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DOE/LC/10961-1705
(DE85004985)

**FRACTURE MECHANICS INVESTIGATION OF OIL SHALE TO AID
IN UNDERSTANDING THE EXPLOSIVE FRAGMENTATION PROCESS**

Comprehensive and Final Technical Report for the Period
January 1983—July 1984

By
Ken P. Chong

September 1984

Work Performed Under Contract No. AS20-82LC10961

For
U. S. Department of Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
University of Wyoming
Laramie, Wyoming

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FINAL TECHNICAL REPORT

Submitted to
U.S. Department of Energy

**FRACTURE MECHANICS INVESTIGATION OF OIL SHALE TO AID
IN UNDERSTANDING THE EXPLOSIVE FRAGMENTATION PROCESS**

Sponsored by the U.S. Department of Energy
Contract No. DE-AS20-82LC10961
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FRACTURE MECHANICS INVESTIGATION OF OIL SHALE TO AID
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BACKGROUND

One of the requirements of processing oil shale is to optimize particle sizes and permeability distributions in fragmentations as indicated by P. J. Hommert [1]. The goal is to develop the technology to "improve the overall efficiency of shale oil recovery processes [1]. Basic to the understanding and planning of in-situ fragmentation and ex-situ mining of oil shale are the mechanical properties. This research proposal is an extension of a research project entitled "Mechanical Properties of Oil Shale" originally funded in February, 1977, by ERDA Fossil Energy Program, through its Division of Oil, Gas and Shale Technology, under Contract Number EF-77-5-04-3954. Later, the project has been extended to 1983 to include physical characterization of selected oil shale. During the past six years, an innovative and unique program was established which developed an efficient methodology for standardized and simplified mechanical testing of the western oil shale. The experiments include precise, representative and duplicable sample preparation; uniaxial static compression testing; "modified" split cylinder testing; uniaxial creep and relaxation testing under extended periods of time; dynamic testing with varying strain rates; fatigue resistance; and three-dimensional constitutive relationships. The variables investigated include organic volume, mineral contents, stratigraphy, strain rates, and stress levels [2-5].

*Assisted by M. D. Kuruppu, post-doctor; and J. A. Weber, assistant.

Numerical modeling and rubbleization experiments have been performed by various investigators. Surface uplift blasting has been successful for shallow formations [6] which also provides opportunities to investigate high strain-rate rock mechanics [5]. Rock rubbleization experiments including the propagation of stress waves were described by Reed and Boade [7]. Improved fracturing methods were evaluated [7]. Time-explicit finite-difference numerical analyses were applied to evaluate the stimulation treatment in the multiple fracturing of a well bore [8], and to study explosively induced fractures in void generation [9]. Influences due to yielding properties, crack propping, gas pressurization, etc., were discussed.

Kipp, et al. [10] have determined that the dynamic fracture stress is a strong function of the strain rate. At high strain rates, fracture stress is insensitive to the crack orientation relative to the bedding planes, and the crack front curvature is no longer important as noted by Chen, et al. [11]. Fragmentation experiments performed by Grady and Kipp [12] have confirmed that fragment size decreases with strain rate.

High-speed motion pictures were used on reduced-scale blasting experiments on limestone under controlled conditions to investigate the role of stress waves and discontinuities in rock fragmentation by Winzer and Ritter [13]. A numerical model involving fluid flow, structural, fracture mechanics, in-situ stresses and shale properties are used to study the hydraulic fracturing of Devonian shale by Advani, et al. [14].

However, as far as the fracture mechanics is concerned, as Edl [15] pointed out, there is still a lack of understanding "of the fundamental explosive rock breakage mechanisms," which "has necessitated extensive reliance on very costly empirical approaches." Britton [6] also stated that

"numerous questions remain regarding high strain rate rock mechanics phenomena and interaction of explosive with surrounding rock medium." Fracture mechanics of oil shale [16-18] has been based on conventional fracture mechanics using notched samples covering one or two oil yields and assuming the material to be isotropic and elastic [18-23]. A data-base of fracture toughness (with oil yields as a variable) is still non-existent. Oil shale is a layer material more accurately characterized as transversely isotropic [24,25] and behaves nonlinearly due to stress dependency. Furthermore, the notches upon which cracks initiate are extremely sensitive to the location of the bedding planes (layers). Consequently, a more promising fracture mechanism should involve the average behavior of a section of oil shale (for example, a 2 cm thick specimen sampled by oil yield) instead of the breaking strength of a particular layer. A realistic data base in fracture mechanics is useful for the joint rock fragmentation experiment program currently carried out by Sandia National Laboratory [1] and Los Alamos National Laboratory [46].

