CONTINUOUS HIGH VELOCITY JET EXCAVATION - PHASE I

FINAL REPORT

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13. ABSTRACT

The objective of this program was to assess the feasibility of rapid excavation of hard rock by means of continuous fluid jets produced by pressures in the range of 20,000 to 80,000 pounds per square inch. A total of eight rock types representative of sedimentary, metasedimentary and igneous groups were selected and appropriate quantities of test specimens were procured. Cutting tests were performed using Bendix-owned pumping equipment and Bendix-designed and developed nozzles. Test data was analyzed to determine optimum settings of jet parameters within experimental ranges that result in rapid and efficient excavation of rock. Power requirements and excavation rates were estimated for a theoretical continuous jet excavation system and compared with those of a conventional system.

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CONTINUOUS HIGH VELOCITY JET EXCAVATION - PHASE I

FINAL REPORT

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SECTION 1

SUMMARY

The objective of this program was to investigate the feasibility of rapid excavation systems for hard rock using high-velocity continuous fluid jets. Both single-cut and kerfing excavation modes were experimentally investigated in order to minimize the specific energy (i.e., energy input per volume excavated) of jet fragmentation. Ranges of variables were nozzle supply pressures from 50,000 to 80,000 psi (34.5 to 55.2 KN/cm^2), feedrates from 50 to 900 inches per minute (2 to 38 cm/sec), standoff distances from 0.5 to 1.5 inches (1.27 to 3.81 cm), and nozzle diameters of 0.008 to 0.0136 inch (0.20 to 0.35 mm). The rock types used in fragmentation tests were Berea Sandstone, Salem Limestone, Tennessee Marble, Westerly Granite, Barre Granite, Charcoal Granite, Sioux Quartzite and Dresser Basalt.

Initial fragmentation tests, employing a 2^4 factorial design, were completed on all rock types to perform screening of the four independent variables. Analyses of variance were completed upon the 2^4 factorial data to determine the two most significant main effects for each rock type, which were then investigated at a third level. Randomization was applied to the sequence of test runs as well as the selection of samples within each rock type. Additional testing was undertaken at higher feedrates than those originally planned, up to a maximum of 38 cm/sec (900 inches per minute) based on predictions from the variance analyses.

Within the experimental range, the minimum specific energies for single cuts were obtained for most rock types at 50,000 psi (34.5 KN/cm^2), at 900 inches per minute (38 cm/sec), using a 0.008 inch (0.20 mm) diameter nozzle. Kerfing tests were conducted for each rock type using the parameters which produced the minimum single-cut specific energy. Minimum specific energies for kerfing runs ranged from 6611 joules/cc, (79,900 ft-lb/in^3) for Sioux Quartzite to 1215 joules/cc (14,685 ft-lb/in^3) for Berea Sandstone.

The kerfing specific energy was found to be too high to justify the use of an excavation system utilizing jet action alone instead of a conventional tunnel excavator. Test data was utilized, however, in the generation of a mechanically assisted fluid jet excavation machine concept having a significantly reduced overall specific energy. The specific energy calculated for the hybrid system does not, however, represent the optimum specific energy for such a system since the jet operating parameters employed in the analysis were those which gave the minimum specific energy for pure jet excavation. These parameters were also observed to give the smallest kerf depths. As kerf depth is increased, the spacing

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between kerfs can also be increased, thereby increasing the volume of material removed by mechanical action. Since the jet excavation energy constitutes the majority of the energy input to the rock, the maximum overall efficiency for a hybrid system may be obtained at the operating parameters which produce the deepest kerf, even though the jet excavation portion of the process is not operating at its minimum specific energy.

Further investigation is indicated to determine specific energy for excavation of *in situ* rock structures as well as for optimization of jet operating parameters in combination with mechanical breakage methods. Combination of the more favorable stress condition of *in situ* rock with optimization of the specific energy of a mechanically assisted jet excavator is expected to reduce the overall system specific energies to levels comparable to those demonstrated by conventional excavation systems operating in hard rocks while preserving the major advantages of the jet approach.

SECTION 2

INTRODUCTION

Increasing emphasis in both urban and defense systems planning has focused upon the desirability of locating many utilities and transportation systems underground. Such a location frees valuable land space within city centers and allows greater flexibility in planning for urban development. In many population centers, tunneling is the only viable method of building mass transportation systems due to the high degree of utilization of surface space. Underground location of facilities has a great advantage from the military standpoint due to decreased vulnerability to attack and sabotage. Additionally, underground systems and structures are impervious to weather conditions and may be maintained in a controlled environment which will reduce both construction and maintenance costs. Protection from weather is a basic requirement for planned future high speed ground transportation systems.

Implementation of a large scale relocation of surface facilities underground will require major advances in present tunneling technology, resulting in the evolution of efficient, cost effective, rapid excavation systems. Present tunneling methods are generally too slow, expensive and not versatile enough for use in other than certain specific applications.

The foremost problem of any mining or tunneling system is to break the material out of the solid matrix at the cutting face of the tunnel and reduce it to a size suitable for removal. Presently, there are two basic material removal methods, the cyclic drill-blast method and the continuous cutting machine method.

The drill-blast method, in which the material is removed by the detonation of explosives loaded into small diameter holes drilled in the face, is the method most commonly used, as it can be used in any rock from sedimentary to the hardest igneous. Disadvantages of this method include explosives hazards, generation of dust and fumes and weakening of the rock strata due to concussion, with attendant overbreakage and rock falls. Although the actual specific energy of the blasting process is low, the fact that the process is cyclic, with the various operations of drilling, charging, blasting, clearing of fumes and muck removal occurring sequentially instead of continuously, contributes to the disproportionately high cost and low excavation rate of the overall operation as compared with continuous excavation processes.

The continuous cutting machine method, wherein material removal is effected by means of mechanical excavating machines with cutter bits mounted on endless chains or rotary drill bits, is in the early development stages and is presently limited to medium hard rock applications.

Within these applications, however, the continuous cutting machine method is comparable to the drill-blast method in both cost and speed of tunneling and mining. In addition to the disadvantage of dust generation by the cutters, the rate of material removal by the continuous excavating machine is limited by the thrust which must be developed in order to push the bits against the work face, in many contemporary machines exceeding one million pounds. The machine structure required to generate forces of this magnitude results in high capital cost, low maneuverability and difficulties in performing maintenance. In the harder or more abrasive rock excavation applications rapid cutter wear occasioned by high loading and cutter bearing failures due to contamination by abrasive particles make the continuous excavation machine uneconomical in comparison with the drill-blast method, in spite of the advantages of continuous operation and superior control of tunnel line, grade and size. It appears, therefore, that the success of any efforts toward increasing the speed with which tunnels or mines can be excavated will depend upon the development of new methods of excavating material at a much faster rate with less part wear.

A novel method of material excavation which is presently under investigation is the use of high pressure fluid jets, a process which, in combination with certain areas of present tunneling and excavation technology, has the potential of producing higher excavation rates than present methods, while simultaneously eliminating or reducing many of their major disadvantages.

The basic technique is not new, since jets of water at low pressures were used for eroding terrain in placer maining in the California gold fields as early as 1870. Within the past several years, hydraulic mining of coal using water pressures of 3000 to 5000 psi has been successfully developed and is now being used extensively in the USSR. As materials and equipment improved, practical generation of higher pressures became possible and investigations were begun into the drilling and breaking of harder rocks. To date, only limited data was available on the use of continuous water jets at pressures above 25,000 psi.

When a moving column of fluid is allowed to impinge on a solid body, the surface of the body at the point of jet impingement is subjected initially to a short-duration high-pressure transient resulting from the water hammer effect; this is followed by decay to some steady-state pressure level. The magnitude of the high-pressure transient is a function of the jet velocity and fluid properties and can be twice the nozzle supply pressure; the steady-state pressure may approach the nozzle supply pressure. For example, a water jet produced by a nozzle supplied at a pressure of 50,000 psi could theoretically generate water hammer and steady state surface pressures of 100,000 and 50,000 psi, respectively. Comparison of these values with the average ultimate compression strengths of some rock and earth materials indicates the merit of investigating high-velocity fluid jets as a means of cutting and fracturing.

Advantages of the water jets for excavation of rock as opposed to conventional tunneling methods are decreased tool wear and decreased reaction forces against the work face. In addition, the fluid jet is safer than conventional methods. The jet action does not weaken the surrounding material, as does blasting, and eliminates the sparking and attendant gas explosion dangers experienced with mechanical cutters. The material and water slurry resulting from continuous jet action also minimizes dust hazards to workers and opens possibilities for material removal by pipeline transport. Establishing the feasibility of fluid jet rock excavation is expected to provide a base for development of efficient and economical systems for tunneling and excavation.

SECTION 3

PROGRAM BACKGROUND

As a part of the Advanced Research Projects Agency (ARPA) Military Geophysics program, the Bendix Research Laboratories has conducted an experimental study to determine the feasibility of a continuous jet excavation system for hard rock using jet supply pressures of 20,000 to 80,000 psi. Efforts were performed under Contract No. H0210034, which was administered by the U.S. Bureau of Mines. Project officers at the Twin Cities Mining Research Center were initially Mr. John Chester and, subsequently, Dr. Peter Lohn.

The primary objective of the program was to generate data in a statistically designed experiment to determine the most optimum operating conditions for a continuous jet excavation system. Existing company-owned high pressure pumping equipment and nozzles were utilized to permit in-depth experimentation in a range of pressures and nozzle diameters beyond that of previous investigations utilizing continuous jets. Included in the present effort were purchase of samples, preparation of a test plan, fracture tests, data compilation, analysis and presentation of results for eight different rock types. Both single cut and kerfing excavation modes were investigated in order to minimize the specific energy (i.e., energy input per volume excavated). Process parameters employed were pressures from 50,000 to 80,000 psi, feedrates from 50 to 900 inches per minute, standoff distances from 0.5 to 1.5 inches, and nozzle diameters of 0.009 to 0.0136 inch. The rock specimens used in fragmentation tests were Berea Sandstone, Salem Limestone, Tennessee Marble, Westerly Granite, Barre Granite, Charcoal Granite, Sioux Quartzite and Dresser Basalt. Compression strengths for the rock types ranged from 8,600 to 54,000 psi.

Early in the program, a specific test plan, described in Sections 5 and 6, was generated, purchase orders were placed for samples of the rock types specified, and fragmentation testing scheduled to commence following receipt of the rock samples. Delays were encountered in both the procurement of rock test specimens and in maintenance of the BRL high pressure intensifier. Due to late deliveries of samples from several vendors, the initiation of fragmentation tests were delayed. In addition, during periodic maintenance of the high pressure pumping system to be used for the fracturing tests, severe scoring of the high pressure pistons and cylinders was discovered. The intensifier was removed from the high pressure facility and shipped to the manufacturer for determination of both the severity of the damage and the length of time required to complete repairs.

Since the repair and return of the intensifier unit was essential to the continuation of the testing, the program was delayed by an amount of time equal to that required for completion of repairs. In the interim, other program tasks were carried as far as possible in order to minimize schedule slippage due to the intensifier failure. After repairs were completed, the high pressure intensifier was returned to Bendix. Rock samples were moved into the test area and initial runs were completed on several rock samples for use in evaluating various methods of determining the material volume removed by the jet.

Fragmentation tests were begun in early January 1972. Samples were fixtured to a traverse mechanism under a stationary fluid jet, with supply pressure, traverse speed and standoff distance as recorded variables. The equipment and test setup is described in Section 4.

Initial fragmentation tests employing a 2^4 factorial design were completed on all rock types to perform screening of the four independent variables. Analyses of variance were completed upon the 2^4 factorial data to determine the most significant main effects, for each rock type, which were then investigated at a third level. Randomization was applied to the sequence of test runs as well as the selection of samples within each rock type. Additional testing was undertaken at higher feedrates than those originally planned, up to a maximum of 900 inches per minute, based on predictions from the variance analyses. Although the variance analyses indicated that further reductions in specific energy value could be obtained at lower pressures and nozzle diameters than those used in the test program, full exploration of this range was beyond the scope of the current contract.

Within experimental ranges, the minimum specific energies for single cuts were obtained for most rock types at the lowest supply pressure, highest feedrate, and smallest nozzle diameter, that is 50,000 psi, 900 inches per minute, and 0.008 inches respectively. Following determination of the minimum specific energy for single cuts, spacing between successive cuts was decreased until kerfing, or excavation of the material between the cuts, was observed, which indicates the condition of minimum overall specific energy. Kerfing tests were conducted for each rock type using the parameters which produced the minimum single-cut specific energy. Specific energies for kerfing runs ranged from 6611 joules/cc (79,900 ft-lb/in^3) for Sioux Quartzite to 1215 joules/cc (14,685 ft-lb/in^3) for Berea Sandstone.

Program test data was utilized in the generation of a mechanically assisted fluid jet excavation machine concept, described in Section 8, for use in an economic comparison with conventional excavation systems. Conclusions and recommendations for further development are presented in Section 9.

SECTION 4

TEST SETUP

Equipment employed in conducting fragmentation testing included a high pressure intensifier with its hydraulic power supply and control system, and a calibrated traversing mechanism for moving the samples under the stationary jet nozzle. All equipment is owned by Bendix Research Laboratories and is employed in investigations of the feasibility of using high pressure jets for cutting and machining of industrial materials.

The high pressure intensifier, shown in Figure 4-1 and schematically in Figure 4-2 is a commercially available double-acting device capable of an output of 1.4 GPM at 80,000 psi, driven by a conventional hydraulic power supply. The high pressure fluid, generally water or water with soluble oil, is plumbed through the outlet check valves into a surge vessel mounted below the intensifier unit. The surge vessel acts as an accumulator, using the compressibility of the water at high pressure to minimize output pressure fluctuations during intensifier piston reversals. The cycling reversals are controlled by a directional control valve, actuated by two limit switches which signal the end of each stroke.

The high pressure fluid is plumbed from the surge vessel to the nozzle assembly, shown projecting from the wall in Figure 4-3, which is a view of the test cell in which the fragmentation tests were run. The nozzles used in all testing were of proprietary Bendix design. The traversing table is capable of moving samples below the nozzle assembly through a 10 inch stroke at feedrates of up to 950 ipm. Feedrates were controlled by means of a calibrated flow control valve in series with the traverse table drive cylinder. The remaining system controls, including the system output pressure gauge, are mounted in a control console shown directly behind the traversing table. Figure 4-4 (a) and (b) are pictures of a cutting test at 50,000 psi conducted upon a sample of Barre Granite.

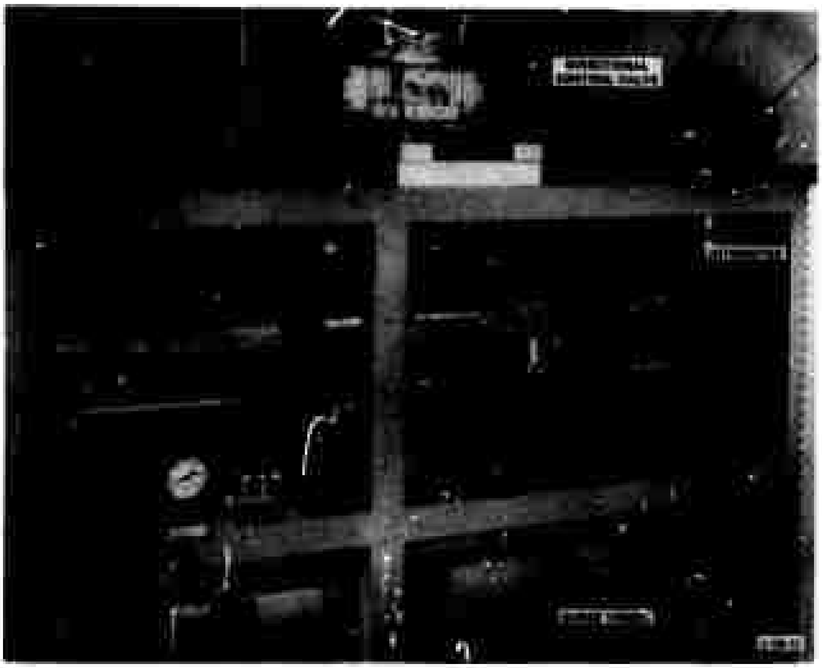


Figure 4-1 - High Pressure Intensifier Pumping System

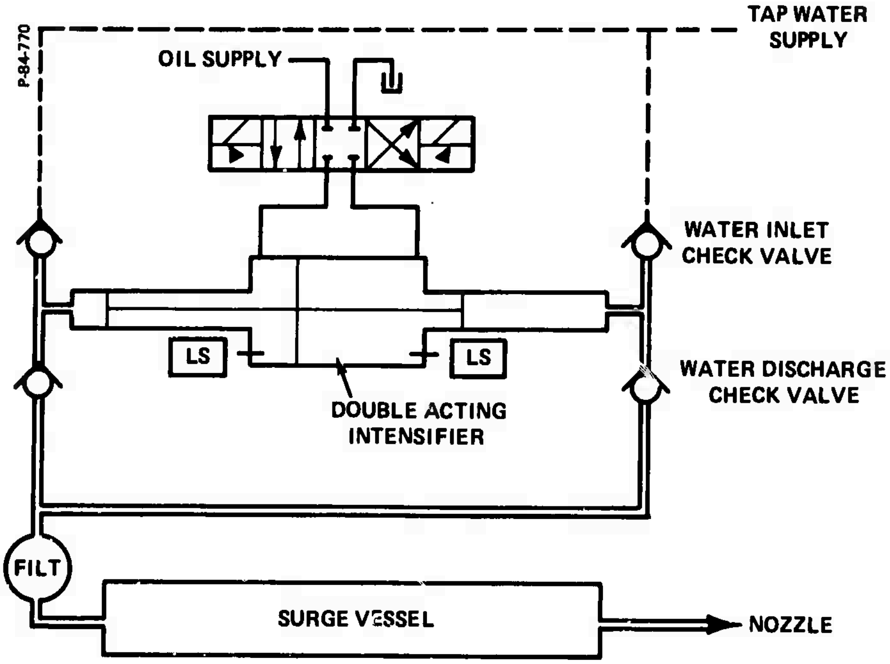


Figure 4-2 - High Pressure Intensifier System Schematic

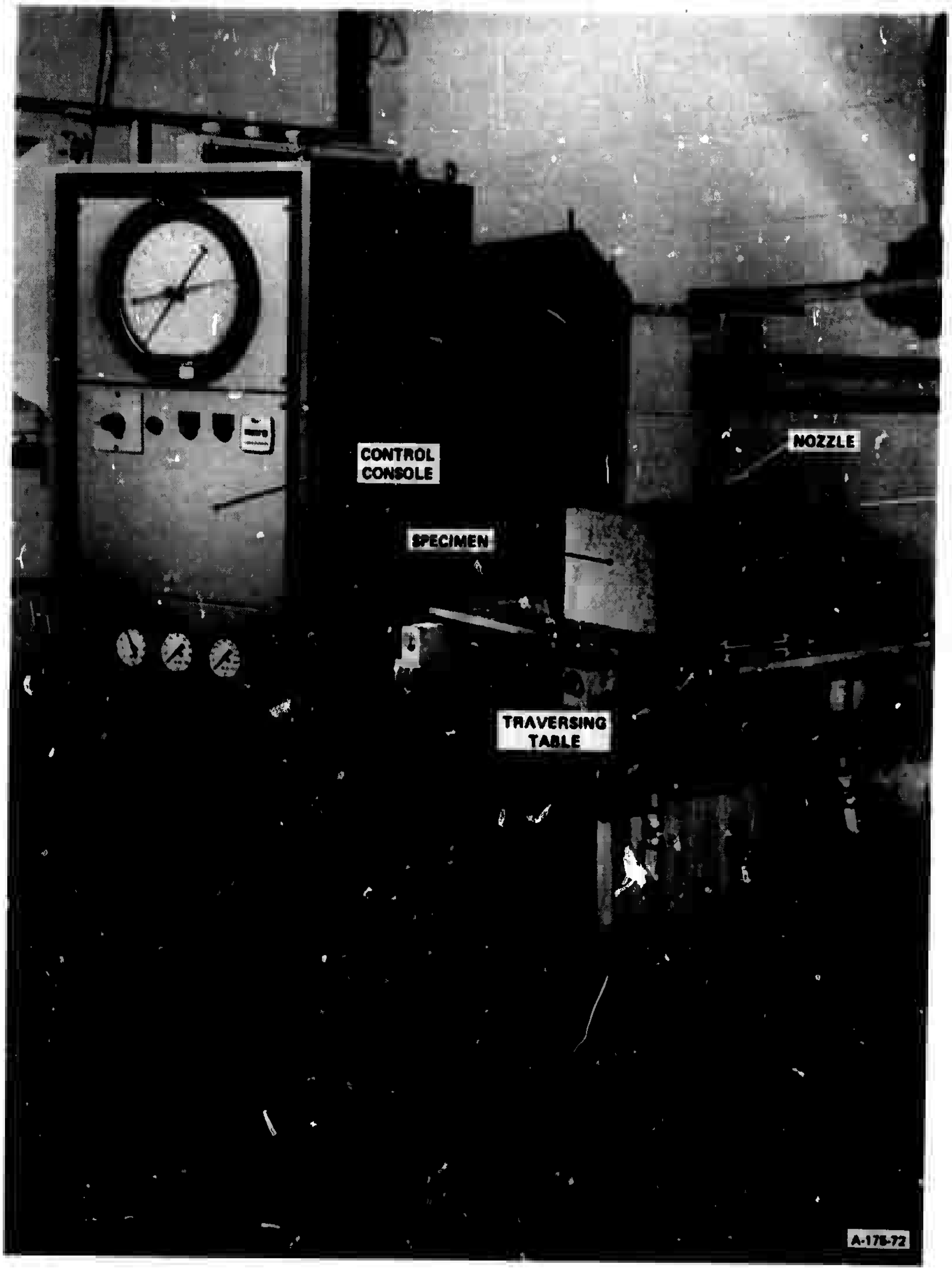
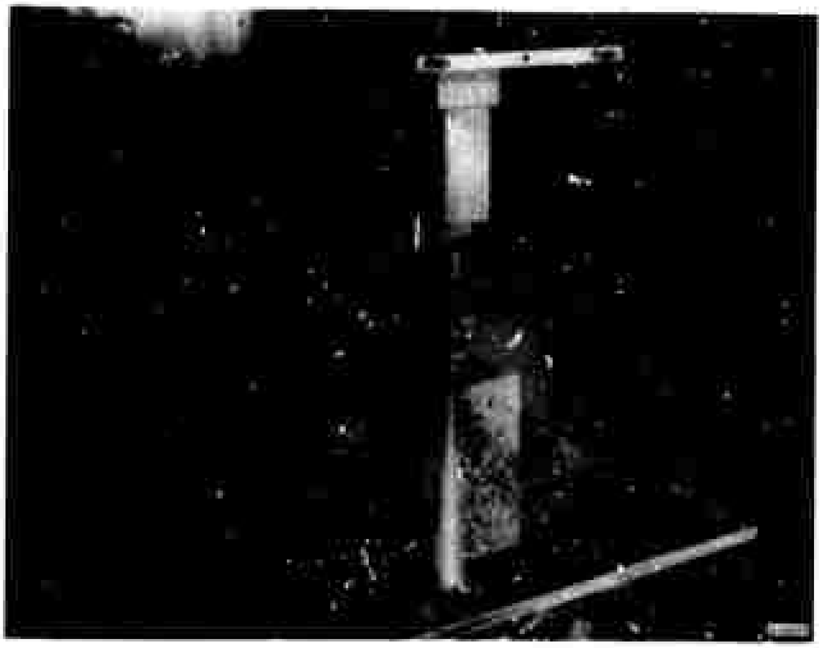
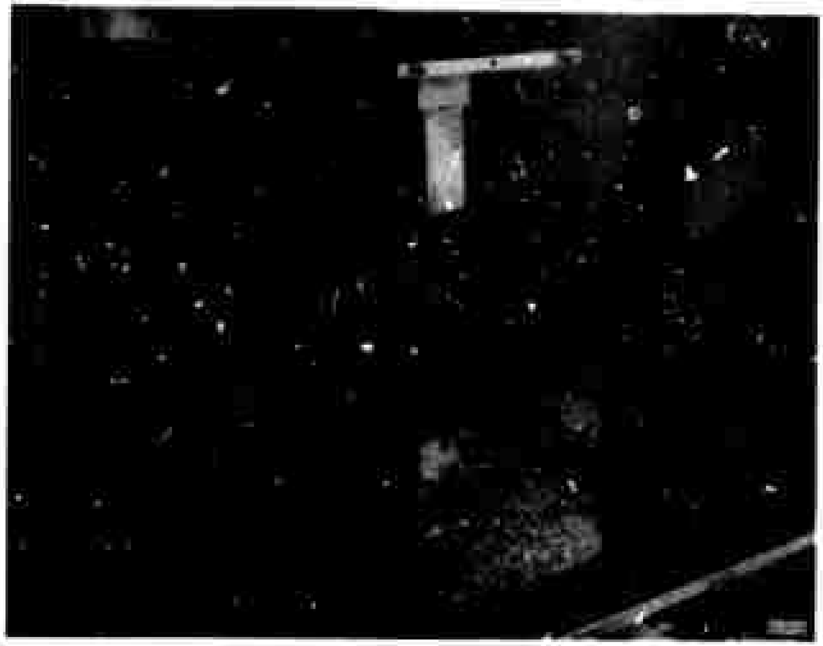


Figure 4-3 - Test Set Up



(a) Starting Cut



(b) Partially Complete Cut

Figure 4-4 - Cutting Test on Barre Granite

SECTION 5

PROGRAM EXPERIMENTAL PLAN

Four major independent variables associated with the fluid jet process were investigated, each at three levels. The two levels of the variable used in 2^4 factorial design experiments for significance determinations are denoted by lower case letters, with upper case letters used to denote the levels used for 3^2 and 3^4 factorial design experiments.

