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DYNAMIC TENSILE FAILURE IN ROCKS

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Covering the Period April 15 to October 15, 1972

DYNAMIC TENSILE FAILURE IN ROCKS

By: Donald A. Shockey

Prepared for: Bureau of Mines
Twin Cities Mining Research Center
Twin Cities, Minnesota 55111

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13. ABSTRACT

A fracture model is being developed based on the hypothesis that dynamic tensile failure in rocks occurs by the activation of preexisting flaws which propagate and may coalesce to produce fragments of various sizes. During the previous year the first two stages of the fracture process--flaw activation and crack growth--were treated quantitatively. The fracture model in its present stage of development allows us to predict the number of cracks, the total fracture surface area, and the energy absorbed by creation of new surface resulting from a known dynamic loading history. The objective of this second year is to treat quantitatively the final two stages of the fracture process-crack coalescence and fragmentation--to obtain the capability to predict fragment size, shape and location.

Crack coalescence was studied and fragment size distributions were measured on Arkansas novaculite following dynamic loading experiments with a gas gun. Crack networks as revealed on a polished section through the specimens yielded information on the size and shape of fragments as a function of position within the specimen, and hence as a function of stress history. Measured fragment size distributions of comminuted specimens are used to formulate and check the model.

Although the model is not complete, procedures to generalize the fracture model to other rocks were initiated by examining petrographically specimens of Sioux quartzite, Westerly granite, and pink Tennessee marble to attempt to reveal and describe quantitatively their inherent flaw structures. The distribution of preexisting flaws, an

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Abstract (concluded)

important parameter in the fracture model, was found to be much more difficult to determine in these rocks than in novaculite because of the obscurity of the flaws.

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I INTRODUCTION

Failure of rock by fracture under dynamic tensile loading conditions is more complex and considerably less well understood than fracture under quasi-static conditions. There is at present no satisfactory theoretical basis for predicting dynamic failure behavior, although the advantages of having such a basis are many. An understanding of rock failure under dynamic tensile loads would be most useful in the solution of practical mining and civil engineering problems. With such knowledge rapid excavation could be done more safely and economically, the stability of structures in rock could be designed and evaluated with more confidence, and the efficiency of rock disintegration processes could be improved. It is the objective of this three-year program to develop a model for rock fracture that can be used to predict failure behavior under dynamic tensile loading. This report summarizes the progress made during the first half of the second year.

The program consists of three phases:

Dynamic Measurements: Flat-plate impact experiments are performed on rock specimens, some of which are instrumented with in-material stress gages or particle velocity gages to determine stress histories in rock during tensile failure.

Residual Measurements: Optical and scanning electron microscope techniques are used to examine the fracture damage in recovered rock specimens.

Model Development: Based on our results and observations, a model for dynamic tensile failure of rock is developed and substantiated. Initially the model is to be applicable to Arkansas novaculite and Sioux quartzite, then later generalized to apply to Westerly granite and pink Tennessee marble (Holston limestone).

In the course of the first year significant progress was made in understanding rock failure in tension.[1,2] The most encouraging result is that an approach has been developed that may lead to a capability for predicting fragment size distributions resulting from known stress pulses.

Our observations during the first year's work led us to hypothesize that dynamic tensile failure in rock occurred by the following sequence of events: (1) a number of preexisting flaws in the rock are activated by an applied stress pulse, (2) the activated cracks begin to grow radially outward on planes normal to the direction of maximum tension, (3) neighboring cracks begin to grow into each other and coalesce, and (4) coalescing cracks isolate integral fragments of rock and free them from the main body. In the first year a model based on this failure mechanism was proposed and the first two stages of the model, flaw activation and crack growth, were treated in some detail. In its present state, the model enables us to calculate the number of cracks, the total fracture surface area, and the energy absorbed in fracture for a known applied dynamic load.

One of the two objectives this year is to obtain quantitative information on the final two stages of the failure process and extend the model to include fragmentation. The other objective is to test and to generalize the novaculite fracture model on other rock types.

This semiannual technical report is presented in three parts: we first describe our model for dynamic tensile failure in rock; we then discuss the experiments and results from studies of crack coalescence and the fragmentation behavior in Arkansas novaculite; and finally we report the methods and results of the characterization work on Sioux quartzite, Westerly granite, and pink Tennessee marble with respect to microstructure, defect structure, quasi-static tensile strength, and response to stress waves.

II DYNAMIC FRACTURE MODEL

We seek to develop a fracture model which relates loading parameters, rock properties, and geometry of specimen and load to permit calculation of fracture parameters. Fracture parameters of interest include number of cracks, total crack surface area, energy absorbed in fracture, shape of fragments, fragment size distribution, and fragment position distribution.

The most important loading parameters are the peak stress and the duration of the stress pulse. We have measured directly the shape of the initial compressive pulse in gas gun experiments with ytterbium stress gages placed near the back surfaces of rock specimens. Computer codes have been used to compute the tensile stresses. In the more complex case in which fracture occurs and begins to relax the stresses, a sophisticated code recently developed at SRI on another project[3] is employed to compute the tensile stress history, and experimental measurements of the fracture signal are used to check the computations. To simplify model development in the first year, the stress pulse was assumed to be square and hence describable by a constant stress level and a constant duration.

The rock properties influential in fracture behavior are size distribution of preexisting flaws, plane strain fracture toughness, crack velocity, and specific fracture surface energy. These parameters must be determined and incorporated into the dynamic fracture model. Values for Arkansas novaculite were determined in the first year's work. Efforts to determine these parameters for other rock types are reported in Section IV.