OBJECTIVES AND REQUIREMENTS

The objectives are to (a) develop theoretical fracture mechanics tools that are applicable to transversely isotropic materials such as sedimentary rock, more particularly oil shale; and (b) develop a fracture mechanics test procedure that can be conveniently used for rock specimens. Such a test procedure would: utilize the geometry of a typical rock core for the test; require a minimum amount of specimen machining; and provide meaningful, reproducible data that corresponds well to test data obtained from conventional fracture mechanics tests.

Specifically, work to be performed includes:

(a) A critical review of the state-of-the-art on the fracture mechanics of oil shale. Recommendations for the fracture mechanics investigation of oil shale.

(b) Numerical analyses of fracture mechanisms using promising fracture specimens and finite elements or other techniques.

(c) Precise, representative, replicate sample preparation with oil yield as a variable. Using precracked disks or semi-circular precracked specimens, fracture mechanics are to be investigated experimentally. The primary variable is the oil yield.

(d) Verification and correlation between numerical/analytical investigations in (b) and experiments in (c).

(e) Comparison of experimental data with limited data in existing literature.

A milestone chart of the above tasks is shown in Figure 1.

APPROACHES

For anisotropic rocks, such as oil shale, the fracture toughness is not a uniform material property; rather, it depends on the crack orientation with respect to the layers or bedding planes. However, there is a definite need for the establishment of a standard test procedure for the determination of fracture toughness of layered materials. Such an endeavor must be backed by developments of appropriate theoretical and numerical methods. For the analysis of fracture properties of layered rocks, it may be necessary to determine the fracture toughness for complex crack geometries as well.

Analytical solutions related to the crack border stress intensity factors are available for transversely isotropic materials where the crack lies in a

Figure 1

Chronological Chart

TASKS	YEAR MONTH	1983												1984									
		4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10			
(a) Critical review of the State-of-the art of Fracture mechanics. Recommendations for innovative and promising methods for oil shale fracture mechanics.		-----																					
(b) Numerical and analytical investigations of fracture mechanisms using precracked cylinders and semi-circular precracked specimens.														-----									
(c) Experimental design and verification/correlation of numerical and analytical investigations in (b). Comparison of exploratory static fracture toughnesses with existing data.														-----									

Note: ----- Continuous Effort

- - - - - Intermittent Effort

plane of elastic symmetry. However, types of cracks encountered in practical applications of layered materials are general in nature; and, therefore, the use of numerical methods is more appropriate. Among the various approaches reported to determine the stress intensity factors, use of special finite elements to represent the stress singularities at the crack tip and strain energy methods are more prominent. Furthermore, orthotropic or transversely isotropic material properties can be handled. The quarter point singular cracktip elements are easily incorporated in ordinary finite element programs employing isoparametric elements and have been shown to yield satisfactory results [26,27]. The stress intensity factor associated with a crack has a strong relationship with the crack opening profile as it is the governing parameter of the local environment of the crack tip. The opening profile of a sharp crack embedded in an elastic solid may be assumed to satisfy an elliptic displacement function and a solution for fracture toughness is derived [26].

