DOE/LC/RI-82-5
(DE82021088)

STRATIGRAPHIC VARIATIONS IN OIL SHALE FRACTURE PROPERTIES

By
Chapman Young
Nancy C. Patti
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September 1982
Date Published

Work Performed Under Contract No. AP20-82LC00389

Laramie Energy Technology Center
Laramie, Wyoming

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STRATIGRAPHIC VARIATIONS
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Chapman Young,* Nancy C. Patti,* and Bruce C. Trent*

ABSTRACT

The proper design and evaluation of in situ oil shale fracture and retorting experiments require that both the extreme values and spatial distribution of the controlling rock properties be adequately known. Many of the in situ technologies being considered for processing within the Green River Formation in Colorado, Wyoming and Utah depend upon the carefully controlled explosive fracturing of the rock such that suitably uniform permeabilities are achieved. The prediction, control and evaluation of explosive oil shale fracturing require a detailed knowledge of tensile strength behavior as a function of shale grade and stratigraphic position. Direct-pull tensile tests, point-load pinch tests, and four-point-bend fracture toughness tests have been utilized to develop detailed logs of the relevant fracture properties for the 37 m thick Mahogany Zone section of the Green River Formation near Anvil Points, Colorado and for the rich, upper 13 m of the Tipton Member near Rock Springs, Wyoming. For the Mahogany Zone shale tensile strengths ranged up to 15.3 MPa (2220 psi) for direct-pull tests and 43.4 MPa (6290 psi) for indirect tests. Fracture energy values for this shale ranged from 8 J/m² to 191 J/m². For the Tipton shale tensile strengths ranged up to 3.7 MPa (536 psi) for direct-pull tests and 12.6 MPa (1830 psi) for indirect tests. Fracture energy values for the Tipton averaged from 5 J/m² to 91 J/m². Detailed statistical analyses were performed on these data and on Fischer assay oil yield data to establish the correlations between them. Data from both tensile strength and fracture energy tests correlate well with lithologic and oil yield characteristics of the Mahogany Zone shale while poor correlations were found for the Tipton shale. Extensive direct-pull tensile testing was performed on 14.6 m of Utah Mahogany Zone shale from the Geokinetics site near Vernal, Utah, but the lack of other fracture property data and oil yields precluded any statistical analyses.

+Work performed in the Geomechanics Laboratory, Civil Engineering Department, Colorado State University, Fort Collins, Colorado.

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INTRODUCTION

With few exceptions the methods being presently considered for the exploitation of oil from oil shale require extensive fracturing and fragmentation of the rock. Where the shale is to be processed by surface retorting, the rock must be mined and crushed. Although relatively conventional mining and crushing operations can be employed, some consideration must be given to the specific fracturing properties of oil shale for process optimization. Many oil-shale processing technologies are designed to fracture and retort the rock in situ. The in situ processing methods are considered as being either true in situ, wherein the rock is adequately fractured by the placement of explosives in wellbores or hydraulic type fractures, and modified in situ, wherein mining operations are employed to provide an initial void volume into which the rock may be explosively fractured. Several research programs have been conducted to evaluate various true in situ approaches with the results being generally disappointing.^{1,2,3*} At present, serious consideration is being given only to modified in situ technologies with the void volume required for adequate fragmentation and permeability development being provided either by surface heave or partial mining.⁴ Successful in situ retorting of oil shale requires that the fractured and fragmented rock have adequately uniform and homogeneous permeability which in turn requires that the explosive fragmentation process be well controlled. The large stratigraphic variations in oil shale, especially with respect to the organic content of the rock, could play an important role in controlling the in situ fragmentation process. If in situ fragmentation is to be controlled and optimized for the recovery of shale oil, the stratigraphic variations in oil-shale fracture properties must be described and understood.

Although significant oil-shale deposits exist in the eastern United States, most consideration has been given to the shales of the Green River Formation in Colorado, Wyoming and Utah. The Green River shales are found in three separate basins representing three distinct inland lakes or seas

* Numbers refer to references at end of paper.

in which the rocks were deposited during the Eocene Epoch of the Tertiary Period. Most consideration of true in situ processing techniques have been done for the Tipton Member of the Green River Formation in the Green River Basin of Wyoming. These research efforts were conducted by the Department of Energy at the Rock Springs Field Site^{1,2} and by Talley Energy Systems Inc. at a site near Green River, Wyoming.³ Most studies of modified in situ methods have been carried out in the Mahogany Zone portion of the Parachute Creek Member of the Green River Formation in the Piceance Creek Basin, Colorado.⁴ A modified in situ technology involving near surface deposits and surface heave during the explosive fragmentation process has been extensively studied by Geokinetics, Inc. in shales stratigraphically equivalent to the Mahogany Zone at a site 30 miles south of Vernal, Utah in the Uintah Basin.⁵ Because of the interest in oil shale processing in these three basins, it is desirable to have sufficient data on the fracture properties of rock from each of these three areas. Core material was obtained by the Laramie Energy Technology Center of the Department of Energy for the specific purpose of obtaining data on the mechanical properties of oil shale and their stratigraphic variations at each of these areas.

An extensive data base exists on the compressive strength and elastic properties of most oil shales of interest.^{6,7,8} In addition these properties have been found to be highly correlatable with the organic content or oil yield of the rock. As complete a data base does not exist for the tensile or fracture properties of oil shale. Since the tensile fracture of the rock would be expected to be controlled by subtle variations in mineralogy (especially the clay mineralogy) it would not be expected that these properties would be as readily correlated to organic content. To the extent that tensile fracture properties cannot be correlated to other rock properties such as organic content these properties must be described on a site specific and stratigraphically controlled basis.

Many standard techniques exist for determining the tensile and fracture properties of a variety of materials including rocks. Most of these techniques, however, are designed for obtaining high-precision data

on a relatively few number of samples and require significant sample preparation. As a proper description of the stratigraphic distribution of oil shale fracture properties would require an unusually large number of tests, it would be desirable if not necessary to develop modified test procedures that could be performed on a production basis with a minimal amount of sample preparation effort. Due to the inherent variability of the mechanical properties of rocks, and especially the fracture properties, it is not necessary that such modified techniques be able to provide the degree of precision often required in mechanical property testing. For the fracture properties of oil shale it is more meaningful to have a large, stratigraphically distributed data base than a few unnecessarily precise data points. A significant portion of the efforts reported upon here involved the development of specialized and modified experimental techniques for testing oil shale on a production basis.

EXPERIMENTAL METHODS

Numerous experimental methods have been developed and evaluated for determining the tensile-strength and fracture-toughness properties of rocks. Although some of these methods have become standardized, it has been necessary to develop methods especially applicable to the testing of oil shale. Three basic types of tests have been developed for determining the stratigraphic variations in oil-shale fracture properties. As the tensile strength is the most basic description of a rock's fracture behavior, a standardized direct-pull tensile strength method was modified for application to the oil shales of interest. Direct-pull tensile strength tests provide data on the weakest zones in a rock. Such tests cannot provide data on the stronger rock between weaker zones. An indirect-tensile test method could provide data on the stronger portions of the rock and could be applied more readily to rock samples of limited dimensions. Due to the difficulty in preparing specimens for the more traditional Brazilian indirect-tensile strength test, a point-load test method was adopted and developed for application to oil shale. While tensile-strength values can provide a good measure of the rock's ability to support certain applied stresses, tensile-strength data alone are not suitable for fracture mechanics calculations of fracture growth and propagation. Consequently, a simple fracture-energy test was modified so that fracture-energy values could be readily obtained on a production basis and on relatively small oil-shale samples.

Direct-Pull Tensile Tests

In determining the stratigraphic variations in tensile strength of an oil-shale section it is necessary to have data both on the stratigraphic occurrence of bedding planes, parting planes and other weak zones and on the tensile strength of the more competent rock lying between the planes of easy separation. Once the naturally occurring parting planes have been logged then the location and strength of weak bedding planes can be best determined by direct-pull tensile tests. Although a standard tensile testing procedure (ASTM D-2936)⁹ has been established for rocks,

it was necessary to modify this procedure for application to oil shale. The most significant modification involved the use of square prism specimens required to minimize desiccation cracking of the samples as discussed under sample preparation below. For some of the Tipton tests and all of the Colorado and Utah Mahogany Zone tests, it was possible to utilize a 3.56 cm diameter core. Both the square prism and cylindrical test specimens were attached to gimballed loading blocks with epoxy cements especially suited to the particular rock types. As illustrated schematically in Figure 1, direct-pull tensile strength data was obtained on the 5 cm square by 10 cm long prism specimens loaded in tension in a standard servo-controlled testing machine.

Flexural loading of the specimens was minimized by using a modified universal joint arrangement, whereby two orthogonal axes of rotation served to keep the tensile loads oriented along the axis of the sample. Development of a system for gripping the sample so that multiple tensile breaks could be obtained was the most difficult task. This task was complicated for the Tipton shale by the need to maintain sample moisture during preparation and testing. Because of the difficulty in finding an epoxy or other glue which would cure in a moist environment, it was decided to test several rapid curing glues so that sample desiccation could be minimized. Several Hysol*epoxies and a cyanoacrylate cement (Super-Glue-3) were evaluated. The shale samples were readied for gluing by placing them in a warm (40 to 50°C) bath of chemically buffered water. Gluing was accomplished by removing the warm sample from the bath, wiping and blow drying the surfaces, applying glue to one of the faces to be glued and then holding the glue joint in compression (at 0.1 to 0.5 MPa) for the three to five minutes required for the various glues to set. Once the glues were cured, the sample, including any attached gripping blocks, were returned to the warm bath where they were kept until tensile testing was to be performed.

Although glue joints of moderate strength were obtained with all of the glues tested, it was found that consistently strong joints were only obtained with the epoxy, Hysol 608. As this epoxy was clear, it was possible to observe that the epoxy had an excellent wetting effect

*Hysol Division, The Dexter Corporation, Olean, New York 14760

Figure 1. Schematic view of gimbal assemblies used to minimize flexural loading in direct-pull tensile tests.

on the clay rich Tipton shale. It is believed that this wetting effect, coupled with the very short three-minute curing time for this epoxy, was responsible for the excellent quality of the glue bonds. Multiple breaks, often with markedly increasing tensile strength values, were obtained by recementing each tensile break with the Hysol 608 epoxy. The fracture surfaces were cleaned of any loose chips and fragments by scratching the surfaces on an orthogonal, one-centimeter grid spacing pattern with a sharp knife point. Once testing was completed on a prism, the samples and gripping blocks were separated by placing the aluminum blocks on a hot plate and heating them to $\sim 150^{\circ}\text{C}$ thus causing enough softening of the glue joint between sample and block that they could be separated with a knife.

For some of the testing on the Tipton shale and all of the testing on the Mahogany Zone shale from Colorado and Utah test specimens were made by coring 3.65 cm diameter core specimens out of the 8.9 and 15.2 cm diameter core pieces obtained for this purpose. For performing tensile tests on the 3.65 cm diameter material the aluminum gripping blocks were remachined so that a 60° included-angle cone served as a transition between the 3.65 cm diameter gripping surface and the 5.1 cm square bearing end of the block. A photograph of a 3.65 cm diameter test specimen installed in the testing apparatus is shown in Figure 2.

By regluing and retesting the specimens, efforts were made to obtain at least one direct-pull tensile strength break per 3 cm of the Tipton shale. For the Colorado Mahogany Zone shale obtained in NOS corehole 26, approximately one tensile break per 5 cm of specimen was obtained and for the Geokinetics Mahogany Zone shale only one tensile break per 10 cm of specimen was obtained. For the Tipton, this usually required that five to seven breaks be made for each 10 cm long test specimen and that unusually weak and friable zones be cut out of the test specimens once tensile data was obtained on them.

Figure 2. View of MTS servo-controlled loading system with 3.65 cm diameter oil shale sample ready for direct-pull tensile test.

Indirect Tensile Strength Tests

Because of the difficulty in preparing and loading direct-pull tensile specimens, indirect testing methods are often used for evaluating the tensile-strength properties of rocks. The Brazilian test, wherein a cylindrical disk of rock is loaded diametrically, is the most commonly utilized method.¹⁰ The Brazilian test is attractive because sample preparation is simple and because linear elastic analyses indicate that a large portion of the sample is subjected to a relatively uniform tensile stress. The Brazilian test is limited in that the inferred tensile strengths are usually calculated for an isotropic linear elastic material and any deviation of the rock from such ideal response (including localized plastic deformation where the load is applied to the sample circumference) will result in unknown deviations in the calculated stress. The stresses and strains in a transversely isotropic Brazilian test specimen have been calculated for the case where the axis of the disk is parallel to the axis of symmetry in the sample.¹¹

A second indirect tensile strength method, often referred to as a "pinch" test, involves the loading to failure of a cylindrical rock specimen by two hardened steel rollers oriented perpendicular to the cylindrical axis of the specimen.¹² As for the Brazilian test, the tensile stresses acting within the rock specimen are calculated utilizing isotropic linear elastic theory. The indirect-tensile strength value, obtained with the pinch test is given by:

$$\sigma_t = 0.96 \frac{P_{\max}}{d^2}$$

where $P_{\max}$ is the load at failure and d is the sample diameter.¹² Again any non-linear non-isotropic response of the sample and especially any plastic deformation of the sample in contact with the hardened steel rollers, will result in an unknown variation in the actual stress causing failure. In an effort to evaluate the importance of local plastic yielding where the rollers contact the samples, a series of experiments were performed on 1.27 cm diameter core material using hardened steel rollers 0.64 cm and 0.95 cm in diameter. By using two parallel (stratigraphically identical) 1.27 cm diameter cores it was observed

that variations in tensile strength along the sample were comparable for both diameters of hardened steel rollers. The larger, 0.95 cm rollers, however, did yield higher tensile-strength values, indicating less plastic deformation of the sample during loading. All of the indirect-tensile-strength data reported upon here was obtained using 0.95 cm diameter hardened steel rollers on 1.27 cm diameter core material of the rock. In general, the indirect tensile strength tests were performed on ~2.5 cm long segments of 1.27 cm diameter core remaining after the fracture energy tests discussed below were performed.

Fracture Energy Tests

Numerous experimental techniques have been developed and evaluated for determining the fracture toughness of brittle materials such as rock. Fracture toughness values, whether expressed in units of energy per square surface area (e.g. J/m²) or in terms of the critical stress intensity factor, K_{IC} , (Nm^{-3/2}) are a measure of the work required to propagate a given fracture. Small scale borehole pressurization experiments,¹³ pressure wedge splitting of 1.27 cm diameter "V" notched specimens,¹⁴ and fatigue crack initiation in three-point-bend specimens,^{15,16} have all been used successfully to measure fracture toughness values in a variety of rock types. Unfortunately, all of these methods require large volumes of sample material and/or extensive sample preparation procedures. For the large number of tests required to develop a stratigraphic "log" of fracture toughness values, a simple and readily interpreted test is required. Three-point-bend tests, wherein the work or energy to fracture a sample of known dimensions, have been developed and extensively utilized on a variety of rock types.^{17,18} The only requirement for performing such energy dissipation fracture experiments is that fracture propagation be stable throughout fracture growth so that the work represented by the load/displacement curve of the testing machine can be directly correlated to the energy of fracture. Cooper¹⁸ analyzed in detail the energy requirements for stable crack propagation. By carefully matching sample geometry to loading machine characteristics, Cooper was able to obtain stable crack propagation in brittle rocks such as Solenhofen limestone.

The experimental apparatus for obtaining fracture toughness values by the energy dissipation method is illustrated schematically in Figure 3. In order to expedite sample preparation and permit the use of small pieces of sample material, a jig for holding and loading a standard 1.27 cm diameter core piece was designed and built. As illustrated in Figure 3 the 1.27 cm diameter pieces to be tested were notched so that the V-shaped segment of material remaining would provide both a sharp stress concentration for easy fracture initiation and an increasing fracture length with propagation for increased stability. As noted by Cooper¹⁸ this V-shaped notch is beneficial, although not always essential, for obtaining stable breaks. The fracture toughness tests were performed on 1.27 cm diameter core pieces up to 10 cm long obtained from either wire-sawn crescent-shaped segments (see sample preparation below) or the 8.9 or 15.2 cm diameter core pieces. These cores were then V-notched on approximately 2.54 cm intervals so that, on average, three fracture toughness values were obtained for each 10 cm of core. The residual, approximately 2.54 cm long, core pieces recovered from the fracture toughness tests were then used for the indirect-tensile-strength tests discussed above. Sample drying and desiccation cracking were minimized during both the fracture-toughness and indirect-tensile-strength tests by carefully keeping the sample material moist at all times. A photograph of the aluminum blocks for holding and loading 1.27 cm diameter samples is shown installed in the test frame in Figure 4.