Specimen geometry and load geometry determine the stress and strain conditions under which fracture occurs and hence whether failure is tensile or shear. In this work we consider cylindrical specimens having a diameter to thickness ratio of about 5 loaded in uniaxial strain, an easily analyzable state which is suitable for model development.

Last year pulse shape and rock properties were related to provide the capability to predict the number of activated flaws, the total fracture surface area, and the energy absorbed in creating new surfaces by a known dynamic load in Arkansas novaculite in uniaxial strain. Our goal this year is to extend this predictive capability to include crack coalescence and fragmentation. Of particular interest are the number and size of fragments.

Simple thought experiments lead us to believe that the number of fragments resulting from a given shock load of duration sufficient for complete coalescence should be proportional to the number of cracks which are formed. (We expect additional fragments to be produced by crack branching events and as debris during the formation of large fragments.) According to our fracture model[1,2] then, the number of fragments is determined mainly by the inherent flaw distribution, the plane strain fracture toughness of the rock, and the amplitude of the stress pulse. The extent to which coalescence proceeds is a function of pulse length, and hence for short term stress pulses the number of fragments will also depend on stress duration.

The size of the fragments is also a function of inherent flaw structure, plane strain fracture toughness, and pulse shape. The pulse shape in a rock undergoing fracture varies strongly from position to position because of the stress relaxing effect of the cracks as they form and grow, and therefore the fragment size distribution also varies strongly. Specifically, the fragments which form in specimen zones where tension first appears are expected to be many in number and small in size; fewer and larger fragments should be produced at increasing distances from this zone. (This trend is exhibited in Figure 2d and indicates erosion of the stress amplitude by developing fracture damage.) At distances away from the zone of first tension where the stress amplitude is lower, fewer and more widely spaced flaws are activated. Stress duration becomes more important here, since the more widely-spaced activated flaws require more time to grow and coalesce.

III FRAGMENTATION IN ARKANSAS NOVACULITE

The experiments described in this section were designed to gain an understanding of crack coalescence and fragmentation, and to produce quantitative data to support the development of the dynamic fracture model.

Gas gun experiments as described in the Annual Technical Report[1] were performed to attain dynamic tensile loads. Flat plexiglass flyer plates are accelerated down the evacuated barrel of a light gas gun upon sudden release of pressurized helium at the gun breech. When flat impact of the flyer plate with the specimen occurs, short-lived tensile pulses result in the rock specimen from the intersection of stress waves. If the stress level is sufficiently high, fracture can occur. Higher velocity recovery experiments than were performed in the first year are required to achieve stress levels sufficient to produce high degrees of crack coalescence and fragmentation. The target arrangement used in the previous work is unsuited for recovery of highly fractured and hence very fragile specimens or for recovering all of thefragments of polarized specimens. Therefore, a target arrangement was designed that allows *in situ* recovery of heavily damaged and even fragmented rock.

Target Design

The method for recovery of heavily damaged rock entails encasing the cylindrical rock specimens completely in a much tougher material of similar shock impedance. Aluminum was found to be a suitable jacket material, first because it does not undergo brittle fracture under the loading conditions of these experiments and therefore contains the cracking and fragmenting rock specimen, and second because its shock impedance is very similar to that of novaculite, so that disturbance of stress waves as they cross the specimen-encasement interface is minimal. The dimensions of the targets were designed to reduce edge effects.

As shown in Figure 1, specimens of Arkansas novaculite 12.7 mm in diameter by 6.35 mm thick were fit tightly in the center of an aluminum disk 50.8 mm in diameter and 9.53 mm thick. An epoxy was applied on the entire specimen surface to ensure intimate contact with the aluminum casing. An aluminum cover plate 50.8 mm in diameter by 3.18 mm thick was then placed over the exposed end of the specimen and held firmly to the disk with four equally spaced screws. This target assembly was then subjected to flat-plate impact with the gas gun.

Dynamic Tensile Experiments

Ten experiments were carried out; the details are given in Table 1. It was planned to subject Specimens 44, 45, and 46 to stresses a factor of about 2.0, 1.5, and 1.25 in excess of the dynamic tensile strengths in an attempt to obtain various degrees of crack coalescence leading to fragmentation. The resulting fracture damage is described in the next section.

The next three experiments, 47, 48, and 49 were performed at stress levels near the dynamic tensile strength to determine whether the aluminum encasement arrangement caused significant stress amplitude attenuation. If so, impact velocities sufficient to cause incipient spall fracture in unencased specimens would not result in damage when encased. Experiments 47 and 49 performed at an impact velocity of 16.4 m/sec produced significant cracking, whereas Experiment 48 at 14.8 m/sec produced no damage. These results are in agreement with the damage threshold velocity of 15.1±0.6 m/sec established for unencased novaculite in the first annual report,[1] and so we conclude that the aluminum encasement had little attenuating effect on the stress.

