the production zone in the interval between 470 feet and 514 feet. It is these two aquifers which the dedicated hydrogeological observation wells (01 thru 06) monitor.

Neither the core from well 01 or the core from well 02 showed any evidence of fracturing in the Upper Tipton Member.

Appendix A describes the lithology that was obtained from well 02 for the upper aquifer; Appendix B describes the lithology for the lower aquifer; and Appendix C for the Upper Tipton Member. Additional evidence of the fracture network in the two aquifers and of the competency of the Upper Tipton Member will be included in Sections 4.2 and 4.7.

4.2 Downhole Television Survey

A downhole television log was produced using a high-resolution camera system including an aboveground monitor, videotape recorder, and calibrated digital depth readout (superimposed on the lower left corner of the picture). All production and injection wells were video logged to identify, locate, and record visual reservoir characteristics for baseline data. The only major prehydraulic-fracture features of any consequence were the two aquifers and the Tipton Member marker bed (M-bed). The marker bed was a thin (one-inch), tuffaceous bed which leaked small but continual quantities of natural gas.

Video tapes were made of all of the prehydrofracture video surveys and are on file at TALLEY ENERGY Corporate offices. These tapes, when compared with later records of the same wells made subsequent to the hydraulic fracturing and explosive fracturing operations, will provide a precise and significant source of general data on changes in the formation.

4.3 High-Resolution Seismic Reflection Survey (HRSRS)

The High-Resolution Seismic Reflection Survey (HRSRS) is a development project designed to provide a convenient seismic reflection system having

higher resolution than existing proprietary systems such as VIBROSEIS™. Historically, conventional seismic reflection systems have been primarily developed and used for petroleum exploration. For economic reasons, its targets have gradually evolved towards great depths and large features. The TALLEY ENERGY oil shale resource is comparatively small and shallow and requires higher resolution to yield usable information concerning the formation.

The HRSRS is a general-purpose, computer-based, high-frequency, seismic-reflection survey system. The system operates by injecting a signal sweeping from 70 Hz to 500 Hz into the ground and then recording signal reflections which are received by arrays of geophones. The system's capabilities are further enhanced by injecting repeated signals and algebraically adding the geophone responses (i.e., stacking) to enhance the returned signal and to suppress ambient background noise. Depending upon the rock properties, the HRSRS should theoretically have a spacial resolution of roughly 12 feet. Free surfaces at depth (open cracks, water cavities, etc.) larger than a few feet across should be detectable at depths of up to 500 feet. In addition, interfaces between regions with different indices of refraction can be resolved. However, these must be much more extensive even for moderately high index changes.

At the time the HRSRS was brought to Site 17 in late February to conduct the prehydrofracture survey, the system was still under development and there had not been an opportunity for extensive testing. HRSRS operations on site were conducted at night to avoid the interference effects of surface equipment and vehicular activity. The initial products of the geophone responses indicated that whenever enough signals were stacked to have a reasonable chance of gathering coherent reflections, nothing but noise would show up. It was only after extensive testing and analysis that the problem was located. The net result of the first field test of the HRSRS was that no usable data on the formation was collected.

The analysis of the difficulties encountered by the HRSRS during its first fielding test were later correlated, and it was discovered that the central problem was a randomly varying time delay between the signal injection computer command and the actual signal injection. This random time delay was a result of using a radio linkage and an analog sweep generator to trigger and

generate the injected signal. The solution of the problem involved hard-wiring the radio linkage and having the sweep signal generated digitally by the computer itself.

4.4 Cross-Hole Seismic Survey (CHSS)

The CHSS system worked successfully and usable information was gathered for comparison subsequent to hydraulic fracturing.

The CHSS consists of an explosive, line-charge sonic source; a set of four clamped geophones; and a surface data recording unit. Each geophone contained three-axis accelerometer arrays which were coupled efficiently to the formation by a clamping system activated when the geophone was in its proper downhole position. The explosive line-charge (Primacord) seismic signal source was located in well S5. This source could be moved vertically in the well so that the seismic waves could be made to traverse different levels of the formation before reaching the geophones (See Figure 4.3).

The initial CHSS field test in late February indicated that the formation was essentially homogeneous and that the only reflective surface that could be consistently detected was of an unknown size and nature at a depth of approximately 490 feet. It is conceivable that this feature is the interface between the Green River formation and the Wasatch formation, but this is not certain. It was discovered during the first CHSS field test that waves of frequencies greater than 300 Hz cannot be detected. This indicates a definite limit to the resolving power of this system (roughly 20 feet), and severely restricts its applicability in small-to-moderate formations.

4.5 Flow Testing

Flow testing was used to determine whether there was significant pre-existing gas and/or liquid permeability within the Upper Tipton Member. As core analyses noted, no fractures in this member were found. Before casing well S1, it was fitted with a formation packer to isolate the Tipton production interval from the rest of the formation. The open-hole section of the well in the production zone beneath the packer had most of the water swabbed out of it. The well was then pressured-up (350 PSI nitrogen gas was injected) to test for gas permeability. No leakage was detected. It was later discovered that some water still existed beneath the packer, which

Figure 4.3 Explosive-Source and Geophone Locations

had some slight effect on the test. It was concluded that liquid permeability through the formation was essentially zero, indicating that the reservoir was basically competent and devoid of significant natural fractures.

4.6 Gamma Ray Logs

Formation-background gamma-ray logs were taken for 13 of the production wells during the prehydraulic-fracture formation evaluation. These logs showed no anomalous activity except for the appearance of a small uranium spike which appeared consistently in the wells at a depth of about 370 feet. Figure 4.4 illustrates gamma-ray logs from five of the production wells.

4.7 Hydrogeological Studies

Hydrogeological studies, including coring, downhole-television, logging, and pump testing, indicated that two aquifers cross the site, one above the Tipton Member and one below. A total of six hydrogeological wells, three for each aquifer, were drilled, pump-tested, and cased to sample selected portions of these two aquifers. Using data obtained from wells 04, 05, and 06, the upper aquifer was found to be confined between 249 and 373 feet, with a specific capacity varying from 0.005 to 0.21 GPM/ft; the lower aquifer was below 449 feet, with a specific capacity varying from 0.002 to 0.009 GPM/ft according to data obtained from wells 01, 02, and 03. Appendix A describes the lithology that was obtained from well 02 for the upper aquifer; Appendix B describes the lithology for the lower aquifer; and Appendix C describes the lithology for the Upper Tipton Member.

Comprehensive water quality analyses are shown as Table 4.3 for both aquifers. A significant difference was found between the upper and lower aquifers. The water from the upper aquifer was of significantly poorer quality than the lower aquifer. However, it must be emphasized that even the lower-aquifer water is of such poor quality that it would not qualify for any known uses. These data are consistent with earlier work presented by Robb and Smith (Ref. 54). They showed that the Wilkins Peak Member of the Green River Formation contained a much greater concentration of the soluble sodium minerals nahcolite and trona than did either the Tipton Member or the Wasatch Formation. Generally speaking, the upper aquifer is in the Wilkins Peak Member of the Green River Formation and the lower aquifer is in the lowest part of the Tipton Member and the upper part of the Wasatch Formation.

Table 4.3 Aquifer Baseline Water Quality (mg/L)

Parameter	Lower Aquifer			Upper Aquifer		
	Well 0-1	Well 0-2	Well 0-3	Well 0-4	Well 0-5	Well 0-6
Sodium	530	420	640	11,650	22,000	11,000
Potassium	10.0	3.0	23	56	98	65
Magnesium	<0.1	0.2	1.2	<0.1	<0.1	<0.1
Calcium	6.0	3.1	6.2	5.9	8.3	<0.1
Ammonia	3.5	1.2	1.5	23	42	24
Chloride	95	81	270	3,650	3,650	3,850
Fluoride	11	11	7.3	52	93	52
Nitrate	0.02	<0.01	0.02	0.02	0.02	<0.01
Sulfate	35	1	143	1,450	123	555
Carbonate	150	135	205	10,650	24,000	10,600
Bicarbonate	870	845	845	2,850	6,650	1,965
Phosphate	0.05	0.16	0.05	30	58	22
TDS	1,445	1,235	1,990	29,600	55,450	28,850
Hardness	15	8.6	21	18	21	<0.1
Total Alkalinity	965	910	1,035	20,050	45,450	19,250
pH	9.05	8.77	8.97	9.93	10.00	9.92

4.8 Mathematical Modeling

Two hydraulic-fracturing modeling studies (Ref's. 25, 57, 58 and 73,) were conducted using as inputs frac-fluid injection rate, frac-fluid viscosity, frac-fluid loss coefficient, fracture radius, and the elastic modulus of the formation. The parameters predicted from these models were fracturing time, injection pressure, fracture width, and fluid volume. The value of the modeling parameters used and the values of the predicted quantities are presented in Section 6.2.7. The immediate value of these two modeling efforts was to allow planning for the fracture-fluid volume and fracture-fluid pump capabilities.

5. HYDRAULIC FRACTURING

5.1 Fracture Fluid

In determining how the hydraulic fracturing would be conducted, it was necessary to concentrate on the fact that these fractures would be used for loading the explosive slurry. Sandia Laboratories had conducted experiments with TALLEY ENERGY TAL-1005E explosive slurry (Ref. 49). These experiments indicated that if significant amounts of sand were present in the hydrofracture there would be a high probability of detonation-wave failure. As a result it was decided that no propping sand would be used in the hydrofractures. The fracturing procedure called for a gelled fracturing fluid (20 lbs Gaur gum and 160 lbs KCl/1,000 gallons water, as consistent with computer models) along with a pad of 1,000 lbs of 100-mesh Oklahoma Fines sand. This sand was used to assist with symmetrical fracture growth by changing the resistance of the open flow-paths.

5.2 Hydrofracture Location

The lithology from well 02 (Appendix C) (Ref. 73) was used to locate the planes of weakness for hydraulic fracturing. The lithology shows three planes of weakness in the lower part of the desired 40-foot production zone. Table 5.1 shows the planes of weakness in which the three bottom fractures were to be made. The uppermost or fourth fracture was located in a competent shale zone because of its distance from the third fracture and not because of a zone of inherent weakness.

5.3 Notching Operations

The jetting operation that created the notches used a four-nozzle jetting tool rotating at approximately 1.5 RPM. A gelled-water/sand/slurry (one pound 20/40 mesh silica sand per gallon of water) was applied at an operating pressure of approximately 4000 PSI for about two hours. This procedure created notches approximately 0.5-inch in width and more than four inches in depth. In each instance, the notches extended well into the formation, providing a horizontal, disc-shaped cavity conducive to a horizontal fracture. Figure 5.1 shows a downhole TV shot of the notch made for the second hydrofracture. The well depth noted in the picture of this notch has not been corrected to the S5 depth.