All three experimental methods discussed in the preceding paragraphs were utilized to evaluate the fracture properties of the rich upper 13.1 m (43 ft) of the Tipton Oil Shale, the 36.6 m (120 ft) of Mahogany Zone shale recovered in NOS corehole 26 and 15.2 m (50 ft) of the Mahogany Zone shale recovered from the Geokinetics site. The Tipton and Colorado Mahogany Zone shales were extensively tested while testing on the Geokinetics shale was limited primarily to direct-pull tensile strength tests. The basic data obtained and the consequent data analyses and interpretations are given in the following sections.

Figure 3. Schematic view of aluminum block jig used to load 1.27 cm diameter test specimens for four-point bend fracture energy tests.

Figure 4. Close-up view of MTS loading frame with jig for holding 1.27 cm diameter core pieces for energy of fracture measurements.

Sample Preparation and Handling

In obtaining the core material to be utilized for the fracture property testing, special precautions were taken to preserve the natural in situ quality of the rock. Most notably, the Tipton Member shale near Rock Springs, Wyoming had been observed in earlier cores to undergo significant desiccation shrinkage and cracking. So as to minimize the effects of desiccation cracking upon test results, a large diameter (15.2 cm) core was taken and was protected from desiccation by wrapping the core in polyethelene bags with a few deciliters of drilling mud. Although the Mahogany Zone shale from the Geokinetics site was not as moisture sensitive, comparable precautions were taken to protect this core which was also 15.2 cm in diameter. As the Mahogany Zone shale of the Piceance Basin has not been noted to display any moisture sensitive behavior, a smaller 8.9 cm diameter core was taken of this rock and techniques to prevent the core from drying were not required.

In order to maximize the amount of material available for testing and minimize the possibilities for desiccation and other mechanical and chemical degradation of the Tipton shale, most sample preparation was done with a diamond wire saw. The wire sawing was performed by the Department of Civil Engineering, University of Wyoming, Laramie. As illustrated in Figure 5 the basic 15.2 cm core was first sectioned into pieces 10.2 cm long with the wire saw and these pieces were in turn cut so as to yield four 5.1 cm square prisms and four crescent shaped segments. One of the 5 cm square prisms and one crescent segment from each 10 cm long piece of core were delivered to Colorado State University (CSU) where the fracture property testing was conducted. When natural core breaks or tuff beds precluded cutting the 15 cm core into prisms then the core segment was delivered to CSU and the required test specimens were cut directly from these pieces.

As the Geokinetics and Colorado NOS 26 Mahogany Zone shales did not contain extensive mixed-layer clays and were relatively insensitive to desiccation cracking, the extensive sample preparation procedures outlined above were not employed for these two rocks. Efforts were made to keep the original 15.2 cm diameter core obtained from the Geokinetics site

Figure 5. Detail of wire-saw cutting and coring operations used to prepare test specimens from 15.2 cm diameter core material.

moist during all phases of sample preparation. 3.65 cm diameter cores were prepared of this rock for the direct-pull tensile tests and a few smaller 1.27 cm diameter samples were prepared for fracture-toughness and indirect-tensile-strength tests. All of these test specimens were kept moist up to the time of actual test execution. As the NOS 26 Mahogany Zone shale contained essentially no mixed-layer clays nor propensity for desiccation cracking, this core material was neither protected as it was recovered in the field nor were special procedures utilized in test specimen preparation to protect sample moisture content. The higher strength values noted for the Geokinetics and especially the NOS 26 shales as compared to the Tipton shale also required that higher strength epoxy be employed in the direct-pull tensile strength tests. Two other Hysol epoxies were found to be quite suitable for attaching oil shale samples to the aluminum grip blocks and to recementing fractures so that multiple fracture tensile strength data could be obtained. Hysol 615 epoxy was found to be quite satisfactory for tensile strengths up to 10 MPa (1450 psi). For unusually strong oil shale test specimens such as regularly encountered in the NOS 26 core material Hysol 907 epoxy was found to be the most satisfactory. This epoxy provided adequate adhesion of the oil shale to the aluminum grip blocks for tensile strength measurements up to 16 MPa (2320 psi). Both the Hysol 907 and 615 epoxies required that the samples be dry for adequate adhesion to the rock to be achieved. In addition, the Hysol 907 epoxy required that the prepared sample be allowed to cure overnight at room temperature or that the sample and aluminum blocks be heated to 60°C for approximately two hours.

EXPERIMENTAL RESULTS

The fracture properties of the NOS 26 Mahogany Zone shale, the rich upper Tipton shale and the Geokinetics shale have been obtained utilizing the experimental methods discussed in the preceding section. These properties were obtained as continuously as possible so that stratigraphic "logs" were developed of the properties over the sections of interest. Such continuous sampling, coupled with careful handling of the sample material, provides a picture of fracture properties which is more representative of the in situ characteristics of the rock than would be obtained by more traditional approaches. Geotechnical and mechanical property data on rocks are usually obtained by testing a few (supposedly representative) samples of material obtained from coring or mining operations. Such limited sampling usually results in the tested material being representative of the more competent and environmentally inert portions of the rock. Zones which are fractured, friable and/or which may suffer degradation once the sample has been taken are often excluded from such selective testing. In the design and analysis of in situ explosive fragmentation methods for oil shale it is important that the weaker and more heterogeneous zones and beds be considered also.

NOS 26 Mahogany Zone Shale

All of the fracture property data obtained for the Mahogany Zone Shale recovered from NOS 26* are illustrated in Figures 6 through 9. The direct-pull tensile strength data, comprising 909 individual direct-pull tests, are illustrated in Figure 6. The small squares represent the tensile strength values and depth for each test conducted over the interval 265 m (870 ft) to 302 m (990 ft). Several different averaging techniques have been evaluated for providing representative formation values. The continuous curve drawn through the data in Figure 6 represents a running average value of tensile strength tabulated for 1.52 m (5 ft) intervals calculated and plotted at 0.76 m (2.5 ft) increments of depth. While the raw data, represented by the small squares in Figure 6, appears to be

* U.S. Naval Oil Shale Reserve No. 1, Corehole 26, SE $\frac{1}{4}$ Sec. 36, T5S, R95W, Garfield County, Colorado ¹⁹

Figure 6. Direct-pull tensile strength data for the 36.6 m Mahogany Zone shale recovered from NOS 26.

quite scattered the running average of this data clearly reveals zones of high and low average tensile strength. The significance of these variations in average tensile strength both in terms of stratigraphic distribution and in terms of correlations with other shale properties will be discussed in further detail below.

As test specimens were being prepared from the 8.9 cm diameter core obtained in NOS 26, all fractures and parting planes were carefully logged. Based upon their morphology, chisel marks and their occurrence at intervals corresponding to core box lengths, it was possible to classify most of the fractures and parting planes as being either natural or induced. The natural parting planes would correspond to natural bedding planes of little or no strength. All of the logged natural parting planes are illustrated in Figure 7 along with the 1.52 m running average curve obtained from the direct-pull tensile strength data. As noted in Figure 7 there is significant agreement between zones of low average tensile strength and the number of natural parting planes. An implied zero tensile strength value for the natural parting planes was not included in the running average of tensile strength.

All of the indirect-tensile strength data, comprising 1079 data points obtained by the pinch test method, are illustrated in Figure 8. As previously noted, the indirect-tensile strength provides a better measure of average rock tensile properties than does the direct-pull test method as the latter samples preferentially the weakest portions of the rock. This aspect of the indirect-tensile strength data is well illustrated by comparing Figures 8 and 6. The indirect-tensile strength data displays less scatter than does the direct-pull data and the measured tensile strength values are significantly higher. As will be discussed in the following section on statistical correlations, good correlations exist between direct-pull and indirect-tensile strength data with the indirect-tensile strength being over 2 times greater than the direct-pull strength.

All of the fracture energy data obtained for the NOS 26 Mahogany Zone shale is illustrated in Figure 9. As discussed in the preceding section (Experimental Methods) the fracture energy values were obtained utilizing

Figure 7. Distribution of natural parting planes (horizontal dashed lines) logged in the 8.9 cm diameter NOS 26 core.

TENSILE STRENGTH -INDIRECT (MPa)

Figure 8. Indirect tensile strength data for NOS 26 Mahogany Zone shale.

Figure 9. Fracture energy data for NOS 26 Mahogany Zone shale.

a modified four-point-bend apparatus in which stable fracture propagation was obtained and the fracture energy calculated from the area under the load displacement curve during this stable fracture propagation. While the raw fracture energy data does display a great deal of variability or scatter, the running average (1.52 m interval calculated each 0.76 m) does reveal zones of distinct high and low fracture energy values. The range of fracture energies measured for the NOS 26 Mahogany Zone, ranging from 8 J/m² to 147 J/m², correspond well with fracture energy values obtained on other rocks.¹⁸ As will be discussed in greater detail below, the fracture energy has a negative correlation with both the direct-pull and indirect-tensile strength properties of the Mahogany Zone shale.

So as to obtain oil yield data with which the shale fracture properties could be directly correlated, Fischer assay oil yields were obtained on the NOS 26 core. The Fischer assay tests were performed by the Laramie Energy Technology Center on samples prepared from the 8.9 cm diameter core remaining after the fracture property test specimens had been taken. The Fischer assays were performed on 0.3048 m (1 ft) samples. The Fischer assay oil yield for the NOS 26 Mahogany Zone is illustrated in Figure 10. The stratigraphic distribution of oil yield for the NOS 26 core correlates well with other Mahogany Zone oil yields in the southeast corner of the Piceance Basin.

Comparisons between the three fracture property values obtained and the oil yield for the NOS 26 Mahogany Zone are illustrated comparatively in Figure 11. As both fracture energy and oil yield have negative correlations with the direct-pull and indirect-tensile strength data, the scale for fracture energy and oil yield (which cover a comparable numerical value range) has been inverted in Figure 11. The running average data presented in Figure 11 suggests strongly that significant correlations should exist between the three fracture property values measured and oil yield. These correlations have been quantified and are discussed in detail in the following section.

Figure 10. Fischer assay oil yield obtained for 30.5 cm (1 ft) intervals from the NOS 26 core (1 gpt = 4.17 ml/kg).

Figure 11. Comparison of oil shale fracture properties and oil yield running averages for NOS 26 Mahogany Zone shale.

Tipton Member - Rock Springs Test Site

All of the direct-pull tensile strength data for the rich upper 13 m (43 ft) of the Tipton Member* of the Green River Formation is illustrated in Figure 12. The small squares represent the tensile strength values and depth for each test conducted. Several different averaging techniques were evaluated so as to obtain representative formation values. The continuous curve drawn through the data represents a running-average value of tensile strength over a .3 m (1 ft) interval with the averages calculated at each .15 m (.5 ft) of depth. Averages tried over smaller intervals tended to be too noisy and averages over larger intervals (up to 1.5 m) tended to filter out details of geologic importance. The range in the .3 m running average value from 1.9 MPa (275 psi) down to .05 MPa (7 psi) is geologically significant and represents the in situ variations that should be expected for the upper Tipton. Numerous natural fractures or partings were either existent within the in situ formation or developed as the original 15 cm diameter core was being taken. These natural fractures, representing the weakest planes within the formation, are indicated in Figure 12 by the horizontal dashed lines. The frequency of these natural partings suggests that they could play an important role in the fracturing and fragmentation of the Tipton Oil Shale by explosive loading.

The indirect tensile strength (pinch test) data for the upper Tipton over the depth interval 55 to 67 m (180 to 200 ft) are plotted in Figure 13. As for the direct-pull tensile strength data, the small squares represent the actual data points and the continuous curve represents the .3 m running average plotted on a .15 m increment. All of the data represented in Figure 13 were obtained using the .95 cm diameter hardened steel rollers. The high strength intervals between 186.5 and 188.5 ft and between 206 and 209 ft are observed in both the direct-pull and pinch test data sets. The different ordinate scales utilized for the plots of direct-pull tensile strength and indirect tensile strength data should be noted. The maximum indirect tensile strength of 12.6 MPa (1827 psi) is a factor of four greater than all but one direct-pull tensile strength data point.

* LETC Field Site, Site 10 Core, Sec. 15, T18N, R106W, Sweetwater County, Wyoming

TENSILE STRENGTH -DIRECT (MPa)

Figure 12. Direct-pull tensile strength values obtained for the 55.2 to 68.3 m depth interval of the Tipton Oil Shale.

The fracture toughness values obtained on the Tipton have been categorized into one of three groups depending upon the stability of fracture propagation and the general quality of the measured data. Group A data includes only those tests in which fracture propagation across the notched, 1.27 cm diameter specimen was completely stable and well behaved. Group B data includes those tests in which rapid load drops or fracture propagation out of the pre-notched region may have yielded questionable values. Group C data includes those tests in which fracture propagation was definitely unstable. Of the total number of tests conducted, approximately 50% fell into Group A and 25% each into Groups B and C. As only slight differences exist between the running average curves for Group A alone and Group A and B combined, further discussion is of Group A data only. The data for the most reliable group (A) of tests is shown in Figure 14. The range of fracture energy values from a minimum of 5 J/m² to a maximum of 87 J/m² bound the value of 24 J/m² obtained for Solenhofen Limestone by Cooper¹⁸ and fall within the range expected for a rock like the Tipton Oil Shale.

The correlations between the direct and indirect tensile strength values and the fracture energy values obtained on the upper 13 m of the Tipton Oil Shale are illustrated in Figure 15 where the running average values for the three types of data are superimposed. Although there appears to be a better correlation between the fracture energy and direct-pull tensile strength data than between either of these data groups and the indirect tensile strength data, the statistical analyses discussed below indicate comparable correlations also exist between fracture energy and indirect tensile strength data.

Geokinetics Mahogany Zone Shale

Direct-pull tensile strength data from the third oil shale site* covered in this report, the Geokinetics Mahogany Zone shale, is illustrated in Figure 16. As the testing of the Geokinetics core involved only two direct-pull tensile breaks per 10 cm long test specimen, fewer data points were obtained and a correspondingly larger averaging interval of .9 m was employed for the running average curve shown in Figure 16. Although the Geokinetics Site encompasses the

* Sec. 2, T14S, R22E, Uintah County, Utah

Figure 14. Fracture energy values vs. depth for the most reliable group (A) of fracture energy tests on the Tipton Oil Shale.

Figure 15. Comparison of the running average curves of direct (A) and indirect (B) tensile strength and fracture energy (C) for the rich upper 11.6 m of the Tipton Oil Shale.

Figure 16. Direct-pull tensile strength data for 14.6 m (48 ft) of the Geokinetics (Utah) Mahogany Zone shale, showing natural parting planes (NPP) and special test horizons (A to E).

Mahogany Zone of the Green River Formation, the shale at that location is significantly different from the Mahogany Zone recovered in NOS 26. Due to an increase in clastic material and a proportionate reduction in precipitated carbonates, the Geokinetics shale is significantly more fragile than the NOS 26 Mahogany Zone shale. The tensile strength characteristics of this rock are much more comparable to those measured for the Tipton Shale at Rock Springs with tensile strength values ranging from less than 1 MPa to 50 MPa and with a high density of low strength planes throughout the section. As noted in Figure 16 there were very few natural parting planes identified in the Geokinetics core.

In addition to the direct-pull tensile strength tests summarized in Figure 16, limited fracture toughness and indirect-tensile strength testing was performed on this shale. These two types of tests were applied at only a few discrete stratigraphic horizons in the core but were performed on samples oriented for fracture both parallel and perpendicular to bedding. These tests were designed to evaluate the degree of fracture anisotropy that might exist in the Geokinetics Mahogany Zone shale.

Data obtained on the five horizons tested are summarized in Table 1. (The zones A to E are also noted in Figure 16 with zones B' and C' being nearly coincident with zones B and C.) The indirect tensile strengths revealed less than a 1.5:1 anisotropy for all horizons tested. One of the horizons tested, C/C' at 23.96 m (78.6 ft), did show significant anisotropy in fracture toughness. This bed gave unusually high fracture toughness values with an average of 374 J/m² being measured for fracture across the bedding. This toughness value should be compared with the 10 to 100 J/m² found to be characteristic of most oil shales. The 4.84:1 to 6.87:1 anisotropy factors for fracture toughness for this bed is unusually large and is not reflected at all in the essentially isotropic indirect tensile strength values obtained for this horizon.