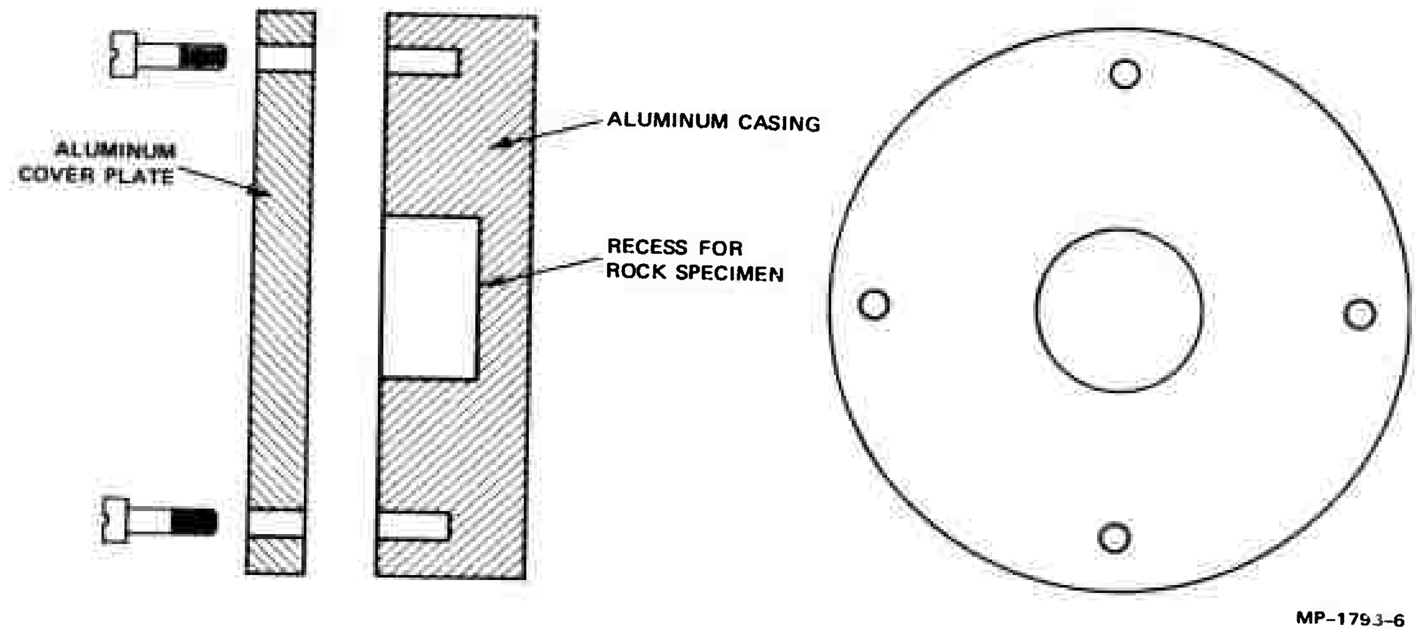


FIGURE 1 TARGET ASSEMBLY USED TO STUDY FRAGMENTATION OF ROCK UNDER DYNAMIC TENSILE LOADS

Table 1

UNINSTRUMENTED DYNAMIC TENSILE EXPERIMENTS

Experiment No.	Specimen Orientation	Impact Velocity (m/sec)	Computed Peak Tensile Stress (Pascal x 10^{-6})	Remarks
44	P	30.0	83.8	Al jacket carefully removed; specimen badly cracked and fell apart in large fragments
45	P	20.8	58.1	Al jacket carefully removed; specimen cracked but intact: subsequently sectioned, incipient crack coalescence
46	P	19.0	53.1	Sectioned; incipient crack coalescence
47	P	16.4	45.8	Sectioned; incipient crack coalescence
48	P	14.8	41.4	Sectioned; no cracking
49	P	16.4	45.8	Sectioned; isolated cracks
50	P	17.1	47.7	Sectioned; isolated cracks
51	N	17.4	48.6	Sectioned; isolated cracks
52	P	49.5	13.8	Sectioned and mounted in epoxy to keep fragments from falling out; severe cracking, coalescence, and fragmentation
53	N	48.9	13.6	Al jacket carefully removed; specimen fell apart; sieve analysis performed

P indicates specimen orientation was such that preexisting flaws lay roughly parallel to the impact direction.
N indicates specimen orientation was such that preexisting flaws lay roughly normal to the impact direction.
All specimens were cylinders 6.35 mm thick by 12.7 mm in diameter fully encased in aluminum as described in the text.
1 Pascal = 1 N/m^2 = 1.45 x 10^{-4} psi.

Specimens 50 and 51 were to be impacted at about 25 m/sec, in the velocity range of advanced stages of crack coalescence and incipient fragmentation (unfortunately much lower velocities, about 17 m/sec, were attained and much less damage resulted than was desired). The final two specimens were shock loaded at significantly higher velocities to produce detached fragments.