The following independent variables were investigated:

Pressure (P) (psi) $P_1 = 50{,}000 = P_o$

$P_2 = 65{,}000$

$P_3 = 80{,}000 = P_1$

Pressure was recorded directly from the system supply pressure gauge.

Feed Rate (F)
(inches/per minute) $F_1 = 50 = f_o$

$F_2 = 100$

$F_3 = 150 = f_1$

Feed rate was set using a calibrated flow control valve to drive the hydraulic cylinder which powers the specimen traversing table. Additional tests were completed at higher feedrates up to 900 ipm.

Standoff (S) (inches) $S_1 = 0.5 = s_o$

$S_2 = 1.0$

$S_3 = 1.5 = s_1$

Standoff distance was determined by leveling the sample and mounting it at the desired distance relative to the jet nozzle.

Nozzle Diameter (N) (inches)	$N_1 = 0.008 = n_o$ $N_2 = 0.012$ $N_3 = 0.0136 = n_1$

The 0.0136-inch diameter nozzle was sized to utilize maximum flow capacity of the Bendix high-pressure pumping system at 80,000 psi.

In order to minimize the effects of extraneous or unknown variables, the order of test runs as well as the order of rock type for each run was randomized. Each test combination was accorded a combination number, which specified a particular set of test conditions. The test number, indicating the order of completion of each test combination, was determined by selection of combination numbers from a random number table, with the exception of the various levels of nozzle diameter, which were run sequentially due to the greater difficulty involved in changing nozzle size as opposed to changing other operating parameters.

The following eight rock types were used in the experimental effort. Sample size was approximately 8 x 8 x 6 inches in most cases.

- Charcoal Granite (Cold Springs, Minnesota)
- Westerly Granite (Westerly, Rhode Island)
- Barre Granite (Barre, Vermont)
- Dresser Basalt (Dresser, Wisconsin)
- Sioux Quartzite (Jasper, Iowa)
- Berea Sandstone (Amhurst, Ohio)
- Tennessee Marble (Knoxville, Tennessee)
- Salem Limestone (Bedford, Indiana)

Contacts were made with operators of quarries recommended by the Contracting Agent as sources of the rock types listed above, and purchase orders placed for samples in 20-piece lots for all rocks except Westerly Granite, for which only five samples were ordered due to high cost, and Dresser Basalt, which was acquired directly from the Bureau of Mines. Tables of properties for each rock type have been obtained from either the Bureau of Mines or the quarry operators. Since no measurement of rock properties was performed under this test program, rock properties are presented in Appendix A for reference only. The effects of rock property differences between specific samples within each rock type was minimized by randomization of the selection of samples for use. The samples were numbered during uncrating and randomly selected for each test run.

The dependent variable of the experiment was specific energy, the amount of energy required to remove a unit volume of rock. Specific energy was determined for both single cuts and for kerfing, wherein interaction between successive cuts results in the excavation of the material between.

Specific energy was calculated from system operating parameters, sample size and material volume removed, based on the calculated actual power level at the nozzle rather than hydraulic system input power, and therefore is not affected by the inefficiencies of the particular hydraulic system and intensifier used.

Derivation of the specific energy equation is as follows:

$$\text{Specific Energy} = \frac{\text{Power x Time}}{\text{Volume of Material Removed}} \qquad (1)$$

The intensifier power delivered to the nozzle is given as

$$\text{Power} = 5\ (Q \times \Delta P) \qquad (2)$$

Where power is expressed in ft-lb/min

Q = flow, in^3/sec

ΔP = nozzle pressure drop, psi

Since the system flow is governed by the nozzle area

$$Q = C_d\ A \sqrt{\frac{2g\ (\Delta P)}{\rho}} \qquad (3)$$

where

Q = flow, in^3/sec

g = gravitational constant = 386 in/sec^2

ρ = fluid density = 0.0361 lb/in^3 for water
(assumed incompressible)

ΔP = nozzle pressure drop, psi

C_d = assumed discharge coefficient = 0.75

A = nozzle orifice area, in^2

Since the total pressure head of the high-pressure fluid is converted to velocity head during its passage through the nozzle, the pressure drop is given as

$$\Delta P = (P - P_{ambient}) = P \tag{4}$$

where

P = nozzle supply pressure, psig

$P_{ambient}$ = 0 psig

Also,

$$A = \frac{\pi}{4} (N)^2 \tag{5}$$

where

N = nozzle diameter, inches

By combining equations (3), (4), and (5) and substituting into (2)

$$\text{Power} = 5\ C_d \left(\frac{\pi}{4} N^2\right) \left(\frac{2g\ P}{\rho}\right)^{1/2} (P)$$

Substituting numerical values gives

$$\text{Power} = 430.7\ N^2\ P^{1.5} \tag{6}$$

The time during which power is delivered is determined as follows:

$$\text{Time} = \frac{L}{F} \qquad (7)$$

where

L = length of cut, inches

F = feedrate, ipm

By substituting equations (6) and (7) into equation (1)

$$SE = 430.7 \frac{N^2 \, P^{1.5} \, L}{F \, V}$$

where

SE = specific energy, ft-lb/in^3

N = nozzle diameter, inches

P = nozzle supply pressure, psig

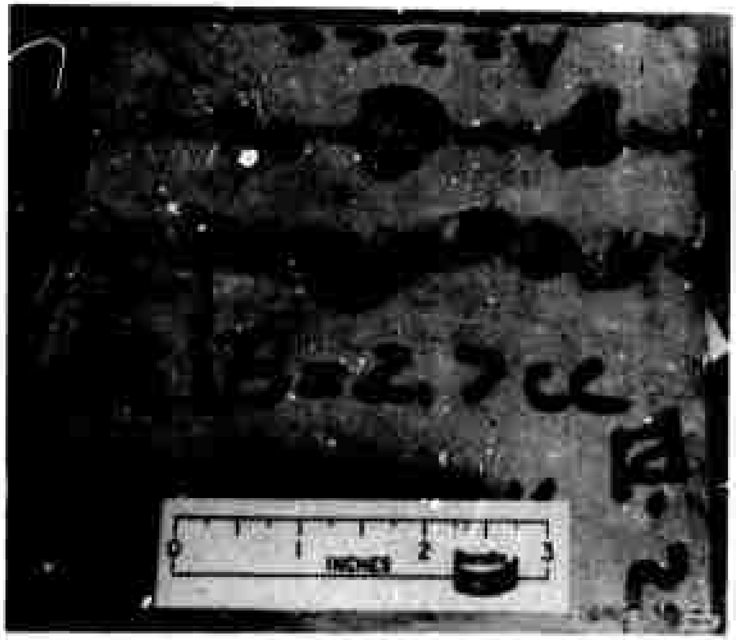
L = length of cut, inches

F = feedrate, ipm

V = volume of material removed, in^3

The volume removed was determined by measuring the volume of material required to fill in the kerf. For the irregular kerf depths and widths obtained in the cutting tests, especially on rocks prone to spalling, measurement of the kerf dimensions and calculation of the volume would be grossly inaccurate as well as extremely time consuming. A variety of materials were used in attempts to fill sample kerfs cut in limestone but were rejected either because of handling difficulties or, in the case of liquids, incomplete kerf filling due to excess surface tension or absorption of the liquid by the rock. The material finally used for the volume measurements was 120 grit emery (aluminum oxide) powder, which has a maximum dimension of approximately 0.004 inch, allowing it to penetrate to the bottom of deep narrow kerfs, but still having sufficient size to permit the material to be poured without caking.

The kerf filling sequence is illustrated in Figure 5-1 for a sample of Dresser Basalt. The ends of the kerf were blocked with tape or putty



(a) Ends of Kerf Prepared for Measurement

(b) Filling Kerf With Powdered Emery

Figure 5-1 - Kerf Measurement Technique

(a) depending upon the regularity of the kerf at the end of the rock. The emery material was poured from a graduated cylinder (b) into the kerf in order to fill the kerf level with the top surface of the rock. For deeper kerfs, the rock was agitated to insure settling of the emery material to the bottom of the kerf. Kerf volume was then equal to the difference between the volume of material in the graduated cylinder before and after filling the kerf. In some cases interaction of the jet with material at the sample edge which had been weakened during sawing or handling resulted in splitting off of a large chunk of material, as shown in Figure 5-2 for a Dresser Basalt sample. In these cases, the kerf was blocked with putty at the ends of the undamaged portion of the sample. Kerf volume and length measurements were taken for the central portion only, eliminating the possibility of the data being influenced or biased by sample stresses induced by the sawing or handling operations.

Figure 5-2 - Effect of Weakened Edge in Dresser Basalt

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SECTION 6

TEST SEQUENCE

Fragmentation tests and analysis were conducted in the following sequence:

- Testing was completed to perform 2^4 factorial experiments for all eight rock types, using the high and low levels of the variables listed previously. Randomization was applied to both the selection of the rock samples and the sequence of the 128 test runs.
- Test data from the 2^4 factorial experiments was processed using Yates algorithm and analysis of variance performed for each rock type to determine the relative significance of main effects and interactions.
- The 2^4 factorial experiments were expanded into 3^4 factorial experiments for both Jasper quartzite, which is the hardest rock specified for the test program, and Barre Granite, which is a relatively common granite for which a variety of information exists.
- Testing was continued to perform, in randomized order, the runs required to complete 3^2 factorial design experiments for the remaining rock types, using the two most significant factors as determined by previous analysis of variance. The remaining two factors were set at the values for which minimum specific energy was obtained.
- Additional test runs were completed for all rock types at higher feedrates up to 900 ipm in order to reduce the single cut specific energy based upon the relatively large significances of the negative feedrate effect as determined from the analyses of variance.
- Kerfing tests were conducted using the minimum specific energy point obtained in the previous testing. Parallel runs across the target face were completed, with spacing between the cuts successively decreased until kerfing occurred between cuts. The kerfing tests were replicated on two additional samples of the same rock type selected at random to minimize the effects of variations in samples within each rock type.

The following number of test runs were completed for each portion of the testing sequence.

2^4 factorial : 2^4 runs x 8 rocks x 2 replications = 256

3^4 factorial: $(3^4 - 2^4)$ runs x 2 rocks x 2 replications = 260

3^2 factorial: $(3^2 - 2^2)$ runs x 6 rocks x 2 replications = 60

Additional:

(2 x 2 x 3) runs x 2 rocks x 2 replications = 48

2^2 runs x 6 rocks x 2 replications = 48

18 extra runs, 2 rocks = 18

Kerfing:

2 runs x 8 rocks x 3 replications = 48

Total number of runs = 738

SECTION 7

DATA AND ANALYSIS

Due to the large amount of data collected for the 738 test runs completed, extensive use was made of the time share computer for data manipulation, calculation of specific energies for each test run and completion of analyses of variance. Computer programs utilized in the test program are listed in Appendix B. Data files are presented so that input data can be retrieved for any run conducted under the test program, if further data analysis is required in future efforts. As mentioned previously, the present effort is devoted specifically to determining for each rock type, the minimum specific energy associated with the jet excavation process within the experimental ranges rather than determination of correlations between specific energy and rock properties. For this reason, as well as the fact that the number of replications is statistically small, regression analyses were not performed on the rock test data. Analysis of the test data will be presented in detail for Barre Granite, which is illustrative of data trends present in most of the rock samples investigated. Due to the total volume of data gathered, however, other rock types will be discussed only with regard to deviations from the established trends. Summaries of process parameters, test conditions, specific energies and analyses of variance are presented for all rock types in Appendices C through J.

As described previously, 2^4 factorial experiments were completed for all rock types for use as screening experiments to determine the relative significances of the jet process independent variables. The results of analyses of variance conducted on the 2^4 factorial data are presented in Table 7-1, with process parameter main effects listed for each rock type in decreasing order of significance. A positive effect, that is, one where the slope of the curve of specific energy versus an independent variable is positive, is denoted by a plus sign before the letter ascribed to the independent variable; a negative effect by a minus. Letters indicating the independent variables are P for pressure, F for feedrate, S for standoff distance and N for nozzle diameter.

The trend for all rock types was for negative feedrate (F) effect, that is, decreasing specific energy with increasing feedrate and a positive nozzle (N) effect. Feedrate was one of the two most significant effects for seven of the eight rock types. The pressure effect was positive for seven rock types, including the three rocks, Barre Granite, Charcoal Granite and Sioux Quartzite, for which it was one of the most significant effects. The standoff effect was positive for the majority of rock types, but was of relatively minor significance compared with the other main effects. Actual significance tests and effect values are presented for each rock type, along with the 2^4 factorial experiment data, in the Appendices.

Table 7-1 - Relative Significances of Main Effects for 2^4 Factorial Fragmentation Test Data

Rock No.	Rock Type	σ comp. (psi)	MAIN EFFECTS (Decreasing Significance →)			
6	Berea Sandstone	8600	-F	+N	-P	+S
8	Salem Limestone	9500	-F	+N	+P	+S
7	Tennessee Marble	16900	+N	-F	+P	+S
2	Westerly Granite	---	+N	-F	+S	+P
3	Barre Granite	23900	-F	+P	+S	+N
1	Charcoal Granite	35100	+P	+N	-F	-S
5	Sioux Quartzite	54000	+P	+N	-F	-S
4	Dresser Basalt	50000	-F	+N	+S	+P

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The 2^4 factorial experimental design was expanded to a 3^4 design for both Barre Granite and Sioux Quartzite, as specified in the test sequence, and into a 3^2 factorial design for the remaining rock types, investigating the two most significant main effects as determined by the previous analyses of variance, in order to provide a better indication of the shape of the specific energy response curves.

Previous research by W. C. McLain et. al.,[1] had indicated that above a certain supply pressure, 12000 psi for Indiana Limestone, and lower for Berea Sandstone, the specific energies became equal for jet impingement both parallel and perpendicular to the specimen bedding planes. Based upon this information, the sample bedding plate orientation was ignored in the current test program, since anticipated supply pressure levels were well above 12000 psi. Berea Sandstone and Salem Limestone samples were ordered with half cut perpendicular and half parallel to the bedding planes, and orientations were distributed among the test sequence by the randomization of the order of sample usage. In order to confirm the validity of this approach, a series of cuts were completed for combination #192 on Indiana Limestone, with two replications each for three faces of the sample to insure impingement both parallel and perpendicular to the bedding plane. The average specific energy for the six tests was 19396 joules/cc and sample variance was 1146 joules/cc. Because of the small differences in the specific energy values obtained in this experiment for three orthogonal rock faces, it appears reasonable to conclude that the orientation of the jet with respect to the rock bedding plane has no effect upon the specific energy values at the pressure levels used in the present test program.

Of particular interest is the extremely high specific energy values associated with the tests conducted in the 2^4, and 3^4 and 3^2 factorial experiments. The minimum specific energy obtained with this series was 5571 joules/cc (67,348 ft-lb/in^3) for Berea Sandstone. A typical cut is shown in Figure 7-1. The maximum value, however, was 386,191 joules/cc (4,667,923 ft-lb/in^3) for Charcoal Granite, shown in Figure 7-2 Additional testing at different operating parameters was indicated in order to bring the specific energy values down to a point where they could be reasonably competitive with conventional processes. Since nozzle diameter and feedrate had the greatest significances, investigation was begun upon methods of lowering the specific energy by variation of these parameters. The smallest nozzle size presently used and stocked by Bendix is a 0.005 inch diameter, use of which would provide a 60 percent area reduction, and a comparable specific energy decrease, providing the volume excavated remained constant with the smaller nozzle. Previous experience in cutting tests (but not data analysis) conducted for the Bureau of Mines indicated, however, that a lower volume removed could be expected when using the smaller nozzle, so consideration of use of a smaller nozzle for the additional test runs was terminated. By increasing the feedrate up to the practical limit of the sample traversing table, 900 ipm, an 85 percent reduction in energy input to the rock could be realized. A much smaller percentage decrease in excavated volume was expected, since jet efficiency increases at higher feedrates, due to reduced interference between the penetrating jet and the spent jet rebounding from the bottom of the kerf. Additional tests were run at increased feedrates, resulting in a decrease in single cut specific energy to the values presented in Table 7-2.

Analyses of variance were performed upon data from the additional test runs. All rock types exhibited main factor effects having the same sense, but much lower magnitudes, than the effects determined from the 2^4 factorial analyses of variance, indicating that increasing feedrates past 900 ipm will have a decreasing negative effect upon the specific energy. This fact is evident from graphs of specific energy versus feedrate, presented in Figure 7-3 for Barre Granite, with pressure effect illustrated, and Figure 7-4 for Sioux Quartzite, with both pressure and nozzle effects shown. Since feedrates higher than those shown would be of limited utility for a continuous mining machine, it appears that the data presented constitutes a practical minimum single cut specific energy for fluid jet excavation in the experimental range.

Additional testing was completed upon Salem Limestone at pressures as low as 5000 psi in order to determine how well the specific energy data for that rock type matched that presented by McLain[1]. This data presented in Figure 7-5 closely matches at the lower pressures, with the

Figure 7-1 - Single Cut Run on Berea Sandstone

Figure 7-2 - Maximum Single Cut Specific Energy Run

Table 7-2 - Average Minimum Specific Energies for Each Rock Type

Rock No.	Rock Type	σ comp. (psi)	Minimum Specific Energy				Kerf Spacing	
			Single Cut		Kerfing Cut			
			(joules/cc)	(ft-lb/in^3)	(joules/cc)	(ft-lb/in^3)	cm.	in.
6	Berea Sandstone	8600	2976	35,977	1215	14,686	0.236	0.093
8	Salem Limestone	9500	6036	72,961	2484	30,028	0.236	0.093
7	Tennessee Marble	16900	5130	62,003	3427	41,417	0.317	0.125
2	Westerly Granite	---	6895	83,343	4289	51,843	0.254	0.100
3	Barre Granite	23900	6985	84,425	3857	46,623	0.236	0.093
1	Charcoal Granite	35100	4249	51,355	3963	47,901	0.317	0.125
5	Sioux Quartzite	54000	10834	130,955	6611	79,708	0.317	0.125
4	Dresser Basalt	50000	9579	115,788	3868	46,748	0.317	0.125

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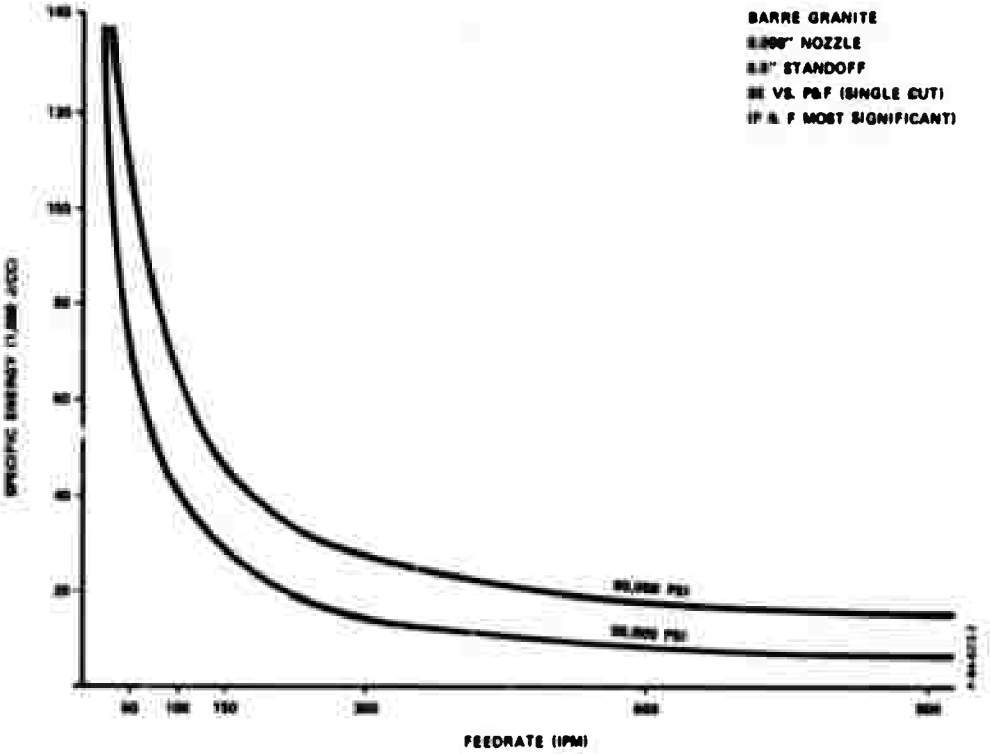

Figure 7-3 - Specific Energy as a Function of Feedrate for Barre Granite

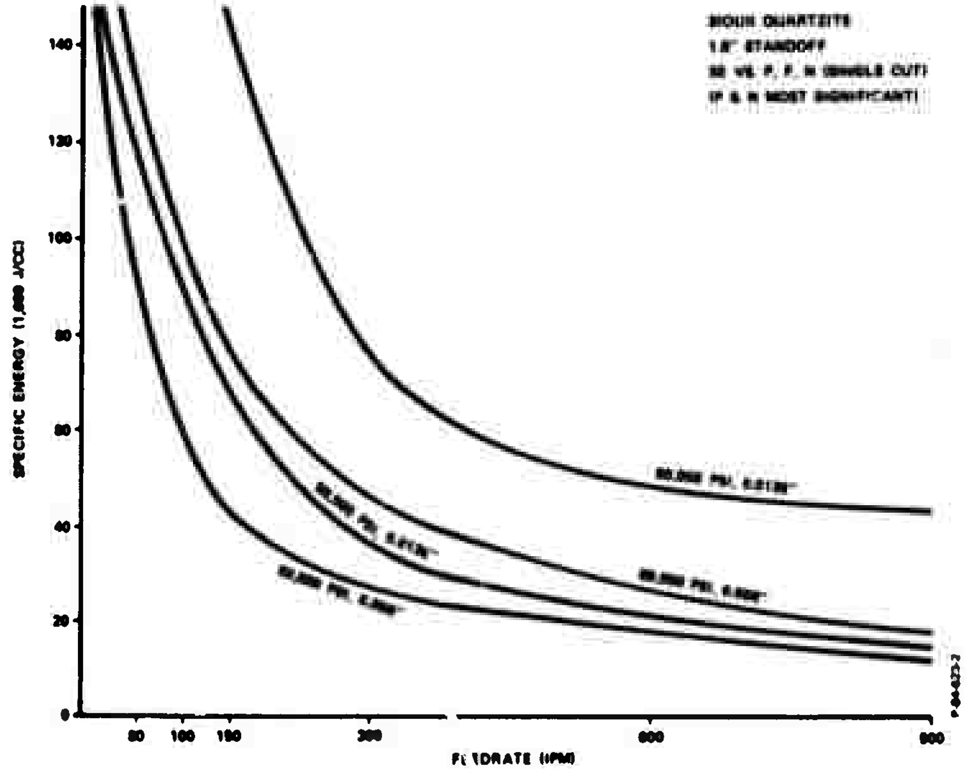

Figure 7-4 - Specific Energy as a Function of Feedrate for Sioux Quartzite

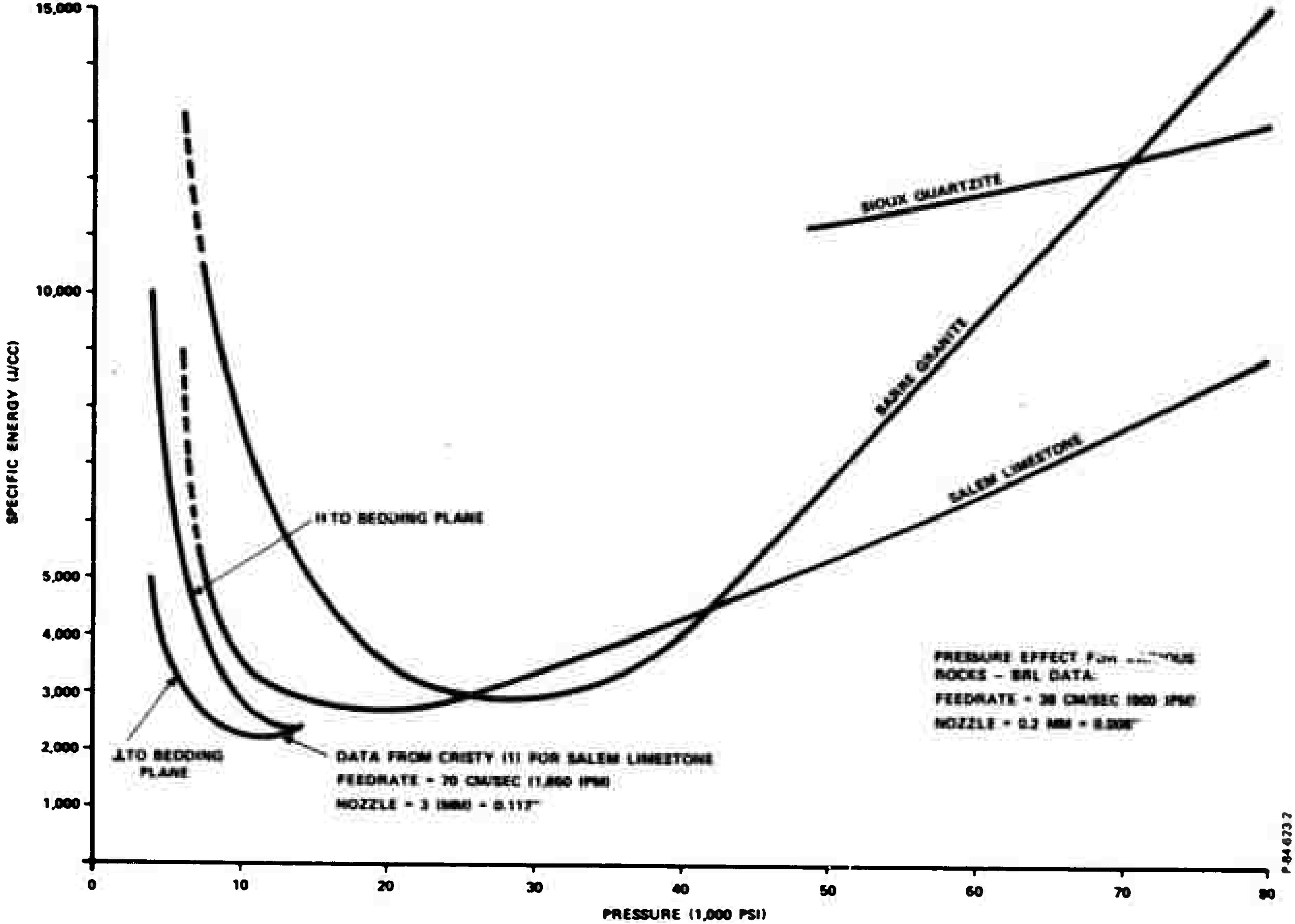

Figure 7-5 - Specific Energy as a Function of Pressure for Sioux Quartzite, Barre Granite and Salem Limestone decreasing feedrate effect evident in the fact that little additional decrease in specific energy is obtained by increasing feedrate from 900 ipm to 1650 ipm.