Input data for analytical model and finite element method would be derived by testing oil shale specimens to fracture. The experimental methods suggested by previous investigators for the determination of fracture toughness of rock materials make use of test specimens designed for testing metallic materials [17,28]. However, there are several problems associated with oil shale which do not qualify it for customary fracture mechanics test methods such as ASTM standard test method [29]. First, the specimens that are used for standardized fracture mechanics test procedures require a great deal of machining which is expensive and difficult to accomplish in rock. Second, oil shale being a rock material, is difficult to load in tension, and tests should be done with compressive loadings where tensile fractures are induced. Third, the fracture toughness needs to be related to the orientation

of bedding planes as the fracture properties of a layered material is highly sensitive to the relative directions of cracks with respect to the bedding planes. In order to overcome these problems, the principal investigator proposes to use a circular core specimen with a center crack subjected to diametrical compressive loading system similar to the Split Cylinder Tests [2,30]. The disk is drilled and precracked at the center (Fig. 2). As shown in Fig. 3, the uncracked specimen, commonly used in the Split Cylinder Test [2], is subjected to relatively uniform horizontal tensile stresses ($\bar{\sigma}_x$) along the loaded vertical diameter. The horizontal tensile stresses will undoubtedly open up the precracked cylinders in Fig. 2. The load-displacement behavior up to fracture would be determined; and using the knowledge of crack geometry, fracture load and material properties, fracture toughness would be evaluated by means of analytical and finite element methods [31]. Alternatively, fracture toughness may be determined by evaluating the J-integral along an appropriate path of the finite element idealization [26,32]. Correlations are made with conventional notched beam tests. These precracked cylinders can be easily fabricated from oil shale cores, requiring a minimum amount of machining. Some results are presented later in this report.

All test specimens must satisfy certain minimum dimensional requirements for valid plane strain fracture toughness results [39]. However, these requirements have not been well established for most rock materials, particularly for layered materials. The effects of the variation of such major dimensions as crack length, uncracked ligament and thickness on the fracture toughness should be investigated. An attempt is made to identify the effect of organic content on the fracture properties of oil shale.

Fig. 2 Disk with a Center Crack

Fig. 3 Stress Distribution in a Split Cylinder Specimen [2]

As an improvement and refinement over the center crack disk, the principal investigator further proposed to use a semi-circular core specimen with an edge crack subjected to three point loading system (Fig. 4). The load-displacement behavior up to fracture is determined; and using the knowledge of crack geometry, fracture load, and material properties, fracture toughness can be evaluated by means of analytical and finite element methods [27,33]. Alternatively, fracture toughness may be determined by evaluating the J-integral along an appropriate path of the finite element idealization [26,32]. Correlations are made with limited data based on conventional fracture toughness tests [17,34]. Using several independent established testing methods, Costin [34] pioneered the investigation of the static and dynamic fracture behavior of a single block of Colorado oil shale about 200 ml/kg (50 gal/ton) in oil yield. Quantification of fracture toughness with respect to oil yields is still non-existent.

These precracked semi-circular cylinders can be easily fabricated from oil shale cores, requiring a minimum amount of machining. The test specimen is obtained by coring perpendicular to the bedding planes. Since the straight boundaries and cracks need to be prepared with utmost care, each disk is cut into two halves with a diamond impregnated wire. Center cracks of specified lengths are also cut by the wire. Conventionally, test samples have been mechanically cut to specimen size by diamond coated saw blades. The impact from the saw blade is known to induce disturbances in the material, quite often resulting in hair-line cracks. The frictional cracks are undesirable since they are caused by external influences, not at all representative of the test material. To avoid these unwanted effects, the specimens were cut using a specially made wire saw. The Model 2008 Wire Saw, designed by Laser

Fig. 4 University of Wyoming Semi-Circular Edge-Cracked Specimen

Technology, Inc., uses a diamond impregnated wire as the cutting tool. The diameter of the wire is 0.25 mm, with a high tensile strength exceeding 3450 MPa. The wire cuts smoothly and accurately to 0.025 mm. Since the tension of the wire is the single most crucial adjustment on the saw, a special counter weight system is used instead of the conventional spring-loading systems. A unique feature about the wire saw is the very low force exerted on the specimen from the wire. This force is usually less than 2.2 N. A sprinkling device was developed and attached to the wire saw to keep the samples cool during cutting. The sprinkled water acted as a lubricant and a carrier of cut dust as well. The wire saw is equipped with an automatic control panel for easy operation. When properly operated, the wire saw is the fastest and best way to cut samples, especially rocks, without damaging the surface of the specimen.