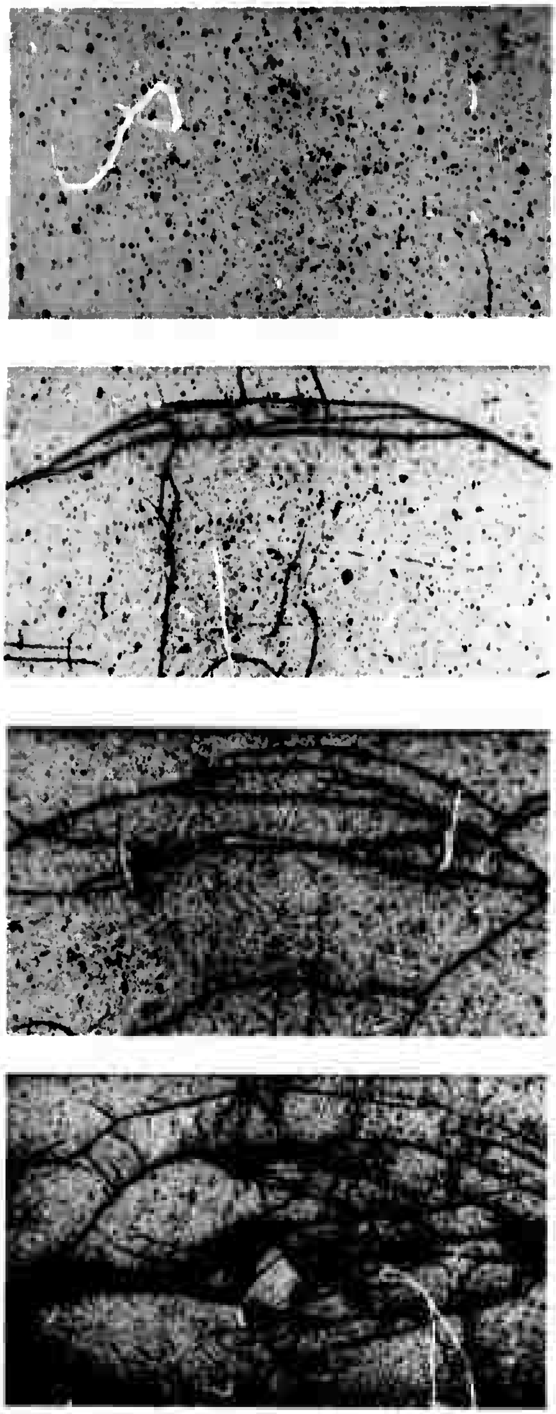
The recovered targets were prepared for fractographic observation and analysis in one of two ways. Either they were cut carefully on a diameter to reveal the cracking pattern on a cross section, or else the aluminum encasement was removed by carefully machining the periphery down to a few mils in a lathe and subsequently dissolving the remaining few mils of aluminum in a 50% HCL solution.

In Situ Observations

Specimens 45 through 52 were sectioned and polished to reveal the cracking patterns. The effect of stress level on the extent of cracking is illustrated in Figure 2, which shows cross sections of specimens impacted at various velocities. The characteristic dome-shaped crack pattern is evident. Damage is usually heaviest in the half nearer the impact surface. Fine particles seem to be produced at midthickness and in the zone encompassed by the dome cracks. Large fragments originate mainly near the flat surfaces. The free-surface side of the specimen is usually least damaged and is often recovered in one piece, even when the remainder of the specimen has fragmented. Free, uncoalesced crack tips are commonly observed in specimens impacted at high as well as at low stresses.

Fragment Size Distribution

We attempted to determine the fragment size distributions produced in Experiments 44, 45, and 53 by carefully removing the aluminum encasements. Specimen 44, however, fell apart in only a few large pieces and



(a) EXPERIMENT 48
41.4×10^6 PASCAL

(b) EXPERIMENT 47
45.8×10^6 PASCAL

(c) EXPERIMENT 46
53.1×10^5 PASCAL

(d) EXPERIMENT 52
138×10^6 PASCAL

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FIGURE 2 POLISHED CROSS SECTIONS OF ARKANSAS NOVACULITE SPECIMENS SHOWING THE EXTENT OF FRACTURE DAMAGE PRODUCED AT INCREASING LEVELS OF DYNAMIC TENSILE STRESS (IMPACT DIRECTION WAS FROM TOP TO BOTTOM) was unsuitable for a sieve analysis. Specimen 45 remained intact after removal of the aluminum and retained considerable strength (firm hand pressure was insufficient to break it up), so it was mounted in epoxy and sectioned as described in the previous discussion.

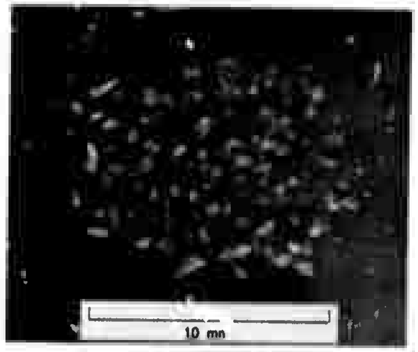
The fragment size distribution for Specimen 53 was determined by placing the collected fragments in the top sieve of a series of U.S. sieves placed in the following order from top to bottom: No. 10, 14, 20, 40, 50, 100, 200, and 400, and a pan to catch the fines. The system was vibrated for a short time, and the particles retained on each screen were counted and weighed. Figure 3 shows the shapes of the particles; the raw data are presented in Table 2 and in Figure 4. Such experimental fragmentation data will be used to develop and check the dynamic fracture model.

UNFRAGMENTED PORTION

RADII GREATFR THAN 1000 microns

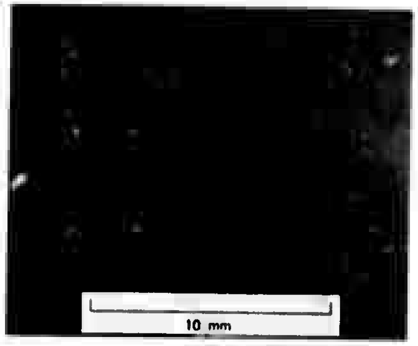
RADII 420 TO 1000 microns

RADII 210 TO 420 microns



RADII 149 TO 210 microns

RADII 74 TO 149 microns



RADII 37 TO 74 microns

RADII 18 TO 37 microns

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FIGURE 3 PHOTOMICROGRAPHS OF VARIOUS SIZED FRAGMENTS FROM EXPERIMENT 53