Data is also presented in Figure 7-5 for Barre Granite, which the explored at pressures as low as 10,000 psi, and for Sioux Quartzite. The curve for Barre Granite indicates that the minimum specific energy point for this rock occurs at approximately 30,000 psi. The pressure effect curve for Sioux Quartzite is positive, as are the curves for other rock types, indicating that the absolute minimum specific energy point occurs below 50,000 psi for most rock types. Since the pressure effect was not among the two most significant main effects for the majority of rocks, further investigation of specific energies at lower pressures was not pursued.

The minimum specific energy values, within the experimental ranges, determined as described above, were obtained at the following process parameters.

Pressure:	34.5 KN/cm^2 (50,000 psi)
Nozzle Dia:	0.2 mm (0.008 inch)
Feedrate:	19 cm/sec (450 ipm) for Dresser Basalt 38 cm/sec (900 ipm) for all others.
Standoff:	3.81 cm (1.5 inch) for Charcoal Granite and Sioux Quartzite, 1.27 cm (0.5 inch) for all others.

Following determination of the minimum specific energy for single cuts as above, tests were completed to determine the spacing between successive cuts for which kerfing, or excavation of the material between the cuts, was observed, approximating the condition of minimum overall specific energy for fluid excavation at the test conditions employed. The kerfing tests were conducted for each rock type using the parameters listed above which produced the minimum single-cut specific energy. Specific energies for kerfing runs are presented in Table 7-2, along with the maximum cut spacing at which kerfing between cuts would occur. Figures 7-6 and 7-7 show the results of kerfing cuts conducted on Salem Limestone and Barre Granite, respectively.

Figure 7-6 - Kerfing Effect on Salem Limestone

Figure 7-7 - Kerfing Effect on Barre Granite

SECTION 8

FLUID JET EXCAVATION SYSTEMS

Economic comparison between fluid jet excavation systems and conventional continuous excavation systems is hampered by the fact that very little actual tunneling has been completed in hard rock structures for which the use of a fluid jet system is proposed. Bruce and Morrell[2] list a total of only twelve tunnels in the United States which have been machine bored since 1955 in rocks of over 20,000 psi compressive strength. In half of these applications, the use of the continuous excavation machine was discontinued in favor of conventional tunneling techniques. The present limit of economic boreability for most rocks using conventional systems appears to be 30,000 psi compressive strength.

Sufficient data exists from the above source, however, to determine the economics of conventional tunneling systems in two specific hard rock applications, one in argillites having 35000 to 45000 psi compressive strength, in the Dorchester Water Tunnel, Boston, Massachusetts, the second in a section of quartzite of 49000 psi compressive strength in the Magma Copper Mine, Superior, Arizona. Both tunnels were bored by 12.5-foot diameter Lawrence HRT-12 excavators of 600 horsepower capacity with 1,500,000 pounds of thrust upon the tungsten carbide cutters. System cost was approximately $600,000 in both cases. Comparative performance for both systems are presented in Table 8-1. The

Table 8-1 - Comparison of Performance of Various Excavation Systems

Excavation System	Power Required (hp)	Excavation Rate (yd^3/hr)	Specific Energy	
			($ft-lb/in^3$)	(joules/cc)
Argillites (σ = 35000 psi)				
Lawrence HRT-12	600	22.7	1122	93
Fluid Jet	51100	22.7	47901	3963
Jet/Mechanical	16450	22.7	15409	1275
Quartzite (σ = 50000 psi)				
Lawrence HRT-12	600	4.5	5608	464
Fluid Jet	17100	4.5	79708	6611
Jet/Mechanical	4096	4.5	19145	1584

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jet specific energy for kerfing cuts in Sioux quartzite and Charcoal granite were used to predict jet excavator performance in quartzite and argillite, respectively.

As is evident from the comparative performance data, the pure fluid jet excavation system, utilizing fluid induced kerfing alone, is at an extreme disadvantage due to its higher specific energy, which is approximately 14 times that for the Lawrence miner operating in quartzite, and 43 times the value for operation in argillites. Assuming an overall machine efficiency of 50 percent, a pure fluid jet excavator would require an installed horsepower of 17,100 to equal the performance of the Lawrence miner in quartzite. Since generation and application of such power levels is impractical in a mobile underground excavation system, it is evident that the use of a hybrid system, combining jet kerf cutting ability with some more efficient method of rock removal, will be required to decrease the overall system specific energy.

The use of a hybrid system utilizing high pressure fluid jets for kerf cutting, with removal of material between kerfs by mechanical means, appears to offer advantages over both pure fluid jet and conventional excavation systems. Such a system, shown schematically in Figure 8-1, will eliminate the high cutter loading and thrust requirements of present conventional excavation systems, as well as minimizing the effect of the high specific energy associated with the pure fluid jet cutting process. Present excavation systems for hard rock use rely on inducing rock spallation due to localized loading of the rock in excess of its compressive strength. Due to the excellent compressive properties of rock *in situ* extremely high cutter loadings are required, with attendant high wear. Also, the spalled material from the rock face tends to contaminate the cutter bearings, resulting in reduced life for these parts. The jet process on the other hand, can remove small kerfs, albeit at high specific energy values, without the need for excessive loading because the machine does not contact the work face. A mechanical device can be inserted into a kerf, as shown, breaking off one rib into the adjacent kerf, and the other rib into the kerf removed by previous passes of the jets and wheel. Although an additional jet kerf must be cut for the first pass in order to insure the removal of two ribs, the extra energy required for the initiating kerf cut will be small when averaged over many succeeding passes, so that, in effect, only one jet excavated kerf will be required for each rib removed. The ribs left in the rock after scoring by the jets are unrestrained, as shown in Figure 8-1, Section A. When loaded by the wheel, the ribs will react similar to end loaded cantilever beams, with a tensile bending load resulting in fracture at the base of the rib, shown in Section B, where the bending moment is largest. Reduced loading and specific energy are required to effect fracture of the rib due to the low tensile strengths of most rocks. In tests to date, Summers and Henry[3] have reported specific energies as low as 0.05 joules/cc for mechanical removal of ribs left between water jet kerfs cut in Berea

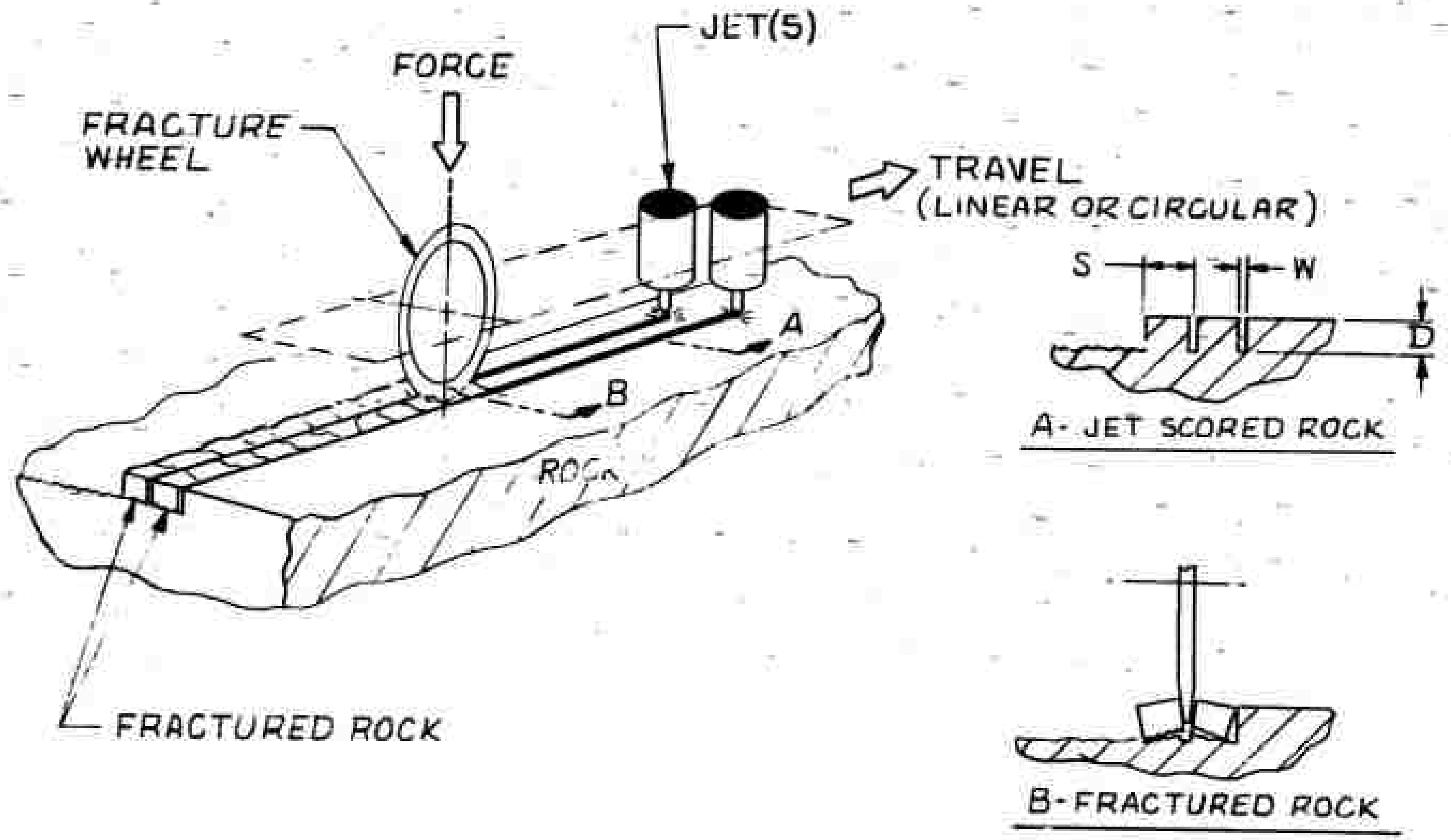

Figure 8-1 - Mechanically Assisted Fluid Jet Excavation Concept

Sandstone. In the tests described, mechanical breakage energy values were determined by dropping weights from a known height, and therefore, a known specific energy, upon wedges set in the jet kerfs, and measuring the material volume.

The strain energy, u, for breakage of a cantilever beam subjected to end loading is given as follows.[4]

$$u = \frac{1}{18} D\ S\ L\ \frac{(\sigma_{max})^2}{E}$$

where

σ_{max} = maximum tensile strength of the beam material

D = length of beam = depth of kerf

S = depth of beam = spacing between cuts

L = width of beam in direction of cut

Since volume removed = V = D S L

$$SE_{theo} = \frac{U}{V} = \frac{(\sigma_{max})^2}{18\ E}$$

For Berea Sandstone, $\sigma_{tensile} = 580$ psi and $E = 9.5 \times 10^6$ psi. Therefore

$$SE_{theo} = 1.9 \times 10^{-3} \text{ psi} = 1.6 \times 10^{-4} \text{ ft-lb/in}^3 = 1.4 \times 10^{-5} \text{ joules/cc}$$

for the mechanical breakage above.

The simplified case described is accurate for conditions where kerfing cuts have been completed in two directions perpendicular to each other, forming an array of free standing cantilever beams, and does not take into account the more complicated stress condition present when fracturing a rib which is fixed both at the bottom, between the cuts, and in the direction of cut, as was the case for the tests by Summers and Henry, described above. In addition, the mechanical wedge, due to friction, imparts a compressive load to the rock which tends to combat the bending load by reducing the tensile stress in the outer fiber of the cantilever beam.

A gross estimate of the actual mechanical specific energy of removal for a specific rock can be made, however, by multiplying that value recorded in the literature for Berea Sandstone by the ratio of theoretical specific energies as determined above.

For Charcoal Granite, $\sigma = 1300$ psi, $E = 9.67 \times 10^6$ psi

$$SE_{theo} = 9.7 \times 10^{-3} \text{ psi} = 8.1 \times 10^{-4} \text{ ft-lb/in}^3 = 6.69 \times 10^{-5} \text{ joules/cc}$$

For Sioux Quartzite, $\sigma = 1300$ psi, $E = 8.5 \times 10^6$ psi

$$SE_{theo} = 11. \times 10^{-3} \text{ psi} = 9.2 \times 10^{-4} \text{ ft-lb/in}^3 = 7.6 \times 10^{-5} \text{ joules/cc}$$

Data reported by Summers and Henry indicates that, for Berea Sandstone, mechanical breakage specific energies of approximately 0.5 joule/cc may be realized in removing ribs where the spacing between kerfs is approximately equal to the depth of the kerf.

The following actual specific energies therefore may be realized for mechanical breakage of other materials where the kerf spacing is equal to the kerf depths. For Charcoal Granite:

$$SE = 0.5 \times \frac{6.69 \times 10^{-5}}{1.4 \times 10^{-5}} = 2.39 \text{ joules/cc}$$

For Sioux Quartzite:

$$SE = 0.5 \times \frac{7.6 \times 10^{-5}}{1.4 \times 10^{-5}} = 2.71 \text{ joules/cc}$$

Although a correlation between jet process parameters and kerf depth was not within the scope of the present research, measurement of several test samples has shown that, at the minimum specific points used, a minimum cut depth of 0.125 inch was obtained for the hardest material, Sioux Quartzite. Cut depth generally increased with increasing supply pressure and nozzle diameter, and decreased with increasing feedrate and rock compressive strength.

A projected overall specific energy for a mechanically assisted fluid jet excavation machine can be determined from specific energy values for each process, the kerf depth and the jet kerf volume. Specific energy and kerf volume for the jet cuts will be as determined from the minimum specific energy runs for each rock type.

For comparison of Charcoal Granite with argillites, the minimum single cut specific energy of 4248.75 joules/cc was the average value obtained for the two test runs on the Granite conducted as combination number 373. Data file ROCKS6, line 125 (presented in Appendix B) indicates that the length of cut for both test runs was 8 inches, and that kerf volumes of 0.85 and 0.9 cc, respectively, were removed. The average volume removed, therefore, was 0.875 cc for a cut length of 8 inches. Kerf depth was approximately 0.125 inch, so that, assuming a comparable spacing between kerfs, the rib volume for the 8 inch cut would be 0.125 x 0.125 x 8 = 0.125 in^3 = 2.048 cc. The two jets and cutter wheel depicted in Figure 8-1 would then remove two kerfs, having volumes of 0.875 cc each, by jet action at a specific energy of 4248.75 joules/cc, and two ribs, having volumes of 2.048 cc each, by mechanical action at 2.39 joules/cc. Total energy input would be 7444 joules to remove a total volume of 5.84 cc, therefore, the overall specific energy would be 1275 joules/cc.

The minimum single cut specific energy for Sioux Quartzite was 10,384.32 joules/cc, determined from the data for combination number 411, listed in data file ROCKS7, line 225. Cut length for this combination was 8 inches, and the average volume removed by the jet was 0.35 cc. Kerf depth was also 0.125 inch. The hybrid system would, therefore, remove 2 kerfs having volumes of 0.35 cc each by jet at 10,834.32 joules/cc, and 2 ribs having volumes of 2.048 cc each mechanically at 2.71 joules/cc. Total energy input would be 7596 joules to remove 4.796 cc of material for an overall specific energy of 1584 joules/cc.

These projected specific energy values are presented in Table 8-1 for comparison with those of the conventional and unassisted jet excavators. Since no correlation of kerf depth with jet operating parameters was completed in this program, further investigation will be required in order to determine whether lower overall specific energies can be attained by adjusting jet parameters to give greater kerf depth, thereby increasing the percentage of total material which is removed by mechanical breaking. For the jet operating parameters used, however, which were those required for minimum jet specific energy, the above analysis indicates potential minimum energy values for a hybrid jet/mechanical excavation system. Using the predicted specific energies above, a comparison between the hybrid system and a Lawrence HRT-12 excavator is presented in Table 8-2 for excavation of a 5000 foot tunnel. Horsepower for the hybrid system (using a 50 percent overall efficiency) was determined in order to equalize the penetration rates of the two systems, thereby equalizing their total operating time, direct labor costs, machine amortization costs, and the required muck removal equipment capacity. Comparisons are made on power

Table 8-2 - Operating Costs for 5000' Tunnel

Excavation System	Power (hp)	Advance Rate (ft/hr)	Cutter Cost $	Total Costs		Grand Total
				Cutter	Power	
Argillites (σ = 35000 psi)						
Lawrence HRT-12	600	5	\$6.30/yd^3	\$143,171	\$ 16,200	\$159,371
Jet/Mechanical	16450	5	\$3.00/yd^3	68,176	444,139	512,315
Quartzite (σ = 50000 psi)						
Lawrence HRT-12	600	1	\$9.50/yd^3	215,893	81,000	296,893
Jet/Mechanical	4096	1	\$3.00/yd^3	68,176	553,035	621,211

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Volume removed = $\frac{\pi}{4}(12.5)^2 \times 5000 = 613,600\ ft^3 = 22,725\ yd^3$ Power @ \$.02/KWHR = 0.027/(hp-hr)

requirements and cutter costs alone. Machine purchase, indirect overhead, roof support and material haulage costs are assumed to be equal. In both of the cases described above, however, 1.5 cc of water is required to remove either 0.366 cc of granite or 0.296 cc of quartzite, resulting in formation of a slurry of rock and water having a concentration of 40 percent or 33 percent, respectively, by weight. These concentrations are within ranges suitable for use in slurry transport by pipeline, which indicates that this mode of muck removal will be suitable for use with jet/mechanical excavators, resulting in cost benefits over systems used with present excavators. Direct maintenance costs of the excavation system itself are not considered, due to a lack of information regarding maintenance of high pressure pumping equipment. Cutter costs given are based on values given by Bruce and Morell.

As shown in Table 8-2, significant savings in cutter costs are gained by use of the hybrid jet/mechanical excavator, however, overall operating costs are higher due to power charges occasioned by the hybrid excavator's higher specific energy.

The specific energy obtained for the hybrid system does not, as mentioned previously, represent the optimum specific energy for such a system. The jet operating parameters employed in the analysis of the hybrid system specific energy were those determined for the minimum specific energy for pure jet excavation. Although no correlation between specific energy and kerf depth were included within the scope of this research, it was observed that kerf depth increased with increasing supply pressure and nozzle diameter, and decreased with increasing feedrate. The jet parameters used to obtain the minimum specific energy, therefore, also produce the smallest kerf depth.

Optimization of the specific energy of excavation for a mechanical/fluid jet excavator depends upon maximizing the proportion of material removed by mechanical action. This will require further testing to determine the jet operating parameters required to maximize jet kerf depth for a given energy input. As kerf depth is increased, the spacing between kerfs can also be increased, so that the volume of material removed by mechanical action increases with the square of the kerf depth. Since the jet excavation energy constitutes the majority of the energy input to the rock, the maximum overall efficiency for a hybrid system may be obtained at the operating parameters which produce the deepest kerf, even though the jet excavation portion of the process is not operating at its minimum specific energy.

In addition, the specific energy data determined in this program for fluid jet excavation was obtained through testing conducted upon unstressed laboratory samples. Further reduction in excavation specific energy can be expected in testing upon *in situ* rock structures due to the compressive stress field underground. Further testing will be required on *in situ* rock either in a tunnel or a quarry in order to further minimize the specific energy both for the jet excavation and the mechanical breakage processes.

Further investigation both of mechanical breakage, maximization of jet kerf depth, and interaction between the two processes both in the laboratory and *in situ* is expected to lead to the evolution of hybrid rapid excavation systems having comparable or lower specific energies than those exhibited by conventional excavators working in hard rock, with the additional advantages of reduced machine and cutter loading, increased mobility, reduced cutter costs, no dust generation and ease of integration with systems for muck removal by slurry transport.

SECTION 9

CONCLUSIONS AND RECOMMENDATIONS

- Within the experimental range employed, the minimum specific energies for single cuts were obtained at the following jet process parameters:

Pressure:	34.5 KN/cm^2 (50,000 psi)
Nozzle Dia:	0.2 mm (0.008 inch)
Feedrate:	19 cm/sec (450 ipm) for Dresser Basalt 38 cm/sec (900 ipm) for all others
Standoff:	3.81 cm (1.5 inch) for Charcoal Granite and Sioux Quartzite 1.27 cm (0.5 inch) for all others

  Minimum single cut specific energies, listed in Table 7-2, ranged from 10,834 joules/cc (130,955 ft-lb/in^3 for Sioux Quartzite to 2976 joules/cc (35,977 ft-lb/in^3) for Berea Sandstone.

- Kerfing tests were conducted for each rock type using the parameters within the experimental range which produced the minimum single-cut specific energy. Specific energies for kerfing runs ranged from 6611 joules/cc, (79,900 ft-lb/in^3) for Sioux Quartzite to 1215 joules/cc (14,685 ft-lb/in^3) for Berea Sandstone, and are presented in Table 7-2.

- The kerfing run specific energies described above were found to be higher than those exhibited by conventional tunnel excavation systems described in the literature (2). The jet excavation specific energy was approximately 14 times that for a Lawrence HRT-12 excavator operating in quartzite, and 43 times the value for operation in argillites.

- A much lower machine specific energy than that for a pure jet system can be obtained in a system utilizing both jet action to cut kerfs in the rock face and mechanical devices to break the material out between the kerfs. Such a system would have the advantages of reduced machine and cutter loading, increased mobility, reduced cutter costs, no dust generation and ease of integration with systems for muck removal by slurry transport.

- Optimization of the specific energy of excavation for a mechanical/ fluid jet excavator depends upon maximizing the proportion of material removed by mechanical action. This will require further testing to determine the jet operating parameters required to maximize jet kerf depth for a given energy input. In general, kerf depth increases with increasing nozzle diameter and supply pressure, and the volume of material removed by mechanical action increases with the square of the kerf depth. Since the jet excavation energy constitutes the majority of the energy input to the rock, the maximum overall efficiency for a hybrid system may be obtained at the operating parameters which produce the deepest kerf, even though the jet excavation portion of the process is not operating at its minimum specific energy.

- Mechanical breakage energies should be determined for harder rock structures both in the laboratory and *in situ* for eventual incorporation in the design of a mechanically assisted fluid jet excavator. Relationships between specific energy, kerf depth and spacing between kerfs should be explored in detail.
- Further investigation is recommended to determine jet excavator performance upon *in situ* rock structures rather than upon unstressed laboratory specimens. Lower specific energies of excavation can be expected for *in situ* rock since the compressive stress field underground favors rock fracturing by the jet kerfing mode.
- Development of a mobile excavation test rig should be completed to facilitate *in situ* testing both in tunnels and quarries. The device should include both jet and mechanical modes of rock fracturing, allowing it to be used for investigation of operating parameters required for a hybrid jet/mechanical excavation system. Pressure and flow capabilities of the jet excavation portion should be comparable to those used in the present test program, that is, 80,000 psi and 1.4 GPM, allowing the device to be used for investigations regarding specific energy minimization or kerf depth maximization; provision should also be included for mounting various mechanical fracturing devices to determine relative effectiveness of each.

SECTION 10

REFERENCES

1. W. C. McClain, et. al., Examination of High Pressure Water Jets for Use in Rock Tunnel Excavation, ORNL-HUD-1, UC-38, January 1970, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
2. Bruce, William E. and Morrell, Roger J.; "Rapid Excavation in Hard Rock - A State-of-the-Art Report," Proceedings of the Conference on Deep Tunnels in Hard Rock - A Solution to Combined Sewer Overflow and Flooding Problems, University of Wisconsin, Milwaukee, Wisconsin, November 1970.
3. Summers, D. A. and Henry, R. L., Water Jet Cutting of Rock With and Without Mechanical Assistance, SPE 3533, New Orleans, La., October 1971.
4. Timoshenko, S. and Young, D. H., Elements of Strength of Materials, 4th Ed., Van Nostrand Co., Inc., Princeton, N. J., 1962, pp 219-221.