RESULTS AND DISCUSSIONS

(a) Critical review of the state-of-the-art of fracture mechanics on layered rocks has been completed. Recommendations are made for innovative and promising methods for oil shale fracture mechanics. These are documented in the published Report of Investigations [35].

(b) Numerical and analytical studies of mixed mode fracture mechanics are investigated. Transversely isotropic properties [36] of oil shale are input using isoparametric finite elements with singular elements at the crack tip. The model is a plate with an edge crack whose angle with the edge varies to study the effect of mixed mode fracture under various conditions. The three-dimensional plate is in tension, and stress, energy methods are used in the fracture analysis. The cracked body is represented geometrically by four finite element grids with the notch at 30, 45, 60, and 90 degrees.

Once a numerical solution is found using the finite element method, it is necessary to be able to estimate the crack tip stress intensity factors using the established crack tip relations. This study uses a direct method in which the displacement field is used to find the stress intensity factors.

The conic-section simulation analysis [26] is a method to determine stress intensity factors when using the finite element analysis. The method involves the mapping of the nodal displacements into a single elliptical function. It has been shown that relatively coarse mesh could be used to obtain reasonably accurate results.

(c) Precracked disks of oil shale cored perpendicular to bedding planes are analyzed numerically. Stress intensity factors are determined by (i) strain energy method, and (ii) elliptic simulation method.

One quarter of the disk was analyzed due to symmetry and a typical finite element idealization is shown in Fig. 5. The material was assumed to possess elastic transversely isotropic properties with z-direction being the axis of symmetry. The stress intensity factor as a function of crack length under diametrical compressive loads is shown in Fig. 6, and values are given in Table 1.

Fig. 5 Finite Element Modeling of Center-Cracked Disk

Fig. 6 Stress Intensity Factor of Center-Cracked Disk vs. Crack Length, under load

TABLE I
COMPARISON OF THE VALUES OF $\frac{K_I}{P\sqrt{\pi a}}$ FOR PRECRACKED DISK SPECIMEN

Crack Length $\frac{a}{R}$	Normalized Stress Intensity Factor $\frac{K_I}{P\sqrt{\pi a}}$	
	Strain Energy Method	Elliptic Simulation Method
0.28	0.0929	0.0900
0.40	0.1003	0.1014
0.50	0.1094	0.1146

The precracked disk is further modeled under displacement loading. The effect of crack length on the non-dimensionalized stress intensity factor is investigated by (i) strain energy method, (ii) ellipse method, and (iii) stress method (using Westergaard's solution for stress at the crack tip element, see for example Fracture, VII, Liebowitz, 1972). Very close agreements are found except for $a/R < 0.3$, as shown in Fig. 7.

Fig. 8 illustrates the influence of center hole radius on the stress intensity factor. Again, three independent methods are used, and the results are quite agreeable.

The horizontal normalized stress distribution across the loaded (vertical) diameter is shown in Fig.9 with and without the crack. It is apparent that the presence of a center hole does not affect the stress distribution away from the crack tip. Furthermore, high tensile stresses (several times higher than the solid disk) are found close to the crack tip as

Fig. 7 Stress Intensity Factor of Center-Cracked Disk vs. Crack Length, under displacement Loading

Fig. 8 Influence of Center Hole Radius on Stress Intensity Factors in Center-Cracked Disks

Fig. 9 Normalized Stress Distribution in a Center-Cracked Disk

expected. These high tensile stresses open the crack when the load is applied.

(d) Semi-circular specimen with an edge crack at center is shown in Fig. 4. The kinematics of the proposed fracture model is shown schematically in Fig. 10. Crack mouth opening displacement measured on the bottom face is related to load line displacement assuming a rigid body rotation about a point lying in the uncracked ligament. Chong and Kuruppu have derived the following equations relating the load line displacement (q) and crack mouth opening (Δv).

$$q = R - (1 - r)(R - a) - [r(R - a) + a + z] \frac{\cos(\alpha + \theta)}{\cos \alpha} + (s - \ell) \sin \theta + z \cos \theta \quad (1)$$

in which

$$\theta = \sin^{-1} \left\{ \frac{(\Delta v + 2\ell) \cos \alpha}{2[r(R - a) + a + z]} \right\} - \alpha \quad (2)$$