Table 2

SIEVE ANALYSIS RESULTS FOR ARKANSAS NOVACULITE: EXPERIMENT 53

U.S. Sieve No.	Sieve Opening (cm)	Sieve Half Opening (cm)	Weight of Retained Fragments (g)	Cumulative Weight of Retained Fragments (g)	Number of Retained Fragments	Cumulative Number of Retained Fragments
10	0.2000	0.1000	0.7951	0.7951	14	14
14	0.1400	0.0700	0.2095	1.0046	22	36
20	0.0840	0.0420	0.0811	1.0857	50	86
40	0.0420	0.0210	0.0645	1.1502	77	163
50	0.0297	0.0149	0.0163	1.1665	195	358
100	0.0149	0.0074	0.0123	1.1788	547	905
200	0.0074	0.0037	0.0046	1.1834	727	1632
400	0.0037	0.0018	0.0010	1.1844*	1204	2836

Specimen volume = 0.773 cm^3; specimen weight = 2.03 g.

* One large unfragmented piece weighed 0.8457.

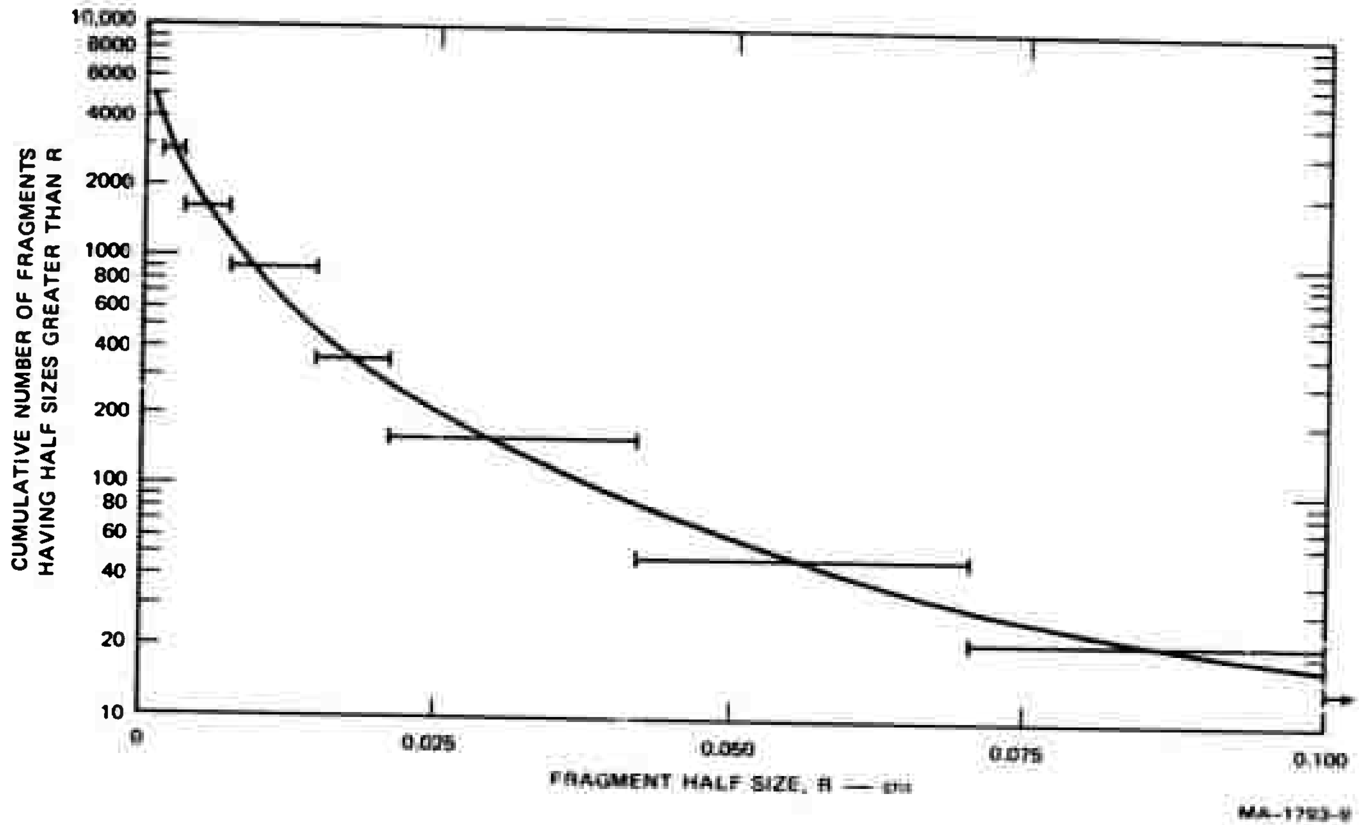


FIGURE 4 FRAGMENT SIZE DISTRIBUTION FOR ARKANSAS NOVACULITE EXPERIMENT 53

IV CHARACTERIZATION OF SIOUX QUARTZITE, WESTERLY GRANITE, AND PINK TENNESSEE MARBLE

Microstructures

One-inch cubes of Sioux quartzite, Westerly granite, and pink Tennessee marble were cut from the large blocks received from the Bureau of Mines and polished on three perpendicular sides in preparation for petrographic examination. Photomicrographs showing the grain structures of the three rock types are presented in Figure 5.

The Sioux quartzite is relatively pure, dense, and homogeneous. Large cracks, pores, and faults are noticeably absent. The grains are equiaxed, randomly oriented, and about 30 times larger than those in Arkansas novaculite (average grain diameter is of the order of 300μ).