TABLE 1. Anisotropy of fracture energy and indirect tensile strength for selected horizons in the Geokinetics Mahogany Zone shale.

ZONE	DEPTH (m)	FRACTURE ENERGY J/m ²		⊥ / RATIO	TENSILE STRENGTH MPa		⊥ / RATIO
		⊥ *	*		⊥ *	*	
A	22.92	34.3 ±5.9(3) ⁺	24.5 ±0.5(2)	1.40	6.44 0.20(3)	4.48 (1)	1.44
B	23.04	47.5 ±7.9(4)	30.0 ±8.5(3)	1.58	3.18 ±0.13(2)	6.22 (1)	0.51
B'	23.05	39.0 ±2.6(4)	37.0 (1)	1.05	3.58 ±0.32(4)	3.84 (1)	0.93
C	23.96	260.3 ±27.9(4)	53.8 ±19.5(4)	4.84	4.90 ±2.17(5)	4.90 (1)	-1.00
C'	23.97	374.3 ±12.5(3)	54.5 ±14.3(4)	6.87	3.54 ±0.27(4)	3.84 (1)	0.92
D	26.21	28.3 ±9.3(4)	13.0 ±5.6(3)	2.17			
E	32.00	47.5 ±10.0(6)	13.3 ±3.3(4)	3.57			

* ⊥ = Fracture Across Bedding, || = Fracture Along Bedding

+ Number in Parentheses is number of tests (For 3 or more tests ± is standard deviation; For 2 tests, ± is range)

STATISTICAL CORRELATIONS

Comparisons between the different types of fracture property data illustrated in Figure 11 for the Mahogany Zone shale from NOS 26 and in Figure 15 for the Tipton shale indicate that significant correlations exist between the various fracture properties and between them and the oil yield or organic content of the rock. Consequently, a detailed statistical analysis was performed on all the data available from the NOS 26 Mahogany Zone shale and the Tipton shale. As only direct-pull tensile strength data was obtained over the entire section of Geokinetics shale, there was no basis to perform a statistical analysis for this rock.

As neither the fracture property tests nor the Fischer assay for oil yield tests were performed on a lithology controlled basis, it was not possible to group and compare the data for samples with comparable lithology. Also, as the direct-pull and indirect tensile strength tests and the fracture energy tests could not be performed at identical stratigraphic levels, it would be difficult to compare the results on an individual test by test basis. Rather, the statistical analysis was performed utilizing values obtained from the running averages of the various data, with several different averaging intervals being tested. Such an analysis effectively defines the correlations between running average curves, such as illustrated in Figures 11 and 15.

NOS 26 Mahogany Zone

All types of data obtained on the NOS 26 core display quite good correlations over test averaging intervals ranging from 2.0 to 0.5 m (6.6 to 1.6 ft). Several type curves were available with the statistical routines employed on the HP 9835 micro-computer used for these analyses, with the resulting correlation coefficients indicating which curves give the best agreement with the data. The best fit curves relating various pairs of data sets and their coefficients of correlation are summarized in Table 2.

Comparisons between the direct-pull tensile strength data and the indirect-strength pinch test data for three different test averaging intervals are illustrated in Figures 17 to 19. As seen in Figures 17

TABLE 2. Best fit curve coefficients and correlation coefficients for rock fracture properties and oil yield for the NOS 26 Mahogany Zone shale.

VARIABLES* x/y	AVERAGING INCREMENT	NO. OF POINTS	BEST FIT CURVE	COEFFICIENT OF CORRELATION (r)	COEFFICIENT OF DETERMINATION (r ²)
DP(MPa)/IT(MPa)	2m	34	IT=5.967+1.679xDP	.96	.917
"	2m	34	IT=5.259+1.947xDP-.022xDP ²	.96	.918
"	2m	34	IT=.541+4.618xDP-.492xDP ² +.026xDP ³	.96	.920
"	1m	70	IT=6.351+1.600xDP	.92	.847
"	1m	70	IT=5.347+1.980xDP-.031xDP ²	.92	.848
"	1m	70	IT=6.091+1.549xDP+.044xDP ² -.004xDP ³	.92	.848
"	.5m	140	IT=7.794+1.344xDP	.76	.576
"	.5m	140	IT=4.087+2.777xDP-.116xDP ²	.77	.600
"	.5m	140	IT=8.017+.347xDP+.324xDP ² -.024xDP ³	.78	.607
OY(gpt)/DP(MPa)	2m	35	DP=9.266-.138xOY	.80	.645
"	2m	35	DP=12.625-.385xOY+3.781E-03xOY ²	-.90	.813
"	2m	35	DP=13.967-.548xOY+.009xOY ² -5.329E-05xOY ³	-.90	.817
"	1m	71	DP=9.087-.131xOY	-.76	.582
"	1m	71	DP=11.866-.334xOY+2.99E-03xOY ²	-.85	.724
"	1m	71	DP=13.453-.523xOY+.009xOY ² -5.353E-05xOY ³	-.86	.738
"	.5m	144	DP=8.720-.117xOY	-.68	.460
"	.5m	144	DP=10.666-.264xOY+2.190E-03xOY ²	-.73	.534
"	.5m	144	DP=11.721-.392xOY+.006xOY ² -3.521E-05xOY ³	-.74	.542
OY(gpt)/IT(MPa)	2m	34	IT=22.172+.258xOY	-.89	.785
"	2m	34	IT=26.492-.568xOY+.005xOY ²	-.93	.871
"	2m	34	IT=28.808-.842xOY+.014xOY ² -8.780E-05xOY ³	-.94	.875
"	1m	70	IT=21.919-.249xOY	-.85	.723
"	1m	70	IT=25.398-.502xOY+.004xOY ²	-.89	.797
"	1m	70	IT=27.574-.760xOY+.002xOY ² -7.293E-05xOY ³	-.90	.806
"	.5m	140	IT=21.348-.226xOY	-.75	.563
"	.5m	140	IT=23.683-.400xOY+.002xOY ²	-.77	.596
"	.5m	140	IT=25.220-.583xOY+.008xOY ² +5.001E-05xOY ³	-.76	.601
OY(gpt)/FE(J/m ²)	2m	34	FE=22.025+.895xOY	.72	.525
"	2m	34	FE=21.901+.904xOY+1.33E-04xOY ²	.72	.525
"	2m	34	FE=12.478+2.022xOY-.037xOY ² +3.571E-04xOY ³	.73	.529
"	1m	70	FE=21.091+.925xOY	.72	.519
"	1m	70	FE=19.449+1.044xOY-.002xOY ²	.72	.520
"	1m	70	FE=25.098+.374xOY+.020xOY ² -1.893E-04xOY ³	.72	.523
"	.5m	142	FE=20.084+.954xOY	.70	.486
"	.5m	142	FE=19.478+.999xOY-6.677E-04xOY ²	.70	.486
"	.5m	142	FE=24.927+.349xOY+.020xOY ² -1.773E-04xOY ³	.70	.489
DP(MPa)/FE(J/m ²)	2m	34	FE=73.809-5.016xDP	-.67	.449
"	2m	34	FE=113.273-19.942xDP+1.247xDP ²	-.72	.521
"	2m	34	FE=180.971-58.275xDP+7.990xDP ² -.371xDP ³	-.74	.549
"	1m	70	FE=72.417-4.777xDP	-.62	.389
"	1m	70	FE=96.987-14.067xDP+.756xDP ²	-.65	.42E
"	1m	70	FE=130.039-33.183xDP+4.111xDP ² -.181xDP ³	-.66	.440
"	.5m	142	FE=69.779-4.300xDP	-.54	.295
"	.5m	142	FE=88.802-11.606xDP+.588xDP ²	-.57	.326
"	.5m	142	FE=101.027-19.107xDP+1.937xDP ² -.072xDP ³	-.57	.330
IT(MPa)/FE(J/m ²)	2m	34	FE=93.835-3.132xIT	-.74	.542
"	2m	34	FE=163.393-12.389xIT+.293xIT ²	-.79	.617
"	2m	34	FE=210.962-22.450xIT+.974xIT ² -.015xIT ³	-.79	.620
"	1m	70	FE=92.519-3.060xIT	-.67	.485
"	1m	70	FE=160.965-12.123xIT+.282xIT ²	-.75	.56E
"	1m	70	FE=165.829-13.169xIT+.353xIT ² -.001xIT ³	-.75	.56E
"	.5m	140	FE=86.404-2.668xIT	-.58	.33E
"	.5m	140	FE=153.386-11.451xIT+.268xIT ²	-.66	.43E
"	.5m	140	FE=188.641-18.642xIT+.727xIT ² -.009xIT ³	-.66	.440

* DP = Direct-Pull Tensile, IT = Indirect Tensile, FE = Fracture Energy, OY = Oil Yield

Figure 17. Best fit curves for correlating direct-pull tensile strength with indirect (pinch) tensile strength for the NOS 26 Mahogany Zone shale using a 2.0 m (6.6 ft) sample averaging interval.

Figure 18. Best fit curves for correlating direct-pull tensile strength with indirect (pinch) tensile strength for the NOS 26 Mahogany Zone shale using a 1.0 m (3.3 ft) sample averaging interval.

Figure 19. Best fit curves for correlating direct-pull tensile strength with indirect (pinch) tensile strength for the NOS 26 Mahogany Zone shale using a 0.5 m (1.6 ft) sample averaging interval.

to 19 and in Table 2, these data show quite good correlation with the somewhat unexpected result that the larger averaging intervals give higher correlation coefficients. These better correlation coefficients result because the larger intervals serve to average out the scatter in the test data which is characteristic of mechanical property data on all rocks and especially on oil shales.

Both direct-pull and indirect tensile strength data for the NOS 26 Mahogany Zone shale are compared with oil yield in Figure 20. Both types of strength correlate well with oil yield, yielding nearly identical correlation coefficients for both the second degree and third degree polynomial fits. The correlation coefficients of 0.90 for direct-pull data versus oil yield and 0.93 / 0.94 for indirect tensile strength versus oil yield are consistent with the good correlations noted between other mechanical properties and oil yield.^{6,7,8} The data and best fit curves in Figure 20 also illustrate the characteristically higher values obtained with the indirect tensile strength test as compared to the direct-pull test.

The raw data and best fit curves comparing fracture energy versus oil yield for the NOS 26 Mahogany Zone shale are illustrated in Figure 21. The correlation coefficients of 0.72, 0.72 and 0.73 for the linear, second-order and third-order polynomial curves, respectively, while quite significant, do not indicate the degree of correlation with oil yield that was noted for the tensile strength data. As indicated in Table 2 decreasing the sample averaging interval from 2.0 m to 1.0 m and 0.5 m serves to increase the scatter in the data and reduce somewhat the correlation coefficients between fracture energy and oil yield.

The good correlation coefficients obtained between all of the fracture property data and between them and oil yield, as summarized in Table 2, illustrate that the Piceance Basin Mahogany Zone shale as represented by NOS 26 data behaves in a predictable manner. The good correlations between all of the fracture property data with oil yield indicate that oil yields alone may be utilized to predict any of the desired fracture properties to a good first approximation. Site specific and stratigraphically controlled fracture property data would be required only if a detailed analysis of oil shale fracture was required.

Figure 20. Best fit curves for correlating direct-pull and indirect tensile strength data with oil yield for the NOS 26 Mahogany Zone shale using a 2.0 m (6.6 ft) sample averaging interval.

Figure 21. Best fit curves for correlating fracture energy with oil yield for the NOS 26 Mahogany Zone shale using a 2.0 m (6.6 ft) sample averaging interval.

Upper Tipton Rock Springs Test Site

The best fit curves, their coefficients and the corresponding correlation coefficients for relating the various Tipton fracture properties and oil yield are summarized in Table 3. As indicated in Table 3 and as will be discussed in more detail below, the correlation coefficients for the Tipton data are much lower than they were for comparable data for the NOS 26 shale. As for the NOS 26 analysis, running average values obtained over different averaging intervals were employed in establishing the correlation relationships.

All of the data points by the running average method and several best fit curves relating direct-pull and indirect tensile strength for the Tipton are illustrated in Figures 22 and 23. The data and curves illustrated in Figure 22 were obtained with a 0.5 m (1.6 ft) running average. As may be seen in Figure 22 the data displays a great deal of scatter and the best correlation coefficient obtained for all the curve forms tested was only 0.42.

The data and best fit curves relating direct-pull and indirect tensile strength for a 2.0 m (6.6 ft) running average are illustrated in Figure 23. As may be noted in Figure 23 and from the correlation coefficients given in Table 3, increasing the running average interval for the Tipton tensile strength data does not serve to improve the correlations as was the case for the NOS 26 data.

Relations between the various oil shale fracture properties and oil yield are illustrated in Figures 24 to 26. Employing a 0.5 m (1.6 ft) averaging interval, the data and best fit curves for direct-pull tensile strength as compared to oil yield are illustrated in Figure 24. The correlation coefficients obtained for the linear, quadratic and third-order polynomial equations are all disappointingly low. No significant improvements in the correlations were obtained by using larger averaging intervals. As indicated in Table 3, a 1.0 m running average yields correlations comparable to the 0.5 m running average, while a 2.0 m running average results in negative coefficients of determination (r^2) indicating no statistically based relation between the two sets of data. In contrast to the NOS 26 direct-pull tensile

TABLE 3. Best fit curve coefficients and correlation coefficients for rock fracture properties and oil yield for the Tipton Oil Shale.

VARIABLES* x/y	AVERAGING INCREMENT	NO. OF POINTS	BEST FIT CURVE	COEFFICIENT OF CORRELATION (r)	COEFFICIENT OF DETERMINATION (r ²)
DP(MPa)/IT(MPa)	2m	10	IT=3.312 + 1.076xDP	NM	-.054
"	2m	10	IT=8.595-12.187xDP+7.710xDP ²	.39	.153
"	2m	10	IT=10.546-19.958xDP+17.301xDP ² -3.745xDP ³	.39	.154
"	1m	22	IT=3.335+1.103xDP	.24	.056
"	1m	22	IT=5.521-3.901xDP+2.592xDP ²	.34	.115
"	1m	22	IT=4.300+.307xDP-1.865xDP ² +1.473xDP ³	.34	.117
"	.5m	46	IT=3.049+1.402xDP	.41	.167
"	.5m	46	IT=2.761+2.112xDP-.372xDP ²	.41	.169
"	.5m	46	IT=1.629+6.736xDP-5.755xDP ² +1.868xDP ³	.42	.175
OY(gpt)/DP(MPa)	2m	10	DP=1.036-3.058E-03xOY	NM	-.122
"	2m	10	DP=2.071-.105xOY+.002xOY ²	NM	-.108
"	2m	10	DP=6.825-.823xOY+.038xOY ² -5.77E-04xOY ³	NM	-.106
"	1m	22	DP=.547+.019xOY	.19	.035
"	1m	22	DP=1.920-.110xOY+.003xOY ²	.19	.076
"	1m	22	DP=-3.244+.638xOY-.032xOY ² +5.32E-04xOY ³	.31	.097
"	.5m	46	DP=.588+1.693xOY	.20	.042
"	.5m	46	DP=.680+.008xOY+1.987E-04xOY ²	.21	.042
"	.5m	46	DP=-2.549+.478xOY-.021xOY ² +3.21E-04xOY ³	.26	.069
OY(gpt)/IT(MPa)	2m	10	IT=2.957+.067xOY	NM	-.056
"	2m	10	IT=-5.693+.923xOY-.021xOY ²	.01	.0002
"	2m	10	IT=109.977-16.531xOY+.843xOY ² -.014xOY ³	.26	.066
"	1m	22	IT=3.715+.031xOY	NM	-.030
"	1m	22	IT=.051+.376xOY-.008xOY ²	NM	-.006
"	1m	22	IT=-34.480+5.378xOY-.242xOY ² -.003xOY ³	.27	.073
"	.5m	46	IT=3.585+.037xOY	.08	.007
"	.5m	46	IT=4.196-.021xOY+.001xOY ²	.09	.008
"	.5m	46	IT=-7.065+1.617xOY-.074xOY ² +.001xOY ³	.20	.039
OY(gpt)/FE(J/m)	2m	10	FE=25.174+.290xOY	NM	-.071
"	2m	10	FE=-2.161+2.995xOY-.065xOY ²	NM	-.047
"	2m	10	FE=296.032-42.003xOY+2.162xOY ² -.036xOY ³	NM	-.028
"	1m	21	FE=17.366+.594xOY	.18	.033
"	1m	21	FE=-12.326+3.391xOY-.063xOY ²	.23	.052
"	1m	21	FE=-224.105+34.047xOY-1.499xOY ² +.022xOY ³	.29	.087
"	.5m	44	FE=18.020+.541xOY	.18	.032
"	.5m	44	FE=-23.291+4.514xOY-.089xOY ²	.28	.080
"	.5m	44	FE=-74.887+12.048xOY-.439xOY ² +.005xOY ³	.29	.086
IT(MPa)/FE(J/m ²)	2m	10	FE=11.645+4.486xIT	.92	.838
"	2m	10	FE=10.294+5.152xIT-.078xIT ²	.92	.838
"	2m	10	FE=-69.385+67.156xIT-15.584xIT ² +1.251xIT ³	.93	.873
"	1m	21	FE=3.081+6.215xIT	.64	.407
"	1m	21	FE=3.580+5.965xIT+.029xIT ²	.64	.407
"	1m	21	FE=-27.570+30.189xIT-5.860xIT ² +.453xIT ³	.64	.413
"	.5m	44	FE=9.253+4.682xIT	.40	.157
"	.5m	44	FE=6.535+6.008xIT-.150xIT ²	.40	.158
"	.5m	44	FE=-44.695+45.825xIT-9.545xIT ² +.683xIT ³	.43	.188
DP(MPa)/FE(J/m ²)	2m	10	FE=20.838+10.654xDP	.42	.172
"	2m	10	FE=44.074-47.686xDP+33.912xDP ²	.59	.342
"	2m	10	FE=21.699+41.396xDP-76.031xDP ² +42.929xDP ³	.59	.347
"	1m	21	FE=9.543+21.323xDP	.64	.408
"	1m	21	FE=43.841-57.066xDP+40.570xDP ²	.76	.583
"	1m	21	FE=64.287-127.875xDP+115.697xDP ² -24.843xDP ³	.77	.590
"	.5m	44	FE=12.224+18.064xDP	.51	.259
"	.5m	44	FE=38.838-47.892xDP+34.606xDP ²	.65	.422
"	.5m	44	FE=48.812-88.870xDP+82.392xDP ² -16.587xDP ³	.65	.427