APPENDIX A

SUMMARY OF ROCK PROPERTIES

CHARCOAL GRANITE

TYPE NO. 1

Property	Test Results (English Units)	Test Results (SI Units)
Compressive strength	35.1×10^3 lb/in^2	244 MN/m^2
Density (apparent)	170.5 lb/ft^3	2.72 g/cm^3
Hardness (Shore scleroscope)	95	95
Poisson's ratio (dynamic)	0.28	0.28
Tensile strength (pull)	1300 lb/in^2	9 MN/m^2
Tensile strength (indirect)	1570 lb/in^2	12.8 MN/m^2
Young's modulus (dynamic)	9.67×10^6 lb/in^2	66.7 GN/m^2
Young's modulus (static)	9.3×10^6 lb/in^2	64.1 GN/m^2

WESTERLY GRANITE

TYPE NO. 2

Property	Test Results (English Units)	Test Results (SI Units)
Density (apparent)	165 lb/ft^3	2.64 g/cm^3
Poisson's ratio (dynamic)		0.24
Poisson's ratio (static)		0.20
Shear modulus (dynamic)	2.6-4.6 x 10^6 lb/in^2	18-32 GN/m^2
Shear modulus (static)	3.83 x 10^6 lb/in^2	26.4 GN/m^2
Velocity (longitudinal pulse)	1955 ft/sec x10^3	5930 m/sec x 10^3
Velocity (shear)	11,000 ft/sec x 10^3	3360 m/sec x 10^3
Young's modulus (dynamic)	5.8-11.6 x 10^6 lb/in^2	39.9-80 GN/m^2
Young's modulus (static)	8.26 x 10^6 lb/in^2	56.9 GN/m^2

BARRE GRANITE

TYPE NO. 3

Property	Test Results (English Units)	Test Results (SI Units)
Compressive strength	23.9×10^3 lb/in^2	167 MN/m^2
Density (apparent)	166 lb/ft^3	2.66 g/cm^3
Shear modulus (dynamic)	2.44×10^6 lb/in^2	16.8 GN/m^2
Shear modulus (static)	$2.2\text{-}2.4 \times 10^6$ lb/in^2	15.2-16.9 GN/m^2
Young's modulus (dynamic)	4.41×10^6 lb/in^2	30.4 GN/m^2
Young's modulus (static)	$3.96\text{-}6.41 \times 10^6$ lb/in^2	27.3-44.2 GN/m^2

DRESSER BASALT

TYPE NO. 4

Property	Test Results (English Units)	Test Results (SI Units)
Compressive strength	50×10^3 lb/in^2	350 MN/m^2
Density (apparent)	187 lb/ft^3	2.99 g/cm^3
Hardness (Shore scleroscope)	90	90
Poisson's ratio (dynamic)	0.285	0.285
Porosity	0.20 percent	
Shear modulus (dynamic)	5.85×10^6 lb/in^2	40 GN/m^2
Tensile strength (pull)	2100 lb/in^2	14 MN/m^2
Tensile strength (indirect)	2750 lb/in^2	19 MN/m^2
Velocity (longitudinal bar)	19.1 ft/sec $\times 10^3$	5.82 m/sec $\times 10^3$
Velocity (longitudinal pulse)	21.7 ft/sec $\times 10^3$	6.62 m/sec $\times 10^3$
Velocity (shear)	11.9 ft/sec $\times 10^3$	3.63 m/sec $\times 10^3$
Young's modulus (dynamic)	14.5×10^6 lb/in^2	100 GN/m^2
Young's modulus (static)	12.5×10^6 lb/in^2	86.2 GN/m^2

48

SIOUX QUARTZITE

TYPE NO. 5

Property	Test Results (English Units)	Test Results (SI Units)
Compressive strength	54×10^3 lb/in^2	350 MN/m^2
Density (apparent)	150 lb/ft^3	2.39 g/cm^3
Hardness (Shore scleroscope)	99	89
Poisson's ratio (dynamic)	0.13-0.28	0.13-0.28
Porosity	<1 percent	
Shear modulus (dynamic)	$4.2\text{-}5.0 \times 10^6$ lb/in^2	29-35 GN/m^2
Tensile strength (pull)	1300 lb/in^2	9 MN/m^2
Tensile strength (indirect)	2900 lb/in^2	20 MN/m^2
Velocity (longitudinal bar)	14.6 ft/sec $\times 10^3$	4.45 m/sec $\times 10^3$
Velocity (longitudinal pulse)	16.2 ft/sec $\times 10^3$	4.9 m/sec $\times 10^3$
Velocity (shear)	11.0 ft/sec $\times 10^3$	3.35 m/sec $\times 10^3$
Young's modulus (dynamic)	8.5×10^6 lb/in^2	58 GN/m^2
Young's modulus (static)	10.1×10^6 lb/in^2	69.6 GN/m^2

BEREA SANDSTONE

TYPE NO. 6

Property	Test Results (English Units)	Test Results (SI Units)
Compressive strength	8.6×10^3 lb/in^2	59 MN/m^2

50

TENNESSEE MARBLE

TYPE NO. 7

Property	Test Results (English Units)	Test Results (SI Units)
Compressive strength	16.9×10^3 lb/in^2	118 MN/m^2
Density (apparent)	167 lb/ft^3	2.69 g/cm^3
Hardness (Shore scleroscope)	56.5	56.5
Poisson's ratio (dynamic)	0.292	0.292
Shear modulus (dynamic)	4.2×10^6 lb/in^2	28.8 GN/m^2
Tensile strength (pull)	1300 lb/in^2	9.2 MN/m^2
Tensile strength (indirect)	745 lb/in^2	5.13 MN/m^2
Velocity (longitudinal bar)	16,850 ft/sec x 10^3	5140 m/sec x 10^3
Velocity (longitudinal pulse)	20,050 ft/sec x 10^3	6100 m/sec x 10^3
Velocity (shear)	10,600 ft/sec x 10^3	3140 m/xec x 10^3
Young's modulus (dynamic)	10.6×10^6 lb/in^2	73.0 GN/m^2
Young's modulus (static)	9.0×10^6 lb/in^2	62.0 GN/m^2

SALEM LIMESTONE

TYPE NO. 8

Property	Test Results (English Units)	Test Results (SI Units)
Compressive strength	9.5×10^3 lb/in^2	65.9 MN/m^2
Density (apparent)	149 lb/ft^3	2.39 g/cm^3
Hardness (Shore scleroscope)	29.5	29.5
Poisson's ratio (dynamic)	0.299	0.299
Shear modulus (dynamic)	2.2×10^6 lb/in^2	15.2 GN/m^2
Tensile strength (pull)	580 lb/in^2	3.9 MN/m^2
Velocity (longitudinal bar)	12,550 ft/sec x 10^3	3800 m/sec x 10^3
Velocity (longitudinal pulse)	14,550 ft/sec x 10^3	4447 m/sec x 10^3
Velocity (shear)	10,000 ft/sec x 10^3	3000 m/sec x 10^3
Young's modulus (dynamic)	4.8×10^6 lb/in^2	34.2 GN/m^2
Young's modulus (static)	3.92×10^6 lb/in^2	27.2 GN/m^2

APPENDIX B

COMPUTER PROGRAMS AND DATA SUMMARY

ENERGY

```
100 PRØGRAM LANGUAGE: FØRTRAN (FØR)
105 INPUT FILE FØRMAT: CØMBINATIØN #,TEST #,SAMPLE #,PRESSURE
110 (50000=-1,65000=0,80000=1),FEEDRATE(50=-1,100=0,150=1),
115 STANDØFF(.5=-1,1.0=0,1.5=1),NØZZLE(.008=-1,.012=0,.0136=1),
120 LENGTH ØF CUT(IN.),VØLUME REMØVED(CUBIC CM.)
125 $FILE (LIST ØUTPUT FILES #1,.....,#8,INPUT FILES #9,....)
130 DIMENSIØNSE(100),SJ(100),SP(100),SB(100)
135 REAL L
140 25 FØRMAT(56H2↑4 FACTØRIAL FRAGMENTATIØN TEST DATA, RØCK TY
145  +PE NUMBER:,I4)
150 30 FØRMAT(68HCØMB.    TEST   SAMPLE       TREATMENT CØMBINATIØN
155  +                  SPECIFIC)
160 35 FØRMAT(67H  #         #         #     PRESSURE    RATE  STAND
165  +ØFF  NØZZLE        ENERGY)
170 36 FØRMAT(53H                            P          F          S
175  +          N)
180 40 FØRMAT(I4,I8,I6,I11,I8,F8.1,F10.4,F15.2)
185 50 FØRMAT(I29,I8,F8.1,F10.4,F15.2)
190 60 FØRMAT(F11.2,F19.2,F19.2)
195 N=0
200 B=0
205 J=1
210 K=9
215 I=0
220 A=2
225 CI=0
230 90 READ (K)J
235 IF(J)410,410,95
240 95 PRINT 25,J
245 PRINT
250 PRINT
255 PRINT 30
260 PRINT 35
265 PRINT 36
270 PRINT
275 100 READ (K)C
280 IF (C)410,340,105
285 105 IF(C-CI) 112,112,106
290 106 IF(A-1)107,107,110
295 107 B=B+1
300 SB(B)=SE(I)
305 110 A=0
310 112 READ (K) T,R,P,F,S,D,L,V
315 IF(1-P)155
320 IF(P)120,130,140
325 120 P=50000
330 GØTØ155
335 130 P=65000
340 GØTØ155
345 140 P=80000
```

ENERGY CONTINUED

```
350 155 IF(1-F)195
355 IF(F)160,170,180
360 160 F=50
365 GOTO195
370 170 F=100
375 GOTO195
380 180F=150
385 195 IF(S)200,210,220
390 200 S=.5
395 GOTO230
400 210 S=1.0
405 GOTO230
410 220 S=1.5
415 230 IF(D)240,250,260
420 240 D=.008
425 GOTO285
430 250 D=.012
435 GOTO285
440 260 D=.0136
445 285 I=I+1
450 B=B+1
455 SE(I)=7059.173*D**2*P*SQRT(P)*L/F/V
460 SB(B)=SE(I)
465 A=A+1
470 IF(C-CI)300,290,300
475 290 PRINT50,P,F,S,D,SE(I)
480 GOTO310
485 300 PRINT40,C,T,R,P,F,S,D,SE(I)
490 310 CI=C
495 GOTO100
500 340 PRINT
505 PRINT
510 PRINT
515 IF(A-1)342,342,343
520 342 B=B+1
525 SB(B)=SE(I)
530 343 PRINT"               SPECIFIC ENERGY"
535 PRINT
540 PRINT"FT.-LB./CU.IN.      JOULES/CU.CM.            PSI"
545 PRINT
550 N=I
555 DO390I=1,N
560 SJ(I)=.082733*SE(I)
565 SP(I)=12*SE(I)
570 390 PRINT60,SE(I),SJ(I),SP(I)
575 P=B
580 REWINDJ
585 DO 395B=1,P
590 395 WRITE(J)SB(B)
595 J=J+1
```

ENERGY CONTINUED

```
600 N=0
605 A=2
610 I=0
615 B=0
620 CI=0
625 PRINT
630 PRINT
635 PRINT
640 PRINT
645 IF (ENDFILEK)405,400
650 400 K=K+1
655 405 GOTO90
660 410 END
```

ANOVA

```
100 PROGRAM LANGUAGE: ADVANCED BASIC (XBAS)
105 FILES (LIST INPUT FILES #1;....;#8)
110 LET Q1=1
115 PRINT
120 PRINT
125 PRINT
130 PRINT
135 PRINT"ANALYSIS OF VARIANCE, ROCK TYPE NUMBER:",Q1
140 PRINT
145 PRINT
150 PRINT"                 MEAN SPECIFIC ENERGY VALUES"
155 PRINT
160 PRINT
165 PRINT"COMBINATION #","MEAN SPECIFIC ENERGY (FT.-LB./CU.IN.)"
170 DIM X(100)
175 DIM Q(100)
180 DIM S(100)
185 DIM A(100)
190 DIM C(100)
195 DIM U(100)
200 DIM P(100)
205 DIM Z(64,6)
210 MAT Z= ZER
215 LET N=(INPUT: NUMBER OF VARIABLES)
220 LET R=(INPUT: NUMBER OF REPLICATIONS)
225 LET V=0
230 LET A(1)=0
235 LET A(2)=0
240 FOR X = 1 TO2↑N
245 LET W=0
250 FOR K =1 TO R
255 READ # Q1,X(K)
260 LET S(K)=X(K)+A(K)
265 LET A(K)=S(K)
270 LET W=X(K)+W
275 LET V=X(K)↑2+V
280 LET Z=X(K)+Z
285 NEXT K
290 LET C(X)=W
295 LET Q2=(INPUT: STATEMENT FOR COMBINATION NUMBER)
300 IF R=1 THEN 310
305 PRINT  Q2,C(X)/R
310 NEXTX
315 DEF FNX(X)=(X+1)/2
320 DEF FNY(X)=(X+1)/2+(2↑N/2)
325 FOR J =1 TO N
330 FORX=1 TO 2↑N STEP 2
335 LET P(FNX(X))=C(X)+C(X+1)
340 LET P(FNY(X))=C(X+1)-C(X)
345 NEXT X
```

ANOVA CONTINUED

```
350 FOR X=1 TO2↑N
355 LET C(X)=P(X)
360 NEXT X
365 NEXT J
370 LET L=0
375 FOR X=2 TO 2↑N
380 LET U(X)=C(X)↑2/(R*2↑N)
385 LET L=(C(X)↑2/(R*2↑N))+L
390 NEXT X
395 FOR I = 1 TO N
400 LET K=I-1
405 FOR S =(2↑K)+1 TO 2↑N STEP 2↑I
410 FOR J=S TO (S+(2↑K-1))
415 LET Z(J,I)=1
420 NEXT J
425 NEXT S
430 NEXT I
435 IF R=1 THEN 460
440 LET B=(A(1)↑2+A(2)↑2)/2↑N-(C(1)↑2/(R*2↑N))
445 LET E=V-(C(1)↑2/(R*2↑N))-L-B
450 LET D=(2↑N*(R-1))-1
455 LET M=E/D
460 PRINT
465 PRINT
470 PRINT "                    ANALYSIS OF VARIANCE TABLE"
475 PRINT
480 PRINT
485 IF R=1 THEN 595
490 PRINT"SOURCE OF","SUMS OF","DF","F RATIO","TREATMENT"
495 PRINT"VARIATION","SQUARES"," "," ","EFFECTS"
500 FOR X=2 TO 2↑N
505 GOSUB 645
510 LET Q(X)=C(X)/(R*2↑(N-1))
515 PRINT " ",U(X),"1",U(X)/M,Q(X)
520 NEXT X
525 PRINT
530 PRINT "REPLICATE",B,(R-1),B/(M*(R-1))
535 PRINT
540 PRINT "ERROR",E,D
545 PRINT
550 PRINT "TOTAL",V-(C(1)↑2/(R*2↑N)),2↑N*R-1
555 PRINT
560 PRINT "ERROR MEAN SQUARE=",M
565 LET G=SQR(M)/SQR(R)
570 PRINT
575 PRINT G;"IS THE SQUARE ROOT OF THE RATIO OF THE MEAN"
580 PRINT "SQUARE ERROR TO THE NUMBER OF REPLICATIONS PER CELL."
590 GO TO 625
595 PRINT "SOURCE OF","SUMS OF"
600 PRINT "VARIATION","SQUARES"
```

ANOVA CONTINUED

```
605 FOR X=2 TO 2*N
610 GOSUB 645
615 PRINT " ",U(X)
620 NEXT X
625 PRINT
630 LET Q1=Q1+1
635 IF(INPUT: CRITERIA FOR NOT ENDING PROGRAM)THEN115
640 STOP
645 IF Z(X,1)=1 THEN 670
650 IF Z(X,2)=1 THEN 680
655 IF Z(X,3)=1 THEN 690
660 IF Z(X,4)=1 THEN 700
665 GO TO 705
670 PRINT "P";
675 GO TO 650
680 PRINT "F";
685 GO TO 655
690 PRINT "S";
695 GO TO 660
700 PRINT "N";
705 RETURN
710 STOP
715 DATA 0
720 END
```

KERF

```
100 PROGRAM LANGUAGE: FORTRAN (FOR)
105 $FILE ROCKS8
110 DIMENSION SE(4,10),SM(4,10),SUM(4),A(4),DIF(4),DIFM(4)
115 REAL L
120 10 FORMAT(50HKERFING FRAGMENTATION TEST DATA, ROCK TYPE
125 + NUMBER:,I4)
130 15 FORMAT(20H           PRESSURE =,I6,6H PSI =,F9.2,15H NEWTONS
135 +/SQ.CM.)
140 20 FORMAT(20H           FEEDRATE =,I6,6H IPM =,F6.2,9H CM./SEC.)
145 25 FORMAT(20H           STANDOFF =,F6.1,6H IN. =,F6.3,4H CM.)
150 30 FORMAT(20H           NOZZLE   =,F6.4,6H IN. =,F6.5,4H MM.)
155 35 FORMAT(32H           SPACING BETWEEN CUTS =,F5.3,6H IN. =,
160 +F5.3,4H CM.)
165 70 FORMAT(56H      CUT NUMBER          AVERAGE SPECIFIC ENERGY
170 +PER CUT)
175 75 FORMAT(57H                          FT.LB./CU.IN.
180 +JOULES/CU.CM.)
185 80 FORMAT(I10,F24.2,F20.2)
190 90 FORMAT(14H      AVERAGE,2F20.2)
195 40 FORMAT(56HCOMB.    TEST    SAMPLE    NUMBER            SP
200  +ECIFIC ENERGY)
205 45 FORMAT(68H  #        #        #      OF CUTS   FT.LB./CU.
210 +IN.        JOULES/CU.CM.)
215 50 FORMAT(I4,I9,I7,I8,F17.2,F20.2)
220 60 FORMAT(I20,I8,F17.2,F20.2)
225 95 READ(1)J
230 X1=0
235 IF(J)300,300,100
240 100 READ(1)P,F,S,D,Q
245 P1=.68966*P
250 F1=.04233333*F
255 S1=2.54*S
260 D1=D*25.4
265 Q1=2.54*Q
270 PRINT10,J
275 PRINT
280 PRINT
285 PRINT15,P,P1
290 PRINT20,F,F1
295 PRINT 25,S,S1
300 PRINT 30,D,D1
305 PRINT
310 PRINT 35,Q,Q1
315 PRINT
320 PRINT
325 PRINT 40
330 PRINT 45
335 PRINT
340 120 READ(1)C
345 IF(C)180,180,125
```