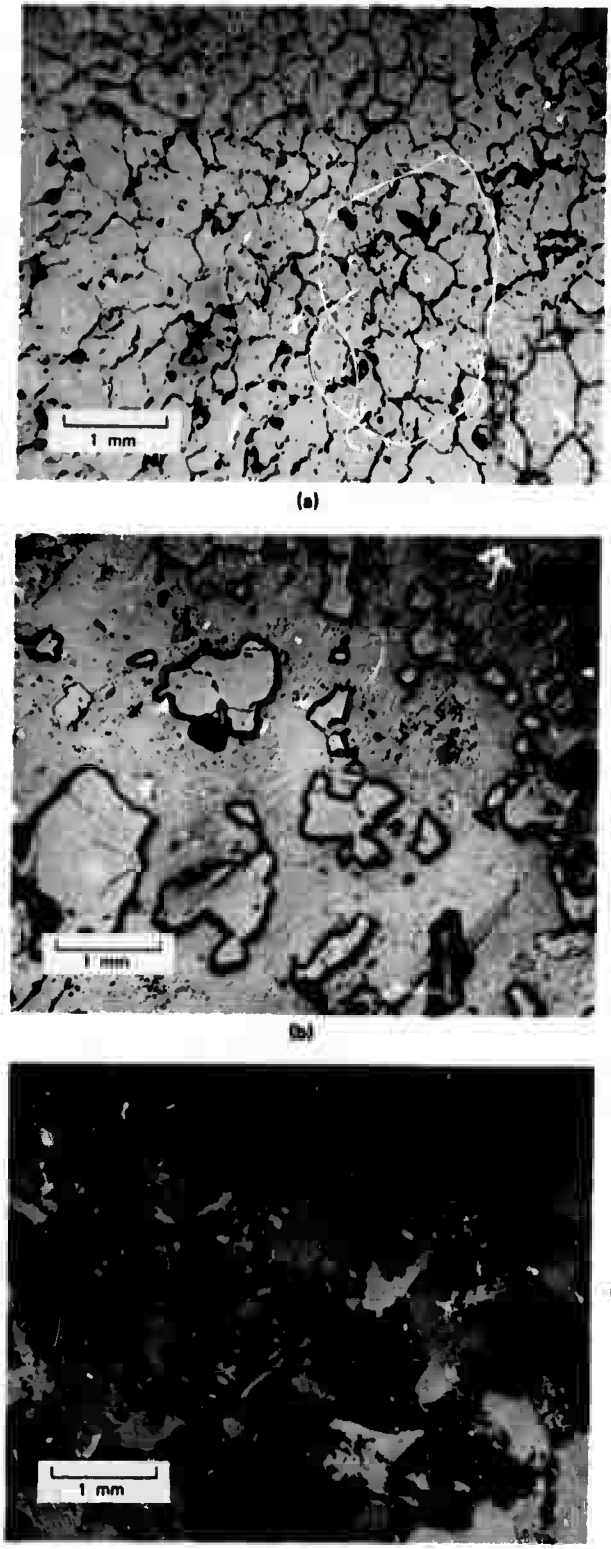
As indicated by the pronounced relief of polished surfaces, Westerly granite consists of hard grains (quartz) in a softer matrix (microcline and plagioclase). The quartz grains are generally irregular with diameters often exceeding 1000μ. The dark biotite phase is randomly oriented.

The grain size in the marble ranged from very small (~10μ) to very large (3000μ) and was easily discernible in 3/4 polarized light. A large majority of the grains exhibited pronounced twinning. No preferred grain orientation was evident.

Values of density and sound speeds which we measured on these rocks are presented in Table 3. Measured grain densities differed from the bulk densities by less than 1%, indicating that porosity was very low.

Inherent Flaw Structures

The model for dynamic tensile failure in rock, which was proposed and partially developed in the course of last year's work, requires a knowledge of the inherent flaw structure of the rock. We were able to determine quantitatively the size distribution of preexisting flaws in Arkansas novaculite and thereby to use our fracture model to calculate the number of flaws activated by a given stress pulse.



(c) MP-1793-10

FIGURE 5 MICROSTRUCTURES OF (a) SIOUX QUARTZITE,
(b) WESTERLY GRANITE,
(c) PINK TENNESSEE MARBLE

Table 3

MEASURED PROPERTIES OF SEVERAL ROCKS

	Density (g/cm^3)	Longitudinal Sound Speed* (mm/μsec)	Transverse Sound Speed* (mm/μsec)	Elastic Modulus ρC_ℓ^2 (Pascal x 10^{-6})†	Quasi-static Tensile Strength (Pascal x 10^{-6})†
Arkansas Novaculite	2.63	5.90	4.03	9.15	44.1±3.0 (6400±440 psi)
Sioux Quartzite	2.64	5.03	3.75	6.65	18.3±2.3 (2660±230 psi)
Westerly Granite	2.65	4.33	2.86	4.92	10.8‡ (1575 psi)
Pink Tennessee Marble	2.71	5.67	3.37	8.46	8.18‡ (1185 psi)

* As measured by time-in-flight method.

† Pascal = 1 N/m^2 = 1.45 x 10^{-4} psi.

‡ Average values measured by Wawersik and Brown (Ref. 6) in a uniaxial stress test.

To apply this model to other rock types, one needs information about their inherent flaw structure also, and so this became one of the tasks in this second year. But whereas the flaw structure in novaculite was readily discernible and hence relatively easily described quantitatively, inherent flaws in Sioux quartzite, Westerly granite, and pink Tennessee marble were very difficult to see.