Dimensions a , ℓ , r , R , s , z , θ , and α are shown in Fig. 10. Based on computer testing, the rotational factor (r), which is a fraction of the ligament, with point Q as the hinge point, shown in Fig. 10, is about 15 percent when a/R ratio is greater or equal to 0.60. Various investigators [38-41] have studied the factor (r) for different specimen configurations and discovered that slight variations in r have negligible effects on the relationship between q and V . Furthermore, r will increase with the amount of plastic deformation [39]. For oil shale, which is quite brittle, the r value of 15 percent is realistic.

Fig. 10 Kinematics of Proposed Fracture Specimen

The precracked semicircular disk is modeled under loading. The effect of crack length on the non-dimensionalized stress intensity factor is investigated numerically by:

(i) Strain energy method.

Let U be the change in strain energy between two crack lengths of (a) and $(a + \Delta a)$. The energy release rate, G , is given by:

$$G = \frac{1}{B} \frac{\Delta U}{\Delta a} \quad (3)$$

and the Stress Intensity Factor (SIF), K_I , is

$$K_I = (GE_x)^{1/2} \quad (4)$$

where, B = specimen thickness;

E_x = Young's modulus in the plane of specimen.

(ii) Ellipse method.

Assuming the crack opening displacement, $b(x)$, to be elliptical [26],

$$b(x) = u_2(x,0)/(1 - \frac{x^2}{a^2})^{1/2} \quad (5)$$

where. u_2 = the crack displacement along y -direction; $2a$ = length of the major axis (along x -direction).

Woo and Kuruppu [26] have shown that,

$$K_I = E_x b(a) \sqrt{\pi a}/(2a) \quad (6)$$

$b(a)$ is obtained by extrapolation of $b(x)$ vs x from computer output.

(iii) Stress method.

By Westergaard's solution (Liebowitz [42]),

$$K_I = \sigma_y \sqrt{2\pi r} \quad (7)$$

σ_y is the opening stress in the y -direction, at the crack tip element. K_I at the crack tip is obtained by extrapolating with respect to the radial distance r ($r = 0$ at crack tip).

Results are shown in Fig 11. Close agreements are observed for these three independent methods.

The fracture toughness K_{IC} is obtained by compressing the specimen in Fig. 4 to failure. Let P_u = ultimate load at fracture, then from Fig. 11, let

$$\bar{K}_I = \frac{K_I}{\sigma_0 \sqrt{\pi a}} \quad (8)$$

where,
$$\sigma_0 = \frac{P}{2Rt} \quad (9)$$

Thus,
$$K_I = \bar{K}_I \sigma_0 \sqrt{\pi a} \quad (10)$$

At fracture,
$$K_{IC} = \bar{K}_I \sigma_u \sqrt{\pi a} \quad (11)$$

where,
$$\sigma_u = \frac{P_u}{2Rt} \quad (12)$$

Fig. 11 Stress Intensity Factor vs. Crack Length
 for Center-Cracked Semi-Circular
 Specimen

(iv) Compliance Method

Considering energy balance of a cracked body

$$G = \frac{P^2}{2t} \frac{\partial C}{\partial a} \quad (13)$$

where

G - Elastic energy release

P - Applied load

t - Specimen thickness

v - Load line displacement

C - Specimen compliance ($\frac{v}{P}$)

a - Crack length

Let
$$\frac{Et v}{P} = F\left(\frac{a}{W}\right) \quad (14)$$

$$G = \frac{P^2}{2t} \left[\frac{1}{E t} \frac{\partial F(a/W)}{\partial a} \right] \quad (15)$$

$$= \frac{P^2}{2Et^2W} \frac{\partial F(a/W)}{\partial (a/W)} \quad (16)$$

Then
$$K = (EG)^{1/2} = \frac{P}{t\sqrt{2W}} \left[\frac{\partial F(a/W)}{\partial (a/W)} \right]^{1/2} \quad (17)$$

Hence, the fracture toughness may be determined using compliance calibration of the test specimen and ultimate load at fracture.