KERF   CONTINUED

```
350 125 READ(1)T,R,L,V,X
355 IF(X-X1)135,135,130
360 130 Y=1
365 135 SE(X,Y)=7059.173*D**2*P*SQRT(P)*X*L/F/V
370 SM(X,Y)=.082733*SE(X,Y)
375 IF(X-X1)150,150,140
380 140 PRINT 50,C,T,R,X,SE(X,Y),SM(X,Y)
385 X1=X
390 GOTO160
395 150 IF(R-R1)160,160,155
400 155 PRINT 60,R,X,SE(X,Y),SM(X,Y)
405 160 A(X)=Y
410 Y=Y+1
415 GOTO120
420 180 PRINT
425 PRINT
430 DO230 X=1,3
435 SUM(X)=0
440 Z=A(X)
445 DO 220Y=1,Z
450 220 SUM(X)=SE(X,Y)+SUM(X)
455 230 SUM(X)=SUM(X)/A(X)
460 X=1
465 PRINT 70
470 DIF(X)=SUM(X)
475 DIFM(X)=.082733*SUM(X)
480 PRINT 75
485 PRINT
490 PRINT 80,X,DIF(X),DIFM(X)
495 DO250X=2,3
500 DIF(X)=X/SUM(X)-(X-1)/SUM(X-1)
505 DIF(X)=1/DIF(X)
510 DIFM(X)=.082733*DIF(X)
515 PRINT
520 250 PRINT 80,X,DIF(X),DIFM(X)
525 PRINT
530 DIFA=(DIF(2)+DIF(3))/2
535 DIFB=(DIFM(2)+DIFM(3))/2
540 PRINT 90,DIFA,DIFB
545 PRINT
550 PRINT
555 PRINT
560 PRINT
565 GOTO95
570 300 END
```

```
R0CKS1


100 $DATA'2↑4 FACT0RIAL FRAGMENTATI0N TEST INPUT DATA'
105 $DATA'CHARC0AL GRANITE'
110 1
115 1,25,12,-1,-1,-1,-1,8.0,1.1,1,25,12,-1,-1,-1,-1,8.0,1.0
120 2,48,2,1,-1,-1,-1,8.1,1.1,2,48,2,1,-1,-1,-1,8.1,1.2
125 3,38,19,-1,1,-1,-1,8.0,1.2,3,38,19,-1,1,-1,-1,8.,.8
130 4,28,5,1,1,-1,-1,8.05,.95,4,28,5,1,1,-1,-1,8.05,1.0
135 5,15,13,-1,-1,1,-1,8.0,1.1,5,15,13,-1,-1,1,-1,8.0,1.4
140 6,46,15,1,-1,1,-1,7.95,1.5,6,46,15,1,-1,1,-1,7.95,1.3
145 7,17,1,-1,1,1,-1,7.95,1.,7,17,1,-1,1,1,-1,7.95,.9
150 8,32,14,1,1,1,-1,8.0,.4,8,32,14,1,1,1,-1,8.,.3
155 9,77,20,-1,-1,-1,1,8.,2.5,9,77,20,-1,-1,-1,1,8.,2.3
160 10,104,16,1,-1,-1,1,7.9,1.2
165 10,104,16,1,-1,-1,1,7.9,1.0,11,102,6,-1,1,-1,1,7.9,.6
170 11,102,6,-1,1,-1,1,7.9,.8,12,111,3,1,1,-1,1,8.,1.,12
175 102,3,1,1,-1,1,8.,1.1,13,70,7,-1,-1,1,1,7.95,1.9
180 13,70,7,-1,-1,1,1,7.95,1.9,14,86,9,1,-1,1,1,8.06,1.5
185 14,86,9,1,-1,1,1,8.06,1.6,15,87,11,-1,1,1,1,7.95,.8
190 15,87,11,-1,1,1,1,7.95,1.,16,105,8,1,1,1,1,8.,1.1
195 16,105,8,1,1,1,1,8.,1.
200 0
205 $DATA'WESTERLY GRANITE'
210 2
215 17,18,2,-1,-1,-1,-1,7.85,1.,17,18,2,-1,-1,-1,-1,7.85,1.
220 18,7,5,1,-1,-1,-1,7.9,1.4,19,8,4,-1,1,-1,-1,8.1,.6
225 20,51,3,1,1,-1,-1,8.,1.,20,51,3,1,1,-1,-1,8.,1.1
230 21,3,1,-1,-1,1,-1,7.9,.8,22,5,3,1,-1,1,-1,8.,1.4
235 22,5,3,1,-1,1,-1,8.,1.4,23,23,5,-1,1,1,-1,7.95,.9
240 23,23,5,-1,1,1,-1,7.95,.6,24,20,1,1,1,1,-1,6.,.8
245 24,20,1,1,1,1,-1,6.,.65,25,96,4,-1,-1,-1,1,8.1,.8
250 25,96,4,-1,-1,-1,1,8.1,1.1,26,92,2,1,-1,-1,1,7.85,2.0
255 26,92,2,1,-1,-1,1,7.85,1.9,27,124,1,-1,1,-1,1,8.,.5
260 27,124,1,-1,1,-1,1,8.,.5,28,72,2,1,1,-1,1,7.95,3.2
265 28,72,2,1,1,-1,1,7.95,3.1,29,123,3,-1,-1,1,1,8.,.95
270 29,123,3,-1,-1,1,1,8.,.8,30,91,4,1,-1,1,1,8.1,1.5
275 30,91,4,1,-1,1,1,8.1,1.5,31,113,1,-1,1,1,1,7.9,.8
280 31,113,1,-1,1,1,1,7.9,.5,32,121,5,1,1,1,1,8.,1.
285 32,121,5,1,1,1,1,8.,1.1
290 0
295 $DATA'BARRE GRANITE'
300 3
305  33,11,7,-1,-1,-1,-1,8.15,.8,33,11,7,-1,-1,-1,-1,8.15,.8
310 +34,13,17,1,-1,-1,-1,8.2,1.3,34,13,17,1,-1,-1,-1,8.2,1.3
315 +35,22,11,-1,1,-1,-1,8.2,.9,35,22,11,-1,1,-1,-1,8.2,1.0
320 +36,43,10,1,1,-1,-1,8.2,1.35,36,43,10,1,1,-1,-1,8.2,1.0
325 +37,50,19,-1,-1,1,-1,8.2,.8,37,50,19,-1,-1,1,-1,8.2,.9
330 +38,31,1,1,-1,1,-1,8.2,1.2,38,31,1,1,-1,1,-1,8.2,1.2
335 +39,19,3,-1,1,1,-1,8.15,.3,39,19,3,-1,1,1,-1,8.15,.5
340 +40,37,2,1,1,1,-1,8.1,1.0,40,37,2,1,1,1,-1,8.1,.95
345 +41,81,6,-1,-1,-1,1,7.95,2.6,41,81,6,-1,-1,-1,1,7.95,2.7
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ROCKS1 CONTINUED

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350 +42,76,8,1,-1,-1,1,8.0,4.4,42,76,8,1,-1,-1,1,8.0,4.4
355 +43,89,16,-1,1,-1,1,7.9,.7
360 +43,89,16,-1,1,-1,1,7.9,.7
365 +44,68,20,1,1,-1,1,7.5,3.0,44,68,20,1,1,-1,1,7.5,2.8
370 +45,82,18,-1,-1,1,1,8.0,2.3,45,82,18,-1,-1,1,1,8.0,2.0
375 +46,85,4,1,-1,1,1,8.0,1.4,46,85,4,1,-1,1,1,8.0,1.4
380 +47,74,5,-1,1,1,1,8.0,1.6,47,74,5,-1,1,1,1,8.0,1.8
385 +48,100,14,1,1,1,1,8.0,1.0,48,100,14,1,1,1,1,8.0,1.2
390 0
395 $DATA'DRESSER BASALT'
400 4
405 49,54,14,-1,-1,-1,-1,6.0,2.0
410 50,34,19,1,-1,-1,-1,6.0,6.1,50,34,19,1,-1,-1,-1,6.0,3.6
415 51,29,8,-1,1,-1,-1,6.0,1.5,51,29,8,-1,1,-1,-1,6.0,.8
420 52,41,1,1,1,-1,-1,5.0,8.0,53,57,3,-1,-1,1,-1,6.0,1.4
425 54,58,12,1,-1,1,-1,6.0,5.8,55,9,20,-1,1,1,-1,6.05,1.1
430 55,9,20,-1,1,1,-1,6.05,1.0,56,35,5,1,1,1,-1,6.15,1.4
435 57,94,13,-1,-1,-1,1,6.1,1.6,57,94,13,-1,-1,-1,1,6.1,1.5
440 58,75,6,1,-1,-1,1,4.125,5.0,59,109,2,-1,1,-1,1,7.95,2.0
445 59,109,2,-1,1,-1,1,7.95,2.7,60,106,10,1,1,-1,1,5.3,4.6
450 60,106,10,1,1,-1,1,5.7,3.4,61,116,15,-1,-1,1,1,5.5,1.22
455 61,116,15,-1,-1,1,1,5.6,1.3,62,90,16,1,-1,1,1,4.55,.7
460 62,90,16,1,-1,1,1,4.5,.6,63,117,7,-1,1,1,1,5.75,1.8
465 63,117,7,-1,1,1,1,5.75,1.5,64,67,17,1,1,1,1,5.25,9.8
470 0
475 $DATA'SIOUX QUARTZITE'
480 5
485 65,24,10,-1,-1,-1,-1,9.6,.9,65,24,10,-1,-1,-1,-1,9.6,1.1
490 66,36,2,1,-1,-1,-1,10.0,1.8,66,36,2,1,-1,-1,-1,10.0,1.5
495 67,21,20,-1,1,-1,-1,9.5,1.2,67,21,20,-1,1,-1,-1,9.6,1.1
500 68,42,3,1,1,-1,-1,9.25,1.2,68,42,3,1,1,-1,-1,10.2,1.1
505 69,60,8,-1,-1,1,-1,7.9,.7,69,60,8,-1,-1,1,-1,7.9,.8
510 70,26,18,1,-1,1,-1,9.5,1.1,70,26,18,1,-1,1,-1,9.5,1.25
515 71,4,4,-1,1,1,-1,10.0,.7,71,4,4,-1,1,1,-1,11.25,.8
520 72,16,7,1,1,1,-1,11.8,1.0,72,16,7,1,1,1,-1,11.8,.8
525 73,65,5,-1,-1,-1,1,10.0,2.8,73,65,5,-1,-1,-1,1,10.0,2.8
530 74,88,13,1,-1,-1,1,10.0,1.5,74,88,13,1,-1,-1,1,10.0,1.6
535 75,73,1,-1,1,-1,1,7.7,1.6,75,73,1,-1,1,-1,1,9.7,1.7
540 76,126,12,1,1,-1,1,9.2,1.3,76,126,12,1,1,-1,1,9.2,1.
545 77,83,6,-1,-1,1,1,8.4,1.8,77,83,6,-1.-1,1,1,8.9,2.3
550 78,71,17,1,-1,1,1,9.0,3.25,78,71,17,1,-1,1,1,9.0,3.25
555 79,93,11,-1,1,1,1,10.8,.8,79,93,11,-1,1,1,1,10.8,.9
560 80,98,16,1,1,1,1,10.8,1.0,80,98,16,1,1,1,1,10.8,1.0
565 0
570 $DATA'BEREA SANDSTONE'
575 6
580 81,6,9,-1,-1,-1,-1,7.9,2.6,81,6,9,-1,-1,-1,-1,7.9,2.9
585 82,53,13,1,-1,-1,-1,8.,7.8,82,53,13,1,-1,-1,-1,8.,7.6
590 83,55,4,-1,1,-1,-1,8.,4.,83,55,4,-1,1,-1,-1,8.,4.
595 84,14,17,1,1,-1,-1,8.,5.1,84,14,17,1,1,-1,-1,8.,5.3
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ROCKS1 CONTINUED

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600 85,1,18,-1,-1,1,-1,8.,3.2,85,1,18,-1,-1,1,-1,8.,3.8
605 86,2,14,1,-1,1,-1,8.,7.5,86,2,14,1,-1,1,-1,8.,7.8
610 87,10,2,-1,1,1,-1,8.05,2.5,87,10,2,-1,1,1,-1,8.05,2.7
615 88,61,1,1,1,1,-1,8.05,4.7,88,61,1,1,1,1,-1,8.05,4.5
620 89,110,11,-1,-1,-1,1,8.,3.2,89,110,11,-1,-1,-1,1,8.,3.6
625 90,118,10,1,-1,-1,1,8.,7.2,90,118,10,1,-1,-1,1,8.,6.4
630 91,103,5,-1,1,-1,1,8.,2.4,91,103,5,-1,1,-1,1,8.,2.6
635 92,80,12,1,1,-1,1,8.05,20.7,92,80,12,1,1,-1,1,8.05,18.1
640 93,107,16,-1,-1,1,1,8.,3.4,93,107,16,-1,-1,1,1,8.,3.2
645 94,97,15,1,-1,1,1,7.95,5.5,94,97,15,1,-1,1,1,7.95,5.4
650 95,99,3,-1,1,1,1,8.,2.5,95,99,3,-1,1,1,1,8.,2.75
655 96,84,6,1,1,1,1,8.,17.9,96,84,6,1,1,1,1,8.,15.6
660 0
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ROCKS2

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100 $DATA'2↑4 FACTORIAL FRAGMENTATION TEST INPUT DATA'
105 $DATA'TENNESSEE MARBLE'
110 7
115 97,59,6,-1,-1,-1,-1,8.0,1.3,97,59,6,-1,-1,-1,-1,8.0,1.2
120 98,47,20,1,-1,-1,-1,8.0,1.3,98,47,20,1,-1,-1,-1,8.0,1.3
125 99,64,11,-1,1,-1,-1,8.0,.85,99,64,11,-1,1,-1,-1,8.0,.85
130 100,12,1,1,1,-1,-1,8.05,.8,100,12,1,1,1,-1,-1,8.05,.7
135 101,63,4,-1,-1,1,-1,8.0,1.9,101,63,4,-1,-1,1,-1,8.0,1.3
140 102,49,7,1,-1,1,-1,8.0,.8,102,49,7,1,-1,1,-1,8.0,1.0
145 103,39,3,-1,1,1,-1,8.1,.8,103,39,3,-1,1,1,-1,8.1,1.6
150 104,62,18,1,1,1,-1,8.1,.9,104,62,18,1,1,1,-1,8.1,.7
155 105,108,13,-1,-1,-1,1,8.0,.5,105,108,13,-1,-1,-1,1,8.0,1.0
160 106,79,19,1,-1,-1,1,8.1,3.1,106,79,19,1,-1,-1,1,8.1,2.9
165 107,66,9,-1,1,-1,1,8.1,1.3,107,66,9,-1,1,-1,1,8.1,1.8
170 108,125,8,1,1,-1,1,8.0,.9,108,125,8,1,1,-1,1,8.0,.9
175 109,112,10,-1,-1,1,1,8.0,1.6,109,112,10,-1,-1,1,1,8.0,2.0
180 110,119,17,1,-1,1,1,7.9,1.2,110,119,17,1,-1,1,1,7.9,1.1
185 111,122,2,-1,1,1,1,7.95,1.5,111,122,2,-1,1,1,1,7.95,1.8
190 112,127,15,1,1,1,1,8.1,.7,112,127,15,1,1,1,1,8.1,.7
195 0
200 $DATA'SALEM LIMESTONE'
205 8
210 113,27,13,-1,-1,-1,-1,8.1,2.5,113,27,13,-1,-1,-1,-1,8.1,2.2
215 114,30,3,1,-1,-1,-1,8.1,16.8,114,30,3,1,-1,-1,-1,8.1,8.5
220 115,44,10,-1,1,-1,-1,8.,1.,115,44,10,-1,1,-1,-1,8.,1.1
225 116,33,9,1,1,-1,-1,8.1,2.7,116,33,9,1,1,-1,-1,8.1,3.2
230 117,52,4,-1,-1,1,-1,8.,1.,117,52,4,-1,-1,1,-1,8.,.9
235 118,40,11,1,-1,1,-1,8.,2.4,118,40,11,1,-1,1,-1,8.,2.5
240 119,45,1,-1,1,1,-1,8.,1.1,119,45,1,-1,1,1,-1,8.,1.3
245 120,56,15,1,1,1,-1,8.05,1.6,120,56,15,1,1,1,-1,8.05,1.4
250 121,69,14,-1,-1,-1,1,8.1,18.,121,69,14,-1,-1,-1,1,8.1,17.4
255 122,95,17,1,-1,-1,1,7.95,1.2,122,95,17,1,-1,-1,1,7.95,2.9
260 123,101,18,-1,1,-1,1,8.1,1.8,123,101,18,-1,1,-1,1,8.1,2.1
265 124,120,5,1,1,-1,1,8.,3.1,124,120,5,1,1,-1,1,8.,3.
270 125,115,19,-1,-1,1,1,8.1,1.8,125,115,19,-1,-1,1,1,8.1,1.75
275 126,114,2,1,-1,1,1,8.,5.1,126,114,2,1,-1,1,1,8.,5.9
280 127,128,6,-1,1,1,1,8.09,1.5,127,128,6,-1,1,1,1,8.09,1.6
285 128,78,12,1,1,1,1,8.05,12.1,128,78,12,1,1,1,1,8.05,13.7
290 0
295 -1
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RØCKS3

100 $DATA'3*2 FACTØRIAL FRAGMENTATIØN TEST INPUT DATA'
105 $DATA'CHARCØAL GRANITE'
110 1
115 140,38,19,-1,1,-1,-1,8.,1.2,140,38,19,-1,1,-1,-1,8.,.8
120 141,144,17,0,1,-1,-1,8.,.5,141,144,17,0,1,-1,-1,8.,.8
125 142,28,5,1,1,-1,-1,8.05,.95,142,28,5,1,1,-1,-1,8.05,1.
130 143,150,10,-1,1,-1,0,8.1,1.5,143,150,10,-1,1,-1,0,8.1,1.6
135 144,149,18,0,1,-1,0,8.,1.5,144,149,18,0,1,-1,0,8.,1.65
140 145,152,4,1,1,-1,0,8.1,2.3,145,152,4,1,1,-1,0,8.1,2.
145 146,102,6,-1,1,-1,1,7.9,.6,146,102,6,-1,1,-1,1,7.9,.8
150 147,166,13,0,1,-1,1,8.1,2.3,147,166,13,0,1,-1,1,8.1,2.
155 148,111,3,1,1,-1,1,8.,1.,148,111,3,1,1,-1,1,8.,1.1
160 0
165 $DATA'WESTERLY GRANITE'
170 2
175 149,7,5,1,-1,-1,-1,7.9,1.4
180 150,141,2,1,0,-1,-1,7.9,1.2,150,141,2,1,0,-1,-1,7.9,1.
185 151,51,3,1,1,-1,-1,8.,1..151,51,3,1,1,-1,-1,8.,1.1
190 152,151,3,1,-1,-1,0,8.06,2.9,152,151,3,1,-1,-1,0,8.06,2.7
195 153,161,1,1,0,-1,0,6.1,2.6,153,161,1,1,0,-1,0,6.1,2.4
200 154,162,3,1,1,-1,0,8.06,4.5,154,162,3,1,1,-1,0,8.06,4.6
205 155,92,2,1,-1,-1,1,7.85,2.,155,92,2,1,-1,-1,1,7.85,1.9
210 156,165,5,1,0,-1,1,6.1,3.1,156,165,5,1,0,-1,1,6.1,2.6
215 157,72,2,1,1,-1,1,7.95,3.2,157,72,2,1,1,-1,1,7.95,3.1
220 0
225 $DATA'DRESSER BASALT'
230 4
235 158,34,19,1,-1,-1,-1,6.,6.1,158,34,19,1,-1,-1,-1,6.,3.6
240 159,143,18,1,0,-1,-1,4.,3.,159,143,18,1,0,-1,-1,4.6,2.9
245 160,41,1,1,1,-1,-1,5.,8.
250 161,153,4,1,-1,-1,0,4.7,6.2,161,153,4,1,-1,-1,0,4.1,2.8
255 162,148,9,1,0,-1,0,4.,11.6
260 163,156,20,1,1,-1,0,6.15,4.5,163,156,20,1,1,-1,0,6.15,5.9
265 164,75,6,1,-1,-1,1,4.125,5.
270 165,167,19,1,0,-1,1,6.,10.7,165,167,19,1,0,-1,1,5.9,6.7
275 166,106,10,1,1,-1,1,5.3,4.6,166,106,10,1,1,-1,1,5.7,3.4
280 0
285 $DATA'BEREA SANDSTØNE'
290 6
295 167,53,13,1,-1,-1,-1,8.,7.8,167,53,13,1,-1,-1,-1,8.,7.6
300 168,140,8,1,0,-1,-1,8.,4.5,168,140,8,1,0,-1,-1,8.,4.
305 169,14,17,1,1,-1,-1,8.,5.1,169,14,17,1,1,-1,-1,8.,5.3
310 170,163,7,1,-1,-1,0,8.06,16.6,170,163,7,1,-1,-1,0,8.06,19.
315 171,158,20,1,0,-1,0,7.95,17.1,171,158,20,1,0,-1,0,7.95,17.5
320 172,159,19,1,1,-1,0,7.95,12.1,172,159,19,1,1,-1,0,7.95,10.4
325 173,118,10,1,-1,-1,1,8.,7.2,173,118,10,1,-1,-1,1,8.,6.4
330 174,168,18,1,0,-1,1,8.,20.9,174,168,18,1,0,-1,1,8.,18.9
335 175,80,12,1,1,-1,1,8.05,20.7,175,80,12,1,1,-1,1,8.05,18.1
340 0
345 $DATA'TENNESSEE MARBLE'
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RØCKS3 CØNTINUED

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350 7
355 176,47,20,1,-1,-1,-1,8.,1.3,176,47,20,1,-1,-1,-1,8.,1.3
360 177,142,5,1,0,-1,-1,7.9,.7,177,142,5,1,0,-1,-1,7.9,1.2
365 178,12,1,1,1,-1,-1,8.05,.8,178,12,1,1,1,-1,-1,8.05,.7
370 179,155,12,1,-1,-1,0,7.6,2.3,179,155,12,1,-1,-1,0,8.,2.7
375 180,147,16,1,0,-1,0,8.,2.1,180,147,16,1,0,-1,0,8.,1.7
380 181,146,14,1,1,-1,0,6.25,1.8,181,146,14,1,1,-1,0,8.1,2.
385 182,79,19,1,-1,-1,1,8.1,3.1,182,79,19,1,-1,-1,1,8.1,2.9
390 183,169,1,1,0,-1,1,8.,2.,183,169,1,1,0,-1,1,8.,2.2
395 184,125,8,1,1,-1,1,8.,.9,184,125,8,1,1,-1,1,8.,.9
400 0
405 $DATA'SALEM LIMESTØNE'
410 8
415 185,30,3,1,-1,-1,-1,8.1,16.8,185,30,3,1,-1,-1,-1,8.1,8.5
420 186,145,16,1,0,-1,-1,8.1,4.5,186,145,16,1,0,-1,-1,8.1,3.7
425 187,33,9,1,1,-1,-1,8.1,2.7,187,33,9,1,1,-1,-1,8.1,3.2
430 188,154,7,1,-1,-1,0,8.1,13.,188,154,7,1,-1,-1,0,8.1,11.
435 189,160,13,1,0,-1,0,8.,9.6,189,160,13,1,0,-1,0,8.,9.5
440 190,157,8,1,1,-1,0,8.,5.4,190,157,8,1,1,-1,0,8.,4.7
445 191,95,17,1,-1,-1,1,7.95,1.2,191,95,17,1,-1,-1,1,7.95,2.9
450 192,164,9,1,0,-1,1,8.,11.1,192,164,9,1,0,-1,1,8.,10.6
455 192,164,9,1,0,-1,1,8.,10.,192,164,9,1,0,-1,1,8.,9.8
460 192,164,9,1,0,-1,1,6.,6.9,192,164,9,1,0,-1,1,6.,7.5
465 193,120,5,1,1,-1,1,8.,3.1,193,120,5,1,1,-1,1,8.,3.
470 0
475 -1
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R0CKS4


100 $DATA'3↑4 FACT0RIAL FRAGMENTATI0N TEST INPUT DATA'
105 $DATA'BARRE GRANITE'
110 3
115 201,11,7,-1,-1,-1,-1,8.15,.8,201,11,7,-1,-1,-1,-1,8.15,.8
120 202,231,8,0,-1,-1,-1,7.9,1.,202,231,8,0,-1,-1,-1,7.9,1.
125 203,13,17,1,-1,-1,-1,8.2,1.3,203,13,17,1,-1,-1,-1,8.2,1.3
130 204,235,4,-1,0,-1,-1,8.,.5,204,235,4,-1,0,-1,-1,8.,.5
135 205,212,7,0,0,-1,-1,8.,.8,205,212,7,0,0,-1,-1,8.,.8
140 206,229,5,1,0,-1,-1,8.,1.,206,229,5,1,0,-1,-1,8.,.9
145 207,22,11,-1,1,-1,-1,8.2,.9,207,22,11,-1,1,-1,-1,8.2,1.
150 208,224,19,0,1,-1,-1,8.1,.85,208,224,19,0,1,-1,-1,7.5,.6
155 209,43,10,1,1,-1,-1,8.2,1.35,209,43,10,1,1,-1,-1,8.2,1.
160 210,233,18,-1,-1,0,-1,8.,.75,210,233,18,-1,-1,0,-1,8.,.8
165 211,216,11,0,-1,0,-1,8.2,.9,211,216,11,0,-1,0,-1,8.2,1.
170 212,236,16,1,-1,0,-1,7.8,1.,212,236,16,1,-1,0,-1,8.,1.1
175 213,221,2,-1,0,0,-1,8.2,.6,213,221,2,-1,0,0,-1,7.5,.4
180 214,223,10,0,0,0,-1,8.2,.8,214,223,10,0,0,0,-1,8.2,.7
185 215,210,12,1,0,0,-1,5.5,.7,215,210,12,1,0,0,-1,5.5,.4
190 216,225,20,-1,1,0,-1,7.9,.6,216,225,20,-1,1,0,-1,7.9,.5
195 217,214,17,0,1,0,-1,8.2,.5,217,214,17,0,1,0,-1,8.2,.75
200 218,209,13,1,1,0,-1,7.9,.7,218,209,13,1,1,0,-1,7.9,.8
205 219,50,19,-1,-1,1,-1,8.2,.8,219,50,19,-1,-1,1,-1,8.2,.9
210 220,232,6,0,-1,1,-1,7.9,.7,220,232,6,0,-1,1,-1,7.9,1.
215 221,31,1,1,-1,1,-1,8.2,1.2,221,31,1,1,-1,1,-1,8.2,1.2
220 222,208,15,-1,0,1,-1,8.,.5,222,208,15,-1,0,1,-1,8.,.8
225 223,217,1,0,0,1,-1,6.8,.5,223,217,1,0,0,1,-1,6.25,.4
230 224,215,3,1,0,1,-1,8.1,.8,224,215,3,1,0,1,-1,8.1,.9
235 225,19,3,-1,1,1,-1,8.15,.3,225,19,3,-1,1,1,-1,8.15,.5
240 226,205,9,0,1,1,-1,7.95,.5,226,205,9,0,1,1,-1,7.95,.5
245 227,37,2,1,1,1,-1,8.1,1.,227,37,2,1,1,1,-1,8.1,.95
250 0
255 3
260 228,290,12,-1,-1,-1,0,5.7,1.8,228,290,12,-1,-1,-1,0,5.7,1.5
265 229,278,16,0,-1,-1,0,6.1,2.0,229,278,16,0,-1,-1,0,6.1,2.1
270 230,250,17,1,-1,-1,0,6.3,2.4,230,250,17,1,-1,-1,0,6.,2.6
275 231,247,12,-1,0,-1,0,6.2,1.4,231,247,12,-1,0,-1,0,6.2,1.
280 232,241,9,0,0,-1,0,6.,2.3,232,241,9,0,0,-1,0,6.,1.8
285 233,273,6,1,0,-1,0,6.1,2.2,233,273,6,1,0,-1,0,6.1,2.3
290 234,245,13,-1,1,-1,0,6.1,1.,234,245,13,-1,1,-1,0,6.1,1.
295 235,279,14,0,1,-1,0,6.,1.4,235,279,14,0,1,-1,0,6.,1.4
300 236,267,20,1,1,-1,0,6.2,1.6,236,267,20,1,1,-1,0,6.2,1.8
305,237,261,2,-1,-1,0,0,6.2,1.3,237,261,2,-1,-1,0,0,6.2,1.35
310 238,266,19,0,-1,0,0,5.4,1.7,238,266,19,0,-1,0,0,5.5,1.8
315 239,239,14,1,-1,0,0,7.9,3.3,239,239,14,1,-1,0,0,7.9,3.
320 240,272,8,-1,0,0,0,6.1,1.2,240,272,8,-1,0,0,0,6.1,1.
325 241,291,7,0,0,0,0,6.3,1.6,241,291,7,0,0,0,0,6.3,1.5
330 242,260,1,1,0,0,0,6.2,1.9,242,260,1,1,0,0,0,5.5,1.5
335 243,252,3,-1,1,0,0,6.3,1.9,243,252,3,-1,1,0,0,6.3,1.9
340 244,277,4,0,1,0,0,6.1,1.3,244,277,4,0,1,0,0,6.1,1.1
345 245,285,15,1,1,0,0,6.1,1.4,245,285,15,1,1,0,0,6.1,1.7
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ROCKS4 CONTINUED

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350 246,243,15,-1,-1,1,0,6.1,1.1,246,243,15,-1,-1,1,0,6.1,.9
355 247,248,7,0,-1,1,0,6.3,2.1,247,247,7,0,-1,1,0,6.3,2.
360 248,274,18,1,-1,1,0,6.1,2.6,248,274,18,1,-1,1,0,6.1,2.7
365 249,283,9,-1,0,1,0,6.,.8,249,283,9,-1,0,1,0,6.,.9
370 250,286,13,0,0,1,0,6.1,1.4,250,286,13,0,0,1,0,6.1,1.3
375 251,292,17,1,0,1,0,6.3,1.5,251,292,17,1,0,1,0,6.3,1.6
380 252,263,10,-1,1,1,0,6.2,.95,252,263,10,-1,1,1,0,6.2,.8
385 253,268,5,0,1,1,0,6.2,1.1,253,268,5,0,1,1,0,6.2,1.3
390 254,259,11,1,1,1,0,6.2,1.6,254,259,11,1,1,1,0,6.2,1.5
395 0
400 3
405 255,81,6,-1,-1,-1,1,7.95,2.6,255,81,6,-1,-1,-1,1,7.95,2.7
410 256,304,8,0,-1,-1,1,6.1,2.,256,304,8,0,-1,-1,1,6.1,2.1
415 257,76,8,1,-1,-1,1,8.,4.4,257,76,8,1,-1,-1,1,8.,4.4
420 258,315,4,-1,0,-1,1,6.1,1.1,258,315,4,-1,0,-1,1,6.1,1.
425 259,328,7,0,0,-1,1,6.2,1.5,259,328,7,0,0,-1,1,6.2,1.6
430 260,299,10,1,0,-1,1,6.2,2.3,260,299,10,1,0,-1,1,6.2,2.3
435 261,89,16,-1,1,-1,1,7.9,.7,261,89,16,-1,1,-1,1,7.9,.7
440 262,321,9,0,1,-1,1,6.,1.5,262,321,9,0,1,-1,1,6.,1.6
445 263,68,20,1,1,-1,1,7.5,3.,263,68,20,1,1,-1,1,7.5,2.8
450 264,298,2,-1,-1,0,1,6.1,1.5,264,298,2,-1,-1,0,1,6.1,1.5
455 265,316,16,0,-1,0,1,6.1,1.5,265,316,16,0,-1,0,1,6.1,1.3
460 266,302,5,1,-1,0,1,6.2,2.9,266,302,5,1,-1,0,1,6.2,2.8
465 267,313,18,-1,0,0,1,6.1,.9,267,313,18,-1,0,0,1,6.1,1.
470 268,324,12,0,0,0,1,6.2,1.8,268,324,12,0,0,0,1,6.2,1.7
475 269,322,15,1,0,0,1,6.1,2.5,269,322,15,1,0,0,1,6.1,2.1
480 270,319,14,-1,1,0,1,6.,1.3,270,319,14,-1,1,0,1,6.,1.2
485 271,300,19,0,1,0,1,6.2,1.5,271,300,19,0,1,0,1,6.2,1.5
490 272,323,13,1,1,0,1,6.1,1.9,272,323,13,1,1,0,1,6.1,1.6
495 273,82,18,-1,-1,1,1,8.,2.3,273,82,18,-1,-1,1,1,8.,2.
500 274,301,20,0,-1,1,1,6.2,2.3,274,301,20,0,-1,1,1,6.2,2.3
505 275,85,4,1,-1,1,1,8.,1.4,275,85,4,1,-1,1,1,8.,1.4
510 276,295,3,-1,0,1,1,6.2,1.8,276,295,3,-1,0,1,1,6.2,1.5
515 277,296,11,0,0,1,1,6.2,1.7,277,296,11,0,0,1,1,6.2,1.6
520 278,311,6,1,0,1,1,6.1,2.2,278,311,6,1,0,1,1,6.1,2.3
525 279,74,5,-1,1,1,1,8.,1.6,279,74,5,-1,1,1,1,8.,1.8
530 280,297,1,0,1,1,1,6.2,1.4,280,297,1,0,1,1,1,6.2,1.6
535 281,100,14,1,1,1,1,8.,1.,281,100,14,1,1,1,1,8.,1.2
540 0
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ROCKS5


100 $DATA'3↑4 FACTORIAL FRAGMENTATION TEST INPUT DATA'
105 $DATA'SIOUX QUARTZITE'
110 5
115 282,24,10,-1,-1,-1,-1,9.6,.9,282,24,10,-1,-1,-1,-1,9.6,1.1
120 283,237,15,0,-1,-1,-1,7.3,.7,283,237,15,0,-1,-1,-1,7.3,.7
125 284,36,2,1,-1,-1,-1,10.,1.8,284,36,2,1,-1,-1,-1,10.,1.5
130 285,202,17,-1,0,-1,-1,7.6,.6,285,202,17,-1,0,-1,-1,7.6,.6
135 286,204,9,0,0,-1,-1,8.4,.7,286,204,9,0,0,-1,-1,8.4,.85
140 287,211,21,1,0,-1,-1,7.7,.9,287,211,21,1,0,-1,-1,7.7,.95
145 288,21,20,-1,1,-1,-1,9.5,1.2,288,21,20,-1,1,-1,-1,9.6,1.1
150 289,206,19,0,1,-1,-1,8.2,.5,289,206,19,0,1,-1,-1,8.2,.6
155 290,42,3,1,1,-1,-1,9.25,1.2,290,42,3,1,1,-1,-1,10.2,1.1
160 291,207,15,-1,-1,0,-1,7.7,.6,291,207,15,-1,-1,0,-1,7.7,.7
165 292,203,14,0,-1,0,-1,8.1,.8,292,203,14,0,-1,0,-1,8.2,.75
170 293,226,5,1,-1,0,-1,7.2,.8,293,226,5,1,-1,0,-1,7.1,.7
175 294,218,23,-1,0,0,-1,7.9,.5,294,218,23,-1,0,0,-1,8.1,.5
180 295,234,19,0,0,0,-1,8.2,.8,295,234,19,0,0,0,-1,8.2,.8
185 296,201,5,1,0,0,-1,7.4,.6,296,201,5,1,0,0,-1,7.5,.7
190 297,219,22,-1,1,0,-1,8.1,.4,297,219,22,-1,1,0,-1,8.2,.5
195 298,230,9,0,1,0,-1,8.4,.6,298,230,9,0,1,0,-1,8.4,.6
200 299,238,21,1,1,0,-1,7.6,.7,299,238,21,1,1,0,-1,7.6,.7
205 300,60,8,-1,-1,1,-1,7.9,.7,300,60,8,-1,-1,1,-1,7.9,.8
210 301,220,26,0,-1,1,-1,8.,.8,301,220,26,0,-1,1,-1,8.,.65
215 302,26,18,1,-1,1,-1,9.5,1.1,302,26,18,1,-1,1,-1,9.5,1.25
220 303,227,17,-1,0,1,-1,7.8,.7,303,227,17,-1,0,1,-1,7.8,.7
225 304,222,24,0,0,1,-1,7.85,.4,304,222,24,0,0,1,-1,7.7,.5
230 305,228,14,1,0,1,-1,8.2,.8,305,228,14,1,0,1,-1,8.2,.65
235 306,4,4,-1,1,1,-1,10.,.7,306,4,4,-1,1,1,-1,11.25,.8
240 307,213,25,0,1,1,-1,7.9,.6,307,213,25,0,1,1,-1,7.9,.6
245 308,16,7,1,1,1,-1,11.8,1.,308,16,7,1,1,1,-1,11.8,.8
250 0
255 5
260 309,254,14,-1,-1,-1,0,7.9,1.5,309,254,14,-1,-1,-1,0,8.1,1.7
265 310,257,15,0,-1,-1,0,7.6,1.55,310,257,15,0,-1,-1,0,7.7,1.7
270 311,256,19,1,-1,-1,0,8.7,3.7,311,256,19,1,-1,-1,0,8.7,3.2
275 312,255,9,-1,0,-1,0,8.1,1.2,312,255,9,-1,0,-1,0,8.1,1.
280 313,265,22,0,0,-1,0,8.,1.5,313,265,22,0,0,-1,0,8.,1.7
285 314,275,17,1,0,-1,0,8.4,2.3,314,275,17,1,0,-1,0,8.4,2.2
290 315,258,21,-1,1,-1,0,8.,1.4,315,258,21,-1,1,-1,0,8.,1.2
295 316,281,19,0,1,-1,0,8.2,1.6,316,281,19,0,1,-1,1,8.2,2.1
300 317,249,24,1,1,-1,0,7.85,1.4,317,249,24,1,1,-1,0,5.2,1.
305 318,240,25,-1,-1,0,0,8.2,1.4,318,240,25,-1,-1,0,0,8.2,1.4
310 319,244,22,0,-1,0,0,7.2,2.,319,244,22,0,-1,0,0,7.9,2.7
315 320,276,14,1,-1,0,0,7.65,2.6,320,276,14,1,-1,0,0,7.75,2.5
320 321,288,23,-1,0,0,0,8.2,1.2,321,288,23,-1,0,0,0,8.2,1.1
325 322,251,5,0,0,0,0,7.,1.6,322,251,5,0,0,0,0,7.2,1.55
330 323,264,23,1,0,0,0,8.1,1.7,323,264,23,1,0,0,0,8.,1.6
335 324,269,26,-1,1,0,0,8.3,1.3,324,269,26,-1,1,0,0,8.2,1.4
340 325,271,5,0,1,0,0,7.2,1.35,325,271,5,0,1,0,0,7.,1.4
345 326,287,25,1,1,0,0,8.6,1.8,326,287,25,1,1,0,0,8.6,1.95
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ROCKS5 CONTINUED

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350 327,262,25,-1,-1,1,0,8.2,1.2,327,262,25,-1,-1,1,0,8.3,1.3
355 328,246,26,0,-1,1,0,8.3,1.9,328,246,26,0,-1,1,0,8.3,1.85
360 329,280,9,1,-1,1,0,8.2,2.3,329,280,9,1,-1,1,0,8.2,2.6
365 330,282,15,-1,0,1,0,7.5,.9,330,282,15,-1,0,1,0,7.5,.85
370 331,253,17,0,0,1,0,8.1,1.3,331,253,17,0,0,1,0,8.1,1.2
375 332,270,24,1,0,1,0,7.7,1.7,332,270,24,1,0,1,0,7.8,1.6
380 333,242,23,-1,1,1,0,8.2,1.,333,242,23,-1,1,1,0,8.3,.9
385 334,284,21,0,1,1,0,7.5,1.2,334,284,21,0,1,1,0,7.3,1.4
390 335,289,22,1,1,1,0,8.,1.6,335,289,22,1,1,1,0,8.,1.65
395 0
400 5
405 336,65,5,-1,-1,-1,1,20.,5.6
410 337,326,17,0,-1,-1,1,7.3,2.3,337,326,17,0,-1,-1,1,6.6,2.
415 338,88,13,1,-1,-1,1,10.,1.5,338,88,13,1,-1,-1,1,10.,1.6
420 339,312,25,-1,0,-1,1,8.7,1.4,339,312,25,-1,0,-1,1,5.,1.
425 340,294,24,0,0,-1,1,7.5,1.4,340,294,24,0,0,-1,1,7.3,1.4
430 341,317,22,1,0,-1,1,8.1,2.5,341,317,22,1,0,-1,1,8.1,2.6
435 342,73,1,-1,1,-1,1,7.7,1.6,342,73,1,-1,1,-1,1,9.7,1.7
440 343,320,24,0,1,-1,1,7.7,1.2,343,320,24,0,1,-1,1,7.5,1.3
445 344,126,12,1,-1,-1,1,9.2,1.3,344,126,12,1,-1,-1,1,9.2,1.
450 345,293,26,-1,-1,0,1,7.9,1.45,345,293,26,-1,-1,0,1,7.6,1.4
455 346,318,26,0,-1,0,1,8.1,2.4
460 346,318,26,0,-1,0,1,8.,2.4
465 347,307,9,1,-1,0,1,8.4,2.8,347,307,9,1,-1,0,1,8.4,2.7
470 348,306,14,-1,0,0,1,8.2,1.4,348,306,14,-1,0,0,1,8.2,1.5
475 349,327,14,0,0,0,1,7.85,1.5,349,327,14,0,0,0,1,7.85,1.35
480 350,310,21,1,0,0,1,7.1,2.,350,310,21,1,0,0,1,7.2,2.1
485 351,305,17,-1,1,0,1,8.1,1.3,351,305,17,-1,1,0,1,8.1,1.2
490 352,308,19,0,1,0,1,6.2,1.5,352,308,19,0,1,0,1,6.3,1.5
495 353,330,19,1,1,0,1,8.2,2.,353,330,19,1,1,0,1,8.2,2.
500 354,83,6,-1,-1,1,1,8.4,1.8,354,83,6,-1,-1,1,1,8.9,2.3
505 355,303,5,0,-1,1,1,6.9,1.8,355,303,5,0,-1,1,1,6.9,1.8
510 356,71,17,1,-1,1,1,18.,6.5
515 357,309,15,-1,0,1,1,7.8,1.,357,309,15,-1,0,1,1,7.6,1.
520 358,314,23,0,0,1,1,8.3,1.3,358,314,23,0,0,1,1,7.,1.
525 359,325,5,1,0,1,1,7.,1.5,359,325,5,1,0,1,1,7.,1.6
530 360,93,11,-1,1,1,1,10.8,.8,360,93,11,-1,1,1,1,10.8,.9
535 361,329,9,0,1,1,1,8.4,1.3,361,329,9,0,1,1,1,8.4,1.4
540 362,98,16,1,1,1,1,10.8,1.,362,98,16,1,1,1,1,10.8,1.
545 0
550 -1
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RØCKS6

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100 $DATA'ADDITIØNAL FRAGMENTATIØN TEST INPUT DATA'
105 $DATA'CHARCØAL GRANITE'
110 1
115 371,389,12,-1,450,1,-1,8.,.65,371,389,12,-1,450,1,-1,8.,.6
120 372,390,12,1,450,1,-1,7.2,.6,372,390,12,1,450,1,-1,7.4,.4
125 373,378,1,-1,900,1,-1,8.,.85,373,378,1,-1,900,1,-1,8.,.9
130 374,377,1,1,900,1,-1,8.,.8,374,377,1,1,900,1,-1,8.,.5
135 0
140 $DATA'WESTERLY GRANITE'
145 2
150 375,381,2,-1,450,-1,-1,6.1,.45,375,381,2,-1,450,-1,-1,6.1,.4
155 376,382,2,1,450,-1,-1,6.1,.6,376,382,2,1,450,-1,-1,6.1,.4
160 377,379,4,-1,900,-1,-1,8.1,.6,377,379,4,-1,900,-1,-1,8.1,.5
165 378,380,4,1,900,-1,-1,8.1,.55,378,380,4,1,900,-1,-1,8.1,.6
170 0
175 $DATA'DRESSER BASALT'
180 4
185 379,385,1,-1,450,-1,-1,5.7,.5,379,385,1,-1,450,-1,-1,6.,.65
190 380,386,1,1,450,-1,-1,6.2,2.4,380,386,1,1,450,-1,-1,6.2,1.6
195 381,371,5,-1,900,-1,-1,6.,.25,381,371,5,-1,900,-1,-1,6.,.4
200 382,372,5,1,900,-1,-1,6.,.5,382,372,5,1,900,-1,-1,6.,.9
205 0
210 $DATA'BEREA SANDSTØNE'
215 6
220 383,396,9,-1,450,-1,-1,8.,2.,383,396,9,-1,450,-1,-1,8.,1.5
225 384,395,9,1,450,-1,-1,8.,2.55,384,395,9,1,450,-1,-1,8.,3.9
230 385,393,14,-1,900,-1,-1,8.,1.2,385,393,14,-1,900,-1,-1,8.,1.3
235 386,392,14,1,900,-1,-1,8.,2.,386,392,14,1,900,-1,-1,8.,1.8
240 0
245 $DATA'TENNESSEE MARBLE'
250 7
255 387,388,3,-1,450,-1,-1,7.75,.75,387,388,3,-1,450,-1,-1,8.,1.55
260 388,387,3,1,450,-1,-1,8.,.55,388,387,3,1,450,-1,-1,8.,.5
265 389,400,20,-1,900,-1,-1,8.,.75,389,400,20,-1,900,-1,-1,8.,.7
270 390,399,20,1,900,-1,-1,8.,.65,390,399,20,1,900,-1,-1,8.,.5
275 0
280 $DATA'SALEM LIMESTØNE'
285 8
290 391,375,10,-1,450,-1,-1,8.,.7,391,375,10,-1,450,-1,-1,8.,.6
295 392,376,10,1,450,-1,-1,8.,1.15,392,376,10,1,450,-1,-1,8.,.95
300 393,373,11,-1,900,-1,-1,8.,.8,393,373,11,-1,900,-1,-1,8.,.5
305 394,374,11,1,900,-1,-1,8.,.8,394,374,11,1,900,-1,-1,8.,.9
310 434,433,7,5000,900,-1,-1,6.,.08,434,433,7,5000,900,-1,-1,6.,.05
315 435,435,8,10000,900,-1,-1,5.8,.05,435,435,8,10000,900,-1,-1,5.8,.1
320 436,436,16,20000,900,-1,-1,6.,.15,436,436,16,20000,900,-1,-1,6.,.25
325 437,432,16,35000,900,-1,-1,6.,.6,437,432,16,35000,900,-1,-1,6.,.6
330 0
335 -1
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ROCKS7

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100 $DATA'ADDITIONAL FRAGMENTATION TEST INPUT DATA'
105 $DATA'BARRE GRANITE'
110 3
115 395,405,14,-1,300,-1,-1,8.,.6,395,405,14,-1,300,-1,-1,8.,.6
120 396,402,4,1,300,-1,-1,8.,.8,396,402,4,1,300,-1,-1,8.,.8
125 397,406,9,-1,600,-1,-1,8.,.7,397,406,9,-1,600,-1,-1,8.,.65
130 398,384,6,1,600,-1,-1,5.5,.4,398,384,6,1,600,-1,-1,6.1,.45
135 399,403,16,-1,900,-1,-1,8.,.45,399,403,16,-1,900,-1,-1,8.,.65
140 400,397,18,1,900,-1,-1,6.,.45,400,397,18,1,900,-1,-1,6.,.3
145 401,412,14,-1,300,-1,1,8.,1.2,401,412,14,-1,300,-1,1,8.,1.15
150 402,409,18,1,300,-1,1,6.,.65,402,409,18,1,300,-1,1,6.,.65
155 403,411,16,-1,600,-1,1,8.,.8,403,411,16,-1,600,-1,1,8.,1.1
160 404,410,4,1,600,-1,1,8.,1.3,404,410,4,1,600,-1,1,8.,1.1
165 405,417,9,-1,900,-1,1,8.,1.3,405,417,9,-1,900,-1,1,8.,1.4
170 406,407,6,1,900,-1,1,6.,.3,406,407,6,1,900,-1,1,6.,.3
175 431,434,14,10000,900,-1,-1,6.,.01,431,434,14,10000,900,-1,-1,6.,.05
180 432,437,3,20000,900,-1,-1,6.1,.2,432,437,3,20000,900,-1,-1,6.1,.2
185 433,431,16,35000,900,-1,-1,6.,.5,433,431,16,35000,900,-1,-1,6.,.5
190 0
195 $DATA'SIOUX QUARTZITE'
200 5
205 407,404,24,-1,300,1,-1,7.5,.5,407,404,24,-1,300,1,-1,7.5,.3
210 408,383,15,1,300,1,-1,7.8,.55,408,383,15,1,300,1,-1,7.8,.5
215 409,391,21,-1,600,1,-1,8.,.45,409,391,21,-1,600,1,-1,8.,.4
220 410,394,25,1,600,1,-1,8.5,.4,410,394,25,1,600,1,-1,8.5,.65
225 411,401,26,-1,900,1,-1,8.,.3,411,401,26,-1,900,1,-1,8.,.4
230 412,398,22,1,900,1,-1,8.75,.5,412,398,22,1,900,1,-1,8.75,1.1
235 413,418,24,-1,300,1,1,7.5,1.15,413,418,24,-1,300,1,1,7.5,.9
240 414,415,22,1,300,1,1,8.2,1.1,414,415,22,1,300,1,1,8.2,.8
245 415,413,21,-1,600,1,1,8.7,1.,415,413,21,-1,600,1,1,8.8,.8
250 416,414,15,1,600,1,1,7.7,.9,416,414,15,1,600,1,1,7.7,.6
255 417,416,26,-1,900,1,1,8.,1.45,417,416,26,-1,900,1,1,8.,1.2
260 418,408,15,1,900,1,1,7.3,.7,418,408,15,1,900,1,1,7.75,.3
265 0
270 -1
```