5.4 Hydraulic Fracturing Procedure

The hydrofracturing operation was sequenced from the bottom up so that as each

Table 5.1 Fracture Selection

Fracture No.	Depth of Weakness Plane, Feet ⁽¹⁾	Fracture
1	408'11"	Quartz Siltstone/Bituminous Shale Interface
2	400'4"	Tuffaceous inclusion
3	393'10"	Dolomite inclusion
4	386'0"	Competent Shale

(1) From Lithology in Appendix C, note that depths are uncorrected to S5

subsequent hydrofracture took place, the previous hydrofracture could be sealed by plugging-back all of the production and injection wells with sand. Well S5, the central well in the pattern, was drilled and cased specifically for the purpose of hydrofracing. The casing extends from the surface to below the production zone (See Figure 4.2). The casing had steel studs welded to the outer diameter so that after it was cemented and notches were created, casing slippage that could close a notch would be eliminated. Tilt-meter instrumentation was installed as the key method whereby the progress of the hydrofracture could be monitored on a real-time basis. Pressure gauges and transducers also were installed.

The hydrofracturing began with formation breakdown which was accomplished by incremental increases of 200 PSI, with each increment lasting one minute. Breakdown occurred for the four fractures at pressures of 610 (fracture 1), 1250 (fracture 2), 730 (fracture 3), and 1450 (fracture 4) PSI. Shortly after formation breakdown, the pump rate was brought to approximately three barrels per minute. As soon as steady flow was established, the 1,000 pounds of Oklahoma Fines sand were added to the frac fluid at the rate of one pound per gallon.

As flow continued, communication with the inner ring of production wells was established and the pressure in these wells rose to lithostatic as indicated by pressure gauges and transducers on the well heads. By the time the wells in the inner production ring had been contacted, tilt-meter data provided a reliable indication of the symmetry of the fracture growth. These real-time data were compared to the observed pressure rise pattern and to the predicted tilt-meter response that was made before each fracture operation. This prediction was made as a function of frac-fluid injection volume and assumed radial growth. As the fracturing proceeded, the tilt-meter monitor provided estimates of how much of the total expected rise had been realized. Utilizing this procedure, the progress of the hydrofracture boundary was monitored on a real-time basis.

Once the outer ring of production wells had been contacted, pumping was continued to ensure total propagation of the fracture throughout the pad. Before each hydrofracture was completed, communication to all of the production wells was established as confirmed by well-head pressure gauges and transducers which indicated pressure rise to lithostatic.

After each hydrofracture, well S5 was shut-in and the pad was allowed to subside undisturbed. Tiltmeter data confirmed no natural fractures communicated with induced fractures.

Figure 5.1 Downhole TV Shot of Notch for Second Hydrofracture

5.5 Other Hydraulic Fracture Measurements

In addition to well-head pressure and tiltmeter data, the following measurements were made during hydraulic fracturing to better characterize hydrofracture procedures and results: (1) Ground-surface resistivity measurements were made to note changes from baseline data due to the movement of the conductive frac fluid along the electrical path; (2) linear variable differential transformers (LVDT) were used to measure crack opening; (3) hydrophones and tape recording equipment were used to measure noise levels of the influx of water into selected wells; and (4) downhole pressure transducers were used to compare downhole pressures with well-head pressures.

Evaluations of the data from the above measurements are discussed in detail in Section 6.

6. POSTHYDRAULIC FRACTURE EVALUATION

6.1 Evaluation of Data Obtained During Hydrofracture Operations

In addition to the use of real-time data to monitor and control the hydraulic fracturing operation, these data can also be used to help evaluate the formation after the fracturing operations are complete. During each of the hydrofracture operations, two arrays of instrumentation were installed by Sandia Laboratories into selected wells. Sandia also provided a surface array of pressure transducers and resistivity stakes. In addition Sandia, through its subcontractor Darrell Wood of Darrell Wood and Associates, provided an array of surface tiltmeters to monitor fracture-growth patterns. Real-time data collection was managed by a computer-directed data signal conditioning system housed in Sandia's B49 instrumentation trailer.

6.1.1 Pressure Measurements

During each hydrofracture pressures were recorded from transducers located at the well head on each production well and downhole as shown in Figure 6.1. In addition, the pump truck had pressure and flow transducers attached to the hydrofracturing flow line. Pressure data were displayed in graphical form during the hydrofrac for use in diagnosing and controlling hydrofracture progress and was also stored on magnetic tape for later processing and evaluation.

Pressure data were reduced to two presentation formats following hydrofracture. One format was a graphical display plotting the pressure of a given transducer as a function of time (See Figure 6.2). The other presentation was a polar coordinate plot of fracture growth as a function of total injected fluid volume (produced by Mr. R. R. Beasley of Sandia) (See Figure 6.3). This polar plot uses the time-of-pressure-rise in the outer production wells to establish an average fluid velocity in each of the eight radial directions determined by the production wells (See Figure 4.1). The plot shows the assumed shape of the first fracture (based on the assumption of constant radial fluid velocity in each of the eight directions NNW (P1), WNW (P2), etc.) at times corresponding to injected fluid volumes equal to

Figure 6.1 Downhole Hydrofracture Instrumentation

CHANNEL

P5

P6

P7

P8

Figure 6.2 Wellhead Pressure VS Time (Typical)

Figure 6.3 Hydrofracture Geometry as a Function of Injected Volume for Hydrofracture No. 1

1/4, 1/2, and total fluid volume injected. Figure 6.4 shows the composite on the final fluid configurations of all four hydrofractures based on these calculations for each of the four hydrofractures.

6.1.2. Resistivity Measurements

As described in Section 5., an array of resistivity stakes were monitored to determine changes from the baseline pattern of resistivity. These were recorded during each hydrofracture for analysis at a later time. The analysis of these data involves the use of a computer model that relates changes in surface resistivity to the movement of the conductive frac fluid at depth. The results of this analysis are presented as a series of contours giving the fracture shape at various times during the hydrofracture. Figure 6.5 shows the location of the 52 measuring points and the fluid contour derived from resistivity data for the first hydrofracture.

The resistivity experiment was difficult to perform because of the need to insulate the blender, pump-truck, and flow line from the ground. As a result of the difficulties encountered in actually making this system work in a field environment, reliable data were not collected for all of the hydrofractures.

6.1.3. Hydrophones

Wells P2, P4, P7, P10, P13, and P16 were equipped with hydrophones during the hydrofracturing operations (See Figure 6.1). The hydrophones were expected to record any noise associated with the interception of the production well by the fracture. For example, this noise might be associated with the cracking of the rock, the influx of water, or the turbulent movement of material within the well. Hydrophone data were recorded as audio signals during each hydrofracture. Reduction of these data involved a determination of overall level and frequency as a function of time. Figure 6.6 presents a typical hydrophone response. While there is some correlation between the hydrophone audio signal and the rise of pressure within the well, it has not been determined what caused each component of the recorded audio signal.

6.1.4. Crack Opening Measurements

As described in Section 5., an attempt was made to measure crack opening of the hydrofracture during each hydrofracture operation. An LVDT string was installed in each of wells P10 and P13 (See Figure 6.1) with the intention of

Figure 6.4 Composite of Final Hydrofracture Geometry Based on Well Pressures Using Wells P1 Thru P8.

Figure 6.5 Resistivity Measurement Points and Calculated Hydrofrac Boundary for Hydrofracture No. 1

Figure 6.6 Typical Hydrophone Response

Figure 6.7 Typical LVDT Response

measuring the change in distance between the magnet and foot as the fracture intercepted the well. Figure 6.7 presents a typical response from an LVDT during hydrofracture operations. While the first movement of the LVDT certainly correlates with the rise of pressure in the well, the subsequent behavior is not easily explained and clearly does not give a true indication of fracture width.

6.1.5 Tiltmeter Data

During each hydrofracture, an array of 10 tiltmeters was used to monitor the fracture-growth pattern. The locations of the tiltmeters are shown in Figure 6.8. The tiltmeters were sensitive in the 10^{-9} radian range, and the radial and tangential tilt components of the fracture were monitored for each tiltmeter. The tiltmeter data were used in two ways: (1) As reported in Section 5.4, real-time graphical displays of the radial extent of each tiltmeter were used to give a dynamic estimate of the fracture growth pattern, and (2) both the radial and tangential tiltmeter responses were recorded for later use in determining the final, theoretical boundaries of each hydrofracture. To do this an estimate of the boundaries of a fracture was input into a tiltmeter fracture model and the radial and tangential responses that were predicted from that input were compared to the responses actually obtained. This curve-fitting process was repeated until a satisfactory fit of the data was obtained. Figure 6.8 presents these derived boundaries for all four fractures.

6.2 Evaluation of Data Obtained After Hydrofracture

After the hydrofracturing was completed, a period of posthydrofracture formation evaluation began. A description of data-gathering procedures and evaluations of the data obtained are presented below.

6.2.1 Downhole Television Survey

After completion of the four hydrofractures, the sand and water were blown out of the production wells and the formation was pumped dry. The downhole television system was then used to survey all of the production wells for the purpose of locating changes (fractures) that had occurred since the prehydrofracture baseline survey had been taken. To allow visualization of the hydrofractures, the following procedure was used.

CODE:

⊗ PRODUCTION WELLS

⊕ TILTMETER SITES

— FRACTURE BOUNDARIES

Figure 6.8 Tiltmeter Locations and Composite Fracture Boundaries

A production well was chosen and air at 125 PSI was injected into it. As the air was being injected, the downhole television camera was lowered into nearby production wells to observe water or bubbles issuing from the cracks where the hydrofractures intercepted the wells. Although this procedure was limited by the fact that the injected air followed the path of least resistance, it was possible to observe a great many fracture intersections. Figure 6.9 presents the data obtained by this means.

Downhole observed fractures took the forms either of clearly discernable fractures issuing water and/or bubbles, or of porous zones exuding water and/or bubbles. Figure 6.10 is a downhole shot taken of fracture number 3 in well P14. The streaks across the picture are actually jets of water being forced from the formation by the air pressure. Other than the fractures observed using the above procedure, the only changes from the pre-hydrofracture baseline survey were that the formation in the open-hole segments of the wells seemed to have undergone some probable oxidation (based on their slightly darker appearance) and that the quantity of natural gas issuing from the M-bed seemed to be somewhat reduced.

Evaluation of the downhole television data indicates that four approximately parallel hydrofractures were created. If the parallel hydrofractures traverse planes of weakness, then this is evidence that in the area of the retort the formation dips approximately two to four degrees to the WNW and strikes to the SE (See Figure 6.9).