* DP = Direct-Pull Tensile, IT = Indirect Tensile, FE = Fracture Energy, OY = Oil Yield, NM = Not Meaningful

Figure 22. Best fit curves for correlating indirect-tensile strength with direct-pull tensile strength for the Tipton shale using a 0.5 m (1.6 ft) sample averaging interval.

Figure 23. Best fit curves for correlating indirect tensile strength with direct-pull tensile strength for the Tipton shale using a 2.0 m (6.6 ft) sample averaging interval.

Figure 24. Best fit curves for correlating direct-pull tensile strength with oil yield for the Tipton shale using a 0.5 m (1.6 ft) sample averaging interval.

Figure 25. Best fit curves for correlating indirect tensile strength with oil yield for the Tipton shale using a 0.5 m (1.6 ft) sample averaging interval.

Figure 26. Best fit curves for correlating fracture energy with oil yield for the Tipton shale using a 0.5 m (1.6 ft) sample averaging interval.

strength data, the Tipton tensile strength is not well correlated to the oil yield of the rock. This poorer correlation is attributed to the clay mineralogy of the Tipton shale which results in a more mineralogically controlled and randomly distributed tensile strength.

Correlations between the indirect tensile strength and oil yield for the Tipton shale employing a 0.5 m averaging interval are illustrated in Figure 25. As may be seen in Figure 25 and Table 3, the correlation coefficients for this data are extremely poor. As indicated in Table 3, somewhat better correlation coefficients between indirect tensile strength and oil yield are obtained for the third-order fits when 1.0 and 2.0 m averaging intervals are employed. For three of the nine cases tested, however, the coefficients of determination are negative indicating no statistically significant correlation between the data sets. As for the direct-pull tensile strength, the indirect tensile strength data appear to be largely controlled by mineralogical variations which are not well related to the oil yield of the rock.

The data and best fit curves relating fracture energy to oil yield utilizing a 0.5 m averaging interval are illustrated in Figure 26. The poor correlations existing between fracture energy and oil yield are apparent in the broad scatter of the raw data points. The best fit curve for the 0.5 m averaging interval, a third order polynomial, yields a correlation coefficient of only 0.29. As noted in Table 3, increasing the sample averaging interval to 1.0 m does not serve to change the correlation coefficient for the third order polynomial fit, but further increase to a 2.0 m averaging interval yields negative coefficients of determination. The very low or negative coefficients of determination attest to the extremely poor relation between fracture energy and oil yield. Again this fracture property is probably controlled by variations in clay mineralogy which are unrelated to oil yield.

As summarized above and illustrated in Figures 24 to 26, only marginal correlations exist between the fracture properties and the oil yield of the Tipton oil shale. Knowledge of oil yield can only provide a very rough estimate of the fracture properties that might be expected for this rock. Consequently, knowledge of site and stratigraphic specific fracture properties can only be crudely inferred from oil yield data and

additional mechanical property testing would be required to provide reasonably accurate representations of the in situ fracture properties. As already noted these marginal correlations are attributed to the influence of the clay mineralogy of the rock upon its fracture and the fact that this clay mineralogy has little correlation with the organic content of the shale.

As noted in Table 3, reasonably good correlation coefficients were obtained only between the indirect tensile strength and fracture energy and the direct-pull tensile strength and fracture energy. The best fits were obtained between indirect tensile strength and fracture energy when a 2.0 m averaging interval was used. As illustrated in Figure 27 the 2.0 m averaging interval data relating fracture energy to indirect tensile strength display only modest scatter and all forms of best fit curves give correlation coefficients greater than 0.92. The 0.93 correlation coefficient obtained for the third order polynomial relating fracture energy to indirect tensile strength implies that a quite predictable relationship exists between these two properties. Much of this agreement, however, must be attributed to the relatively few (10) data points obtained with the 2.0 running average. Reducing the running average to 0.5 m, which yields 44 data points, results in a correlation coefficient of only 0.43 for the third order polynomial fit. The somewhat better correlations that were obtained between the oil shale fracture properties than between them and oil yield can be attributed to the fact that the fracture properties are mutually controlled by the clay mineralogy which is not in itself well related to oil yield. The positive correlation noted between fracture energy and tensile strength for the Tipton shale, as opposed to the negative correlation between fracture energy and tensile strength for the NOS 26 shale, is as would be expected if tensile strength was controlled by fracture energy rather than initial flaw size.

Figure 27. Best fit curves for correlating fracture energy with indirect tensile strength for the Tipton shale using a 2.0 m (6.6 ft) sample averaging interval.

CONCLUSIONS

The development of specialized testing techniques combined with the careful handling of core material provide the means to obtain detailed stratigraphic logs of the tensile strength and fracture toughness properties of oil shales and other rocks. Stratigraphic logs of fracture properties for the NOS 26 Mahogany Zone shale, the rich upper 13 m of the Tipton shale and 14.6 m of the Geokinetics Mahogany Zone shale demonstrate the degree of stratigraphic variability in fracture properties that can be expected for oil shales.

The detailed statistical analyses performed on the fracture property data reported here indicates that good correlations may or may not exist between the fracture properties and oil yield depending upon the site specific mineralogy of the rock. The NOS 26 Mahogany Zone shale, with a predominate carbonate / kerogen mineralogy, gives good correlations between the fracture properties and between them and oil yield. Somewhat surprisingly the NOS 26 data give a negative correlation coefficient between tensile strength and fracture energy. This negative correlation has been noted by previous workers¹⁶ and may be attributed to the control of tensile strength more by flaw size rather than fracture energy. The good correlation between fracture energy and tensile strength and between these properties and oil yield requires that the inherent rock flaws controlling tensile strength be related to a kerogen related mineralogy of the rock. The intrinsically fine grained nature of the carbonate / kerogen mineralogy of the NOS 26 shale would be expected to yield increases in ductility and thus fracture energy with increases in kerogen content and decreases in inherent flaw size with increases in kerogen content. The positive, but with a much lower correlation coefficient, relation between fracture energy and tensile strength of the Tipton shale can be attributed to the partial control of tensile failure by fracture energy and the partial control by a clay mineralogy not related to kerogen content.

A most important conclusion to be drawn from the results presented here relates to the extreme variability of oil shale fracture properties with variations in stratigraphic position, mineralogy and field location. Variations in the rock fracture energy values by a factor of 20 for the NOS 26 shale and a factor of 17 for the Tipton shale and the variations in tensile strength from essentially 0 to over 40 MPa for the NOS 26 shale attest to the variability in rock fracture properties that should be expected in the natural in situ environment. This variability underscores the risks that are taken when a rock such as oil shale is treated as a homogeneous isotropic engineering material in the design and analysis of field experiments. The natural and inevitable variations in rock fracture properties must be properly taken into account in the design, execution and analysis of any in situ fracturing and fragmentation experiments to be carried out in the development of viable oil shale processing methods.

REFERENCES

1. Stevens, A.L., P.C. Lysne, and G.B. Griswold, "Rock Springs Oil Shale Fracturization Experiment: Experimental Results and Concept Evaluation", Sandia Laboratories Report, SAND 74-0372, Albuquerque, New Mexico (1975).
2. Parrish, R.L., R.R. Boade, A.L. Stevens, A. Long, and T.F. Turner "The Rock Springs Site 12 Hydraulic/Explosive True In Situ Oil Shale Fracturing Experiment", Sandia Laboratories Report, SAND 80-0836, Albuquerque, New Mexico (1980).
3. Boasley, R.R. and R.R. Boade, "Instrumentation and Evaluation of the Talley Energy Systems, Inc. Oil Shale Project, Part II", Sandia Laboratories Report, SAND 78-1886, Albuquerque, New Mexico (1980).
4. Ridley, R.D., "Progress in Occidental's Shale Oil Activities", Proc. 11th Oil Shale Symposium, Golden, Colorado (1978).
5. Lekas, M.A., "Progress Report on the Geokinetics Horizontal In Situ Retorting Process", Proc. 12th Oil Shale Symposium, Golden, Colorado (1979).
6. Chong, K.P., K. Uenishi, J.W. Smith, and A.C. Munari, "Nonlinear Three-Dimensional Mechanical Characterization of Colorado Oil Shale", Int. J. Rock Mech. Min. Sci., 17, 339-347 (1980).
7. Johnson, J.N. and E.R. Simonson, "Analytic Failure Surfaces for Oil Shales of Varying Kerogen Content", Los Alamos Scientific Laboratory, Report LA-UR-77-1005, Los Alamos, New Mexico (1977).
8. Olinger, B., "Elastic Constants of Oil Shale", Los Alamos Scientific Laboratory, Report LA-6817-PR, p. 24-26, Los Alamos, New Mexico (1977).
9. ASTM D-2936, Standard Method of Test for Direct Tensile Strength of Rock Core Specimens. American Society of Testing Materials, pp. 862-864 (1972).
10. Jaeger, J.C. and N.G.W. Cook, Fundamentals of Rock Mechanics, London, England (1969).
11. Wang, K.A. and K.P. Chong, Diametrical Compression of Transversely Isotropic Disks, Proc. 21st U.S. Symposium on Rock Mechanics, Rolla, Missouri, pp. 243-248 (1980).
12. Reichmuth, D.R., Correlations of Force-Displacement Data with Physical Properties of Rock for Percussive Drilling Systems. Proc. Symposium on Rock Mechanics, 5th, Macmillan, New York, 33 (1963).

13. Clifton, R.J. E.R. Simonson, A.H. Jones, and S.J. Green, Determination of the Critical-Stress-Intensity Factor K_{IC} from Internally Pressurized Thick-Walled Vessels, *Expl. Mech.* 16 (6), pp. 233-238 (1976).
14. Barker, L.M., A Simplified Method for Measuring Plane Strain Fracture Toughness, *Eng. Frac. Mech.* 9, 361 (1977).
15. Schmidt, R.A., Fracture-Toughness Testing of Limestone, *Expl. Mech.* 16 (5), pp. 161-167 (1976).
16. Schmidt, R.A., Fracture Mechanics of Oil Shale - Unconfined Fracture Toughness, Stress Corrosion Cracking, and Tension Test Results, Proceedings of the 18th U.S. Symposium on Rock Mechanics, Colorado School of Mines, 2A2-1-2A2-6 (1977).
17. Friedman, M., J. Handin, and G. Alani, Fracture Surface Energy of Rocks. *Int. J. Rock Mech. and Min. Sci.* 9, pp. 757-766 (1972).
18. Cooper, G.A., Optimization of the Three-Point Bend Test for Fracture Energy Measurement. *J. Mat. Sci.* 12, pp. 277-289 (1977).
19. Smith, J.W., T.N. Beard, and L.G. Trudell, Oil Shale Resources of the Naval Oil Shale Reserve No. 1, Colorado, Report of Investigations, LETC/RI-79/2, Laramie Energy Technology Center (1979).

APPENDICES

Tabulated Test Data for Fracture Property Tests on NOS 26 and Tipton Oil Shales

TABLE A-1. NOS 26 Direct-Pull Tensile Strength Data vs. Depth of Fracture. page 1 of 4

DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)
265.82	5.3	266.82	3.0	267.94	2.1	269.44	7.5	270.78	.2	272.35	6.1	273.87	2.4
265.83	8.5	266.83	3.9	267.98	4.2	269.47	1.7	270.83	5.7	272.36	7.3	273.89	.5
265.87	1.6	266.86	3.8	268.02	4.3	269.49	3.1	270.86	1.9	272.42	2.9	273.94	4.7
265.91	2.1	266.91	6.3	268.04	2.2	269.50	1.0	270.90	.7	272.46	4.3	273.94	3.5
265.96	5.1	266.92	2.4	268.07	1.0	269.55	1.9	270.98	8.5	272.47	7.9	274.00	5.3
265.96	2.5	266.94	6.0	268.08	1.0	269.56	1.0	271.03	6.3	272.53	4.4	274.05	5.2
266.02	6.0	267.07	1.9	268.13	3.8	269.58	.1	271.04	.6	272.55	5.8	274.07	4.7
266.04	.8	267.10	6.1	268.19	3.7	269.60	2.7	271.08	8.2	272.57	9.5	274.14	4.4
266.06	.3	267.17	6.4	268.20	.9	269.64	.4	271.14	6.4	272.62	10.9	274.17	4.1
266.07	4.1	267.19	1.8	268.21	2.8	269.67	1.1	271.21	2.1	272.69	10.3	274.17	3.6
266.10	.5	267.20	5.6	268.32	2.8	269.72	3.5	271.26	1.6	272.72	10.1	274.24	3.9
266.11	4.1	267.23	3.4	268.37	4.4	269.75	1.6	271.30	3.6	272.74	8.6	274.26	9.8
266.13	1.0	267.26	5.1	268.43	4.5	269.79	5.1	271.33	1.2	272.78	7.6	274.30	9.5
266.17	4.1	267.33	7.2	268.45	3.5	269.82	3.0	271.35	3.7	272.82	9.0	274.35	6.1
266.18	.8	267.33	4.9	268.50	5.0	269.83	4.0	271.40	1.6	272.87	5.3	274.37	3.4
266.19	.3	267.33	5.0	268.58	3.3	269.88	5.8	271.42	6.8	272.88	9.1	274.46	3.7
266.21	1.1	267.40	5.1	268.59	4.9	269.92	3.6	271.50	2.9	272.90	8.8	274.49	7.0
266.26	.4	267.41	2.9	268.70	2.5	269.94	4.1	271.54	7.0	272.98	9.6	274.56	3.3
266.27	.3	267.45	2.3	268.71	3.1	269.97	4.8	271.61	9.0	273.01	10.8	274.57	4.8
266.30	.5	267.47	3.4	268.82	8.2	270.00	2.8	271.63	8.5	273.07	7.4	274.61	3.7
266.34	1.2	267.49	2.5	268.86	5.3	270.00	1.8	271.66	10.2	273.11	9.9	274.76	1.8
266.36	3.1	267.50	.4	268.87	7.4	270.08	10.3	271.70	2.8	273.19	7.5	274.77	3.1
266.38	2.8	267.52	2.0	268.92	7.5	270.10	1.6	271.71	.6	273.21	8.9	274.78	3.2
266.42	1.1	267.57	4.1	268.96	6.2	270.17	6.0	271.74	7.4	273.24	9.8	274.84	.8
266.44	.4	267.58	1.1	268.99	2.4	270.19	4.7	271.83	8.5	273.27	7.9	274.88	2.6
266.47	1.4	267.60	2.2	269.04	9.1	270.20	3.5	271.86	7.3	273.33	2.2	274.91	1.5
266.52	3.2	267.65	5.5	269.10	1.0	270.27	1.1	271.89	6.3	273.33	1.7	274.95	2.3
266.55	.7	267.66	2.4	269.13	5.1	270.28	7.8	271.94	5.0	273.33	11.3	274.97	2.1
266.56	1.7	267.69	3.3	269.16	4.5	270.32	8.4	271.95	6.9	273.38	9.8	275.02	1.9
266.57	3.0	267.74	2.4	269.20	5.0	270.37	8.2	271.99	7.2	273.45	11.3	275.04	4.7
266.57	1.1	267.76	3.9	269.24	2.4	270.40	8.8	272.03	10.3	273.48	7.2	275.09	4.1
266.61	2.8	267.77	3.6	269.25	5.0	270.43	9.5	272.08	7.4	273.56	3.6	275.12	3.3
266.63	.5	267.79	3.7	269.25	6.0	270.46	8.8	272.10	11.0	273.57	14.0	275.12	2.7
266.65	2.6	267.80	4.7	269.32	3.6	270.49	1.5	272.18	8.4	273.63	5.3	275.16	2.9
266.72	.8	267.85	5.1	269.35	.8	270.58	6.3	272.18	8.3	273.68	11.5	275.19	1.0
266.73	3.6	267.89	3.2	269.40	8.5	270.62	5.0	272.20	11.5	273.80	4.4	275.20	3.8
266.76	2.5	267.91	4.4	269.40	5.2	270.69	.9	272.26	9.7	273.84	2.8	275.25	4.8
266.79	3.0	267.93	2.3	269.41	6.1	270.74	.9	272.32	9.1	273.84	4.2	275.27	1.6