Nearly all flaws in these latter rocks are associated with grain boundaries and could be detected only by focusing painstakingly up and down with the optical microscope at magnifications greater than 100X. Occasional transgranular cracks were observed in the feldspar grains of the Westerly granite.

Special viewing and crack decoration techniques were tried in attempting to observe the flaw structure. Phase contrast photography and scanning electron microscopy proved ineffective; likewise swabbing polished rock surfaces with silver nitrate and vacuum impregnation with an organic fluorescing agent to decorate the microcracks was of little use. Thermal grooving was not attempted, but seems of doubtful value since the flaws are associated almost exclusively with grain boundaries which themselves should be attacked by the thermal grooving process. A procedure recently reported by Brace, et al.[4] which uses ion thinning to reveal cracks in Westerly granite and Rutland quartzite appears promising.

Direct observation and measurement of the flaw structure in these rocks thus poses a difficult problem. Perhaps a more fruitful approach is to attempt to relate grain size or some other readily observable characterizing parameter of the grain boundaries to the number, sizes, and shapes of crack-like defects between the grains. This approach will be given more consideration in future work.

Quasi-static Tensile Strengths

To predict gas gun flyer plate velocities necessary for dynamic fracture in rock specimens, the tensile strengths of the rocks of interest were determined quasi-statically. The quasi-static tensile strength also serves as a baseline for comparison of tensile strengths measured at the high strain rates attained in the gas gun experiments.

The quasi-static tensile strength of Sioux quartzite was measured using the expanding ring test.[5] Nine ring-like specimens having inside diameters of 8.14 cm, 2.64-cm widths and various wall thicknesses were stressed at the rate of 20.7×10^6 Pascal/sec (3000 psi/sec). The results are presented in Table 4 and indicate an average tensile strength of $18.3 \pm 2.28 \times 10^6$ Pascal (2660±230 psi). Average values of the quasi-static tensile strength of Westerly granite and pink Tennessee marble have been reported by Wawersik and Brown[6] to be 1575 psi and 1185 psi, respectively.

Table 4

QUASI-STATIC TENSILE TESTS ON SIOUX QUARTZITE

Ring No.	O.D. (cm)	Wall Thickness (cm)	Pressure* (Pascal x 10^{-6})	Tensile Strength* (Pascal x 10^{-6})
1	10.10	0.985	3.81	17.8
2	9.97	0.921	3.72	18.4
3	9.42	0.643	2.30	15.7
4	9.95	0.901	4.24	21.4
5	9.85	0.855	3.46	18.4
6	9.62	0.746	2.41	14.5
7	9.75	0.802	3.13	17.6
8	9.87	0.868	3.82	20.0
9	9.42	0.643	3.04	20.9

* Pascal = 1 N/m^2 = 1.45×10^{-4} psi.

Stress History Measurements

The experimental arrangement depicted in Figure 6 is being used to measure the stress history experienced by rock specimens as they undergo fracture. An ytterbium grid sandwiched tightly between the specimen and a backing plexiglass plate acts as a piezoresistant stress gage and records the magnitude of the stress as a function of time. A signal from a conducting foil covering a small area of the impact surface determines the arrival time of the flyer plate. The stress history in the specimen is calculated by one-dimensional wave propagation codes from the information on the gage record. The stress gage located at the back surface of the specimen is first loaded in compression by the initial shock wave and begins to unload as the wave reflects from the specimen-backing plate boundary. Before the gage is completely unloaded and begins to experience tension, recompressive waves emitted from the crack surfaces as they form and propagate impinge on the gage and reload it. This second peak is known as the spall signal and provides a quantitative measure of the dynamic tensile strength of the rock.

Two experiments instrumented as indicated in Figure 6 were carried out on Westerly granite to determine the stress history and to record the spall signal. The gage records indicated that peak pressures of 75×10^6 and 338×10^6 Pascals, respectively, were attained, but because of excessive electrical noise, the fracture signals were unintelligible. Two additional specimens have been prepared and instrumented, and the experiments will be performed in the near future.