6.2.2 HRSRS (High-Resolution Seismic Reflection Survey)

Between the testing of the HRSRS during the prehydraulic-fracture formation evaluation and late June when the system was again brought to Rock Springs, system evaluation, modification, and verification was accomplished in La Jolla, California. The changes mentioned in Section 4.3 were implemented. The hard-wire connection delivering the computer-generated wave form to the shaker amplifiers provided to be a reliable method of provided a precisely generated ground injection signal using an accurate and unvarying time delay.

Once this problem was overcome and another unexpected problem involving shaker wiring was discovered and corrected, the system was subjected to a preliminary test. Three sets of geophones were strung out and recordings were made of the signals that were injected from a single shaker. One of the geophone strings was installed in a small rectangular pattern near the shaker. The other strings were laid out on the ground approximately

Figure 6.9 Downhole TV Log of Post-Fracture Well Intersection Depths

BEFORE

AFTER

6.10 Downhole TV Shot of Fracture No.3 in Well P14

100 feet from the shaker. The computer was instructed to run three sequences of input and geophone data recording.

The first sequence involved taking 10 successive inputs to each geophone and stacking their outputs. Subsequently, 32 and 64 inputs and stacked outputs were successfully recorded. After the experiment was completed, the stacked responses were cross-correlated with the input wave form to see if any significant reflections had been obtained. Figure 6.11 shows results of one of these tests. The output wave-forms of the cross-correlated data show that reflections from some underground feature was obtained.

It must be emphasized that these tests merely establish the capability of the HRSRS to generate, inject, receive, stack, and sort swept seismic signals ranging in frequency from 70 to 300 Hz. Simply stated, the system only proved its ability to detect reflected signals from an unknown reflector. The system's ability to actually operate in a high-resolution mode and resolve small (approximately 20 feet) features has not been established to date. In addition, the above test used only one shaker and was carried out under well-controlled conditions at La Jolla, California and thus does not represent a true field result.

Following the above test, the system was brought to Wyoming to conduct posthydraulic-fracturing formation evaluation. The first tests on site involved systematic verification of HRSRS component equipment performances. The first of this series of tests involved placing geophones in various production wells and recording their responses to the shaker input. These tests successfully recorded and stacked the shaker inputs at depths of up to 450 feet. Figure 6.12 illustrates the locations used during this testing.

The next test involved measuring the responses of surface geophones to the shakers as a result of seismic transmission across the earth's surface. These experiments showed an unusually high sonic velocity for the signal traversing the surface from the shakers to the geophones. This has been attributed, however, to a shallow layer of high-sonic-velocity rock near the surface in the vicinity of the pad.

Beyond these tests, much time was spent attempting to diagnose a problem that had arisen in the incoming geophone signals. Interference signals connected with the injection wave-form was found to be disrupting the first portions of each geophone signal. It was thus impossible to use these signals.

Figure 6.11 Typical HRSRS Stacked Response (La Jolla, California)

Figure 6.12 Location of Shakers During HRSRS Tests

Although this problem was at least partially resolved in the field, the fact that no reflections had been seen on the downhole geophone responses during the prehydrofracture component test led to the conclusion that further system refinement would be necessary before a reflection survey could be successfully accomplished. Testing of the HRSRS ended once this conclusion had been reached. The net result of this HRSRS test was that no usable formation data were obtained.

6.2.3 CHSS (Cross-Hole Seismic Survey)

The posthydrofracture testing of the CHSS occurred in mid-June, 1978. The CHSS system was run in a very similar manner to the prehydrofracture tests. The few changes in the tests involved the fact that well S5 was now cased, whereas in the prehydrofracture it had been uncased. There were also different amounts of water in the wells.

As before hydrofracture, the geophones were clamped in production wells and the explosive line charge seismic source was again detonated at various depths in well S5 (See Figure 4.3).

Each geophone contained three orthogonal, single-axis accelerometers as sensing components. Figure 6.13A, 6.13B, and 6.13C provide examples of geophone response traces. The vertical component represents the most unequivocal data in that this response is in a known direction. The results of these tests were essentially the same as those done prior to hydrofracture. As mentioned in Section 4.4, it would not be expected that any but the largest interface features would be detected; thus, the primary useful information obtained relates to the sonic velocity in the rock (time-of-arrival data). Table 6.1 presents a comparison of the time-of-arrival data as a function of source depth for both the prehydrofracture and posthydrofracture test runs.

In some instances the transient time increased and in others it decreased; thus, no clear interpretation of this data can be made. Except for time-of-arrival data for wave formation, the geophone responses contained no usable information other than a reflection feature from a reflector located at a depth of approximately 490 feet. As mentioned in Section 4.4, this unidentified reflector had been detected on most of the prehydrofracture traces; however, during the posthydrofracture testing, only the traces from well P8 show this feature. No conclusions have been drawn from these data.

Figure 6.13A Typical CHSS Geophone Response (Vertical Component)

Figure 6.13B Typical CHSS Geophone Response (Longitudinal Component)

6.20

Figure 6.13C Typical CHSS Geophone Response (Tangential Component)

Table 6.1

Comparisons of Time-Of-Arrival-Data Before and After Hydraulic Fracturing, msec.

Depth of Geophone From Surface (feet) ¹	INNER WELLS			
	Well P12		Well P14	
	Prehydrofrac	Posthydrofrac	Prehydrofrac	Posthydrofrac
432	11.250	11.875	9.875	11.250
416	9.000	-	8.750	10.250
406	8.500	9.250	8.125	9.250
396	8.500	8.750	8.000	9.125
386	8.000	8.375	7.500	8.000
376	8.000	8.500	7.000	7.375

Depth of Geophone From Surface (feet) ¹	OUTER WELLS			
	Well P4		Well P5	
	Prehydrofrac	Posthydrofrac	Prehydrofrac	Posthydrofrac
432	11.125	12.750	14.500	-
416	10.750	12.000	13.375	-
406	10.375	11.250	12.625	11.500
396	-	10.625	12.375	12.250
386	10.375	10.000	11.625	11.500
376	11.000	9.625	11.125	11.000

¹ Not corrected to well S5

In light of the demonstrated lack of spacial resolution and the inability to interpret the time-of-arrival data, the CHSS system has not demonstrated the capability to provide useful information on our formation.

6.2.4 Flow Testing

The flow testing portion of the posthydrofracture formation evaluation was carried out in two stages. The first stage involved determination of air flows using pressurized air from wells S2 and P16 to other wells. The second stage involved determining air flows using tracer gases from well P16 to other wells. The original plan called for using wells S1 thru S4 for injecting air pressure and tracers but the lack of communication, due to bore-hole damage, from these wells to other wells in the pattern prevented this and after the first test well P16 was used.

6.2.4.1 Pressurized Air Flows

The pressurized air-flow tests were accomplished in three experiments. The first used well S2 to pressurize the formation in an open-hole fashion, the second used well P16 in a like manner, and the third used well packers to make flow tests from well P16 to selected sections in other wells.

6.2.4.1.1 Well S2 Test

In this test all wells except the S wells were shut in and air was injected into well S2 until the pressure reached 100 PSI. Well S2 was then shut in and after 18 hours the pressure in the other wells was noted. Table 6.2 lists the pressures in the other wells. Figure 6.14 is a schematic illustration of this penetration.

It is also possible from these data to calculate the average width, δ , of the four fractures. This calculation is based on injected air volume and pressure, on aerial extent of fracture, on pressure-rise data, and on the volumetric capacity of the wells in the pattern. Assuming no leakage through wells S1, S3, and S4 the average width of the four fractures was 0.04 inches. Subsequent air-flow tests indicate that gas did escape from well S1 when the retort is under pressure. With this in mind and by making the necessary corrections, the results give $\delta \leq 0.01$ inches.

6.2.4.1.2 Well P16 Open-hole Pressure Tests

Air was injected into well P16 at a pressure of 44 PSI for the first 200 minutes at which time the injection pressure was increased to 100 PSI for the

Table 6.2 System Pressures Existing 18 Hours After
Well S2 Shut-In at 100 PSIG

Well	Pressure (PSIG)
S2	50
P1	10
P2	10
P3	13
P4	7
P5	0
P6	0
P7	0
P8	>0
P9	9
P10	7
P11	11
P12	12
P13	~0
P14	0
P15	~0
P16	15

Figure 6.14 Schematic showing air pressure throughout fracture system 18 hours after well S2 had been shut in at a pressure of 100 PSI.

remaining 106 minutes of the test. The first portion of this test was intended to clear the fractures of water. Data from the high-pressure portion was intended to be used to determine fracture volumes, flow uniformity, and fracture widths. Water levels existing in the production wells prior to and subsequent to this pressurization test are shown in Table 6.3. Variations in the water levels are considered in the analysis of crack width taken from pressure data obtained during the first 200 minutes of testing. However, the water was assumed to have migrated into the wellbore prior to the time at which the P16 pressure was increased to 100 PSI. Following this test, all wells were bailed to a depth of at least 415 feet.

The system response to the well P16 pressurization test is shown in Figures 6.15 and 6.16. The nonuniformity in pressure rise in the other production wells is obvious. During the low-pressure phase of this test, the response is better illustrated in the schematic shown in Figure 6.17. During the first hour of this test, air-volume and air-flow calculations implied four fractures each having a width of .012 inches. After 2 1/2 hours, the implied fracture width is .025 inches. However, data taken during the high-injection-pressure portion of this test indicate a fracture width of .001 inches.

6.2.4.1.3 Well P16 Fracture Pressure Tests

Straddle packers were placed in the P wells as shown in Figure 6.18 to isolate individually each of the fractures for air injection. The data from the 44 PSI pressure-test portion of tests A, B, C, and D indicate fracture widths of 0.0016", 0.0029", 0.0016", and 0.0011" for fracture 1 thru 4 respectively. The total flow through fractures of these dimension at a pressure of 44 PSI is calculated to be 4.2 SCFM. The observed open hole flow rate at 44 PSI from P16 was five times that or 22.3 SCFM. This difference in flow rate implies that either the fractures are not at the depths stated or there are additional fractures that contribute to the open-hole flow but are blocked during the flows using the straddle packers.

6.2.4.2 Tracer Gas Flow Tests

Tests A and C shown in Figure 6.18 were used to provide a direct measure of gas penetration from well P16 through the field both in the horizontal and vertical directions. A semiquantitative determination of the horizontal penetrations evidenced by these tests supported the conclusion that the hydrofractures were more open in the north and northwest sections of the field than they were in the south and southeast sections of the field.

Table 6.3 Summary of Water Levels in Production Wells

DATE	TIME	DEPTH TO WATER SURFACE (feet)															
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16
10 June	1600-1800	*	*	388*	396*	430	430	425	415	*	441	*	492*	435	425	437	391*
11 June	1115-1154	445	420	448	446	475	426	422									
12 June	0911-1054								409	413	428	422	429	427	435	436	420
15 June	1000																402
16 June**	0900-1100	411	406	416	395	402	402	399	404	400	404	404	396	409	427	428	395
21 June	1350					419											

* to be bailed

** after this sounding all wells bailed as required to lower water level to 415 feet.

Figure 6.15 Production wells P1 through P8 pressure history during the P16 open hole pressurization test.