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DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)
275.28	3.1	276.82	3.9	278.43	4.1	280.08	5.2	281.46	4.0	282.91	6.5	284.43	5.9
275.35	4.2	276.83	1.7	278.44	4.8	280.09	1.6	281.48	.8	282.94	3.6	284.49	5.1
275.40	3.1	276.86	6.1	278.45	.8	280.09	2.3	281.50	2.4	282.98	6.6	284.54	2.9
275.42	3.6	276.88	4.4	278.51	1.6	280.15	3.5	281.54	1.1	283.03	4.7	284.57	2.3
275.44	3.1	276.93	2.3	278.54	4.3	280.18	2.6	281.56	3.0	283.07	.8	284.60	3.0
275.45	4.0	276.95	3.0	278.58	.7	280.23	7.0	281.63	3.3	283.12	1.8	284.71	3.3
275.56	3.5	276.97	3.2	278.60	6.0	280.25	7.7	281.64	1.9	283.16	1.7	284.73	2.9
275.57	4.2	276.98	2.6	278.61	5.4	280.28	5.5	281.66	3.5	283.23	4.7	284.81	6.0
275.59	4.4	277.02	3.3	278.65	.8	280.31	5.0	281.71	4.7	283.24	4.4	284.84	4.6
275.68	3.0	277.06	3.3	278.71	3.8	280.39	5.3	281.75	4.9	283.28	3.9	284.86	6.8
275.71	5.2	277.09	2.3	278.75	5.7	280.42	4.4	281.84	3.6	283.29	1.5	284.90	5.1
275.74	3.9	277.14	1.5	278.83	4.9	280.47	4.6	281.88	1.8	191.90	6.3	284.92	3.1
275.78	4.6	277.17	3.3	278.89	9.3	280.49	1.7	281.90	4.4	283.42	.9	284.94	6.1
275.82	4.6	277.23	1.2	278.93	3.3	280.50	3.5	281.93	6.8	283.45	2.1	284.97	5.6
275.86	5.1	277.24	.5	278.95	3.9	280.54	3.0	281.98	3.6	283.46	4.8	284.98	5.1
275.89	4.7	277.41	.8	279.01	5.6	280.57	7.6	282.01	5.4	283.48	2.4	285.06	4.7
275.97	4.1	277.45	2.2	279.03	1.5	280.60	5.5	282.03	2.7	283.52	.8	285.12	7.3
276.00	4.7	277.46	1.6	279.07	8.3	280.61	8.0	282.08	3.0	283.55	2.1	285.17	6.4
276.07	3.2	277.47	1.1	279.12	1.2	280.66	2.9	282.12	4.2	283.67	5.5	285.21	6.7
276.08	5.8	277.50	.7	279.15	2.2	280.66	1.3	282.20	5.6	283.71	4.8	285.25	5.0
276.09	3.2	277.53	.7	279.29	4.1	280.72	1.5	282.21	3.0	283.81	.4	285.28	7.8
276.14	5.5	277.73	3.6	279.32	4.3	280.76	8.8	282.24	.6	283.82	4.0	285.35	2.9
276.17	4.5	277.75	4.7	279.33	3.9	280.82	3.6	282.28	2.5	283.86	3.9	285.39	5.2
276.24	2.2	277.78	1.6	279.34	2.8	280.83	4.4	282.31	2.7	283.87	1.8	285.44	1.6
276.26	4.7	277.80	5.2	279.53	3.8	280.87	9.2	282.37	6.3	283.94	2.5	285.48	3.6
276.32	4.7	277.84	4.4	279.54	5.7	280.93	4.1	282.38	6.1	283.96	2.5	285.50	4.7
276.34	2.3	277.91	5.7	279.58	2.8	280.95	6.4	282.42	5.8	283.98	1.9	285.55	4.5
276.49	2.0	277.94	3.0	279.64	4.4	280.97	4.0	282.46	4.5	284.02	3.2	285.60	3.7
276.51	5.3	278.01	4.0	279.69	3.3	281.06	1.6	282.47	5.0	284.04	4.0	285.63	4.4
276.56	1.7	278.04	4.4	279.74	4.4	281.07	5.8	282.52	4.2	284.08	5.0	285.64	3.9
276.58	1.6	278.05	1.5	279.79	4.7	281.12	5.6	282.53	5.9	284.14	4.1	285.70	4.6
276.62	1.8	278.10	2.2	279.80	4.4	281.14	4.2	282.60	6.4	284.15	3.2	285.72	4.3
276.65	1.8	278.12	3.4	279.83	5.7	281.24	3.9	282.64	4.7	284.22	5.2	285.78	4.0
276.66	2.5	278.16	3.6	279.86	7.4	281.26	5.4	282.66	3.8	284.23	2.7	285.83	7.3
276.69	.1	278.29	4.7	279.93	3.7	281.30	3.7	282.71	5.6	284.24	8.3	285.86	7.8
276.75	2.0	278.32	4.5	279.95	4.5	281.31	1.5	282.77	3.3	284.30	6.1	285.91	4.1
276.75	1.6	278.36	2.5	280.02	1.3	281.36	4.5	282.81	2.1	284.34	6.3	285.96	2.2
276.77	.9	278.40	4.6	280.05	6.3	281.43	3.6	282.88	5.2	284.39	5.9	285.99	9.9

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DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)
286.02	4.5	287.71	3.8	289.52	1.5	291.00	4.8	292.50	8.7	294.46	5.6	296.24	13.1
286.09	5.9	287.76	4.2	289.62	1.8	291.03	3.2	292.52	10.0	294.53	10.0	296.31	3.8
286.11	.7	287.86	4.6	289.64	2.3	291.08	9.1	292.61	5.8	294.53	11.4	296.40	1.2
286.13	.3	287.87	4.7	289.67	2.8	291.12	9.5	292.62	11.0	294.58	11.5	296.51	6.6
286.18	3.1	287.98	3.0	289.70	1.4	291.16	1.5	292.63	8.0	294.68	10.8	296.68	2.6
286.24	2.5	288.00	5.8	289.78	6.0	291.24	8.8	292.70	11.6	294.71	9.0	296.73	13.1
286.29	8.6	288.05	2.9	289.83	4.4	291.29	9.7	292.78	11.8	294.75	7.8	296.75	6.8
286.31	7.0	288.10	4.2	289.83	1.0	291.30	5.5	292.85	11.9	294.78	7.8	296.82	13.9
286.35	7.4	288.17	4.2	289.91	2.8	291.32	3.7	293.01	10.1	294.82	3.9	296.93	8.3
286.40	9.2	288.19	5.4	289.93	.8	291.36	8.2	293.06	6.9	294.82	11.9	296.93	10.6
286.42	8.0	288.25	4.8	289.98	.8	291.42	3.2	293.07	11.7	294.90	9.1	296.96	8.2
286.44	6.9	288.30	2.6	290.00	3.0	291.45	7.0	293.14	3.5	294.99	9.2	296.98	9.3
286.44	8.1	288.38	7.0	290.03	.8	291.48	6.7	293.17	2.3	295.00	9.2	297.11	11.2
286.45	6.8	288.41	2.7	290.13	1.0	291.51	5.8	293.22	5.4	295.06	11.4	297.13	11.6
286.53	8.0	288.43	7.4	290.14	5.5	291.55	8.5	293.25	11.0	295.07	6.7	297.20	8.0
286.59	5.2	288.47	10.0	290.18	1.0	291.61	7.7	293.29	.4	295.16	8.9	297.25	3.4
286.64	3.4	288.50	7.3	290.20	10.7	291.63	10.6	293.34	7.4	295.19	9.7	297.27	2.9
286.70	2.4	288.56	5.2	290.21	11.3	291.68	14.1	293.36	3.2	295.21	9.3	297.36	.9
286.77	9.1	288.58	6.6	290.24	10.9	291.72	13.1	293.40	9.3	295.24	11.9	297.38	1.9
286.79	6.2	288.62	4.8	290.25	2.7	291.72	10.2	293.43	11.8	295.31	10.8	297.51	2.6
286.84	5.1	288.68	9.1	290.27	9.2	291.73	10.5	293.46	9.6	295.34	6.5	297.52	2.0
286.88	6.3	288.70	5.9	290.30	13.1	291.79	6.6	293.49	13.9	295.42	3.8	297.54	2.7
286.95	6.5	288.85	3.1	290.34	10.0	291.84	9.0	293.51	11.8	295.43	6.8	297.60	3.0
286.98	4.4	288.91	2.9	290.38	9.6	291.87	12.5	293.53	6.0	295.47	3.1	297.63	1.8
287.07	4.4	288.94	2.1	290.48	11.8	291.94	7.4	293.59	8.8	295.49	3.4	297.64	1.8
287.09	3.0	288.98	5.4	290.49	1.6	291.98	14.5	293.63	10.0	295.52	10.2	297.72	6.1
287.15	6.3	289.04	4.5	290.58	10.2	291.98	8.0	293.74	2.9	295.53	6.3	297.75	10.3
287.18	4.0	289.07	3.1	290.62	4.4	292.06	11.3	293.91	14.4	295.57	7.9	297.79	11.1
287.21	6.1	289.10	4.1	290.65	1.3	292.13	7.2	293.99	10.2	295.60	4.4	297.79	13.6
287.26	3.7	289.16	.9	290.67	4.0	292.14	4.4	294.12	6.2	295.68	9.1	297.84	1.5
287.30	4.8	289.18	1.1	290.70	3.8	292.18	8.4	294.16	9.0	295.71	4.2	297.92	3.6
287.34	3.8	289.22	4.7	290.76	9.4	292.18	8.3	294.21	6.6	295.80	12.8	297.95	1.8
287.38	6.4	289.24	3.7	290.78	8.1	292.23	.0	294.23	8.2	295.85	12.3	298.04	9.3
287.47	4.7	289.32	2.1	290.79	1.2	292.25	8.5	294.24	8.8	295.90	7.9	298.07	9.0
287.49	7.8	289.36	2.0	290.84	8.1	292.28	2.3	294.29	5.6	296.03	13.1	298.12	11.3
287.56	5.2	289.42	.9	290.88	11.0	292.36	8.9	294.35	12.5	296.03	10.6	298.13	9.6
287.59	3.8	289.44	2.1	290.89	3.8	292.41	11.0	294.36	8.0	296.18	9.1	298.15	4.3
287.67	4.9	289.50	1.6	290.96	7.3	292.45	11.8	294.42	11.5	296.19	6.9	298.19	13.6

TABLE A-1. page 4 of 4

DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)
298.21	5.0	298.70	9.3	299.30	13.1	299.75	5.3	300.40	10.3	300.96	5.2	301.48	7.7
298.27	6.7	298.76	14.0	299.33	9.4	299.81	13.6	300.42	2.0	301.02	11.6	301.49	6.5
298.30	6.5	298.77	10.7	299.33	8.7	299.83	4	300.46	7.2	301.06	14.2	301.55	5.9
298.40	4.3	298.82	6.9	299.45	9.3	299.87	8.4	300.53	7.5	301.09	10.3	301.58	6.2
298.43	4.1	298.93	10.8	299.48	8.0	299.99	14.2	300.61	9.7	301.11	9.7		
298.48	10.4	298.98	4.6	299.56	11.5	300.00	14.8	300.69	10.9	301.18	12.7		
298.53	4.1	299.01	5.4	299.56	10.3	300.04	10.3	300.80	13.5	301.19	12.2		
298.60	7	299.05	6.3	299.60	11.4	300.11	12.5	300.76	10.7	301.25	9.0		
298.63	8.7	299.08	3.3	299.66	13.5	300.15	6.3	300.86	13.4	301.27	5.2		
298.64	8.8	299.09	8.9	299.67	15.3	300.16	11.0	300.90	13.2	301.30	7.7		
298.66	10.4	299.14	15.2	299.68	10.1	300.27	8.5	300.92	10.2	301.33	7.2		
298.69	3	299.22	12.4	299.71	11.1	300.32	12.0	300.93	12.7	301.34	9.1		
298.70	9.3	299.25	13.6	299.74	10.5	300.35	11.5	300.96	5.2	301.39	8.3		

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TABLE A-2. NGS 26 Natural Core Break Depths (DP Strength = 0.0).

DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)
296.72	0.0	299.78	0.0	276.39	0.0	277.26	0.0	278.89	0.0	279.50	0.0	282.17	
297.60	0.0	300.17	0.0	276.42	0.0	277.33	0.0	279.36	0.0	279.59	0.0		
298.34	0.0	302.46	0.0	276.52	0.0	277.37	0.0	279.39	0.0	279.60	0.0		
299.25	0.0	303.32	0.0	276.90	0.0	277.63	0.0	279.44	0.0	280.20	0.0		
299.78	0.0	275.94	0.0	277.19	0.0	277.68	0.0	279.46	0.0	280.45	0.0		

TABLE A-3. NOS 26 Indirect Tensile Strength Data vs. Depth of Fracture. page 1 of 4

DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)
265.80	15.2	267.11	11.7	268.40	14.4	269.55	11.8	270.89	14.8	272.27	9.5	273.42	26.7
265.83	13.0	267.16	10.9	268.42	4.2	269.60	9.9	270.91	17.0	272.28	15.9	273.45	18.3
265.85	15.8	267.19	14.8	268.47	7.5	269.67	7.5	270.98	14.2	272.30	15.0	273.45	22.9
265.87	20.7	267.23	16.2	268.49	12.6	269.71	9.5	271.01	14.3	272.31	20.4	273.48	16.8
265.89	17.2	267.26	14.0	268.54	7.4	269.74	11.4	271.03	6.9	272.33	21.2	273.53	19.5
265.92	13.9	267.28	18.0	268.57	9.0	269.76	10.6	271.07	15.2	272.35	16.3	273.56	25.2
265.94	8.2	267.30	13.2	268.60	6.5	269.83	11.4	271.10	14.4	272.38	7.9	273.58	19.6
265.97	15.4	267.33	14.2	268.64	13.0	269.86	12.8	271.13	14.4	272.62	22.8	273.61	16.0
266.00	15.6	267.36	14.7	268.66	19.3	269.90	12.3	271.17	16.8	272.64	13.6	273.63	14.3
266.03	4.4	267.38	15.1	268.68	15.6	269.93	9.1	271.21	17.3	272.66	15.0	273.65	5.0
266.05	14.4	267.41	21.4	268.68	18.9	269.96	9.0	271.24	16.4	272.71	15.9	273.70	21.4
266.12	11.9	267.44	14.6	268.71	18.5	270.00	10.9	271.28	16.7	272.71	26.4	273.70	34.7
266.15	11.7	267.48	10.9	268.71	5.8	270.03	11.3	271.31	13.5	272.74	15.4	273.73	21.2
266.21	13.5	267.53	13.0	268.73	7.3	270.05	11.3	271.33	15.2	272.75	11.9	273.75	22.5
266.28	10.7	267.56	8.7	268.78	18.3	270.07	9.3	271.39	16.2	272.78	14.8	273.79	12.2
266.30	11.1	267.58	10.2	268.81	15.6	270.08	15.5	271.43	19.5	272.78	16.4	273.82	8.7
266.33	9.8	267.63	11.3	268.84	17.2	270.09	11.7	271.47	17.7	272.81	15.4	273.90	9.4
266.36	10.3	267.65	8.2	268.88	19.7	270.12	15.8	271.53	12.8	272.83	11.8	273.93	13.8
266.39	5.8	267.68	18.5	268.91	17.9	270.13	13.2	271.62	21.4	272.86	25.0	273.95	16.7
266.41	12.3	267.68	6.9	268.93	18.0	270.15	15.6	271.65	21.7	272.88	11.3	273.96	5.8
266.43	14.2	267.69	15.9	268.96	16.8	270.18	14.2	271.67	17.6	272.90	17.0	273.98	12.7
266.54	11.0	267.79	16.3	268.98	17.3	270.19	13.2	271.71	13.5	272.93	14.0	274.00	7.8
266.56	7.4	267.82	19.2	269.01	19.5	270.21	15.0	271.74	18.4	272.95	19.7	274.03	13.4
266.58	9.7	267.84	15.9	269.04	19.5	270.22	15.6	271.77	35.6	272.98	15.1	274.06	11.4
266.61	6.1	267.88	12.3	269.05	17.2	270.26	12.2	271.82	20.3	273.00	16.8	274.08	13.8
266.63	12.3	267.90	6.6	269.09	14.2	270.28	12.3	271.86	9.9	273.03	18.9	274.10	10.9
266.68	9.8	267.93	10.3	269.11	15.1	270.31	15.4	271.90	15.2	273.06	18.9	274.13	9.1
266.71	7.3	267.98	9.9	269.15	17.1	270.32	13.6	271.92	17.7	273.09	15.5	274.17	14.0
266.74	13.2	268.01	16.8	269.20	14.0	270.37	17.7	271.95	16.3	273.10	15.0	274.18	19.1
266.77	11.4	268.04	15.4	269.22	15.0	270.39	17.1	272.01	22.6	273.13	19.2	274.22	17.7
266.82	14.0	268.07	3.8	269.25	13.0	270.42	13.6	272.05	20.1	273.15	12.0	274.25	14.8
266.84	12.4	268.10	7.7	269.28	11.4	270.46	13.9	272.10	14.6	273.18	19.5	274.26	13.6
266.87	13.6	268.12	13.5	269.31	9.7	270.51	14.4	272.14	20.4	273.20	26.7	274.30	11.9
266.89	17.0	268.19	9.8	269.34	11.5	270.57	12.6	272.17	11.5	273.24	16.7	274.32	12.4
266.92	21.6	268.24	4.6	269.38	7.3	270.61	16.3	272.20	14.0	273.26	15.5	274.35	10.9
266.94	15.6	268.28	12.0	269.41	10.6	270.64	13.1	272.23	16.7	273.28	28.1	274.43	11.3
266.99	17.6	268.31	14.7	269.46	13.0	270.71	13.6	272.23	18.1	273.32	7.5	274.46	12.2
267.06	16.0	268.33	6.6	269.48	10.6	270.73	17.7	272.24	20.0	273.36	24.6	274.48	14.4
267.09	18.5	268.37	15.6	269.51	10.1	270.75	18.3	272.25	11.0	273.40	20.0	274.51	17.0

TABLE A-3. page 2 of 4

DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)
274.54	15.5	275.98	14.0	277.62	8.3	279.12	13.9	280.39	13.6	281.64	10.2	282.83	11.3
274.57	14.3	275.99	11.9	277.69	7.8	279.14	15.1	280.41	13.5	281.66	12.7	282.87	13.2
274.61	14.4	276.02	11.4	277.72	5.3	279.16	13.5	280.43	14.0	281.71	10.2	282.92	15.5
274.64	7.2	276.09	12.6	277.79	5.7	279.21	14.0	280.47	11.1	281.74	12.6	282.95	15.6
274.67	15.6	276.07	11.5	277.82	9.9	279.24	12.3	280.50	10.2	281.76	11.9	282.99	14.6
274.74	6.8	276.12	9.1	277.83	10.2	279.27	12.2	280.54	10.2	281.80	11.5	283.01	11.4
274.76	14.4	276.19	8.5	277.89	10.1	279.30	15.1	280.57	14.0	281.82	11.8	283.03	15.0
274.79	11.1	276.22	9.1	277.92	12.4	279.36	10.3	280.60	13.1	281.85	11.7	283.05	12.0
274.83	15.0	276.24	8.6	277.94	12.6	279.40	14.8	280.62	15.5	281.87	11.8	283.08	11.5
274.89	14.3	276.28	8.5	277.96	7.9	279.43	16.7	280.66	11.8	281.90	11.4	283.11	10.6
274.94	13.8	276.34	8.2	277.99	12.2	279.47	14.6	280.68	13.1	281.92	11.9	283.14	14.8
274.99	11.8	276.47	8.7	278.02	8.1	279.50	15.9	280.72	14.8	281.96	11.5	283.17	8.7
275.02	13.4	276.50	9.3	278.05	8.5	279.51	9.5	280.74	14.7	281.99	11.5	283.19	11.4
275.06	13.4	276.54	9.7	278.08	12.2	279.54	11.5	280.78	13.0	282.01	10.3	283.21	13.0
275.09	11.4	276.56	3.6	278.11	11.0	279.56	10.2	280.82	17.0	282.04	9.5	283.25	12.3
275.13	11.7	276.61	10.3	278.14	9.8	279.62	13.5	280.84	12.8	282.07	8.6	283.28	12.4
275.17	12.7	276.64	2.8	278.30	10.2	279.65	13.5	280.87	13.6	282.10	8.1	283.33	10.6
275.20	14.6	276.69	7.3	278.33	11.1	279.67	15.9	280.92	11.9	282.11	9.4	283.39	10.9
275.21	15.5	276.74	10.3	278.37	10.3	279.72	16.6	280.94	11.4	282.14	8.5	283.41	11.0
275.25	15.0	276.76	3.1	278.41	10.1	279.76	15.5	280.97	13.9	282.18	11.0	283.43	13.6
275.27	13.9	276.79	8.2	278.43	9.5	279.77	14.7	281.01	13.8	282.21	9.3	283.48	11.1
275.29	14.4	276.81	9.9	278.45	10.1	279.82	12.6	281.06	15.1	282.25	11.9	283.50	15.0
275.33	13.5	276.84	10.3	278.50	10.1	279.85	16.0	281.07	13.0	282.29	9.3	283.52	10.3
275.34	14.6	276.87	9.4	278.53	10.6	279.86	13.0	281.12	14.2	282.31	11.7	283.55	13.5
275.38	16.2	276.91	8.2	278.55	10.9	279.92	14.3	281.15	14.6	282.38	11.3	283.58	10.2
275.43	10.6	276.94	7.4	278.61	13.0	279.95	12.4	281.17	12.7	282.40	10.7	283.60	9.7
275.52	12.8	276.99	8.7	278.64	11.9	279.97	11.9	281.21	14.4	282.42	11.5	283.62	15.1
275.55	12.8	277.01	7.5	278.67	10.6	280.03	11.9	281.24	15.1	282.45	12.7	283.65	16.7
275.58	13.2	277.04	7.0	278.72	11.1	280.08	13.4	281.25	10.9	282.49	12.6	283.68	4.5
275.59	13.5	277.05	5.6	278.73	12.4	280.09	11.1	281.30	13.1	282.52	12.6	283.71	14.8
275.63	13.0	277.09	5.0	278.76	12.2	280.17	12.8	281.34	7.2	282.55	13.5	283.74	13.5
275.67	11.9	277.19	7.5	278.84	13.0	280.20	14.0	281.37	13.0	282.59	12.7	283.79	12.0
275.70	7.2	277.23	7.9	278.86	11.9	280.22	13.0	281.41	6.6	282.63	11.4	283.82	11.4
275.72	11.9	277.41	7.4	278.90	13.5	280.24	12.3	281.44	14.4	282.68	12.7	283.87	10.6
275.77	11.7	277.43	7.0	278.94	15.2	280.25	12.8	281.45	13.8	282.70	11.0	283.89	10.5
275.80	12.2	277.50	6.6	278.95	16.3	280.28	10.9	281.48	14.6	282.73	13.5	283.92	11.8
275.81	13.4	277.52	6.2	279.01	11.1	280.31	12.4	281.51	13.2	282.76	13.2	283.94	11.8
275.87	5.8	277.55	1.3	279.04	11.1	280.33	14.0	281.53	6.9	282.78	13.6	283.98	7.0
275.90	11.9	277.59	5.7	279.08	14.0	280.36	14.8	281.55	11.9	282.81	6.1	284.03	11.0

TABLE A-3. page 3 of 4

DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)
284.05	10.2	285.22	14.6	286.55	15.1	287.62	12.7	288.77	15.0	289.99	11.8	291.49	11.5
284.06	10.6	285.35	18.8	286.57	15.4	287.65	10.6	288.83	12.2	290.19	16.2	291.50	14.3
284.13	9.5	285.37	16.7	286.60	15.2	287.67	16.7	288.84	13.8	290.21	15.1	291.53	17.5
284.17	13.1	285.38	11.4	286.64	14.3	287.69	18.9	288.90	11.9	290.26	18.1	291.55	18.5
284.21	13.8	285.45	10.9	286.66	14.4	287.72	11.7	288.94	13.8	290.32	16.3	292.48	18.5
284.23	11.4	285.48	11.9	286.68	14.4	287.75	15.1	288.98	11.5	290.35	19.2	291.58	18.9
284.28	15.1	285.51	13.5	286.71	12.2	287.77	13.5	289.00	9.3	290.36	17.5	291.61	11.9
284.31	12.4	285.54	12.4	286.74	12.2	287.79	17.6	289.02	13.0	290.46	19.3	291.63	19.1
284.32	13.8	285.58	10.6	286.76	12.7	287.84	12.7	289.07	10.6	290.49	20.9	291.66	17.7
284.38	15.0	285.63	14.3	286.78	13.6	287.88	17.7	289.11	11.0	290.53	7.7	291.71	11.5
284.40	17.2	285.65	13.1	286.84	14.7	287.94	16.0	289.22	11.0	290.57	19.3	291.73	18.0
284.42	15.2	285.70	9.7	286.86	12.0	287.96	16.4	289.25	6.6	290.59	20.4	291.75	19.2
284.47	14.6	285.72	11.9	286.89	14.7	287.98	16.7	289.30	9.9	290.61	14.0	291.78	17.6
284.49	17.0	285.74	12.8	286.91	14.7	288.01	11.3	289.32	10.1	290.65	19.9	291.81	19.7
284.52	15.6	285.81	14.0	286.94	13.6	288.05	12.3	289.34	11.4	290.69	23.4	291.84	22.4
284.57	15.6	285.83	12.6	286.96	17.3	288.07	15.9	289.37	10.9	290.71	20.7	291.88	20.9
284.59	15.1	285.86	14.7	286.98	17.1	288.09	15.4	289.39	11.4	290.75	20.3	291.91	21.4
284.62	13.6	285.91	13.5	287.01	18.9	288.12	15.1	289.40	12.2	290.78	8.3	291.94	21.7
284.67	9.5	285.93	16.7	287.04	17.7	288.14	11.8	289.41	10.6	290.80	7.7	291.99	24.4
284.70	13.0	285.95	16.3	287.06	15.4	288.16	15.9	289.43	11.9	290.85	14.0	292.01	23.0
284.73	14.7	285.98	17.1	287.09	17.0	288.18	15.1	289.44	11.7	290.88	18.4	292.04	27.0
284.75	17.0	286.00	20.3	287.11	17.5	288.21	12.2	289.50	13.0	290.90	18.1	292.06	22.5
284.78	14.0	286.02	15.1	287.14	11.9	288.27	13.0	289.52	12.3	290.95	22.5	292.09	21.2
284.81	16.2	286.04	19.1	287.16	13.0	288.30	14.3	289.54	11.5	290.99	22.0	292.12	27.1
284.82	13.5	286.09	13.2	287.18	12.4	288.37	13.5	289.57	11.8	291.04	17.5	292.15	22.4
284.87	14.3	286.14	17.5	287.24	12.4	288.40	14.6	289.60	13.9	291.06	22.4	292.20	18.9
284.90	17.1	286.18	15.2	287.26	14.8	288.42	13.8	289.64	12.2	291.11	17.2	292.26	22.4
284.95	12.2	286.20	19.9	287.28	12.0	288.46	13.4	289.67	11.3	291.14	19.3	292.29	1.6
284.98	12.2	286.22	22.4	287.32	12.2	288.49	14.6	289.69	12.4	291.16	16.0	292.32	20.4
285.01	14.0	286.25	18.3	287.34	10.3	288.50	13.8	289.72	13.2	291.22	20.4	292.35	19.3
285.01	13.8	286.28	20.5	287.36	12.2	288.53	14.6	289.82	17.6	291.24	16.2	292.37	23.8
285.04	18.9	286.31	20.9	287.39	13.0	288.56	14.4	289.84	17.2	291.26	15.9	292.43	25.2
285.06	13.5	286.37	20.4	287.45	13.9	288.59	14.0	289.90	20.7	291.33	20.9	292.46	19.3
285.07	14.3	286.39	22.0	287.47	13.4	288.61	15.6	289.93	13.5	291.35	17.2	292.50	18.3
285.08	19.9	286.42	21.6	287.49	11.9	288.66	14.6	289.98	13.5	291.38	15.2	292.53	20.9
285.11	17.0	286.45	19.7	287.52	12.2	288.66	16.3	290.04	13.9	291.40	10.9	292.56	23.6
285.15	13.6	286.48	19.6	287.55	7.9	288.68	15.5	290.06	12.4	291.43	19.5	292.57	22.4
285.17	17.2	286.50	21.8	287.57	11.4	288.70	14.8	290.09	15.1	291.44	18.0	292.61	27.0
285.20	13.5	286.53	16.3	287.59	13.5	288.74	13.5	290.12	12.7	291.48	14.2	292.63	25.4