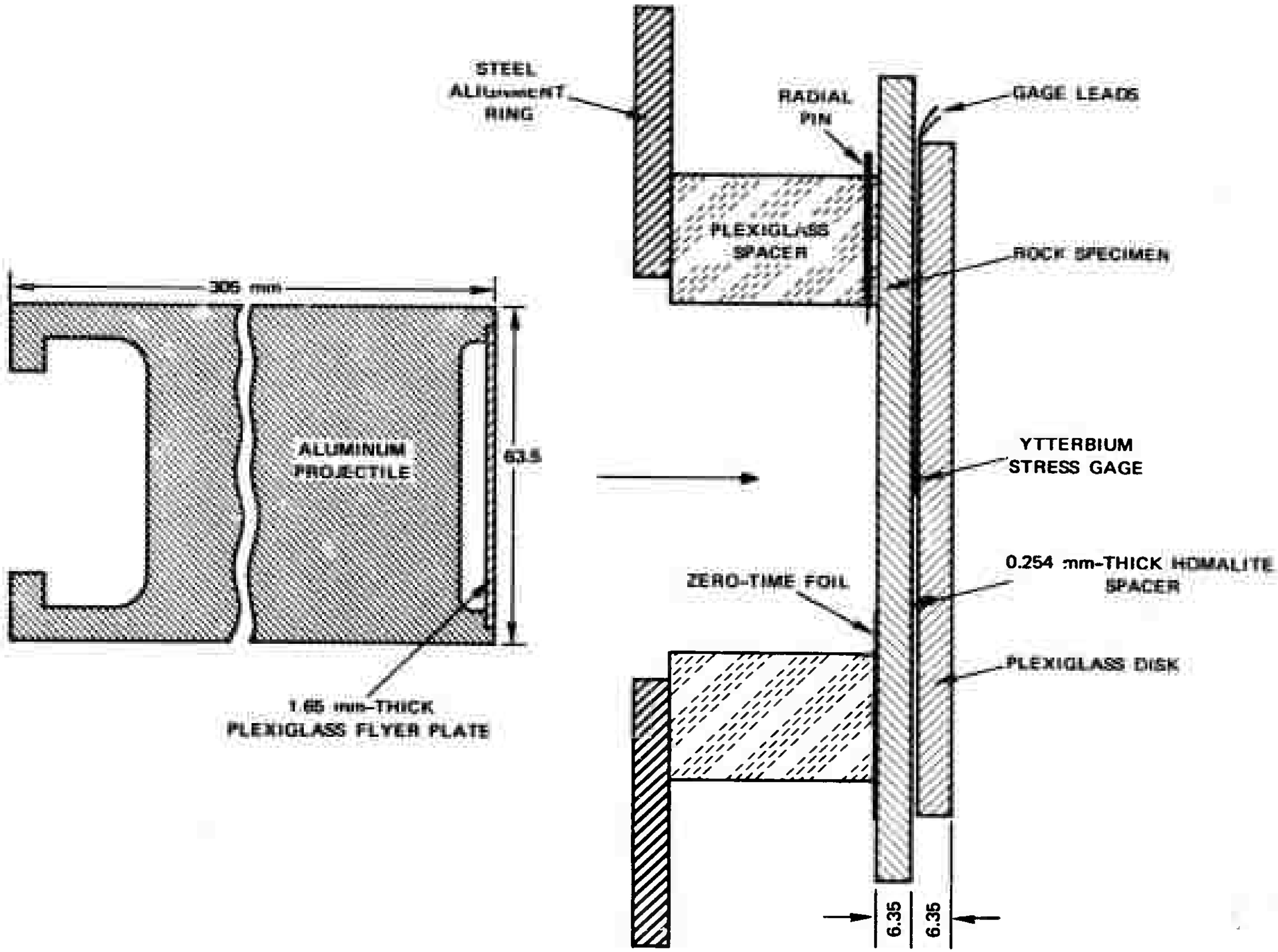


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FIGURE 6 EXPERIMENTAL ARRANGEMENT FOR MEASURING STRESS HISTORIES

SUMMARY

This report has reviewed the technical progress achieved during the first six months of the second year of a program whose objective is to develop and substantiate a model for dynamic tensile failure of rock. The program consists of three phases: (1) flat plate impact experiments on rock specimens, some of which are instrumented with stress or particle velocity gages to measure stress histories during tensile failure, (2) microscopic examination of the fracture damage in recovered rock specimens, and (3) development of a quantitative model for predicting fracture behavior of rock under dynamic tensile loads. Initially the model is to be applicable to Arkansas novaculite, then later generalized to other rock types.

In the first year we hypothesized that fracture occurred by the activation of many preexisting flaws which propagated, coalesced and produced loose fragments of various sizes. The first two stages of the process, flaw activation and growth, were treated quantitatively last year. Our objectives this year are to (1) further develop the model by treating the final two stages--crack coalescence and fragmentation, and (2) begin to characterize other rock types to test and then generalize and novaculite model. The accomplishments of the first six months are summarized below.

A target arrangement was designed to allow recovery of rock specimens which have been heavily damaged and fragmented under dynamic tensile loads in gas gun experiments. Using this arrangement ten experiments were performed at various stress levels on Arkansas novaculite and the extent of fracture damage was assessed. Information concerning the coalescence behavior of cracks was obtained from the cracking patterns as revealed on polished surfaces of section through the rock specimen, and the fragment size distribution resulting from a known dynamic stress history was determined quantitatively for one specimen. Additional crack coalescence

and fragmentation information will be obtained in the next six months and used to further develop and extend the dynamic fracture model.

Specimens of Sioux quartzite, Westerly granite, and pink Tennessee marble were examined petrographically and found to have more complex microstructures and less easily distinguishable flaw structures than Arkansas novaculite. The inaccessibility of the flaw structure is particularly distressing, because a quantitative description is a necessary parameter for the dynamic fracture model. The possibility of deducing this information from the grain structure is currently being explored. The quasi-static tensile strength of Sioux quartzite was measured using the expanding ring test to be $18.3 \pm 2.28 \times 10^{6}$ Pascal (2660±230 psi). Efforts to measure the stress histories in specimens of Westerly granite undergoing fracture and fragmentation are continuing.

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UNITED STATES
DEPARTMENT OF THE INTERIOR

Date October 1972

SUMMARY REPORT OF INVENTIONS AND SUBCONTRACTS

The following report must be submitted in *triplicate* as part of the interim or final report as provided for by the REPORTS and/or PATENT ARTICLE in the grant or contract.

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(Check appropriate boxes)

1. Type of Report:

[X] Interim
From April 15, 19 72
To October 15, 19 72

[ ] Final.

2. Interim Report Data:

A. Invention made [ ], not made [X], during interval of (1).

B. If invention(s) made, provide the following information:

[ ] Previously fully disclosed in Invention Disclosures. Give dates submitted, and Contractor's docket numbers.

[ ] Invention Disclosures attached herewith. Give Contractor's docket numbers.