Figure 6.16 Production wells P9 through P15 pressure history during the P16 open hole pressurization test.

NORTH

- Region of Rapid Air Flow
- Region of Moderate Air Flow
- Zero Flow

Figure 6.17 Schematic showing air flow through fracture system resulting from application of 44 PSIG air pressure in Well P16.

Figure 6.18 Schematic Showing Post Fracture Well Intersection Depths And Packer Positions

The tracer-gas data were also used to give an estimate of the penetration of the tracer from fracture 1 to fractures 2, 3, and 4 (Test A) and from fracture 3 to fractures 1, 2, and 4 (Test C). Many conclusions are allowed by examination of the tracer-gas data. A summary of these conclusions is that the data do indeed show vertical penetration between the hydraulic fractures. This vertical flow is shown to be greater from hydrofracture 3 than the flow along hydrofracture 3. This cannot occur unless there are vertical fractures present.

6.2.4.3 Estimated Flows in Center of Field and Fracture Nonuniformity

System pressurization rates, sustained differential pressures, and tracer gas velocities among the sixteen production wells are all consistent with average fracture widths between 0.001 inches and 0.006 inches. Unfortunately, there are no flow data available from wells S1 thru S5 in the center of the field. If the average fracture width for the entire field is 0.01 inches, then the average fracture within the 50 foot radius is calculated to be 0.05 inches. If the average for the entire field is only .001 inches then the average within the 50 foot radius is correspondingly larger.

The test data indicate that the fractures within the retort are nonhomogeneous and that some fractures do not penetrate all sixteen production wells. These indications are not surprising when one considers the complexity of the formation and the fact that following each hydrofracture, the formation attempted to return to its original character. The lack of homogeneity of each resulting fracture is the product of the lack of the formation to make this return complete.

6.2.4.4 Summary of Flow Testing

In general, the posthydrofracture tracer gas pressurization studies indicate that the retort region is fractured. However, the fracture widths are small, thus air flow within the system is generally restricted. In the region of the production wells, typical fracture widths are on the order of 0.001 inches. If, as indicated by pressure data, the average fracture width for the entire retort is 0.01 inches, then the corresponding increased void space most likely occurs in the center of the field. If this void space is contained within a 50 foot radius of well S5, then the fracture width in this region may be on the order of 0.05 inches.

These tests were carried out using air at driving pressures (≤ 100 PSI) much lower than the lithostatic pressure. Given this driving pressure, a moderate to high viscosity liquid will not readily flow through the narrow

fractures. The ease of reopening the fractures as necessary to obtain the required liquid flow depends not only on the initial fracture width as measured during these tests but also on the material strengths, overburden, fluid viscosity, and fluid pressure. As a result it cannot be expected that the slurried-explosive flow patterns will necessarily be identical to the open-flow patterns obtained during these low-pressure air tests.

Sufficient data were obtained during these tests to characterize the hydrofracture flow properties of the TALLEY ENERGY retort, particularly in the region of the 16 production wells. These data may be used as a base for evaluation of the results of the next series of tracer gas pressurization tests scheduled to occur after the retort is explosively-fractured.

6.2.5 Gamma-Ray Logs

Gamma-ray logs were obtained shortly after each hydrofracture and also three weeks after the fourth and final hydrofracture. Radioactive iodine ^{131}I was added to the frac fluid for the first hydrofracture. Ideally, then, the gamma-ray log taken immediately after the first fracturing step would show a ^{131}I "spike" at the location of that fracture with each production well. Figure 6.19 is the gamma-ray log of wells P1, P5, P8, P20, and P11. These logs do not show the interception of the hydrofracture with the wells. However, they do show that wells P8 and P11 had large amounts of radioactivity below 385 feet, that wells P5 and P10 had a slight increase below 385 feet, and that well P1 remained unchanged from the prehydrofracture log shown in Figure 4.4.

These data then show that the fracturing fluid reached wells P8 and P11 in quantity, that it reached wells P5 and P10 to a lesser degree, and did not reach well P1. These data are not entirely supportive of the pressure, resistivity, tiltmeter, TV, and flow tests which unanimously indicate that hydrofracture number one progressed more to the north and northwest than to the south and southeast. On the other hand the gamma logs shown in Figure 6.19 do not completely deny these conclusions. That is they show the largest communication to the north and west (P8 and P1) with none reaching the far north-northwest well (P2) and a lesser communication to the northwest (P10) and to the southeast (P5).

For the second hydrofracture, radioactive scandium (^{46}Sc) was added to the Oklahoma Fines sand to see if the fracture intersections could be discerned by a gamma log following the hydrofracturing. Figure 6.20 shows the gamma

logs of the same five P-wells as Figure 6.19 showed for the first hydrofracture. For this test, well P1 remained unchanged from prehydrofracture and well P5 had returned nearly to the prehydrofracture level, well P10 showed a major accumulation of radioactive material below 385 feet, and wells P8 and P11 showed additional major accumulation below 375 feet. Thus the interpretation of the gamma-ray log data from the second hydrofracture are not significantly different than from the first one. The labelled sand penetrated northwesterly to a line between wells P8 and P11 but not as far as well P1. Southeasterly the sand did not penetrate to well P5.

Figure 6.21 shows the gamma-ray logs of the same five production wells taken three weeks after the fourth and final hydraulic fracture. Before the logs were obtained, the sand and water were blown out of the production wells and the formation was pumped dry. The noteworthy thing that is evident from these logs is that the gamma activity in each well had returned to its prehydrofracture level (Figure 4.4).

6.2.6 Hydrogeologic Testing

Posthydraulic-fracture water quality samples were taken from each of the six hydrogeologic observation wells (01 thru 06) ten days after completion of the fourth and final hydrofracturing operation. See Figure 4.1 for the location and Figure 4.2 for the well completion details of these wells. Water-level tests were conducted in the observation wells in conjunction with the taking of the water quality samples.

6.2.6.1 Lower Aquifer Testing

Table 6.4 shows the water quality of prehydrofracture and posthydrofracture samples for the lower aquifer (wells 01 thru 03). Table 6.5 lists the static water level for these wells. These water-level data are shown graphically in Figure 6.23 together with the daily and monthly precipitation data for the two month period in which the hydrofractures were accomplished. It is interesting to note that the static water levels in wells 01 and 03 rose dramatically during the period of hydrofracturing. In fact the level in 01 rose about 175 feet to about the same level as

Table 6.4

Comparison of Prehydrofracture and Posthydrofracture
Water Quality From the Lower Aquifer (mg/l)

Parameter	Well 01		Well 02		Well 03	
	Pre-	Post-	Pre-	Post-	Pre-	Post-
Sodium	530	530	420	220	640	610
Potassium	10.0	3.6	3.0	2.5	23	12
Magnesium	<0.1	<0.1	0.2	6.1	1.2	1.1
Calcium	6.0	5.6	3.1	35	6.2	6.2
Ammonia	3.5	1.4	1.2	29	1.5	0.3
Chloride	95	90	81	45	270	270
Fluoride	11	9.4	11	3.6	7.3	6.2
Nitrate	0.02	0.01	<0.01	<0.01	0.02	0.02
Sulfate	35	19	1	150	143	156
Carbonate	150	180	135	15	205	130
Bicarbonate	870	830	845	510	845	920
Phosphate	0.05	0.04	0.16	0.07	0.05	0.11
TDS	1,445	1,200	1,235	1,060	1,990	1,750
Total Alkalinity	965	980	910	441	1,035	980
pH	9.05	9.41	8.77	8.45	8.97	9.24

Table 6.5

Results of Prehydrofracture and Posthydrofracture Static Water Level Tests¹

Well	<u>Water Level, ft /day of measurement</u>			
	April	May	June	July
01	198'4"/13	24'0"/25	23'4"/22	23'1"/21
02	31'6"/1	31'0"/25	28'0"/22	27'0"/21
03	190'1"/11	112'0"/24	98'9"/22	99'2"/21
04	243'0"/9	246'0"/25	247'1"/22	246'3"/21
05	251'0"/10	247'0"/24	247'2"/22	246'4"/21
06	242'0"/13	243'0"/25	243'3"/22	242'5"/21

¹ Date of first hydrofracture: 19 April 1978
Date of final hydrofracture: 14 May 1978

NOTES:

TOTAL PRECIPITATION
IN APRIL = 1.54"
(VS APRIL AVG OF 1.16")

TOTAL PRECIPITATION
IN MAY = 1.70"
(VS MAY AVG OF 0.46")

Figure 6.23

in 02 both prior to and following the hydrofracturing. It is almost as if wells 01 and 02 have a common hydrostatic source following the hydrofracture operations. The level in 03 rose about one-half the distance (about 80 feet) to the level of 02 showing that these two wells are not connected to the same hydrostatic reservoir.

In contrast to these changes of water levels in 01 and 03 and the lack of any change in 02, the water quality (Table 6.4) showed just the opposite. The water quality in wells 01 and 03 was virtually unchanged from prehydrofracture to posthydrofracture whereas the ionic concentrations for those ions in greater concentration in the water from well 02 were reduced by about one-half. This change can be explained by assuming intrusion of rain water from the spring rains (See Figure 6.23) into the reservoir to which well 02 is attached. However, the increase in the concentration of the minor ions (i.e., magnesium, calcium, ammonium, and sulfate) does not support the explanation of rain water intrusion.

The consistency of the prehydrofracture and posthydrofracture quality of the samples from wells 01 and 03, when viewed with the change in static levels, is then inconsistent with the rain-water intrusion explanation. In fact, it is quite clear that the source of the water that raised the hydrostatic head in well 01 and 03 had indeed the same source as the water existing in these two wells before hydrofracture operations began.

In summary, there are no data that would link the changes in either quality or static level of water in the lower aquifer to the hydrofracture operations conducted in late April and early May 1978.

6.2.6.2 Upper Aquifer Testing

Table 6.6 shows the water quality of prehydrofracture and posthydrofracture samples for the upper aquifer (wells 04 thru 06). Table 6.5 lists the static water levels for these wells. These water-level data are shown graphically in Figure 6.24 together with daily and monthly precipitation data.

There were no significant changes in static water levels in these upper aquifer wells.