TABLE A-3. page 4 of 4

DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)
292.66	17.2	294.03	14.0	295.43	10.6	296.83	26.1	298.32	19.3	299.58	14.8	300.88	30.3
292.68	20.4	294.07	21.2	295.46	9.3	296.86	23.4	298.43	26.0	299.64	17.0	300.90	17.2
292.71	13.9	294.11	21.4	295.49	6.9	296.89	17.7	298.45	22.0	299.68	36.8	300.96	22.5
292.73	27.1	294.14	16.2	295.51	15.6	296.92	31.9	298.49	32.6	299.70	40.3	300.98	20.1
292.77	33.1	294.18	15.4	295.55	13.0	296.98	18.7	298.53	24.6	299.72	13.6	301.00	19.3
292.81	18.5	294.21	14.4	295.57	16.7	297.02	22.5	298.62	17.5	299.74	12.8	301.06	21.7
292.83	23.3	294.25	15.0	295.59	15.6	297.04	20.1	298.65	6.9	299.80	22.4	301.09	18.0
292.86	24.9	294.28	11.7	295.62	18.3	297.08	20.5	298.67	19.6	299.83	6.6	301.13	22.0
292.92	25.4	294.31	18.0	295.64	15.6	297.12	20.9	298.70	11.9	299.84	12.3	301.16	20.4
292.95	29.7	294.34	14.0	295.67	14.3	297.20	13.6	298.72	23.0	299.91	37.3	301.18	23.6
292.97	16.3	294.36	17.0	295.70	16.4	297.24	17.0	298.75	15.5	299.94	24.9	301.20	20.5
293.01	23.7	294.41	21.1	295.72	18.8	297.26	4.2	298.77	18.7	299.96	25.0	301.24	13.6
293.06	18.8	294.45	19.9	295.74	19.1	297.37	5.0	298.79	16.7	299.98	23.8	301.26	8.5
293.08	23.3	294.49	22.5	295.77	19.6	297.51	5.0	298.82	18.3	300.04	26.7	301.31	25.0
293.14	15.2	294.52	20.8	295.79	22.0	297.56	3.4	298.84	13.9	300.07	24.9	301.33	21.6
293.18	17.0	294.54	19.6	295.92	23.0	297.58	2.9	298.87	16.0	300.09	23.8	301.36	18.8
293.25	18.5	294.56	22.0	295.95	23.9	297.61	4.4	298.88	29.8	300.14	22.4	301.39	14.6
293.27	19.5	294.65	17.5	295.98	23.6	297.65	11.0	298.91	20.4	300.16	19.9	301.41	17.5
293.30	17.1	294.71	13.0	296.01	8.5	297.67	6.8	298.95	27.4	300.18	12.2	301.44	11.9
293.32	13.0	294.76	19.3	296.05	33.8	297.72	16.2	298.97	31.0	300.26	24.6	301.48	10.6
293.34	13.1	294.80	20.4	296.07	27.4	297.74	17.0	298.99	17.7	300.28	21.4	301.51	17.3
293.39	14.6	294.84	24.6	296.11	30.7	297.76	16.8	299.02	21.4	300.30	19.9	301.55	10.6
293.42	18.4	294.87	20.4	296.15	31.5	297.80	16.4	299.05	15.6	300.34	19.6	301.57	26.7
293.44	17.7	294.91	19.7	296.21	21.4	297.83	14.3	299.07	20.7	300.37	19.3	301.60	24.9
293.47	27.8	294.94	12.3	296.24	18.7	297.85	15.9	299.09	22.2	300.39	27.8	301.72	33.4
293.50	21.4	294.97	15.5	296.28	14.6	297.87	17.3	299.13	27.0	300.45	27.9		
293.53	28.7	295.00	17.1	296.31	12.7	297.91	15.9	299.16	22.8	300.47	13.2		
293.57	30.7	295.06	18.3	296.34	15.6	297.93	18.9	299.18	35.8	300.50	22.8		
293.60	32.6	295.09	16.3	296.38	18.5	297.95	20.3	299.26	18.5	300.52	15.4		
293.62	32.6	295.12	18.8	296.42	23.0	298.01	22.0	299.30	28.3	300.55	25.8		
293.64	26.5	295.15	12.7	296.44	22.9	298.03	24.6	299.34	16.7	300.57	20.7		
293.67	20.5	295.19	8.1	296.47	23.7	298.06	27.0	299.36	43.4	300.59	34.3		
293.78	29.5	295.22	16.7	296.51	21.4	298.11	19.6	299.39	2.6	300.66	36.5		
293.81	30.6	295.24	18.9	296.61	15.4	298.13	17.7	299.43	21.4	300.68	40.5		
293.87	24.0	295.28	20.8	296.64	31.0	298.15	14.0	299.45	21.7	300.72	20.9		
293.92	30.7	295.32	17.2	296.67	28.9	298.20	18.3	299.47	19.5	300.76	20.1		
293.95	19.2	295.34	27.3	296.71	26.3	298.22	16.3	299.50	17.1	300.78	26.2		
293.97	27.1	295.37	15.1	296.75	28.7	298.27	19.3	299.54	14.3	300.80	40.1		
294.00	33.6	295.39	15.0	296.80	27.5	298.30	17.5	299.56	12.3	300.85	36.3		

TABLE A-4. NOS 26 Fracture Energy Data vs. Fracture Depth. page 1 of 2

DEPTH (m)	FE (J/m ²)	DEPTH (m)	FE (J/m ²)	DEPTH (m)	FE (J/m ²)	DEPTH (m)	FE (J/m ²)	DEPTH (m)	FE (J/m ²)	DEPTH (m)	FE (J/m ²)	DEPTH (m)	FE (J/m ²)
265.86	43	268.23	37	270.32	41	273.69	15	276.54	56	279.53	66	282.13	110
265.93	38	268.28	12	270.32	65	273.74	139	276.67	43	279.58	137	282.19	52
265.95	18	268.29	122	270.34	83	273.88	36	276.71	50	279.63	29	282.32	44
266.01	53	268.32	88	270.38	24	273.95	14	276.76	61	279.68	24	282.41	87
266.04	81	268.34	102	270.43	51	274.04	24	276.86	111	279.74	30	282.46	62
266.13	38	268.38	91	270.47	63	274.09	99	276.93	58	279.83	38	282.53	78
266.16	38	268.50	57	270.90	48	274.15	111	276.99	35	279.89	27	282.57	92
266.20	41	268.55	92	270.99	22	274.23	66	277.04	92	279.93	25	282.60	84
266.29	51	268.58	24	271.13	14	274.29	49	277.08	107	280.06	32	282.67	99
266.34	41	268.70	14	271.32	46	274.34	41	277.23	76	280.19	47	282.72	111
266.37	94	268.79	45	271.53	53	274.45	40	277.44	69	280.22	67	282.77	64
266.42	75	268.89	53	271.75	22	274.50	36	277.48	97	280.29	62	282.82	40
266.45	47	268.92	70	271.85	24	274.55	28	277.54	147	280.38	79	282.90	97
266.58	52	268.94	78	271.91	19	274.60	24	277.66	57	280.48	54	282.97	39
266.62	117	268.99	57	271.93	42	274.65	49	277.70	72	280.56	59	283.01	31
266.65	81	269.04	29	272.16	18	274.70	48	277.75	91	280.71	74	283.07	36
266.69	34	269.10	59	272.21	22	274.75	37	277.80	98	280.76	30	283.13	23
266.72	46	269.13	67	272.26	35	274.86	22	277.85	88	280.81	18	283.18	62
267.03	36	269.15	35	272.31	13	274.90	41	277.95	64	280.86	35	283.23	24
267.07	20	269.23	53	272.36	24	275.10	40	278.00	49	280.91	37	283.29	38
267.10	64	269.26	134	272.46	36	275.18	96	278.09	64	280.96	38	283.34	48
267.12	56	269.32	38	272.54	86	275.23	19	278.15	69	281.09	47	283.45	27
267.15	78	269.35	99	272.60	16	275.26	36	278.31	82	281.14	44	283.49	22
267.24	21	269.39	80	272.63	27	275.31	41	278.33	70	281.22	49	283.59	13
267.27	51	269.42	61	272.67	24	275.36	44	278.42	102	281.27	34	283.64	20
267.32	50	269.50	23	272.72	14	275.42	23	278.47	68	281.32	39	283.69	15
267.34	41	269.57	52	272.77	80	275.50	82	278.51	77	281.36	30	283.80	22
267.40	85	269.68	97	272.82	34	275.56	37	278.70	58	281.42	34	283.96	29
267.42	72	269.75	86	272.92	42	275.62	47	278.75	65	281.52	40	284.03	35
267.51	23	269.84	83	272.97	40	275.68	77	278.82	61	281.57	42	284.09	57
267.54	33	269.92	86	273.02	16	275.73	80	278.92	50	281.62	65	284.15	47
267.60	21	269.94	105	273.07	30	275.78	62	278.96	72	281.67	11	284.20	42
267.64	23	270.01	57	273.17	99	275.83	60	279.06	50	281.72	97	284.25	36
267.74	33	270.09	51	273.20	44	276.01	67	279.12	37	281.79	108	284.29	69
267.83	139	270.12	45	273.30	17	276.10	46	279.17	19	281.84	89	284.34	69
267.86	113	270.14	65	273.34	28	276.18	80	279.22	42	281.88	75	284.38	40
267.89	82	270.14	30	273.39	44	276.26	64	279.28	61	281.93	74	284.44	83
267.99	92	270.17	29	273.48	27	276.31	70	279.33	20	281.97	89	284.48	61
268.02	54	270.20	63	273.54	26	276.35	65	279.41	43	282.02	191	284.54	18
268.13	134	270.25	37	273.63	37	276.48	110	279.48	36	282.08	49	284.63	18

TABLE A-4. page 2 of 2

DEPTH (m)	FE (J/m ²)	DEPTH (m)	FE (J/m ²)	DEPTH (m)	FE (J/m ²)	DEPTH (m)	FE (J/m ²)	DEPTH (m)	FE (J/m ²)	DEPTH (m)	FE (J/m ²)	DEPTH (m)	FE (J/m ²)
284.69	10	287.35	39	289.46	89	292.13	9	294.74	59	297.59	36	300.01	11
284.79	10	287.41	57	289.50	106	292.18	28	294.78	32	297.63	28	300.05	13
284.84	18	287.45	30	289.55	128	292.27	16	294.83	31	297.68	56	300.10	12
284.89	14	287.51	41	289.80	67	292.33	14	294.93	26	297.73	73	300.14	22
284.94	19	287.55	58	289.91	28	292.40	38	294.98	19	297.87	32	300.19	13
284.99	24	287.66	62	289.96	70	292.44	31	295.04	49	297.92	23	300.27	9
285.16	10	287.71	37	290.01	51	292.49	13	295.18	24	298.07	31	300.32	20
285.21	21	287.76	39	290.06	61	292.59	8	295.23	49	298.12	54	300.35	18
285.30	33	287.81	49	290.13	61	292.64	18	295.31	56	298.19	59	300.41	13
285.35	8	287.85	16	290.18	34	292.69	17	295.36	77	298.24	35	300.51	14
285.41	21	287.85	48	290.23	65	292.74	18	295.41	87	298.28	88	300.61	30
285.59	16	287.91	27	290.28	45	292.85	21	295.50	55	298.34	29	300.66	39
285.62	40	288.00	63	290.33	43	292.99	35	295.58	64	298.42	71	300.72	25
285.66	55	288.05	41	290.38	21	293.09	33	295.63	54	298.47	101	300.77	37
285.82	18	288.10	20	290.47	20	293.16	26	295.68	43	298.52	39	300.82	38
285.87	21	288.15	30	290.52	13	293.24	52	295.73	60	298.56	112	300.86	18
285.96	22	288.20	54	290.58	20	293.31	22	295.83	34	298.58	45	300.91	52
286.01	29	288.23	27	290.63	23	293.36	44	295.89	47	298.68	65	300.96	53
286.07	25	288.33	57	290.68	24	293.41	50	295.99	46	298.71	43	301.01	32
286.13	19	288.37	66	290.77	15	293.46	61	296.04	19	298.76	34	301.07	28
286.19	24	288.43	97	290.82	21	293.51	94	296.08	12	298.81	22	301.12	31
286.29	13	288.48	23	290.91	21	293.56	24	296.22	23	298.85	15	301.17	31
286.36	10	288.53	62	290.96	57	293.61	22	296.27	14	298.91	15	301.23	49
286.41	16	288.60	57	291.08	51	293.66	26	296.32	23	298.96	22	301.28	69
286.49	15	288.67	50	291.12	20	293.79	20	296.37	61	299.01	13	301.34	46
286.55	19	288.76	27	291.17	18	293.85	21	296.42	16	299.06	23	301.40	37
286.59	23	288.82	30	291.22	54	293.90	25	296.48	17	299.11	16	301.45	62
286.65	15	105.98	127	291.28	38	293.96	25	296.54	43	299.16	35	301.49	55
286.70	14	288.91	26	291.32	32	294.06	65	296.63	11	299.21	19	301.54	27
286.75	21	288.99	30	291.37	40	294.12	27	296.68	26	299.27	24	301.59	46
286.80	19	289.05	81	291.41	31	294.17	63	296.72	21	299.33	27		
286.85	12	289.05	81	291.47	25	294.22	67	296.79	21	299.45	27		
286.90	9	289.06	70	291.51	71	294.27	71	296.85	17	299.50	20		
286.95	12	289.09	62	291.57	49	294.32	51	296.90	15	299.55	35		
287.00	12	289.12	98	291.67	28	294.42	50	296.95	26	299.60	30		
287.05	8	289.23	55	291.72	29	294.47	17	296.99	50	299.66	34		
287.10	13	289.27	61	291.77	33	294.53	68	297.04	34	299.71	26		
287.15	36	289.31	80	291.87	24	294.58	36	297.09	40	299.75	34		
287.25	38	289.36	63	292.03	31	294.63	18	297.14	56	299.80	27		
287.30	42	289.41	62	292.08	44	294.69	39	297.35	34	299.92	15		

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TABLE A-5. Upper Tipton Direct-Pull Tensile Strength Data vs. Fracture Depth. page 1 of 3

DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)
55.31	.8	56.01	.2	56.67	.6	57.60	.6	58.47	1.3	59.20	1.0
55.32	1.0	56.06	.6	56.68	.8	57.63	.6	58.48	.6	59.21	1.5
55.38	.8	56.07	.5	56.70	.3	57.66	.6	58.49	.9	59.30	1.3
55.40	.7	56.07	.3	56.70	.8	57.67	.6	58.50	1.2	59.30	1.5
55.40	.9	56.09	.3	56.72	1.1	57.73	.7	58.56	.9	59.34	1.4
55.45	.7	56.10	.2	56.75	.8	57.74	.7	58.56	.5	59.37	1.1
55.45	.5	56.12	.1	56.77	.2	57.75	.6	58.59	.8	59.39	1.0
55.45	.7	56.15	.3	56.78	.6	57.75	.6	58.61	1.0	59.41	1.4
55.52	.4	56.16	.2	56.81	.8	57.76	.5	58.61	.4	59.45	.8
55.53	.8	56.20	.3	56.81	.3	57.77	.5	58.61	.7	59.46	.4
55.56	.9	56.20	.4	56.82	.7	57.94	.4	58.66	1.1	59.47	1.6
55.61	1.1	56.20	.5	56.88	1.0	57.94	.5	58.66	.6	59.52	2.4
55.62	.8	56.21	.4	56.91	1.0	57.95	.4	58.71	1.7	59.54	1.6
55.65	.8	56.23	.2	56.92	.3	57.98	.4	58.72	.8	59.54	1.8
55.67	.8	56.26	.5	56.98	1.4	58.01	.5	58.75	1.5	59.55	2.2
55.68	.9	56.28	.1	56.99	1.2	58.02	.4	58.76	1.3	59.58	1.8
55.72	.5	56.38	.6	57.03	2.8	58.06	.5	58.78	1.3	59.66	1.1
55.73	.4	56.42	.7	57.07	3.7	58.06	.3	58.78	1.1	59.66	.7
55.74	.5	56.42	.7	57.08	1.3	58.07	.6	58.81	1.5	59.67	1.1
55.75	.3	56.43	.9	57.16	1.6	58.09	.1	58.84	.9	59.67	.7
55.90	.2	56.46	1.0	57.20	1.2	58.15	.8	58.84	1.0	59.68	1.2
55.90	.3	56.48	.6	57.22	1.1	58.17	.7	58.92	1.5	59.69	.5
55.91	.7	56.49	1.0	57.23	1.9	58.18	.8	58.92	1.5	59.72	1.1
55.91	.3	56.50	.4	57.29	1.8	58.20	.7	58.93	2.1	59.75	1.7
55.92	.3	56.51	.3	57.33	1.4	58.20	.9	58.95	1.2	59.77	1.2
55.93	.4	56.53	.2	57.34	1.2	58.22	.5	58.95	1.2	59.80	1.2
55.93	.6	56.54	.3	57.37	1.2	58.23	.9	58.99	2.5	59.82	1.1
55.93	.3	56.55	.7	57.40	1.1	58.26	.7	59.00	1.9	59.91	.5
55.94	.6	56.56	.2	57.42	.9	58.27	.3	59.00	1.4	59.92	.3
55.94	.1	56.56	.6	57.44	1.5	58.31	.8	59.05	1.7	59.92	1.5
55.94	.3	56.56	.6	57.51	.9	58.33	1.8	59.06	.8	59.93	1.1
55.95	.6	56.57	.7	57.51	.4	58.35	1.0	59.10	1.2	59.93	.6
55.95	.6	56.60	1.1	57.51	.8	58.36	.6	59.12	1.2	59.95	.9
55.96	.1	56.63	.8	57.55	.6	58.36	.4	59.12	1.4	59.98	.4