(e) Minimum specimen size requirements for valid plane strain fracture toughness tests.

Schmidt (17) suggested that the minimum specimen size requirements for valid plane strain fracture toughness testing of oil shale are the same as those for metallic materials, as given in ASTM-E399 (29). It is given as $2.5 (K_{IC}/\sigma_u)^2$ where K_{IC} is the fracture toughness and σ_u is the ultimate tensile strength as applicable for rock materials.

Case (i)

For S.G. = 1.9 (200 ml/kg or 50 G/T) organic volume, $O_c = 50\%$ and for Colorado and Utah oil shale (Ref. 2)

$$\begin{aligned}\sigma_u &= (3.359 - 0.051 O_c) \text{ksi} \\ &= 1.10 \text{ Ksi } (7.59 \text{ N/mm}^2)\end{aligned}$$

From Fig. 12, $K_{IC} \approx 21.0 \text{ N/mm}^{3/2}$

$$\begin{aligned}\text{Therefore, minimum specimen size} &= 2.5 \times \left(\frac{21.0}{7.59}\right)^2 \\ &= 19.1 \text{ mm}\end{aligned}$$

Case (ii)

For S.G. = 2.3 (80 ml/kg or 20 G/T), $O_c = 22\%$

$$\sigma_u = 1.59 \text{ Ksi } (10.98 \text{ N/mm}^2)$$

From Fig. 12, $K_{IC} \approx 15.0 \text{ N/mm}^{3/2}$

$$\begin{aligned}\text{Minimum specimen size} &= 2.5 \times \left(\frac{15.0}{10.98}\right)^2 \\ &= 4.6 \text{ mm}\end{aligned}$$

Therefore, specimen sizes larger than about 20 mm satisfy the plane strain requirements, even for the rich oil shale tested during the program.

Exploratory test results (Fig.12) indicated that for rich oil shale (with specific gravity of about 1.9) from the Green River formation, the fracture toughness is around $25 \text{ N/mm}^{3/2}$ which is comparable to the data obtained by

Fig. 12 Fracture Toughness Variation of Oil Shale
with Specific Gravity

Costin [34] and Schmidt [17]. However, for lean oil shale (specific gravity about 2.3), the fracture toughness measured around $17 \text{ N/mm}^{3/2}$ which is about one-half of that measured by Schmidt [17]. Physically, rich oil shale is more ductile (Chong, et al. [43]), requiring more energy to fracture, which is consistent with field and laboratory fragmentation experiments [44,45,47]. Results can be summarized as follows:

1. Oil shale which contains organic material in its structure behaves nonlinearly under stress. For rich oil shales, the stress-strain behavior is quite similar to that of a ductile material. Ductility decreases for lean oil shales.
2. Analytical methods based on stresses, displacements, strain energy, and compliance were employed for fracture toughness determination, and all methods yield agreeable results.
3. Rich oil shale is found to have a higher fracture toughness, thus absorbing more energy for fracture compared to leaner oil shale.
4. Dimensional requirements for valid plane strain fracture toughness is apparently similar to those for metallic materials as proposed by Schmidt in Ref. 17. This means that the required minimum size of specimens of rich oil shale is larger than that of leaner material.
5. Fracture toughness of Utah oil shale varies from about $26 \text{ N/mm}^{3/2}$ for 200 ml/kg (50 G/T) shale grade to about $18 \text{ N/mm}^{3/2}$ for 80 ml/kg (20 G/T) material. The minimum size requirements for valid plane strain fracture toughness tests were identified.

In summary, all the objectives and requirements of this research contract

have been fulfilled or exceeded. New semi-circular precracked specimen developed should be extremely useful for the static and dynamic fracture characterization of oil shale.

ACKNOWLEDGMENTS

This research is supported by the U.S. Department of Energy under Contract No. AS20-82LC10961, Dr. Theodore C. Bartke, COR. Stimulating and useful discussions by Dr. Bartke, preparation of specimens by Jeff Weber, and superior typing by Anita Biggs are also gratefully acknowledged.

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