The increase in the overall quality of the water from wells 04 thru 06 show the influence of the intrusion of the water from the spring rains into the upper aquifer. There are two exceptions: Potassium and chloride both show increases in every instance from the prehydraulic fracture samples to the posthydraulic-fracture samples. This is an interesting observation in the light of the fact that 2% by weight of potassium chloride was added to the fracturing fluid to improve the sensitivity of the resistivity tests that

Table 6.6
Comparison of Prehydrofracture and Posthydrofracture
Water Quality From the Upper Aquifer (mg/l)

Parameter	Well 04		Well 05		Well 06	
	Pre-	Post-	Pre-	Post-	Pre-	Post-
Sodium	11,650	9,500	22,000	21,000	11,000	9,500
Potassium	56	320	98	500	65	110
Magnesium	<0.1	0.3	<0.1	0.3	<0.1	<0.1
Calcium	5.9	7.3	8.3	3.0	<0.1	<0.1
Ammonia	23	21	42	40	24	17
Chloride	3,650	4,800	3,650	3,800	3,850	5,200
Fluoride	52	38	93	74	52	33
Nitrate	0.02	0.02	0.02	-	<0.01	-
Sulfate	1,450	1,390	123	73	555	1,290
Carbonate	10,650	8,200	24,000	21,000	10,600	6,300
Bicarbonate	2,850	1,700	6,650	8,800	1,965	5,100
Phosphate	30	18	58	40	22	15
TDS	29,600	25,300	55,450	51,400	28,850	25,000
Total Alkalinity	20,050	15,100	45,450	-	19,250	14,600
pH	9.93	10.21	10.00	10.15	9.92	9.98

were made to outline the limits of the penetration of the fracturing fluid. (See Section 6.1.1.2). Table 6.7 lists the barrels of frac fluid that would be necessary to add to each 100 barrels of aquifer water to achieve this change. If these two calculations, i.e. rain-water intrusion and frac-fluid intrusion, are valid then additional frac-fluid intrusion would be necessary to effect the dilution caused by rain-water intrusion. No attempt will be made here to report a quantification of phenomenon. Also if they are valid then the flow rate through the upper aquifer must indeed be small to have the evidence of the frac-fluid intrusion still evident nine days following the fourth and final fracture. (Final fracture: 14 May 1978; water sampled: 23 May 1978).

It is true that these are not very sensitive tests but they do support the flow-test data that show vertical communication following hydrofracture. (See Section 6.2.4.2). This is the only evidence that would link the changes in the water quality in the upper aquifer to the hydrofracturing operations.

6.2.7 Mathematical Modeling

Table 6.8 lists the inputs and the values of predicted parameters for two frac-fluid injection models. As stated in Section 4.8, the immediate value of these predictions was to allow for planning for the requirements for frac-fluid volume and for frac-fluid pump capabilities. The observed values that were necessary to achieve the fracturing for the third fracture fall reasonably near the values that were predicted.

Table 6.7

Frac-fluid necessary to achieve observed decrease in K^+ and Cl^- in upper aquifer observation wells, bbls frac-fluid per 100 bbls aquifer water.

Well Number	Ion	
	K^+	Cl^-
04	3	10
05	4	4
06	0.4	30

Table 6.8

Mathematical Modeling for Hydrofracturing Operations^{1/}

<u>Parameter</u>	<u>Model 1^{2/}</u>	<u>Model 2^{3/}</u>	<u>Field Data^{1/}</u>
INPUT			
Frac-Fluid Injection Rates, bbl/min	3	2	3 ^{4/}
Frac-Fluid Viscosity, cp	10	25	-
Frac-Fluid Loss Coefficient, ft/min ^{-1/2}	-	5x10 ⁻⁴	1.5x10 ⁻⁴ ^{5/}
Fracture Radius, ft	150	131	197 ^{5/}
Formation Elastic Modulus, PSI	4x10 ⁶	4x10 ⁶	-
PREDICTED			
Fracturing Time, min	36	44	21 ^{4/}
Formation Breakdown Pressure, PSI	560	500-2,000	730 ^{4/}
Fracture Width, in	0.04	0.03	0.01-0.05 ^{5/}
Fracture-Fluid Volume, bbl	100	-	77 ^{4/}

^{1/} Third hydrofracture^{2/} Halliburton Services^{3/} Fracturing Technology, Inc.^{4/} Values used or necessary for fracture^{5/} Calculated value

7. SUMMARY

Between August 1977 and April 1978, TALLEY ENERGY's Site Section 17 was selected, surveyed, evaluated, and prepared for the hydraulic fracturing phase of Contract No. ET-77-C-03-1791 between the U.S. Department of Energy and Talley Energy Systems, Inc. The prehydraulic fracturing evaluation showed the following:

- (1) The Upper Tipton Member of the oil shale formation was approximately 40 feet in thickness for the interval beginning approximately 377 feet below ground level. The Fischer assay on this interval averaged 22.4 gpt.
- (2) The Upper Tipton Member was competent and unfractured with only a few, narrow porous zones to allow interwell communication.
- (3) One fractured aquifer was located immediately above the desired production zone in the Wilkins Peak Member. A second fractured aquifer was found considerable below the desired production zone extending from the lowest portion of the Lower Tipton Member into the upper portion of the Wasatch formation.
- (4) Water quality tests indicated that the water in the upper aquifer contains 30,000 to 55,000 mg/l of total dissolved solids (TDS). The water in the lower aquifer contains 1,200 to 2,000 mg/l TDS.

The hydraulic fracturing operations were carried out between mid-April and mid-May 1978. Four hydrofractures were created, all approximately parallel and horizontal. The first fracture was created some ten feet above the bottom of the Upper Tipton Member, the second was located seven feet above the first, the third was about seven feet above the second fracture, and the fourth was approximately eight feet above the third and an equal distance below the top of the Upper Tipton Member.

The following hydrofracture evaluation tests were conducted during the hydrofrac operations: Tiltmeter, downhole pressure, wellhead pressure, crack-opening, downhole noise level, frac fluid pump rates, and ground-surface resistivity. The evaluation tests that were conducted after the hydraulic fracturing was completed and that were useful in formation evaluation were: Downhole television survey, pressurized air flow studies, tracer gas flows, radioisotope labelling with gamma-ray logging, and hydrogeological monitoring.

These tests showed that the four hydraulically induced fractures were adequately sized and appropriately configured to allow injection and detonation of TALLEY ENERGY's TAL-1005E slurried explosive.

In addition high-resolution seismic reflection surveys and cross-hole seismic surveys were completed. Neither of these tests produced data that were useful in evaluating the oil-shale formation following the hydrofracturing operations.

More specifically, the hydrofracture evaluation data were used to define the following characteristics of the hydrofractures: (1) Aerial extent, (2) fracture widths, (3) vertical communication within the proposed production zone, and (4) effect of the hydrofracture operations upon the two identified aquifers.

If the tiltmeter data are used to define the aerial extent of the fracture, it is more to the northwest and less to the northeast and all fractures extended out at least to the ring of outer production wells. These conclusions are either substantiated or are not denied by downhole pressure data, well-head pressure data, television survey, radioactive tracing with gamma-ray logging, crack-opening times, downhole hydrophone responses, pressurized air flow tests, and tracer gas flow tests.

The widths of the four fractures were estimated from the various flow-test data. The estimates varied from as large as 0.05 inches for the average width within a 50 foot radius to as small as 0.0011 for an average of all four of the fractures.

Vertical communication between the fracture was estimated by determining the vertical tracer gas penetration from one fracture to an adjacent fracture. These tracer-gas tests did show that there was vertical flow and in the case of hydrofracture 3 it was shown to be greater than the flow along the hydrofracture itself.

Water-quality and water-level tests were conducted following hydrofracture. None of the changes noted in the data from the lower aquifer can be linked to the hydrofracture operations. An increase in the concentration of potassium and chloride ions in the upper aquifer could be linked to the hydrofracture operations and may well support the theory of the vertical communication.

8. RECOMMENDATIONS

As a result of the posthydraulic-fracturing evaluation tests on TALLEY ENERGY's True In Situ demonstration, there are four sets of recommendations. These are covered in the following sections.

8.1 Future Effort in Phase I

The size, location, and configuration of the four hydrofractures are such that the explosive-fracturing effort should proceed without delay.

8.2 Tests Recommended for Phase I Explosive Fracture Evaluation

From the useful posthydraulic-fracture evaluation tests, the following are recommended for postexplosive fracturing evaluation: Downhole TV logging, pressurized air flow studies, tracer gas flows, and hydrogeological monitoring.

In addition it is recommended that air-flow logging be used following caliper logging of the injection and production wells.

8.3 Evaluation Tests Recommended for TALLEY ENERGY Phase II

One of the objectives of the hydrofracture evaluation was to test the applicability of various tests to describe the hydrofractures. Many of the tests gave redundant results and need not necessarily be used in future hydrofracture evaluations. The following tests are recommended for use in our Phase II program:

(1) *Well-Head Pressure*

This test is made during the hydrofracture operation with the production-well boreholes filled with water. It responds to the entry of hydrofracture fluid into the borehole. The responses of the well-head pressure vs time can be used to calculate the lineal growth and final geometry of the hydraulically induced fracture.

(2) *Tiltmeter*

This test is also made during the hydrofracture operation and gives a real-time graphical display of radial extent of the hydrofracture. Following hydrofracture the radial and tangential responses can be used to determine the final, theoretical aerial boundaries of each hydrofracture.

(3) *Downhole TV Logging*

This test, when run in conjunction with air pressure being applied in an adjacent well, allow visual observation of the hydrofracture intersection with the various wells in the pattern. It describes the vertical location of the hydrofracture.

(4) *Pressure Air Flows*

These tests make it possible to estimate the average vertical dimension (width) of the cracks. This then becomes a measure of the gross formation resistance to air flow.

(5) *Tracer Gas Flow*

When used with straddle packers to isolate the various fractures, these tests can be used to estimate the penetration of gases from one hydrofracture to another. This gives an estimation of the vertical fracture following hydrofracturing.

(6) *Air-Flow Logging*

This test was not made following the Phase I hydrofracture. It needs to be evaluated in the initial part of Phase II to determine if it could supplement the data from Pressure-Air-Flow and Tracer-Gas-Flow tests.

(7) *Hydrogeological Monitoring*

These tests are necessary to document the impact of hydrofracture operation on the various aquifers that intersect the area of operations.

8.4 Evaluation Tests NOT Recommended for TALLEY ENERGY's Phase II

Several of the Phase I evaluation tests gave no useable data or data of limited use. The following are three tests that are *not* recommended for use in TALLEY ENERGY's Phase II:

(1) *High-Resolution Seismic Reflection Survey*

This test was not a proven test for formation evaluation within the limited size of our Phase I operations. The attempt to develop this test to give meaningful data on Phase I was not successful. Additional R&D may result in a successful system, but TALLEY ENERGY recommends that the R&D *not* be a part of the Phase II operations.

(2) *Cross-Hole Seismic Survey*

This test did not provide useful data. Therefore, TALLEY ENERGY recommends that it *not* be used as cited during Phase II.