R0CKS8

```
100 $DATA'KERFING FRAGMENTATI0N TEST INPUT DATA'
105 $DATA'CHARC0AL GRANITE'
110 1,50000,900,1.5,.008,.125
115 373,378,1,8.,.85,1,373,378,1,8.,.9,1
120 421,421,5,7.9,1.9,2,421,421,18,7.9,2.,2,421,421,10,7.8,2.,2
125 421,421,5,7.9,2.7,3,421,421,18,7.9,2.6,3,421,421,10,7.8,3.,3
130 0
150 $DATA'WESTERLY GRANITE'
155 2,50000,900,.5,.008,.100
160 377,379,4,8.1,.6,1,377,379,4,8.1,.5,1
165 422,422,2,6.,.8,2,422,422,4,6.,.9,2,422,422,1,6.,1.2,2
170 422,422,2,6.,1.8,3,422,422,4,6.,1.7,3,422,422,1,6.,1.8,3
175 0
200 $DATA'BARRE GRANITE'
205 3,50000,900,.5,.008,.093
210 399,403,16,8.,.45,1,399,403,16,8.,.65,1
215 423,423,16,7.9,1.7,2,423,423,14,7.9,1.3,2,423,423,3,8.,1.3,2
220 423,423,16,7.9,2.6,3,423,423,14,7.9,2.6,3,423,423,3,8.,2.2,3
225 0
250 $DATA'DRESSER BASALT'
255 4,50000,450,.5,.008,.125
260 379,385,1,5.7,.5,1,379,385,1,6.,.65,1
265 424,424,18,6.,1.8,2,424,424,4,6.,1.6,2,424,424,20,5.8,2.7,2
270 424,424,18,6.,3.6,3,424,424,4,6.,2.9,3,424,424,20,5.8,4.,3
275 0
300 $DATA'SI0UX QUARTZITE'
305 5,50000,900,1.5,.008,.125
310 411,401,26,8.,.3,1,411,401,26,8.,.4,1
315 425,425,22,8.3,1.,2,425,425,15,7.7,1.,2,425,425,21,7.1,1.,2
320 425,425,22,8.3,1.5,3,425,425,15,7.7,1.3,3,425,425,21,7.1,1.6,3
325 0
350 $DATA'BEREA SANDST0NE'
355 6,50000,900,.5,.008,.093
360 385,393,14,8.,1.2,1,385,393,14,8.,1.3,1
365 426,426,2,7.8,3.9,2,426,426,8,7.9,4.4,2,426,426,20,7.9,3.7,2
370 426,426,2,7.8,7.3,3,426,426,8,7.9,7.6,3,426,426,20,7.9,7.0,3
375 0
400 $DATA'TENNESSEE MARBLE'
405 7,50000,900,.5,.008,.125
410 389,400,20,8.,.75,1,389,400,20,8.,.7,1
415 427,427,5,7.8,1.9,2,427,427,14,8.,2.,2,427,427,16,8.,1.9,2
420 427,427,5,7.8,3.,3,427,427,14,8.,2.9,3,427,427,16,8.,2.8,3
425 0
450 $DATA'SALEM LIMEST0NE'
455 8,50000,900,.5,.008,.093
460 393,373,11,8.,.8,1,393,373,11,8.,.5,1
465 428,428,16,8.,3.5,2,428,428,7,7.9,2.4,2,428,428,8,7.9,1.2,2
470 428,428,16,8.,5.6,3,428,428,7,7.9,5.,3,428,428,8,7.9,2.2,3
475 0
500 -1
```

APPENDICES C THROUGH J

TEST RESULTS

```
↑4 FACTØRIAL FRAGMENTATIØN TEST DATA, RØCK TYPE NUMBER:    1

ØMB.   TEST   SAMPLE        TREATMENT CØMBINATIØN                        SPECIFIC ENERGY
 #       #       #      PRESSURE    RATE  STANDØFF  NØZZLE
                            P         F       S        N         FT.-LB./CU.IN.      JØULES/CU.CM.

  1      25     12        50000       50      .5     .0080          734710.25          60784.78
                          50000       50      .5     .0080          808181.27          66863.26
  2      48      2        80000       50      .5     .0080         1505535.90         124557.50
                          80000       50      .5     .0080         1380074.50         114177.71
  3      38     19        50000      150      .5     .0080          224494.80          18573.13
                          50000      150      .5     .0080          336742.20          27859.69
  4      28      5        80000      150      .5     .0080          577497.08          47778.07
                          80000      150      .5     .0080          548622.22          45389.16
  5      15     13        50000       50     1.5     .0080          734710.25          60784.78
                          50000       50     1.5     .0080          577272.34          47759.47
  6      46     15        80000       50     1.5     .0080         1083614.10          89650.64
                          80000       50     1.5     .0080         1250323.90         103443.05
  7      17      1        50000      150     1.5     .0080          267710.05          22148.46
                          50000      150     1.5     .0080          297455.61          24609.39
  8      32     14        80000      150     1.5     .0080         1363036.60         112768.11
                          80000      150     1.5     .0080         1817382.10         150357.47
  9      77     20        50000       50      .5     .0136          934257.56          77293.93
                          50000       50      .5     .0136         1015497.50          84015.14
 10     104     16        80000       50      .5     .0136         3889936.00         321826.08
                          80000       50      .5     .0136         4667923.20         386191.29
 11     102      6        50000      150      .5     .0136         1281360.20         106010.77
                          50000      150      .5     .0136          961020.15          79508.08
 12     111      3        80000      150      .5     .0136         1575670.30         130359.93
                          80000      150      .5     .0136         1432427.50         118509.03
 13      70      7        50000       50     1.5     .0136         1221603.20         101066.90
                          50000       50     1.5     .0136         1221603.20         101066.90
 14      86      9        80000       50     1.5     .0136         3174975.60         262675.26
                          80000       50     1.5     .0136         2976539.70         246258.06
 15      87     11        50000      150     1.5     .0136          967102.55          80011.29
                          50000      150     1.5     .0136          773682.04          64009.04
 16     105      8        80000      150     1.5     .0136         1432427.50         118509.03
                          80000      150     1.5     .0136         1575670.30         130359.93


                    ANALYSIS ØF VARIANCE TABLE

ØURCE ØF         SUMS ØF          DF               F RATIØ        TREATMENT
ARIATIØN         SQUARES                                          EFFECTS
                  1.00064 E 13    1                 273.26          1.11839 E 6
                  4.31037 E 12    1                 117.71         -734028.
F                 1.74281 E 12    1                 47.5936        -466745.
                  4.05308 E 10    1                 1.10684        -71178.3
S                 1.39690 E 10    1                 .381473        -41786.6
S                 5.65016 E 11    1                 15.4298         265758.
FS                1.04131 E 12    1                 28.4368         360783.
                  7.59949 E 12    1                 207.5[illegible]1         974647
N                 1.44698 E 12    1                 39.515          42[illegible].
N                 1.30472 E 12    1                 35.63          -403844.
FN                2.58716 E 12    1                 70.6518        -568679.
N                 4.25534 E 11    1                 11.6207        -230633.
SN                5.32457 E 11    1                 14.5407        -257987.
SN                6.38599 E 10    1                 1.74392        -89344.8
FSN               3.31682 E 10    1                 .905778         64389.7

EPLICATE          1.41017 E 10     1                .385098

RRØR              5.49278 E 11    15

ITAL              3.22771 E 13    31

RRØR MEAN SQUARE=                 3.66185 E 10
```

```
3↑2 FACTØRIAL FRAGMENTATIØN TEST DAT

CØMB.   TEST   SAMPLE        TREATMENT
  #       #       #      PRESSURE   RAT
                             P        F

 140      38     19        50000     15
                           50000     15
 141     144     17        65000     15
                           65000     15
 142      28      5        80000     15
                           80000     15
 143     150     10        50000     15
                           50000     15
 144     149     18        65000     15
                           65000     15
 145     152      4        80000     15
                           80000     15
 146     102      6        50000     15
                           50000     15
 147     166     13        65000     15
                           65000     15
 148     111      3        80000     15
                           80000     15
```

```
ADDITIØNAL FRAGMENTATIØN TEST DATA,

CØMB.   TEST   SAMPLE        TREATMENT
  #       #       #      PRESSURE   RAT
                             P        F

 371     389     12        50000     45
                           50000     45
 372     390     12        80000     45
                           80000     45
 373     378      1        50000     90
                           50000     90
 374     377      1        80000     90
                           80000     90


                    ANALYSIS ØF VARIAN

SØURCE ØF           SUMS ØF          DF
VARIATIØN           SQUARES
P                    4.46523 E 10    1
F                    4.24360 E 10    1
PF                   5.64180 E 9     1

REPLICATE            6.29398 E 9      1

ERRØR                7.00101 E 9      3

TØTAL                1.06025 E 11     7

ERRØR MEAN SQUARE=                   2.333
```

```
ST DATA, ROCK TYPE NUMBER:    1

TMENT COMBINATION                          SPECIFIC ENERGY
  RATE  STANDOFF  NOZZLE
   F        S        N       FT.-LB./CU.IN.      JOULES/CU.CM.

  150      .5      .0080       224494.80           18573.13
  150      .5      .0080       336742.20           27859.69
  150      .5      .0080       798605.97           66071.07
  150      .5      .0080       499128.73           41294.42
  150      .5      .0080       577497.08           47778.07
  150      .5      .0080       548622.22           45389.16
  150      .5      .0120       409141.77           33849.53
  150      .5      .0120       383570.41           31733.93
  150      .5      .0120       598934.48           49553.30
  150      .5      .0120       544504.07           45048.46
  150      .5      .0120       540029.17           44678.23
  150      .5      .0120       621033.54           51379.97
  150      .5      .0136      1281360.20          106010.77
  150      .5      .0136       961020.15           79508.08
  150      .5      .0136       508004.55           42028.74
  150      .5      .0136       584205.23           48333.05
  150      .5      .0136      1575670.30          130359.93
  150      .5      .0136      1432427.50          118509.03
```

```
DATA, ROCK TYPE NUMBER:    1

TMENT COMBINATION                          SPECIFIC ENERGY
  RATE  STANDOFF  NOZZLE
   F        S        N       FT.-LB./CU.IN.      JOULES/CU.CM.

  450     1.5      .0080       138150.65           11429.62
  450     1.5      .0080       149663.20           12382.09
  450     1.5      .0080       272607.32           22553.62
  450     1.5      .0080       420269.61           34770.17
  900     1.5      .0080        52822.31            4370.15
  900     1.5      .0080        49887.73            4127.36
  900     1.5      .0080       113586.38            9397.34
  900     1.5      .0080       181738.21           15035.75


VARIANCE TABLE

OF                 F RATIO          TREATMENT
                                    EFFECTS
1                  19.1339           149419.
1                  18.1842          -145664.
1                  2.41756          -53112.1

 1                 2.69703

 3

 7

 2.33367 E 9
```