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TABLE A-5. page 2 of 3

DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)
60.01	1.2	61.08	1.1	61.50	.8	62.19	.7	62.96	2.0	63.62	1.3
60.03	1.2	61.08	1.6	61.52	.7	62.20	.5	62.97	1.8	63.64	1.8
60.11	1.1	61.08	.9	61.54	.9	62.21	1.0	63.01	1.6	63.65	2.3
60.12	1.1	61.11	2.2	61.56	.7	62.22	.8	63.02	1.3	63.66	1.3
60.16	2.9	61.13	1.1	61.58	.9	62.23	.7	63.04	1.7	63.77	.5
60.18	1.2	61.13	1.6	61.61	.7	62.26	.9	63.04	1.7	63.80	.9
60.22	1.2	61.13	.4	61.63	.4	62.31	.8	63.06	1.5	63.81	1.8
60.24	.4	61.15	3.0	61.64	.6	62.33	.8	63.07	1.3	63.82	1.2
60.24	1.1	61.17	1.2	61.65	.5	62.33	.8	63.08	1.6	63.84	1.2
60.27	1.4	61.17	1.8	61.65	.3	62.34	.9	63.09	1.9	63.86	2.5
60.28	.0	61.17	.9	61.66	.2	62.36	.9	63.09	1.9	63.88	1.1
60.28	.5	61.21	1.0	61.66	.7	62.37	.4	63.20	2.0	63.90	1.3
60.30	1.2	61.21	2.1	61.67	.8	62.40	.7	63.21	2.0	63.91	1.5
60.30	1.2	61.23	1.1	61.79	1.0	62.40	.8	63.21	2.0	63.92	1.8
60.32	1.7	61.24	1.2	61.81	.7	62.42	.7	63.22	2.8	63.92	1.5
60.57	.9	61.25	1.5	61.82	1.0	62.43	1.0	63.25	1.7	63.94	.7
60.60	.4	61.25	.8	61.83	.7	62.44	.8	63.26	2.0	63.94	1.2
60.60	1.0	61.28	1.1	61.86	.5	62.44	.6	63.29	1.8	63.97	1.1
60.64	1.0	61.29	.8	61.87	.7	62.46	1.0	63.29	1.0	63.97	.8
60.68	1.6	61.32	.6	61.88	1.0	62.47	.7	63.30	1.6	63.99	1.4
60.69	2.4	61.32	.8	61.89	.6	62.50	.5	63.32	1.0	64.02	1.3
60.72	.7	61.32	.8	61.90	.7	62.51	1.1	63.34	.7	64.05	.7
60.72	1.0	61.32	.8	61.90	.4	62.53	.5	63.35	1.1	64.05	.6
60.73	1.1	61.33	1.9	61.91	.7	62.55	.4	63.36	.8	64.05	.6
60.73	2.2	61.33	1.4	61.93	1.1	62.55	.4	63.37	1.4	64.08	.1
60.89	1.0	61.34	2.7	61.94	1.7	62.55	.7	63.38	1.3	64.10	.5
60.93	1.0	61.38	2.5	61.96	1.9	62.56	.9	63.40	1.5	64.11	.5
60.94	1.1	61.40	1.3	61.97	1.5	62.57	.8	63.41	1.9	64.11	.3
60.94	.9	61.41	.7	62.06	.9	62.80	1.1	63.43	2.8	64.12	.1
60.95	.3	61.41	1.4	62.07	.6	62.82	1.5	63.45	1.4	64.15	.7
60.98	1.6	61.41	1.7	62.07	.7	62.84	1.2	63.46	.9	64.18	.3
61.00	1.1	61.42	1.9	62.08	1.1	62.85	1.0	63.47	1.3	64.18	.1
61.01	.4	61.43	1.5	62.10	1.0	62.86	1.6	63.47	1.7	64.19	.2
61.01	.3	61.43	1.4	62.11	.8	62.89	3.0	63.47	.7	64.19	.3
61.05	.6	61.44	1.0	62.12	1.0	62.91	1.7	63.48	1.5	64.21	.1
61.05	1.8	61.44	2.9	62.14	1.0	62.94	1.5	63.61	1.0	64.21	.1

TABLE A-5. page 3 of 3

DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)
64.22	.2	64.79	.5	65.41	1.5	66.07	.6	66.68	.8	67.30	.1
64.23	.4	64.79	.7	65.57	.9	66.07	1.0	66.74	.1	67.31	.1
64.23	.1	64.80	1.2	65.58	1.1	66.12	.7	66.75	.0	67.32	.0
64.25	.7	64.81	.7	65.61	.1	66.12	.5	66.76	.2	67.74	.1
64.33	.1	64.81	.7	65.61	.5	66.13	.6	66.78	.1	67.72	.0
64.35	.1	64.93	2.0	65.62	.7	66.14	.2	66.78	.2	67.74	.3
64.37	.1	64.96	.7	65.63	.6	66.24	.7	66.81	.1	67.75	.4
64.39	.6	64.96	.8	65.63	.7	66.27	.3	66.82	.1	67.77	.4
64.40	.1	64.97	.7	65.64	.8	66.36	1.2	66.84	.1	67.78	.2
64.43	.5	64.99	.2	65.66	.6	66.36	1.2	66.85	.1	67.80	.1
64.45	.5	64.99	.2	65.74	.1	66.38	2.0	66.88	.1	67.82	.1
64.46	.3	65.00	.5	65.74	.1	66.40	.7	66.91	.1	67.98	.2
64.49	.4	65.11	.1	65.76	.0	66.40	1.0	66.97	.1	67.99	.1
64.49	.6	65.12	.6	65.79	.1	66.41	1.9	66.99	.1	68.01	.5
64.50	.4	65.13	.5	65.79	.3	66.44	1.6	67.03	.1	68.03	.1
64.54	.2	65.16	.4	65.80	.3	66.47	1.4	67.04	.1	68.04	.4
64.56	.4	65.17	.6	65.81	.1	66.47	1.4	67.11	.2	68.09	.1
64.61	.3	65.26	1.1	65.82	.3	66.50	.9	67.11	.2	68.11	.1
64.64	.1	65.27	.6	65.82	.1	66.50	.6	67.12	.0	68.13	.1
64.65	.2	65.27	.9	65.83	.2	66.51	1.5	67.13	.2	68.14	.3
64.66	.3	65.29	.9	65.84	.2	66.53	1.7	67.14	.0	68.15	.2
64.66	.3	65.30	1.0	65.85	.6	66.53	1.3	67.17	.2	68.16	.1
64.67	.1	65.31	.9	65.86	.3	66.54	1.8	67.17	.2	68.16	.3
64.68	.2	65.34	.3	65.88	.0	66.60	1.6	67.17	.1		
64.70	1.0	65.35	1.4	65.89	.2	66.61	1.3	67.18	.1		
64.71	.7	65.35	.8	65.90	.2	66.64	.6	67.19	.2		
64.73	.5	65.36	.5	65.91	.7	66.64	.3	67.20	.0		
64.73	.7	65.36	.5	65.91	.5	66.64	.7	67.27	.1		
64.77	.8	65.36	.8	65.96	.3	66.65	.6	67.28	.1		
64.78	.6	65.39	1.1	65.99	.4	66.67	.4	67.28	.1		
64.78	.6	65.39	1.1	66.06	.1	66.68	.5	67.29	.0		
64.79	.5	65.41	.2	66.07	.4	66.68	.6	67.30	.1		

TABLE A-6. Upper Tipton Natural Core Break Depths (DP Strength = 0).

DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)	DEPTH (m)	DP (MPa)
55.72	0.0	57.46	0.0	59.63	0.0	61.71	0.0	65.72	0.0	67.54	0.0
56.30	0.0	57.91	0.0	59.87	0.0	64.54	0.0	66.59	0.0	67.57	0.0
56.44	0.0	58.05	0.0	60.06	0.0	64.87	0.0	67.40	0.0	67.60	0.0
56.87	0.0	58.64	0.0	60.36	0.0	65.44	0.0	67.50	0.0	67.69	0.0

TABLE A-7. Upper Tipton Indirect Tensile Strength Data vs. Fracture Depth. page 1 of 2

DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)
55.18	4.1	56.50	3.2	57.60	3.2	58.59	4.0	59.50	6.3
55.21	1.6	56.53	2.9	57.62	5.4	58.61	3.8	59.52	4.5
55.23	2.9	56.55	3.4	57.65	3.9	58.74	3.9	59.55	5.3
55.28	3.3	56.66	3.2	57.67	2.9	58.75	4.2	59.58	5.8
55.31	3.0	56.68	3.1	57.70	4.0	58.77	5.0	59.65	4.3
55.33	3.5	56.71	2.4	57.72	2.8	58.81	3.7	59.68	3.8
55.36	3.1	56.73	3.2	57.75	4.0	58.84	5.4	59.70	3.9
55.39	2.5	56.76	3.7	57.77	3.8	58.87	4.6	59.72	5.2
55.41	1.9	56.78	3.5	57.80	3.7	58.89	4.5	59.75	5.0
55.44	1.8	56.81	2.0	57.82	3.3	58.91	6.2	59.78	3.3
55.50	2.8	56.83	4.1	57.85	3.4	58.94	4.5	59.80	3.3
55.53	2.1	57.06	5.4	57.88	3.4	58.97	3.8	59.83	4.0
55.55	2.8	57.09	4.7	57.98	2.9	58.99	4.3	59.97	3.4
55.61	3.3	57.11	5.0	58.00	2.3	59.02	4.3	59.99	3.7
55.65	2.5	57.14	8.5	58.13	3.0	59.04	4.0	60.02	4.7
55.82	2.2	57.16	7.3	58.15	3.1	59.07	4.0	60.16	5.9
55.87	1.9	57.19	2.2	58.20	3.0	59.09	4.2	60.19	4.6
55.89	1.6	57.21	2.0	58.23	3.4	59.12	3.7	60.21	4.7
55.94	2.5	57.24	1.8	58.26	2.9	59.14	4.0	60.24	6.1
55.97	1.5	57.27	4.1	58.26	2.6	59.17	1.4	60.26	5.9
56.10	1.4	57.29	4.8	58.28	3.1	59.20	2.4	60.29	4.3
56.12	.7	57.31	4.8	58.31	3.6	59.22	3.5	60.31	4.4
56.20	1.9	57.34	5.8	58.33	3.2	59.20	2.5	60.34	3.2
56.22	3.0	57.37	4.4	58.36	2.1	59.22	3.6	60.57	3.2
56.25	3.2	57.39	3.9	58.38	3.9	59.25	3.8	60.59	3.6
56.28	2.3	57.42	5.1	58.41	3.8	59.27	2.1	60.62	3.8
56.32	1.8	57.47	4.6	58.43	3.2	59.40	2.7	60.64	2.9
56.35	2.5	57.49	4.6	58.46	4.2	59.42	2.5	60.67	4.6
56.38	3.4	57.52	4.4	58.49	3.7	59.45	3.1	60.69	4.9
56.45	1.5	57.54	3.8	58.51	3.2	59.45	2.5	60.72	4.0
56.48	.9	57.57	1.8	58.55	3.3	59.48	5.2	60.74	.1

TABLE A-7. page 2 of 2

DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)	DEPTH (m)	IT (MPa)
60.77	5.5	61.81	5.9	62.93	4.1	64.05	2.6	65.34	4.4
60.80	5.8	61.84	5.9	62.95	4.1	64.07	4.0	65.37	5.0
60.82	6.1	61.86	4.6	62.98	1.0	64.10	4.2	65.39	5.6
60.85	5.4	61.89	6.4	63.08	8.2	64.15	2.2	65.54	1.9
60.87	6.3	61.91	5.7	63.11	7.0	64.33	4.1	65.57	3.6
60.92	4.6	61.94	6.1	63.13	7.0	64.35	3.8	65.60	5.2
60.95	4.7	61.96	3.5	63.16	3.9	64.38	3.1	65.62	3.3
61.08	5.4	62.07	3.8	63.21	4.4	64.40	2.8	66.07	3.8
61.10	5.7	62.09	4.3	63.23	6.8	64.43	3.6	66.10	7.0
61.12	5.4	62.12	4.6	63.26	8.1	64.45	3.8	66.12	4.0
61.15	6.4	62.14	5.2	63.29	6.0	64.61	3.7	66.15	3.4
61.18	5.4	62.19	3.8	63.31	5.7	64.64	4.4	66.18	1.5
61.20	4.7	62.22	4.7	63.33	5.5	64.66	4.1	66.36	8.1
61.23	4.5	62.24	5.2	63.41	9.8	64.71	2.4	66.38	8.2
61.25	4.6	62.30	5.2	63.44	8.5	64.76	5.9	66.41	7.6
61.28	4.9	62.32	4.2	63.46	8.3	64.78	5.9	66.43	9.3
61.30	5.2	62.34	4.3	63.49	7.1	64.93	6.0	66.46	6.3
61.33	7.6	62.37	5.7	63.61	6.9	64.96	3.2	66.49	5.7
61.35	6.9	62.40	5.4	63.64	12.6	64.99	4.4	66.51	3.4
61.38	7.3	62.42	5.3	63.67	6.4	65.01	6.4	66.53	6.7
61.41	7.2	62.45	4.1	63.69	5.6	65.04	7.0	66.97	5.7
61.43	3.9	62.47	3.2	63.77	4.0	65.06	3.1	66.99	2.9
61.46	6.6	62.50	3.8	63.79	5.9	65.09	3.9	67.02	3.3
61.51	5.1	62.55	4.4	63.82	7.2	65.11	4.1		
61.53	5.0	62.70	9.5	63.84	7.5	65.14	6.5		
61.56	4.6	62.78	3.0	63.87	6.6	65.16	5.4		
61.58	5.6	62.80	2.4	63.90	4.9	65.19	4.1		
61.61	4.2	62.83	3.6	63.92	7.9	65.22	6.3		
61.63	4.3	62.85	4.0	63.97	6.8	65.25	5.4		
61.66	3.2	62.88	2.9	64.00	6.6	65.29	5.6		
61.79	5.3	62.90	3.8	64.02	6.6	65.32	7.5		

TABLE A-8. Upper Tipton Fracture Energy Data vs. Fracture Depth.

DEPTH (m)	FE (J/m ²)	DEPTH (m)	FE (J/m ²)	DEPTH (m)	FE (J/m ²)	DEPTH (m)	FE (J/m ²)
55.19	35	58.88	37	60.94	49	63.07	72
55.25	31	58.90	33	61.09	39	63.22	37
55.32	24	58.95	34	61.11	53	63.32	53
55.43	28	58.98	35	61.11	38	63.35	49
55.50	45	59.06	44	61.14	45	63.42	76
55.61	10	59.08	46	61.24	27	63.45	54
55.96	10	59.11	23	61.29	57	63.45	41
56.03	5	59.21	69	61.29	35	63.47	31
56.11	15	59.31	35	61.32	35	63.63	30
56.52	11	59.34	25	61.34	75	63.65	57
56.56	10	59.36	26	61.42	58	63.65	41
56.59	24	59.42	20	61.44	35	63.68	40
56.59	7	59.45	11	61.52	14	63.68	47
56.67	23	59.46	34	61.59	13	63.80	34
56.72	3	59.50	37	61.65	13	63.83	27
56.77	3	59.54	25	61.80	15	63.88	26
56.79	29	59.54	31	61.85	11	63.91	20
57.07	17	59.56	70	61.90	20	64.18	12
57.10	35	59.79	22	61.90	10	64.34	19
57.13	33	59.79	22	61.95	13	64.36	22
57.17	25	59.80	26	62.08	17	64.39	9
57.20	26	60.02	26	62.20	14	64.44	38
57.23	49	60.02	20	62.23	36	64.47	65
57.30	22	60.17	38	62.26	15	64.64	23
57.33	86	60.20	21	62.31	14	64.77	10
57.40	28	60.22	23	62.33	16	65.28	26
57.51	30	60.27	12	62.41	20	65.33	13
57.74	10	60.30	13	62.43	16	65.36	37
57.84	45	60.33	17	62.43	12	65.68	35
57.86	20	60.68	36	62.51	18	65.61	91
58.17	20	60.71	48	62.54	24	66.09	7
58.24	16	60.73	28	62.81	66	66.12	41
58.27	12	60.78	47	62.84	34	66.37	41
58.29	8	60.78	52	62.92	51	66.42	26
58.34	19	60.81	28	62.94	74	66.47	34
58.39	19	60.83	57	62.97	42	66.52	64
58.47	17	60.83	82	63.02	34		
58.50	19	60.88	22	63.04	86		