(3) *Resistivity*

The data from the resistivity test conducted during hydrofracture did support other data with respect to the radial extent of the hydrofracture. However, the experiments were difficult to perform in the field and TALLEY ENERGY recommends that resistivity *not* be used as a test during Phase II.

(4) *Downhole Hydrofracture Instrumentation*

The downhole instrument string consisted of downhole pressure transducers, crack-opening gauges, and hydrophones. Even though the data from these tests were used to support the conclusions reached from other tests, they were not needed to reach unique conclusions. Specifically, the downhole pressure transducers read the lithostatic pressure plus the hydrostatic head, whereas the lithostatic pressure itself was obtained from the well-head pressure instruments. Likewise the arrival of the fracture fluid at the production wells was noted from both the crack-opening gauges and hydrophones but this event was also noted on the well-head pressure instruments. TALLEY ENERGY recommends that this downhole instrumentation *not* be used during Phase II.

(5) *Gamma-Ray Logging*

The data from the gamma-ray logs were not uniquely useful in the posthydrofracture evaluation. The fact that fracture fluid did indeed intersect the various production wells, as shown by the gamma-ray logs, is not sufficiently useful to justify the cost of these logs. TALLEY ENERGY recommends that gamma-ray logging *not* be used for a Phase II hydrofracture evaluation test.

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APPENDIX A

LITHOLOGY OF THE UPPER AQUIFER AT THE TALLEY ENERGY TEST SITE

From/To (Feet) *	Description
247'11" to 260'9"	MUDSTONE - light greenish-gray to dark greenish-gray, slightly calcareous to calcareous, slightly micaceous, massive to poorly bedded, pyritic along bedding planes; occasional CALCILUTITE and CALCARENITE - thin (~ 1/8") beds, gray, moderately hard, dense, fractures at 249'3" with iron staining along joint, 250'8" with iron staining, 256'1" with crushed dark green shale parting, 253'8" with iron staining, 256'1" with crushed dark green shale parting, 253'11", 256'10". Slightly wet at 252' and 256'. RQD = 1.00. Fracture at 80° angle at 258' to 260'9", heavily iron stained, some heavily coated with calcite, wet at this fracture, numerous similar horizontal fractures. RQD = 0.00.
260'9" to 272'0"	MUDSTONE - light gray to light brownish-gray with depth, massive to poorly bedded, dense, moderately hard, very pyritic especially on bedding planes, occasional CALCILUTITE and CALCARENITE - thin (~ 1/8"), light gray to light brown beds, medium pyrite crystals, increasingly pyritic with depth, bottom contact gradational. Fractures at 261'0", 268'7". RQD = 1.00.
272'0" to 277'9"	MUDSTONE - light greenish-gray to light brownish-gray, slightly calcareous, pyritic, massive to poorly bedded, contains several thin (~ 1/10") coal stringers at 274', moderately hard, dense, occasional CALCILUTITE and CALCARENITE - thin beds (~ 1/8"), slightly dolomitic. Fracture at 273'11". RQD = 1.00.

From/To (Feet) *

Description

277'9" to 278'1"	DOLOMITE - gray, small white inclusions (?), hard, poorly bedded, pyritic, fracture at 277'10". RQD not calculated.
278'1" to 281'9"	MUDSTONE - light greenish-gray to light brownish-gray, slightly dolomitic, very slightly calcareous, micaceous, pyritic, massive to poorly bedded, very occasional CALCILUTITE and CALCARENITE - very thin ($\leq 1/8"$), light gray to light brown, dense, moderately hard, medium pyrite crystals on bedding planes, fracture at 280'2". RQD = 1.00.
281'9" to 284'3"	MUDSTONE - brown, slightly bituminous, slightly dolomitic, hard, dense, massive to poorly bedded, extremely micaceous along bedding. RQD = 1.00.
284'3" to 286'5"	MUDSTONE - light greenish-gray to light brownish-gray, slightly dolomitic, very slightly calcareous, micaceous, pyritic, massive to poorly bedded, from 284'3" to 285'2" with alternating beds of MUDSTONE - as above, and CALCILUTITE and CALCARENITE - light gray, beds ($1/2"$), siliceous, dense, but fractures easily along bedding planes. Fracture at 284'4" with slight iron staining. RQD = 1.00.
286'5" to 292'0"	MUDSTONE - light greenish-gray, massive to poorly bedded, slightly dolomitic, moderately hard, pyritic on bedding planes, micaceous, very occasional CALCILUTITE and CALCARENITE - thin ($\sim 1/8"$), dense. Fractures at 287'0", 287'3". Gradational contact at bottom. RQD = 0.95.
292'0" to 296'2"	MUDSTONE - light gray to light brownish-gray, dense, massive to poorly bedded, very pyritic throughout, moderately hard, occasional thin ($\sim 1/8"$) light gray to light brown beds of CALCILUTITE and CALCARENITE which are also pyritic, pyrite crystal up to medium sand size. RQD = 1.00.
296'2" to 297'7"	MUDSTONE - light gray, thinly bedded but dense, calcareous with CALCILUTITE and CALCARENITE - light gray, hard, thin beds ($1/10"$ to $1/4"$). RQD = 1.00.

From/To (Feet) *	Description
297'7" to 305'7"	MUDSTONE - light greenish-gray to dark greenish-gray; massive to poorly bedded; slightly calcareous, slightly dolomitic, pyritic throughout, very pyritic at ~302'. Fracture at 298'2" with $\frac{1}{2}$ " dark green shale parting. RQD = 1.00.
305'7" to 308'1"	Slightly BITUMINOUS SHALE - light brown to dark brown, abundant crystallization, hard, thin bedded ($\frac{1}{4}$ " to $\frac{1}{2}$ "). RQD = 1.00.
308'1" to 311'10"	MUDSTONE - light gray, hard, very dense, occasional CALCARENITE and CALCILUTITE - thin ($\leq 1/8$ ") beds, very pyritic, massive to poorly bedded. Fracture at 310'11" slightly wet and iron stained. Fracture at 310'4" with iron stain.
311'10" to 315'3"	MUDSTONE - gray, hard, very pyritic along thin veinlets ($\leq 1/10$ "), slightly dolomitic, massive to poorly bedded. RQD = 1.00.
315'3" to 317'8"	SHALE - dark greenish-gray, thinly bedded ($\sim 1/10$ "), abundant CALCILUTITE and CALCARENITE - wavy beds ($\frac{1}{4}$ "), light gray, unit discs easily along shales between limestones, wet. Fractures at 315'4", 316'1", multiple fractures at 316'3" to 316'7". RQD = 0.30.
317'8" to 330'11"	MUDSTONE - light gray, dense, hard, dolomitic, pyritic, massive to poorly bedded, micaceous on bedding planes, MUDSTONE - light brown, thinly bedded ($\frac{1}{4}$ " to $\frac{1}{2}$ ") with dolomite interbeds, heavily pyritized, hard from 318'5" to 319'3". Fractures at 321'0", 321'6", 323'9", 329'5"; with iron staining, some medium crystalline calcite, some pyrite, some secondary horizontal fractures, wet. QUARTZ SANDSTONE - fine, heavily micaceous, calcareous, iron stained, light gray, slightly wet from 327'10" to 327'11".

330'11" to 334'2"	MUDSTONE - light brown to brown, pyritic, hard, dense, poorly bedded, contains rare very thin anthracite parting. RQD = 1.00.
334'2" to 336'5"	MUDSTONE - light gray, dense, hard, dolomitic, pyritic, massive to poorly bedded, micaceous on bedding plane, gradational contact at bottom of unit. RQD = 1.00.
336'5" to 339'11"	MUDSTONE - light gray to dark gray, poorly bedded ($\sim \frac{1}{2}$ "), hard, dense, pyritic, dolomitic, occasional CALCILUTITE - light gray, thin ($\sim \frac{1}{8}$ "). Alternating MUDSTONE and SANDSTONE - thin ($\frac{1}{2}$ " to 1"), heavily pyritized, heavily micaceous, calcareous, with iron staining, slightly wet at 338'2" and 339'10". Fracture at 338'3" filled with ($\sim \frac{1}{8}$ ") calcite. Fracture at 338'9" and 337'1". RQD = 0.95.
339'11" to 341'9"	MUDSTONE - brown, slightly bituminous, crystallization, dense, hard, poorly bedded. RQD = 1.00.
341'9" to 342'5"	MUDSTONE - light brown, abundant crystallization, hard, massive, dense, RQD = 1.00.
342'5" to 346'10"	MUDSTONE - light gray, very pyritic, dolomitic, hard, massive to poorly bedded, micaceous along bedding planes. RQD = 1.00.
346'10" to 349'10"	MUDSTONE - alternating bands of light gray to dark gray ($\sim \frac{1}{4}$ "); CALCILUTITE - thin ($\sim \frac{1}{8}$ ") (very occasional), hard, poorly bedded, dense, slightly dolomitic. Fracture at 348'6", ($\frac{1}{2}$ ") alternating mudstones and thin sandstone, heavily pyritized, heavily micaceous, calcareous, fine with iron staining, slightly wet. RQD = 1.00.
349'10" to 355'11"	MUDSTONE - light gray, dense, hard, dolomitic, pyritized. SANDSTONE and MUDSTONE - heavily pyritized, heavily micaceous, calcareous, fine, 1" thick at 353'2". RQD = 1.00.

From/To (Feet) *

Description

355'11" to 363'5"	MUDSTONE - gray, hard, dense, poorly bedded, alternating DOLOMITE - thin ($\sim\frac{1}{4}$ ") beds, fine crystalline, light gray, heavily pyritized. Fracture at 358'2" with ($\frac{1}{2}$ ") mudstone parting, and thin fracture at 358'4". -RQD = 1.00.
363'5" to 368'7"	MUDSTONE - light gray, light brown to brown, abundant crystalization, hard, dense, pyritic with veinlets, massive to poorly bedded. RQD = 1.00.
368'7" to 371'9"	MUDSTONE - gray, hard, dense, poorly bedded, alternating DOLOMITE - fine, crystalline, light gray, heavily pyritized. Thin ($\sim\frac{1}{4}$ ") sandstone parting at 369'3". Fracture at 371'1" with $\frac{1}{2}$ " mudstone parting. RQD = 1.00.
371'9" to 373'7"	MUDSTONE - light brownish-gray, dense, hard, dolomitic, massive. Fracture with iron staining at 373'4". RQD = 1.00.
373'7" to 374'2"	MUDSTONE - brown, dense, hard, dolomitic, massive. RQD = 1.00.
374'2" to 375'5"	MUDSTONE - light brownish-gray, dense, hard, dolomitic, massive. RQD = 1.00.

* Not adjusted to S5.