APPENDIX C

TEST RESULTS - CHARCOAL GRANITE (NO.

```
KERFING FRAGMENTATION TEST DATA, ROCK TYPE NUMBER:    1

          PRESSURE = 50000 PSI  = 34483.00 NEWTONS/SQ.CM.
          FEEDRATE =    900 IPM = 38.10 CM./SEC.
          STANDOFF =    1.5 IN. = 3.810 CM.
          NOZZLE   = .0080 IN.  = .20320 MM.

          SPACING BETWEEN CUTS = .125 IN. = .317 CM.

COMB.     TEST    SAMPLE    NUMBER          SPECIFIC ENERGY
  #         #        #      OF CUTS   FT.LB./CU.IN.       JOULES/CU

 373       378       1         1         52822.31             4370.1
                     1         1         49857.73             4127.3
 421       421       5         2         46671.29             3861.2
                    18         2         44337.72             3668.1
                    10         2         43776.49             3621.7
 421       421       5         3         49264.14             4075.7
                    18         3         51158.91             4232.
                    10         3         43776.49             3621.7

     CUT NUMBER              AVERAGE SPECIFIC ENERGY PER CUT
                              FT.LB./CU.IN.      JOULES/CU.CM.

          1                     51355.02            4248.75

          2                     39931.51            3303.65

          3                     55871.10            4622.38

       AVERAGE                  47901.30            3963.02
```

```
ACTØRIAL FRAGMENTATIØN TEST DATA, RØCK TYPE NUMBER:   2

 TEST  SAMPLE      TREATMENT CØMBINATIØN                             SPECIFIC ENERGY
   #      #     PRESSURE     RATE   STANDØFF   NØZZLE
                   P           F        S         N        FT.-LB./CU.IN.       JØULES/CU.CM.

   18     2       50000       50       .5      .0080        793027.88            65609.58
                  50000       50       .5      .0080        793027.88            65609.58
    7     5       80000       50       .5      .0080       1153713.10            95450.15
    8     4       50000      150       .5      .0080        454601.97            37610.58
   51     3       80000      150       .5      .0080        545214.63            45107.24
                  80000      150       .5      .0080        495649.67            41006.58
    3     1       50000       50      1.5      .0080        997598.76            82534.34
    5     3       80000       50      1.5      .0080       1168317.10            96658.38
                  80000       50      1.5      .0080       1168317.10            96658.38
   23     5       50000      150      1.5      .0080        297455.61            24609.39
                  50000      150      1.5      .0080        446183.41            36914.09
   20     1       80000      150      1.5      .0080        511138.72            42288.04
                  80000      150      1.5      .0080        629093.81            52046.82
   96     4       50000       50       .5      .0136       2956049.30           244562.83
                  50000       50       .5      .0136       2149854.00           177863.87
   92     2       80000       50       .5      .0136       2319189.70           191873.52
                  80000       50       .5      .0136       2441252.30           201972.13
  124     1       50000      150       .5      .0136       1557095.90           128823.22
                  50000      150       .5      .0136       1557095.90           128823.22
   72     2       80000      150       .5      .0136        489319.49            40482.87
                  80000      150       .5      .0136        505103.99            41788.77
  123     3       50000       50      1.5      .0136       2458572.50           203405.08
                  50000       50      1.5      .0136       2919554.90           241543.53
   91     4       80000       50      1.5      .0136       3190732.30           263978.86
                  80000       50      1.5      .0136       3190732.30           263978.86
  113     1       50000      150      1.5      .0136        961020.15            79508.08
                  50000      150      1.5      .0136       1537632.20           127212.93
  121     5       80000      150      1.5      .0136       1575670.30           130359.93
                  80000      150      1.5      .0136       1432427.50           118509.03


              ANALYSIS ØF VARIANCE TABLE

E ØF          SUMS ØF          DF                 F RATIØ        TREATMENT
TIØN          SQUARES                                            EFFECTS
               1.27446 E 10    1                   .30421          39913.4
               8.40697 E 12    1                  200.672         -1.02512 E 6
               2.45483 E 11    1                  5.85961         -175172.
               4.19421 E 11    1                  10.0115          228971.
               4.66346 E 11    1                  11.1315          241440.
               3.12295 E 10    1                  .745439         -62479.5
               1.15835 E 11    1                  2.76494          120330.
               1.14985 E 13    1                  274.465          1.19888 E 6
               2.02170 E 11    1                  4.82573         -158969.
               1.81412 E 12    1                  43.3025         -476198.
               9.39236 E 10    1                  2.24193         -108353.
               2.66304 E 11    1                  6.35661          182450.
               5.23524 E 11    1                  12.4964          255813.
               2.78782 E 6     1                  6.65444 E-5      590.32
               1.26235 E 10    1                  .301319          39723.2

CATE           6.13587 E 9      1                 .146462

               6.28412 E 11     15

               2.47437 E 13     31

MEAN SQUARE=                   4.18941 E 10
```

```
3'2 FACTØRIAL FRAGMENTATIØN TEST DATA, R

CØMB.    TEST   SAMPLE       TREATMENT CØMB
  #        #       #      PRESSURE     RATE   S
                              P          F

 149       7       5        80000        50
 150     141       2        80000       100
                            80000       100
 151      51       3        80000       150
                            80000       150
 152     151       3        80000        50
                            80000        50
 153     161       1        80000       100
                            80000       100
 154     162       3        80000       150
                            80000       150
 155      92       2        80000        50
                            80000        50
 156     165       5        80000       100
                            80000       100
 157      72       2        80000       150
                            80000       150
```

```
ADDITIØNAL FRAGMENTATIØN TEST DATA, RØCK

CØMB.    TEST   SAMPLE       TREATMENT CØMB
  #        #       #      PRESSURE     RATE   ST
                              P          F

 375     381       2        50000       450
                            50000       450
 376     382       2        80000       450
                            80000       450
 377     379       4        50000       900
                            50000       900
 378     380       4        80000       900
                            80000       900


                  ANALYSIS ØF VARIANCE TA

SØURCE ØF        SUMS ØF            DF
VARIATIØN        SQUARES
P                 2.08079 E 10     1
F                 2.13647 E 10     1
PF                1.25317 E 9      1

REPLICATE         2.30223 E 9       1

ERRØR             4.75837 E 9       3

TØTAL             5.04863 E 10      7

ERRØR MEAN SQUARE=                 1.58612 E
```

APPENDIX D

TEST RESULTS - WESTERLY GRANITE (N

```
 TEST OATA, RØCK TYPE NUMBER:    2

REATMENT CØMBINATIØN                        SPECIFIC ENERGY
URE    RATE  STANOØFF  NØZZLE
         F       S        N      FT.-LB./CU.IN.        JØULES/CU.CM.

00      50      .5     .0080     1153713.10            95450.15
00     100      .5     .0080      672999.31            55679.25
00     100      .5     .0080      807599.17            66815.10
00     150      .5     .0080      545214.63            45107.24
00     150      .5     .0080      495649.67            41006.58
00      50      .5     .0120     1278551.80           105778.43
00      50      .5     .0120     1373259.40           113613.87
00     100      .5     .0120      539644.53            44646.41
00     100      .5     .0120      584614.91            48366.95
00     150      .5     .0120      274651.87            22722.77
00     150      .5     .0120      268681.18            22228.80
00      50      .5     .0136     2319189.70           191873.52
00      50      .5     .0136     2441252.30           201972.13
00     100      .5     .0136      581346.10            48096.51
00     100      .5     .0136      693143.42            57345.83
00     150      .5     .0136      489319.49            40482.87
00     150      .5     .0136      505103.99            41788.77
```

```
ST OATA, RØCK TYPE NUMBER:    2

REATMENT CØMBINATIØN                        SPECIFIC ENERGY
URE    RATE  STANOØFF  NØZZLE
         F       S        N      FT.-LB./CU.IN.        JØULES/CU.CM.

00     450      .5     .0080      152157.59            12588.45
00     450      .5     .0080      171177.28            14162.01
00     450      .5     .0080      230953.98            19107.93
00     450      .5     .0080      346438.46            28661.39
00     900      .5     .0080       75766.99             6268.43
00     900      .5     .0080       90920.39             7522.12
00     900      .5     .0080      167281.76            13839.72
00     900      .5     .0080      153341.62            12686.41


ØF VARIANCE TABLE


   OF                  F RATIØ        TREATMENT
                                      EFFECTS
0  1                   13.1187         102000.
0  1                   13.4697        -103355.
   1                   .790081        -25031.6

    1                  1.45148

    3

0   7

    1.58612 E 9
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KERFING FRAGMENTATIØN TEST OATA, RØCK TYPE NUMBER:    2

              PRESSURE = 50000 PSI = 34483.00 NEWTØNS/SO.CM.
              FEEORATE =    900 IPM = 38.10 CM./SEC.
              STANOØFF =     .5 IN. = 1.270 CM.
              NØZZLE   = .0080 IN. = .20320 MM.

              SPACING BETWEEN CUTS = .100 IN. = .254 CM.

CØMB.      TEST      SAMPLE    NUMBER          SPECIFIC ENERGY
  #          #          #      ØF CUTS   FT.LB./CU.IN.        JØULES

 377        379         4        1         75766.99            626
                        4        1         90920.39            752
 422        422         2        2         84185.55            696
                        4        2         74831.60            619
                        1        2         56123.70            464
 422        422         2        3         56123.70            464
                        4        3         59425.09            491
                        1        3         56123.70            464

       CUT NUMBER           AVERAGE SPECIFIC ENERGY PER CUT
                           FT.LB./CU.IN.         JØULES/CU.CM.

           1                 83343.69              6895.27

           2                 62931.88              5206.54

           3                 40755.28              3371.81

         AVERAGE             51843.58              4289.17
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 FACTØRIAL FRAGMENTATIØN TEST DATA, RØCK TYPE NUMBER:   3

MB.    TEST   SAMPLE       TREATMENT CØMBINATIØN                      SPECIFIC ENERGY
        #       #    PRESSURE    RATE  STANDØFF  NØZZLE
                        P          F       S        N      FT.-LB./CU.IN.      JØULES/CU.CM.

33      11      7      50000      50      .5     .0080     1029168.30          85146.18
                       50000      50      .5     .0080     1029168.30          85146.18
34      13     17      80000      50      .5     .0080     1289642.30         106695.98
                       80000      50      .5     .0080     1289642.30         106695.98
35      22     11      50000     150      .5     .0080      306809.56          25383.28
                       50000     150      .5     .0080      276128.60          22844.95
36      43     10      80000     150      .5     .0080      413959.26          34248.09
                       80000     150      .5     .0080      558845.00          46234.92
37      50     19      50000      50     1.5     .0080     1035482.30          85668.55
                       50000      50     1.5     .0080      920428.67          76149.83
38      31      1      80000      50     1.5     .0080     1397112.50         115587.31
                       80000      50     1.5     .0080     1397112.50         115587.31
39      19      3      50000     150     1.5     .0080      914816.30          75685.50
                       50000     150     1.5     .0080      548889.78          45411.30
40      37      2      80000     150     1.5     .0080      552029.81          45671.08
                       80000     150     1.5     .0080      581084.02          48074.82
41      81      6      50000      50      .5     .0136      892710.04          73856.58
                       50000      50      .5     .0136      859646.71          71121.15
42      76      8      80000      50      .5     .0136     1074320.70          88881.77
                       80000      50      .5     .0136     1074320.70          88881.77
43      69     16      50000     150      .5     .0136     1098308.70          90866.38
                       50000     150      .5     .0136     1098308.70          90866.38
44      68     20      80000     150      .5     .0136      492396.97          40737.48
                       80000     150      .5     .0136      527568.18          43647.30
45      82     18      50000      50     1.5     .0136     1015497.30          84015.14
                       50000      50     1.5     .0136     1167821.90          96617.41
46      85      4      80000      50     1.5     .0136     3376436.40         279342.71
                       80000      50     1.5     .0136     3376436.40         279342.71
47      74      5      50000     150     1.5     .0136      486592.48          40257.26
                       50000     150     1.5     .0136      432526.65          35784.23
48     100     14      80000     150     1.5     .0136     1575670.30         130359.93
                       80000     150     1.5     .0136     1313058.60         108633.28


                ANALYSIS ØF VARIANCE TABLE

RCE ØF        SUMS ØF          OF                F RATIØ          TREATMENT
IATIØN        SQUARES                                             EFFECTS
                1.60981 E 12   1                 191.864           448583.
                3.81429 E 12   1                 454.601          -690497.
                9.36008 E 11   1                 111.557          -342054.
                1.43654 E 12   1                 171.212           423753.
                1.49492 E 12   1                 178.17            432278.
                3.86182 E 11   1                 46.0267          -219711.
S               1.33236 E 11   1                 15.8796          -129053.
                1.24872 E 12   1                 148.827           395083.
                5.88687 E 11   1                 70.1619           271267.
                1.04248 E 10   1                 1.24247          -36098.5
)               2.57925 E 11   1                 30.7405          -179557.
                6.25208 E 11   1                 74.5147           279555.
)               1.86372 E 12   1                 222.125           482664.
)               9.01995 E 11   1                 107.503          -335782.
ØN              3.65760 E 6    1                 4.35927 E-4       676.166

LICATE          7.81140 E 9     1                .930992

ØR              1.25856 E 11    15

AL              1.54413 E 13    31

ØR MEAN SQUARE=                8.39040 E 9
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ADDITIØNAL FRAGMENTATIØN TEST DATA, R

CØMB.    TEST   SAMPLE      TREATMENT C
  #        #       #     PRESSURE   RATE
                            P         F

 395      405     14       50000     300
                           50000     300
 396      402      4       80000     300
                           80000     300
 397      406      9       50000     600
                           50000     600
 398      384      6       80000     600
                           80000     600
 399      403     16       50000     900
                           50000     900
 400      397     18       80000     900
                           80000     900
 401      412     14       50000     300
                           50000     300
 402      409     18       80000     300
                           80000     300
 403      411     16       50000     600
                           50000     600
 404      410      4       80000     600
                           80000     600
 405      417      9       50000     900
                           50000     900
 406      407      6       80000     900
                           80000     900
 431      434     14       10000     900
                           10000     900
 432      437      3       20000     900
                           20000     900
 433      431     16       35000     900
                           35000     900


ANALYSIS ØF VARIANCE, RØCK TYPE NUMBE


                MEAN SPECIFIC ENERG


CØMBINATIØN #  MEAN SPECIFIC ENERGY (
 395            224495.
 396            340759.
 399            84425.4
 400            189311.
 401            331447.
 402            909041.
 405            96249.1
 406            656529.


                ANALYSIS ØF VARIANC


SØURCE ØF       SUMS ØF         OF
VARIATIØN       SQUARES
P                4.61736 E 11   1
F                1.51799 E 11   1
PF               205813129      1
N                3.33088 E 11   1
PN               2.10096 E 11   1
FN               9.62276 E 9    1
PFN              8.80356 E 6    1

REPLICATE        168992768       1

ERRØR            3.29421 E 9     7

TØTAL            1.17002 E 12    15

ERRØR MEAN SQUARE=              4.7060
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APPENDIX E

TEST RESULTS - BARRE GRANITE (NO

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T DATA, RØCK TYPE NUMBER:    3

EATMENT CØMBINATIØN                            SPECIFIC ENERGY
RE    RATE   STANDØFF   NØZZLE
       F        S         N        FT.-LB./CU.IN.       JØULES/CU.CM.

0     300      .5       .0080       224494.80            18573.13
0     300      .5       .0080       224494.80            18573.13
0     300      .5       .0080       340759.15            28192.03
0     300      .5       .0080       340759.15            28192.03
0     600      .5       .0080        96212.06             7959.91
0     600      .5       .0080       103612.98             8572.21
0     600      .5       .0080       234271.91            19382.02
0     600      .5       .0080       230958.98            19107.93
0     900      .5       .0080        99775.47             8254.72
0     900      .5       .0080        69075.32             5714.81
0     900      .5       .0080       151448.51            12529.79
0     900      .5       .0080       227172.76            18794.68
0     300      .5       .0136       324394.99            26838.17
0     300      .5       .0136       338499.12            28005.05
0     300      .5       .0136       909040.55            75207.65
0     300      .5       .0136       909040.55            75207.65
0     600      .5       .0136       243296.24            20128.63
0     600      .5       .0136       176942.72            14639.00
0     600      .5       .0136       303013.52            25069.22
0     600      .5       .0136       358106.89            29627.26
0     900      .5       .0136        99813.84             8257.90
0     900      .5       .0136        92684.28             7668.05
0     900      .5       .0136       656529.29            54316.64
0     900      .5       .0136       656529.29            54316.64
0     900      .5       .0080       301191.38            24918.47
0     900      .5       .0080        60238.28             4983.69
0     900      .5       .0080        43304.81             3582.74
0     900      .5       .0080        43304.81             3582.74
0     900      .5       .0080        39443.42             3263.27
0     900      .5       .0080        39443.42             3263.27

YPE NUMBER:        3

FIC ENERGY VALUES

 ENERGY [FT.-LB./CU.IN.]




F VARIANCE TABLE

 OF                  F RATIØ          TREATMENT
                                      EFFECTS
 1                    981.16           339756.
 1                    322.563         -194807.
 1                    .43734          -7173.09
 1                    707.792          288569.
 1                    446.44           229181.
 1                    20.4478         -49047.8
 1                    .018707         -1483.54

  1                   .359099

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  15

  4.70602 E 8
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KERFING FRAGMENTATIØN TEST DATA, RØCK TYPE NUMBER:    3

          PRESSURE = 50000 PSI = 34483.00 NEWTØNS/SQ.CM.
          FEEDRATE =    900 IPM = 38.10 CM./SEC.
          STANDØFF =     .5 IN. = 1.270 CM.
          NØZZLE   = .0080 IN. = .20320 MM.

          SPACING BETWEEN CUTS = .093 IN. = .236 CM.

CØMB.    TEST    SAMPLE    NUMBER          SPECIFIC ENERGY
  #        #        #      ØF CUTS    FT.LB./CU.IN.        JØULES/C

 399      403      16         1          99775.47             8254.
                   16         1          69075.32             5714.
 423      423      16         2          52162.03             4315.
                   14         2          68211.88             5643.
                    3         2          69075.32             5714.
 423      423      16         3          51158.91             4232.
                   14         3          51158.91             4232.
                    3         3          61225.85             5065.

     CUT NUMBER            AVERAGE SPECIFIC ENERGY PER CUT
                          FT.LB./CU.IN.       JØULES/CU.CM.

          1                 84425.39             6984.77

          2                 50438.88             4172.96

          3                 42807.46             3541.59

       AVERAGE              46623.17             3857.27
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3*4 FACTORIAL FRAGMENTATION TEST DATA, ROCK TYPE NUMBER: 3

COMB. #	TEST #	SAMPLE #	TREATMENT COMBINATION				SPECIFIC ENERGY	
			PRESSURE P	RATE F	STANDOFF S	NOZZLE N	FT.-LB./CU.IN.	JOULES/CU.CM.
201	11	7	50000	50	.5	.0080	1029168.30	85146.18
			50000	50	.5	.0080	1029168.30	85146.18
202	231	8	65000	50	.5	.0080	1182935.10	97867.77
			65000	50	.5	.0080	1182935.10	97867.77
203	13	17	80000	50	.5	.0080	1289642.30	106695.98
			80000	50	.5	.0080	1289642.30	106695.98
204	235	4	50000	100	.5	.0080	808181.27	66863.26
			50000	100	.5	.0080	808181.27	66863.26
205	212	[illegible]	65000	100	.5	.0080	748693.10	61941.63
			65000	100	.5	.0080	748693.10	61941.63
206	229	5	80000	100	.5	.0080	817821.95	67660.86
			80000	100	.5	.0080	908691.06	75178.74
207	22	11	50000	150	.5	.0080	306809.56	25383.28
			50000	150	.5	.0080	276128.60	22844.95
208	224	19	65000	150	.5	.0080	475640.32	39351.15
			65000	150	.5	.0080	623910.92	51618.02
209	43	10	80000	150	.5	.0080	413959.26	34248.09
			80000	150	.5	.0080	558845.00	46234.92
210	233	18	50000	50	1.0	.0080	1077575.00	89151.02
			50000	50	1.0	.0080	1010226.60	83579.08
211	216	11	65000	50	1.0	.0080	1364285.20	112871.41
			65000	50	1.0	.0080	1227856.70	101584.27
212	236	16	80000	50	1.0	.0080	1594752.80	131938.68
			80000	50	1.0	.0080	1486949.00	123019.75
213	221	2	50000	100	1.0	.0080	690321.51	57112.37
			50000	100	1.0	.0080	947087.43	78355.38
214	223	10	65000	100	1.0	.0080	767410.43	63490.17
			65000	100	1.0	.0080	877040.49	72560.19
215	210	12	80000	100	1.0	.0080	803217.99	66452.63
			80000	100	1.0	.0080	1405631.50	116292.11
216	225	20	50000	150	1.0	.0080	443377.23	36681.93
			50000	150	1.0	.0080	532052.67	44018.31
217	214	17	65000	150	1.0	.0080	818571.12	67722.84
			65000	150	1.0	.0080	545714.08	45148.56
218	209	13	80000	150	1.0	.0080	769142.07	63633.43
			80000	150	1.0	.0080	672999.31	55679.25
219	50	19	50000	50	1.5	.0080	1035482.30	85668.55
			50000	50	1.5	.0080	920428.67	76149.83
220	232	6	65000	50	1.5	.0080	1689907.30	139811.10
			65000	50	1.5	.0080	1182935.10	97867.77
221	31	1	80000	50	1.5	.0080	1397112.50	115587.31
			80000	50	1.5	.0080	1397112.50	115587.31
222	208	15	50000	100	1.5	.0080	808181.27	66863.26
			50000	100	1.5	.0080	505113.30	41789.54
223	217	1	65000	100	1.5	.0080	1018222.60	84240.61
			65000	100	1.5	.0080	1169833.00	96783.79
224	215	3	80000	100	1.5	.0080	1035055.90	85633.28
			80000	100	1.5	.0080	920049.69	76118.47
225	19	3	50000	150	1.5	.0080	914816.30	75685.50
			50000	150	1.5	.0080	548889.78	45411.30
226	205	9	65000	150	1.5	.0080	793614.69	65658.12
			65000	150	1.5	.0080	793614.69	65658.12
227	37	2	80000	150	1.5	.0080	552029.81	45671.08
			80000	150	1.5	.0080	581084.02	48074.82
228	290	12	50000	50	.5	.0120	719786.45	59550.09
			50000	50	.5	.0120	863743.74	71460.11
229	278	16	65000	50	.5	.0120	1027581.30	85014.88
			65000	50	.5	.0120	978648.84	80966.55
230	250	17	80000	50	.5	.0120	1207565.20	99905.49
			80000	50	.5	.0120	1061595.80	87829.01
231	247	12	50000	100	.5	.0120	503309.32	41640.29
			50000	100	.5	.0120	704633.05	58296.41
232	241	9	65000	100	.5	.0120	439450.30	36357.04
			65000	100	.5	.0120	561519.83	46456.22
233	273	6	80000	100	.5	.0120	637761.72	52763.94
			80000	100	.5	.0120	610032.95	50469.86
234	245	13	50000	150	.5	.0120	462178.67	38237.43
			50000	150	.5	.0120	462178.67	38237.43
235	279	14	65000	150	.5	.0120	481302.71	39819.62
			65000	150	.5	.0120	481302.71	39819.62
236	267	20	80000	150	.5	.0120	594198.76	49159.85
			80000	150	.5	.0120	528176.68	43697.64
237	261	2	50000	50	1.0	.0120	1084050.80	89686.78
			50000	50	1.0	.0120	1043900.80	86365.05
238	266	19	65000	50	1.0	.0120	1070190.70	88540.09
			65000	50	1.0	.0120	1029453.00	85169.74
239	239	14	80000	50	1.0	.0120	1101271.60	91111.50
			80000	50	1.0	.0120	1211398.80	100222.65
240	272	8	50000	100	1.0	.0120	577723.33	47796.78
			50000	100	1.0	.0120	693268.00	57356.14
241	291	7	65000	100	1.0	.0120	663295.29	54876.41
			65000	100	1.0	.0120	707514.98	58534.84

3*4 FACTO

COMB. #
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3↑4 FACTORIAL FRAGMENTATION TEST DATA, ROCK TYPE NUMBER: 3

COMB. #	TEST #	SAMPLE #	TREATMENT COMBINATION PRESSURE P	RATE F	STANDOFF S	NOZZLE N	SPECIFIC ENERGY FT.-LB./CU.IN.	JOULES/CU.CM.
242	260	1	80000	100	1.0	.0120	750566.86	62096.65
			80000	100	1.0	.0120	843378.89	69775.27
243	252	3	50000	150	1.0	.0120	251227.40	20784.80
			50000	150	1.0	.0120	251227.40	20784.80
244	277	4	65000	150	1.0	.0120	526964.76	43597.38
			65000	150	1.0	.0120	622776.53	51524.17
245	285	15	80000	150	1.0	.0120	668131.33	55276.51
			80000	150	1.0	.0120	550225.80	45521.83
246	243	15	50000	50	1.5	.0120	1260487.30	104283.89
			50000	50	1.5	.0120	1540595.60	127458.09
247	248	7	65000	50	1.5	.0120	1010735.70	83621.20
			65000	50	1.5	.0120	1061272.50	87802.26
248	274	18	80000	50	1.5	.0120	1079289.10	89292.82
			80000	50	1.5	.0120	1039315.40	85985.68
249	283	9	50000	100	1.5	.0120	852378.69	70519.85
			50000	100	1.5	.0120	757669.95	62684.31
250	286	13	65000	100	1.5	.0120	733986.63	60724.92
			65000	100	1.5	.0120	790447.14	65396.06
251	292	17	80000	100	1.5	.0120	966052.18	79924.39
			80000	100	1.5	.0120	905673.92	74929.12
252	263	10	50000	150	1.5	.0120	494479.33	40909.76
			50000	150	1.5	.0120	587194.21	48580.34
253	268	5	65000	150	1.5	.0120	632985.99	52368.83
			65000	150	1.5	.0120	535603.53	44312.09
254	259	11	80000	150	1.5	.0120	594198.76	49159.85
			80000	150	1.5	.0120	633812.01	52437.17
255	81	6	50000	50	.5	.0136	892710.04	73856.58
			50000	50	.5	.0136	859646.71	71121.15
256	304	8	65000	50	.5	.0136	1319871.10	109196.89
			65000	50	.5	.0136	1257020.10	103997.04
257	76	8	80000	50	.5	.0136	1074320.70	88881.77
			80000	50	.5	.0136	1074320.70	88881.77
258	315	4	50000	100	.5	.0136	809512.94	66973.43
			50000	100	.5	.0136	890464.23	73670.78
259	328	7	65000	100	.5	.0136	894338.87	73991.34
			65000	100	.5	.0136	838442.69	69366.88
260	299	10	80000	100	.5	.0136	796398.57	65888.44
			80000	100	.5	.0136	796398.57	65888.44
261	89	16	50000	150	.5	.0136	1098308.70	90866.38
			50000	150	.5	.0136	1098308.70	90866.38
262	321	9	65000	150	.5	.0136	576992.82	47736.35
			65000	150	.5	.0136	540930.77	44752.83
263	68	20	80000	150	.5	.0136	492396.97	40737.48
			80000	150	.5	.0136	527568.18	43647.30
264	298	2	50000	50	1.0	.0136	1187285.60	98227.70
			50000	50	1.0	.0136	1187285.60	98227.70
265	316	16	65000	50	1.0	.0136	1759828.10	145595.86
			65000	50	1.0	.0136	2030570.90	167995.22
266	302	5	80000	50	1.0	.0136	1263252.90	104512.70
			80000	50	1.0	.0136	1308369.10	108245.30
267	313	18	50000	100	1.0	.0136	989404.70	81856.42
			50000	100	1.0	.0136	890464.23	73670.78
268	324	12	65000	100	1.0	.0136	745282.39	61659.45
			65000	100	1.0	.0136	789122.53	65286.47
269	322	15	80000	100	1.0	.0136	720869.16	59639.67
			80000	100	1.0	.0136	858177.57	70999.60
270	319	14	50000	150	1.0	.0136	449162.29	37160.54
			50000	150	1.0	.0136	486592.48	40257.26
271	300	19	65000	150	1.0	.0136	596225.91	49327.56
			65000	150	1.0	.0136	596225.91	49327.56
272	323	13	80000	150	1.0	.0136	632341.37	52315.50
			80000	150	1.0	.0136	750905.37	62124.65
273	82	18	50000	50	1.5	.0136	1015497.30	84015.14
			50000	50	1.5	.0136	1167821.90	96617.41
274	301	20	65000	50	1.5	.0136	1166529.00	96510.44
			65000	50	1.5	.0136	1166529.00	96510.44
275	85	4	80000	50	1.5	.0136	3376436.40	279342.71
			80000	50	1.5	.0136	3376436.40	279342.71
276	295	3	50000	100	1.5	.0136	502812.23	41599.16
			50000	100	1.5	.0136	603374.67	49919.00
277	296	11	65000	100	1.5	.0136	789122.53	65286.47
			65000	100	1.5	.0136	838442.69	69366.88
278	311	6	80000	100	1.5	.0136	819169.50	67772.35
			80000	100	1.5	.0136	783553.44	64825.73
279	74	5	50000	150	1.5	.0136	486592.48	40257.26
			50000	150	1.5	.0136	432526.65	35784.23
280	297	1	65000	150	1.5	.0136	638813.48	52850.96
			65000	150	1.5	.0136	558961.79	46244.59
281	100	14	80000	150	1.5	.0136	1575670.30	130359.93
			80000	150	1.5	.0136	1313058.60	108633.28