APPENDIX B

LITHOLOGY OF THE LOWER AQUIFER AT THE TALLEY ENERGY TEST SITE

From/To (Feet) *	Description
444'5" to 445'9"	MUDSTONE - dark gray, calcareous, cleaves readily along bedding planes, laminated, moderately hard. QUARTZ SANDSTONE - light gray, moderately hard at 444'6" to 444'8". Fracture at 445'1" with thin shale parting. RQD = 1.00.
445'9" to 446'0"	SILTSTONE - tan, slightly dolomitic, massive, hard, dense, micaceous. RQD = 1.00.
446'0" to 447'6"	Slightly BITUMINOUS SHALE - dark gray to nearly white, thinly laminated (1mm)(poker chip shale), slightly micaceous, calcareous, moderately hard, wet at 446'2" to 446'9", brecciated zone at 446'6" to 446'9". Fracture at 446'2", 446'3". RQD = 0.50.
447'6" to 448'7"	MUDSTONE - light gray, calcareous, cleaves readily along bedding planes, laminated, moderately hard. RQD = 1.00.
448'7" to 448'10"	MUDSTONE - dark brown to nearly black, carbonaceous, thin coal partings (non-horizontal), slightly dolomitic, hard, massive, dense, 1" wet brecciated zone at 448'9". RQD not calculated.
448'10" to 453'7"	MUDSTONE - light gray-brown to dark gray-brown, laminated but dense, cleaves along bedding planes, slightly micaceous, calcareous, contains some black specks of carbonaceous material, hard. Fractures at 452'4", 452'7" with shale parting. RQD = 1.00.
453'7" to 462'2"	MUDSTONE - light gray-brown to dark gray-brown, laminated but dense, cleaves along bedding planes, slightly micaceous, calcareous, some specks of carbonaceous material, hard. SILTSTONE - gray, hard, dense, at 461'8", (1/2"). Fractures

From/To (Feet) *	Description
453'7" to 462'2" (Continued)	at 453'10", 453'11" to 454'1" crushed, 454'4", 454'6", 454'9", 456'6" 1" breccia zone, 457'11" to 458'2" 3" breccia zone, wet, 460'0" ½" breccia zone wet, 461'2".
462'2" to 464'2"	MUDSTONE - dark gray-brown, slightly bituminous, laminated but dense, cleaves along bedding planes, slightly micaceous, dolomitic, hard. Fractured at 463'1", 464'2". RQD = 1.00.
464'2" to 468'6"	SHALE - light gray to dark brown, non-to slightly calcareous, slightly bituminous near bottom of unit, hard, poker chip. Fractured at 464'11", 465'1", 466'5" ½" crushed, 466'6" with shale parting, 468'0", 45° slickenside. RQD = 0.85.
468'6" to 468'10"	SILTSTONE - tan, slightly dolomitic, massive, hard, dense, micaceous, RQD - 1.00.
468'10" to 469'9"	MUDSTONE - light greenish-gray, hard, micaceous, with calcite cementation between lamina. RQD = 1.00.
469'9" to 470'0"	QUARTZ SANDSTONE - medium, subrounded to well rounded, calcareous, porous, feldspathic, arkosic, low hardness, fractured, conglomeritic. RQD not calculated.
470'0" to 480'1"	MUDSTONE - light gray-brown to dark gray-brown, laminated but dense, cleaves along bedding planes, slightly calcareous to non-calcareous. Fractured at 472'9", 472'11". SILTSTONE - tan, 2" at 476'8" to 476'10", slightly dolomitic, massive, hard, dense, micaceous. RQD = 0.95.
480'1" to 480'9"	SHALE - dark brown, slightly bituminous; with MUDSTONE - alternating thin (~ 1/8") beds, light brown, moderately hard. Fractured at 480'7". RQD = 1.00.
480'9" to 483'4"	SHALE - dark gray, moderately hard, dense, micaceous, cleaves readily along bedding. RQD = 1.00.
483'4" to 484'11"	Slightly BITUMINOUS SHALE with MUDSTONE, thin (~ 1/8") beds, light brown, moderately hard. SANDSTONE - thin (~ ¼"), calcareous seam at 484'5". RQD = 1.00.

484'11" to 489'11"	SLIGHTLY BITUMINOUS SHALE - very dark gray, cleaves readily along lamina, slightly micaceous, hard, contains SILTSTONE - brown to light gray, thin (~ 1"), slightly calcareous, abundant foram tests at 487'9" and 489'7". Fractured at 489'7". RQD = 1.00.
489'11" to 497'8"	SHALE - dark gray, cleaves readily along bedding, oolitic (?), globular manganese (?), rare, contains MUDSTONE - occasional thin (~ 1/2"), light gray, dolomitic, hard, dense. Contains SILTSTONE - very occasional, black, pyritic. Fractured at 492'6" and 496'0". Very thin (~ 1/8") coal seam at bottom. RQD = 1.00.
497'8" to 500'4"	SHALE - black to dark gray, cleaves readily along bedding, poker chip, hard, dense. RQD = 1.00.
500'4" to 501'1"	SHALE - dark gray, numerous partings throughout, wet, calcareous, thin seams of gilsonite (?) or coal (?), moderately hard. RQD = 0.00.
501'1" to 501'11"	SILTSTONE - gray, tuffaceous, slightly calcareous, tuffaceous angular inclusions, porous, low hardness, contains bituminized plant material, glass shards (some iron stained), micaceous. RQD = 1.00.
501'11" to 502'9"	SILTSTONE - gray, calcareous, abundant foram tests (10%), moderately hard. RQD = 1.00.
502'9" to 504'5"	SHALE - dark gray, richly fossiliferous, contains mostly goniobasis shells, hard. RQD = 1.00.
504'5" to 504'9"	QUARTZ SANDSTONE - light gray, fossiliferous, abundant foram tests, calcareous, moderately hard, slightly wet. Fractured at 504'8". RQD = 0.00.
504'9" to 515'1"	SHALE - light gray to dark gray, calcareous, contains abundant goniobasis and brachiopods throughout, thin coal (?), gilsonite (?) seam at 514'5". Base of Tipton member.

From/To (Feet) *	Description
504'9" to 515'1" (Continued) Wasatch Formation	Fractured at 509'9", 511'1", 30 ⁰ , 511'10", 514'4". RQD = 1.00.
515'1" to 515'11"	SHALE - dark gray, cleaves readily along bedding (poker chip), hard, dense. RQD = 1.00.
515'11" to 530'3"	QUARTZ SANDSTONE - light gray, porous, micaceous, calcareous, moderately hard, fine grained, gradational contact. RQD = 1.00.
530'3" to 536'0"	SILTSTONE - micaceous, gray, pyritic, moderately hard, gradational contact. RQD = 1.00.
536'0" to 538'9"	SANDSTONE - light gray, porous, micaceous, calcareous, moderately hard, fine grained, gradational contact. RQD = 1.00.
538'9" to 540'6"	SILTSTONE - micaceous, gray, pyritic, moderately hard, gradational contact. RQD = 1.00.
540'6" to 541'7"	QUARTZ SANDSTONE - light gray, highly micaceous, silty, moderately hard to low hardness, porous, fine grained, non-calcareous to slightly calcareous. RQD = 1.00.

* Not adjusted to SS.

APPENDIX C

LITHOLOGY OF THE UPPER TIPTON MEMBER AT THE TALLEY ENERGY TEST SITE

<u>From/To (Feet)</u> *	<u>Description</u>
371'9" to 373'7"	MUDSTONE - light brownish-gray, dense, hard, dolomitic, massive. Fracture with iron staining at 373'4". RQD = 1.00.
373'7" to 374'2"	MUDSTONE - brown, dense, hard, dolomitic, massive. RQD = 1.00.
374'2" to 375'5"	MUDSTONE - light brownish-gray, dense, hard, dolomitic, massive. RQD = 1.00.
375'5" to 376'3"	BITUMINOUS MUDSTONE - dark brown, dense, hard, massive to poorly bedded. RQD = 1.00.
376'3" to 376'6"	BITUMINOUS MUDSTONE - brown, dense, hard, massive to poorly bedded. RQD = 1.00.
376'6" to 377'2"	BITUMINOUS SHALE - light brown to brown, dense, hard, extremely thinly bedded (~ 1mm). RQD = 1.00.
377'2" to 377'5"	BITUMINOUS SHALE - light brown, dense, hard, extremely thinly bedded (~ 1mm). RQD = 1.00.
377'5" to 377'10"	BITUMINOUS SHALE - light brown to brown, dense, hard, with some crystalization, extremely thinly bedded (~ 1mm). RQD = 1.00.

From/To (Feet) *	Description
377'10" to 378'1"	BITUMINOUS SHALE - light brown, dense, hard, extremely thinly bedded (~ 1mm). RQD = 1.00.
378'1" to 378'7"	BITUMINOUS SHALE - light brown to brown, dense, hard, with some crystalization, extremely thinly bedded (~ 1mm). RQD = 1.00.
378'7" to 379'8"	BITUMINOUS SHALE - light brown to brown, dense, hard, extremely thinly bedded (~ 1mm). RQD = 1.00.
379'8" to 379'10"	BITUMINOUS SHALE - nearly black, dense, hard, extremely thin bedded (~ 1mm), some BITUMINOUS SILTSTONE - horizontal veinlets, micaceous, RQD = 1.00.
379'10" to 380'8"	BITUMINOUS SHALE - light brown, dense, hard, extremely thin bedded (~ 1mm), occasional small pieces of anthracite. RQD = 1.00.
380'8" to 382'3"	MUDSTONE - light greenish-gray, slightly dolomitic, pyritic on bedding planes, dense, hard, massive to poorly bedded, rare thin anthracite partings. RQD = 1.00.
382'3" to 382'9"	MUDSTONE - light gray-brown, slightly dolomitic, pyritic on bedding planes, dense, hard, massive to poorly bedded, rare thin anthracite partings. RQD = 1.00.
382'9" to 385'9"	BITUMINOUS SHALE - light brownish-gray, dense, hard, extremely thin (~ 1mm) bedded, some crystalization. RQD = 1.00.
385'9" to 389'2"	BITUMINOUS SHALE - light brown to light brownish gray, crystalization, rare extremely thin (~ 1mm) anthracite partings, very regularly bedded (~ 1mm), dense, hard, rare extremely thin (~ 1mm) pyritized veinlets. RQD = 1.00.
389'2"	QUARTZ SANDSTONE - light gray, extremely micaceous, hard, ½" thick, porous. RQD not calculated.

From/To (Feet) *	Description
389'2" to 392'0"	BITUMINOUS SHALE - brown, dense, hard, extremely thin (~ 1mm) bedded, some crystalization. RQD = 1.00. Fracture at 391'0" ($\frac{1}{2}$ ") and 391'6" (~ 1/8") with shale parting.
390'11" to 391'3"	QUARTZ SANDSTONE - extremely micaceous, fine grained, porous, low hardness, wet, occurs in pocket. RQD not calculated.
392'0" to 392'5"	QUARTZ SANDSTONE - yellowish-brown, slightly wet, calcareous, very micaceous, low hardness, tuffaceous, porous, massive, some oil staining. Fractures at 392'1" with iron staining and 392'4". RQD = 0.00.
392'5" to 392'11"	BITUMINOUS SHALE - brown, dense, hard, extremely thin (~ 1mm) bedded, some crystalization. RQD = 1.00.
392'11" to 393'10"	Slightly BITUMINOUS MUDSTONE - light greenish-gray to light brownish-gray, very dense, hard, massive. RQD = 1.00.
393'10"	DOLOMITE - ($\frac{1}{4}$ ") light brown, hard, fracture through middle of zone. RQD not calculated.
393'10" to 393'11"	Slightly BITUMINOUS MUDSTONE - light greenish-gray to light brownish-gray, very dense, hard, massive. RQD = 1.00.
393'11"	DOLOMITE - ($\frac{1}{2}$ "), light brown, hard, fractured through middle of zone. RQD not calculated.
393'11" to 394'9"	BITUMINOUS SHALE - light brown to light gray, some crystalization, hard, dense, extremely thin (~ 1mm) regular beds, occasionally micaceous along bedding planes. RQD = 1.00.
394'9"	DOLOMITE - $\frac{1}{4}$ ", light brown, hard. RQD not calculated.
394'9" to 396'3"	BITUMINOUS SHALE - brown, dense, hard, extremely thin (~ 1mm) bedded, some crystalization. RQD = 1.00.
396'3" to 396'11"	BITUMINOUS SHALE - dark brown, dense, hard, extremely thin (~ 1mm) bedded, some crystalization. RQD = 1.00.

From/To (Feet) *	Description
396'11" to 397'3"	BITUMINOUS SHALE - dark brown to nearly black, dense, hard, extremely thin (~ 1mm) bedded, some crystalization. RQD = 1.00.
397'3" to 398'2"	BITUMINOUS SHALE - dark brown, dense, hard, extremely thin (~ 1mm) bedded, some crystalization. RQD = 1.00.
398'2" to 398'10"	BITUMINOUS SHALE - dark brown, dense, hard, extremely thin (~ 1mm) bedded, some crystalization, some pyrite at 398'2". RQD = 1.00.
398'10" to 399'9"	BITUMINOUS SHALE - brown, dense, hard, extremely thin (~ 1mm) bedded, some crystalization. RQD = 1.00.
399'9" to 400'3"	BITUMINOUS SHALE - dark brown, dense, hard, extremely thin (~ 1mm) bedded, some crystalization. RQD = 1.00.
400'3" to 400'4"	QUARTZ SANDSTONE - yellowish-brown, slightly wet, calcareous, tuffaceous, very micaceous, low hardness, porous, some oil staining. RQD not calculated.
400'4" to 400'9"	BITUMINOUS SHALE - dark brown, some crystalization, hard, dense, extremely thin (~ 1mm) regular beds, occasionally micaceous on bedding planes. RQD = 1.00.
400'9"	DOLOMITE - $\frac{1}{4}$ ", mixed with tuffaceous SANDSTONE - brown to yellowish-brown, hard (dolomite) to low hard (sandstone), porous, no bedding, slightly oil stained, weak zone but not fractured. RQD not calculated.
400'9" to 401'4"	BITUMINOUS SHALE - dark brown, some crystalization, hard, dense, extremely thin (~ 1mm) regular beds, occasionally micaceous along bedding planes. RQD = 1.00.
401'4"	DOLOMITE - ($\frac{1}{2}$ "), light brown, hard, weak zone, fractured through middle.

From/To (Feet) *

Description

401'4" to 401'8"	BITUMINOUS SHALE - light grayish-brown, some crystalization, hard, dense, extremely thin (~ 1mm) regular beds, occasionally micaceous on bedding planes. RQD not calculated.
401'8" to 401'9"	X. TUFF - tan, silicious, calcareous, low hardness, fine grained, irregularly bedded with dolomite inclusion, fractured in middle, weak zone. RQD = 0.00.
401'9" to 402'5"	BITUMINOUS SHALE - dark brown, some crystalization, hard, dense, extremely thin (~ 1mm) regular beds, occasionally micaceous along bedding planes, abundantly pyritic. RQD = 1.00.
402'5" to 402'6"	DOLOMITE - brown to light brown, hard. RQD not calculated.
402'6" to 402'11"	BITUMINOUS SHALE - grayish-brown, some crystalization, hard, dense, extremely thin (~ 1mm) regular beds, occasionally micaceous on bedding planes. RQD = 1.00.
402'11" to 403'0"	DOLOMITE - brown, very hard but brittle, well bedded. Fractured at 402'11(½)".
403'0" to 403'8"	BITUMINOUS SHALE - dark brown, dense, hard, extremely thin (4mm) beds, some crystalization, occasionally micaceous on bedding plane. RQD = 1.00.
403'8"	BITUMINOUS SHALE - light brown, dense, hard, extremely thin (~ 1mm) beds, some crystalization, occasionally micaceous on bedding plane (½"). RQD = 1.00.
403'8" to 405'9"	BITUMINOUS SHALE - very dark brown, dense, hard, extremely thin (~ 1mm) beds, well laminated, breaks readily upon bedding planes, some crystalization, occasionally micaceous along bedding plane, weak zone at 404'3" with some thin light brown DOLOMITE parting within shale. RQD = 1.00.
405'9" to 406'9"	BITUMINOUS SHALE - dark brown, dense, hard, extremely thin (4mm) beds, some crystalization, occasionally micaceous along bedding plane. RQD = 1.00.

From/To (Feet) *	Description
406'9" to 406'10"	SANDSTONE QUARTZ - gray to dark gray, fine grained, micaceous, irregularly bedded, hard to mod hard, dense, slightly porous and oil stained. RQD not calculated.
406'10" to 407'5"	BITUMINOUS SHALE - dark brown, dense, hard, extremely thin (4mm) beds, some crystalization, occasionally micaceous on bedding plane. RQD = 1.00.
407'5" to 407'7"	MUDSTONE - tan, dense, hard, massive, dolomitic, contains fine sand sized specks of a black mineral.
407'7" to 408'7"	BITUMINOUS SHALE - dark brown, dense, hard, extremely thin (4mm) beds, some crystalization, occasionally micaceous on bedding plane, thin veinlets of finely crystalline galena. RQD = 1.00.
408'7" to 408'11"	QUARTZ SILTSTONE - light brown to dark brown, very hard, contains fine sand-sized specks of a black mineral (perhaps biotite), dense. Fracture at 408'11". RQD = 0.00.
408'11" to 409'6"	BITUMINOUS SHALE - dark brown, dense, hard, extremely thin (4mm) beds, some crystalization, occasionally micaceous along bedding plane. RQD = 1.00.
409'6" to 410'6"	BITUMINOUS SHALE - light brown, dense, hard, extremely thin (4mm) beds, some crystalization, occasionally micaceous along bedding plane.
410'6" to 410'10"	GEODES - irregular pockets, silicious crystals and plates, light gray to dark gray to brown, small amount of calcareous cementing, bituminous, small oil staining, some iron staining. Abundant (~ 1mm) globules of dark reddish-brown mineral, soft, sticky (nacholite?, gilsonite?), weak zone. Fracture at 410'7".
410'10" to 411'5"	BITUMINOUS SHALE - light brown, dense, hard, extremely thin (4mm) beds, some crystalization, occasionally micaceous on bedding plane with QUARTZ SILTSTONE - light brown to dark

From/To (Feet) *	Description
410'10" to 411'5" (Continued)	brown, very hard, contains fine sand-sized specks of a black mineral (perhaps biotite), dense, interbeds. SILTSTONE - ($\frac{1}{2}$ "). Fracture at 411'3".
411'5" to 411'10"	BITUMINOUS SHALE - light brown, dense, hard, extremely thin (4mm) beds, some crystalization, occasionally micaceous on bedding plane.
411'10" to 412'2"	BITUMINOUS SHALE - light brown, dense, hard, extremely thin (4mm) beds, some crystalization, occasionally micaceous on bedding plane, with QUARTZ SILTSTONE - light brown to dark brown, very hard, contains fine sand sized specks of a black mineral (perhaps biotite), dense, interbeds. SILTSTONE - ($\frac{1}{2}$ "). Fracture at 412'1 $\frac{1}{2}$ " at interface between siltstone and shale. Weaker area. RQD = 0.00.
412'2" to 413'1"	BITUMINOUS SHALE - light brown, dense, hard, extremely thin (4mm) beds, some crystalization, occasionally micaceous along bedding plane.
413'1" to 413'5"	MUDSTONE - gray, dense, hard, extremely thinly laminated, cleaves readily along lamina, thin shale parting at 413'1", veinlets of galena. RQD = 1.00.
413'5" to 414'0"	BITUMINOUS SHALE - dark brown, dense, hard, extremely thin (4mm) beds, some crystalization, occasionally micaceous along bedding plane. RQD = 1.00.
414'0" to 414'3"	QUARTZ SILTSTONE - (~ 1/8") white, tuffaceous at 414'0" and geode - thin (~ $\frac{1}{4}$ ") as 410'6" to 410'10". QUARTZ SANDSTONE - light maroon, fine grained, micaceous, moderately hard. Fractures at 414'1", 414'2", weak zone. RQD = 0.00.
414'3" to 417'0"	BITUMINOUS SHALE - light brown to light gray, hard, dense, some crystalization, occasionally micaceous on bedding plane, extremely thin (~ 1mm) beds, alternating with MUDSTONE - light brownish-gray to light gray, laminated but dense, ($\leq \frac{1}{2}$ ") layers, hard. Fractures at 414'11", 416'1".

From/To (Feet) *	Description
417'0" to 419'10"	MUDSTONE.- gray, hard, dense, slightly dolomitic, micaceous, massive to poorly bedded; DOLOMITE - thin ($\frac{1}{4}$ "), gray. Fractures occur at dolomite beds, 418'0", 418'5", 418'10", 419'9". RQD = 1.00.
419'10" to 421'7"	BITUMINOUS SHALE - light brown, alternating with thin (~ 1/8") beds of MUDSTONE - light brown, irregularly bedded, rare small pockets of galena, hard, dense, some crystalization. RQD = 1.00.
421'7" to 423'6"	Slightly BITUMINOUS SHALE - dark brown with MUDSTONE - dark gray, very irregularly bedded, hard, dense, slightly dolomitic. RQD = 1.00.
423'6" to 424'3"	QUARTZ SANDSTONE - light gray, tuffaceous, calcareous, micaceous, low hardness, silty, contains numerous forams, porous. Fractures at 423'6", 423'9", 423'10". RQD = 0.00.

* Not adjusted to S5.