```
ORIAL FRAGMENTATION TEST DATA, ROCK TYPE NUMBER:   4

TEST  SAMPLE       TREATMENT COMBINATION                          SPECIFIC ENERGY
 #      #     PRESSURE   RATE  STANDOFF   NOZZLE
                 P        F       S         N       FT.-LB./CU.IN.      JOULES/CU.CM.

  54    14     50000      50      .5      .0080       303067.98           25073.72
  34    19     80000      50      .5      .0080       201103.76           16637.92
               80000      50      .5      .0080       340759.15           28192.03
  29     8     50000     150      .5      .0080       134696.88           11143.88
               50000     150      .5      .0080       252556.65           20894.77
  41     1     80000     150      .5      .0080        42594.89            3524.00
  57     3     50000      50     1.5      .0080       432954.25           35819.60
  58    12     80000      50     1.5      .0080       211505.68           17498.50
   9    20     50000     150     1.5      .0080       185208.21           15322.83
               50000     150     1.5      .0080       203729.03           16855.11
  35     5     80000     150     1.5      .0080       299381.25           24768.71
  94    13     50000      50      .5      .0136      1113080.30           92088.47
               50000      50      .5      .0136      1187285.60           98227.70
  75     6     80000      50      .5      .0136       487473.00           40330.10
 109     2     50000     150      .5      .0136       386841.02           32004.52
               50000     150      .5      .0136       286548.90           23707.05
 106    10     80000     150      .5      .0136       226930.78           18774.66
               80000     150      .5      .0136       330195.61           27318.07
 116    15     50000      50     1.5      .0136      1316192.80          108892.58
               50000      50     1.5      .0136      1257654.40          104049.52
  90    16     80000      50     1.5      .0136      3840696.30          317752.33
               80000      50     1.5      .0136      4431572.70          366637.30
 117     7     50000     150     1.5      .0136       310878.53           25719.91
               50000     150     1.5      .0136       373054.23           30863.90
  67    17     80000     150     1.5      .0136       105513.64            8729.46


               ANALYSIS OF VARIANCE TABLE

OF        SUMS OF          DF                F RATIO          TREATMENT
ON        SQUARES                                             EFFECTS
           3.16893 E 11    1                 26.3894           199027.
           5.25911 E 12    1                 437.954          -810795.
           6.46169 E 11    1                 53.8099          -284203.
           1.94608 E 12    1                 162.06            493213.
           1.44520 E 12    1                 120.35            425030.
           1.77285 E 12    1                 147.635          -470751.
           1.31625 E 12    1                 109.611          -405624.
           4.76621 E 12    1                 396.907           771865.
           6.00401 E 11    1                 49.9986           273953.
           3.79444 E 12    1                 315.983          -688698.
           9.03540 E 11    1                 75.2425          -336069.
           1.35263 E 12    1                 112.64            411191.
           1.33414 E 12    1                 111.101           408372.
           2.14280 E 12    1                 178.443          -517543.
           2.13780 E 12    1                 178.026          -516938.

TE         2.80681 E 10     1                2.33738

           1.80125 E 11    15

           2.99427 E 13    31

EAN SQUARE=                1.20084 E 10
```

```
3↑2 FACTORIAL FRAGMENTATION TEST DATA, ROCK

COMB.    TEST   SAMPLE       TREATMENT COMBINA
  #        #       #     PRESSURE    RATE  STAN
                            P          F

 158      34      19      80000       50
                          80000       50
 159     143      18      80000      100
                          80000      100
 160      41       1      80000      150
 161     153       4      80000       50
                          80000       50
 162     148       9      80000      100
 163     156      20      80000      150
                          80000      150
 164      75       6      80000       50
 165     167      19      80000      100
                          80000      100
 166     106      10      80000      150
                          80000      150


ADDITIONAL FRAGMENTATION TEST DATA, ROCK TY

COMB.    TEST   SAMPLE       TREATMENT COMBINAT
  #        #       #     PRESSURE    RATE  STAND
                            P          F

 379     385       1      50000      450
                          50000      450
 380     386       1      80000      450
                          80000      450
 381     371       5      50000      900
                          50000      900
 382     372       5      80000      900
                          80000      900


                    MEAN SPECIFIC ENERGY VALU

COMBINATION #  MEAN SPECIFIC ENERGY (FT.-LB
 379           115788.
 380           73357.9
 381           109441.
 382           106014.

                    ANALYSIS OF VARIANCE TABL

SOURCE OF       SUMS OF        DF
VARIATION       SQUARES
P                1051427455     1
F                3.46103 E 8    1
PF               760592865      1

REPLICATE        1.40706 E 9     1

ERROR            2.43052 E 9     3

TOTAL            5.99570 E 9     7

ERROR MEAN SQUARE=               810171908
```

APPENDIX F

TEST RESULTS - DRESSER BASALT (NO. 4

```
 OATA, ROCK TYPE NUMBER:    4

IENT COMBINATION                           SPECIFIC ENERGY
 RATE  STANOOFF  NOZZLE
  F       S        N      FT.-L8./CU.IN.       JOULES/CU.CM.

  50     .5     .0080      201103.76            16637.92
  50     .5     .0080      340759.15            28192.03
 100     .5     .0080      136303.66            11276.81
 100     .5     .0080      162154.35            13415.52
 150     .5     .0080       42594.89             3524.00
  50     .5     .0120      348728.51            28851.36
  50     .5     .0120      673607.81            55729.60
 100     .5     .0120       79314.63             6561.94
 150     .5     .0120      209566.87            17338.10
 150     .5     .0120      159839.14            13223.97
  50     .5     .0136      487473.00            40330.10
 100     .5     .0136      165666.27            13706.07
 100     .5     .0136      260161.98            21523.98
 150     .5     .0136      226930.78            18774.66
 150     .5     .0136      330195.61            27318.07
```

```
ATA, ROCK TYPE NUMBER:    4

MENT COMBINATION                           SPECIFIC ENERGY
 RATE  STANOOFF  NOZZLE
  F       S        N      FT.-LB./CU.IN.       JOULES/CU.CM.

 450     .5     .0080      127962.04            10586.68
 450     .5     .0080      103612.98             8572.21
 450     .5     .0080       58686.30             4855.29
 450     .5     .0080       88029.45             7282.94
 900     .5     .0080      134696.88            11143.88
 900     .5     .0080       84185.55             6964.92
 900     .5     .0080      136303.66            11276.81
 900     .5     .0080       75724.25             6264.89

 ENERGY VALUES

ERGY [FT.-LB./CU.IN.]



ARIANCE TABLE

F                 F RATIO       TREATMENT
                                EFFECTS
                  1.29778       -22928.4
                  .427196        13154.9
                  .938804        19501.2

 1                1.73675

 3

 7

 810171908
```

```
KERFING FRAGMENTATION TEST DATA, ROCK TYPE NUMBER:    4

          PRESSURE = 50000 PSI = 34483.00 NEWTONS/SQ.CM.
          FEEDRATE =    450 IPM = 19.05 CM./SEC.
          STANOOFF =     .5 IN. = 1.270 CM.
          NOZZLE   = .0080 IN. = .20320 MM.

          SPACING BETWEEN CUTS = .125 IN. = .317 CM.

COMB.    TEST    SAMPLE    NUMBER            SPECIFIC ENERGY
  #        #        #      OF CUTS    FT.LB./CU.IN.          JOULES/CU.

 379      385       1         1        127962.04             10586.68
                    1         1        103612.98              8572.21
 424      424      18         2         74831.60              6191.04
                    4         2         84185.55              6964.92
                   20         2         48224.81              3989.78
 424      424      18         3         56123.70              4643.28
                    4         3         69670.80              5764.07
                   20         3         48827.62              4039.66

      CUT NUMBER           AVERAGE SPECIFIC ENERGY PER CUT
                          FT.LB./CU.IN.        JOULES/CU.CM.

          1                115787.51              9579.45

          2                 49224.33              4072.48

          3                 44270.91              3662.67

       AVEPAGE              46747.62              3867.57
```

```
FACTØRIAL FRAGMENTATIØN TEST OATA, RØCK TYPE NUMBER:    5

8.    TEST  SAMPLE      TREATMENT CØMBINATIØN                          SPECIFIC ENERGY
        #      #     PRESSURE   RATE  STANOØFF  NØZZLE
                         P        F       S        N       FT.-LB./CU.IN.      JØULES/CU.CM.

5       24     10      50000      50      .5     .0080      1077575.00          89151.02
                       50000      50      .5     .0080       881652.30          72941.74
6       36      2      80000      50      .5     .0080      1135863.80          93973.42
                       80000      50      .5     .0080      1363036.60         112768.11
7       21     20      50000     150      .5     .0080       266587.57          22055.59
                       50000     150      .5     .0080       293884.10          24313.91
8       42      3      80000     150      .5     .0080       525337.02          43462.71
                       80000     150      .5     .0080       631953.32          52283.39
9       60      8      50000      50     1.5     .0080      1140112.90          94324.96
                       50000      50     1.5     .0080       997598.76          82534.34
0       26     18      80000      50     1.5     .0080      1765751.90         146085.95
                       80000      50     1.5     .0080      1553861.70         128555.64
1        4      4      50000     150     1.5     .0080       481060.28          39799.56
                       50000     150     1.5     .0080       473543.72          39177.69
2       16      7      80000     150     1.5     .0080       804191.58          66533.18
                       80000     150     1.5     .0080      1005239.50          83166.48
3       65      5      50000      50      .5     .0136      1042698.20          86265.55
                       50000      50      .5     .0136      1042698.20          86265.55
4       88     13      80000      50      .5     .0136      3939175.70         325899.83
                       80000      50      .5     .0136      3692977.20         305531.09
5       73      1      50000     150      .5     .0136       468345.26          38747.61
                       50000     150      .5     .0136       555287.89          45940.63
6      126     12      80000     150      .5     .0136      1393862.20         115318.40
                       80000     150      .5     .0136      1812020.80         149913.92
7       83      6      50000      50     1.5     .0136      1362458.90         112720.32
                       50000      50     1.5     .0136      1129740.80          93465.85
8       71     17      80000      50     1.5     .0136      1636273.00         135373.77
                       80000      50     1.5     .0136      1636273.00         135373.77
9       93     11      50000     150     1.5     .0136      1313799.70         108694.59
                       50000     150     1.5     .0136      1167821.90          96617.41
0       98     16      80000     150     1.5     .0136      2127154.90         175985.91
                       80000     150     1.5     .0136      2127154.90         175985.91


                  ANALYSIS ØF VARIANCE TABLE

RCE ØF        SUMS ØF        OF              F RATIØ        TREATMENT
IATIØN        SQUARES                                       EFFECTS
               5.65761 E 12   1                323.009       840953.
               3.09415 E 12   1                176.654      -621908.
               2.18146 E 11   1                12.4546      -165131.
               1.12143 E 10   1                .640255       37440.4
               5.71312 E 11   1                32.6178      -267234.
               1.32288 E 12   1                75.5269       406645.
               4.93181 E 11   1                28.1571       248289.
               4.53794 E 12   1                259.084       753155.
               1.57923 E 12   1                90.1624       444301.
               2.62656 E 10   1                1.49957       57299.2
               1.38108 E 11   1                7.88498      -131391.
               3.81037 E 11   1                21.7545      -218242.
               1.15377 E 12   1                65.8718      -379764.
               1.28486 E 12   1                73.3563       400759.
N              7.02432 E 11   1                40.1038       296317.

LICATE         416874496       1               2.38005 E-2

ØR             2.62730 E 11   15

AL             2.14353 E 13   31

ØR MEAN SQUARE=                1.75153 E 10
```

```
AOOITIØNAL FRAGMENTATIØN TEST OATA, RØ

CØMB.    TEST   SAMPLE       TREATMENT CØ
  #        #       #     PRESSURE    RATE
                             P         F

 407      404     24       50000      300
                           50000      300
 408      383     15       80000      300
                           80000      300
 409      391     21       50000      600
                           50000      600
 410      394     25       80000      600
                           80000      600
 411      401     26       50000      900
                           50000      900
 412      398     22       80000      900
                           80000      900
 413      418     24       50000      300
                           50000      300
 414      415     22       80000      300
                           80000      300
 415      413     21       50000      600
                           50000      600
 416      414     15       80000      600
                           80000      600
 417      416     26       50000      900
                           50000      900
 418      408     15       80000      900
                           80000      900


ANALYSIS ØF VARIANCE, RØCK TYPE NUMBER

                 MEAN SPECIFIC ENERGY

CØMBINATIØN #   MEAN SPECIFIC ENERGY (F
 407              336742.
 408              507421.
 411              130955.
 412              144564.
 413              361418.
 414              871765.
 417              98810.
 418              595175.


                 ANALYSIS ØF VARIANCE

SØURCE ØF        SUMS ØF          OF
VARIATIØN        SQUARES
P                 3.54620 E 11    1
F                 3.06828 E 11    1
PF                7.31462 E 9     1
N                 1.63008 E 11    1
PN                1.69095 E 11    1
FN                2.16765 E 8     1
PFN               5.11860 E 9     1

REPLICATE         5.74353 E 10     1

ERRØR             1.34294 E 11     7

TØTAL             1.19793 E 12    15

ERRØR MEAN SQUARE=                1.91849
```

```
TA, ROCK TYPE NUMBER:    5

ENT COMBINATION                            SPECIFIC ENERGY
 RATE  STANDOFF  NOZZLE
  F        S        N       FT.-LB./CU.IN.        JOULES/CU.CM.

 300      1.5     .0080      252556.65             20894.77
 300      1.5     .0080      420927.75             34824.62
 300      1.5     .0080      483258.42             39981.42
 300      1.5     .0080      531584.27             43979.56
 600      1.5     .0080      149663.20             12382.09
 600      1.5     .0080      168371.10             13929.85
 600      1.5     .0080      362056.59             29954.03
 600      1.5     .0080      222804.06             18433.25
 900      1.5     .0080      149663.20             12382.09
 900      1.5     .0080      112247.40              9286.56
 900      1.5     .0080      198776.17             16445.35
 900      1.5     .0080       90352.80              7475.16
 300      1.5     .0136      317342.92             26254.73
 300      1.5     .0136      405493.73             33547.71
 300      1.5     .0136      734119.11             60735.88
 300      1.5     .0136     1009413.80             83511.83
 600      1.5     .0136      211667.73             17511.91
 600      1.5     .0136      267625.86             22141.49
 600      1.5     .0136      421272.96             34853.18
 600      1.5     .0136      631909.44             52279.76
 900      1.5     .0136       89488.27              7403.63
 900      1.5     .0136      108131.66              8946.06
 900      1.5     .0136      342333.13             28322.25
 900      1.5     .0136      848017.00             70158.99

NUMBER:       5

ENERGY VALUES

RGY [FT.-LB./CU.IN.]



RIANCE TABLE


              F RATIO          TREATMENT
                               EFFECTS
               18.4843          297750.
               15.9932         -276960.
               .38127          -42762.8
               8.49668          201871.
               8.81396          205606.
               1.12988 E-2      7361.48
               .266804          35772.2

               2.99378


6

.91849 E 10
```

APPENDIX G

TEST RESULTS - SIOUX QUARTZITE (NO. 5)

```
KERFING FRAGMENTATION TEST DATA, ROCK TYPE NUMBER:   5

          PRESSURE = 50000 PSI = 34483.00 NEWTONS/SQ.CM.
          FEEORATE =    900 IPM = 38.10 CM./SEC.
          STANOOFF =    1.5 IN. = 3.810 CM.
          NOZZLE   = .0080 IN. = .20320 MM.

          SPACING BETWEEN CUTS = .125 IN. = .317 CM.

COMB.    TEST    SAMPLE   NUMBER           SPECIFIC ENERGY
  #        #        #     OF CUTS   FT.LB./CU.IN.        JOULES/CU.CM.

 411      401      26        1        149663.20            12382.09
                   26        1        112247.40             9286.56
 425      425      22        2         93165.34             7707.85
                   15        2         86430.50             7150.65
                   21        2         79695.65             6593.46
 425      425      22        3         93165.34             7707.85
                   15        3         99727.50             8250.76
                   21        3         74714.68             6181.37

     CUT NUMBER           AVERAGE SPECIFIC ENERGY PER CUT
                         FT.LB./CU.IN.         JOULES/CU.CM.

         1                130955.30              10834.32

         2                 64500.37               5336.31

         3                 95316.50               7885.82

      AVERAGE              79908.44               6611.06
```

3*4 FACTORIAL FRAGMENTATION TEST DATA, ROCK TYPE NUMBER: 5

COMB. #	TEST #	SAMPLE #	TREATMENT COMBINATION PRESSURE P	RATE F	STANDOFF S	NOZZLE N	SPECIFIC ENERGY FT.-LB./CU.IN.	JOULES/CU.CM.
282	24	10	50000	50	.5	.0080	1077575.00	89151.02
			50000	50	.5	.0080	881652.30	72941.74
283	237	15	65000	50	.5	.0080	1561559.90	129192.53
			65000	50	.5	.0080	1561559.90	129192.53
284	36	2	80000	50	.5	.0080	1135863.80	93973.42
			80000	50	.5	.0080	1363036.60	112768.11
285	202	17	50000	100	.5	.0080	639810.18	52933.42
			50000	100	.5	.0080	639810.18	52933.42
286	204	9	65000	100	.5	.0080	898431.72	74329.95
			65000	100	.5	.0080	739884.94	61212.90
287	211	21	80000	100	.5	.0080	874615.14	72359.53
			80000	100	.5	.0080	828582.77	68551.14
288	21	20	50000	150	.5	.0080	266587.57	22055.59
			50000	150	.5	.0080	293884.10	24313.91
289	206	19	65000	150	.5	.0080	818571.12	67722.84
			65000	150	.5	.0080	682142.60	56435.70
290	42	3	80000	150	.5	.0080	525337.02	43462.71
			80000	150	.5	.0080	631953.32	52283.39
291	207	15	50000	50	1.0	.0080	1296457.50	107259.81
			50000	50	1.0	.0080	1111249.30	91936.98
292	203	14	65000	50	1.0	.0080	1516103.50	125431.79
			65000	50	1.0	.0080	1637142.20	135445.69
293	226	5	80000	50	1.0	.0080	1840099.40	152236.94
			80000	50	1.0	.0080	2073762.80	171568.62
294	218	23	50000	100	1.0	.0080	798079.01	66027.47
			50000	100	1.0	.0080	818283.54	67699.05
295	234	19	65000	100	1.0	.0080	767410.43	63490.17
			65000	100	1.0	.0080	767410.43	63490.17
296	201	5	80000	100	1.0	.0080	1260808.80	104310.50
			80000	100	1.0	.0080	1095297.30	90617.23
297	219	22	50000	150	1.0	.0080	681902.95	56415.88
			50000	150	1.0	.0080	552257.20	45689.90
298	230	9	65000	150	1.0	.0080	698780.22	57812.18
			65000	150	1.0	.0080	698780.22	57812.18
299	238	21	80000	150	1.0	.0080	739934.15	61216.97
			80000	150	1.0	.0080	739934.15	61216.97
300	60	8	50000	50	1.5	.0080	1140112.90	94324.96
			50000	50	1.5	.0080	997598.76	82534.34
301	220	26	65000	50	1.5	.0080	1497386.20	123883.25
			65000	50	1.5	.0080	1842936.90	152471.69
302	26	18	80000	50	1.5	.0080	1765751.90	146085.95
			80000	50	1.5	.0080	1553861.70	128555.64
303	227	17	50000	100	1.5	.0080	562840.53	46565.49
			50000	100	1.5	.0080	562840.53	46565.49
304	222	24	65000	100	1.5	.0080	1469310.20	121560.44
			65000	100	1.5	.0080	1152987.40	95390.10
305	228	14	80000	100	1.5	.0080	1047834.40	86690.48
			80000	100	1.5	.0080	1289642.30	106695.98
306	4	4	50000	150	1.5	.0080	481060.28	39799.56
			50000	150	1.5	.0080	473543.72	39177.69
307	213	25	65000	150	1.5	.0080	657186.16	54370.98
			65000	150	1.5	.0080	657186.16	54370.98
308	16	7	80000	150	1.5	.0080	804191.58	66533.18
			80000	150	1.5	.0080	1005239.50	83166.48
309	254	14	50000	50	.5	.0120	1197118.50	99041.21
			50000	50	.5	.0120	1083022.30	89601.69
310	257	15	65000	50	.5	.0120	1651955.10	136671.20
			65000	50	.5	.0120	1526012.70	126251.61
311	256	19	80000	50	.5	.0120	1081680.00	89490.63
			80000	50	.5	.0120	1250692.50	103473.55
312	255	5	50000	100	.5	.0120	767140.82	63467.86
			50000	100	.5	.0120	920568.98	76161.43
313	265	22	65000	100	.5	.0120	898431.72	74329.95
			65000	100	.5	.0120	792733.87	65585.25
314	275	17	80000	100	.5	.0120	840045.37	69499.47
			80000	100	.5	.0120	878229.25	72658.54
315	258	21	50000	150	.5	.0120	432954.26	35819.60
			50000	150	.5	.0120	505113.30	41789.54
316	281	19	65000	150	.5	.0120	575557.82	47617.63
			65000	150	.5	.0136	563254.89	46599.77
317	249	24	80000	150	.5	.0120	859808.35	71134.52
			80000	150	.5	.0120	797376.40	65969.34
318	240	25	50000	50	1.0	.0120	1331334.30	110145.28
			50000	50	1.0	.0120	1331334.30	110145.28
319	2	22	65000	50	1.0	.0120	1212882.80	100345.43
			65000	50	1.0	.0120	985779.25	81556.47
320	276	14	80000	50	1.0	.0120	1353534.60	111981.98
			80000	50	1.0	.0120	1426077.00	117983.63
321	288	23	50000	100	1.0	.0120	776611.69	64251.42
			50000	100	1.0	.0120	847212.76	70092.45

3*4 FACTO

COMB. #
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3↑4 FACTORIAL FRAGMENTATION TEST DATA, ROCK TYPE NUMBER: 5

COMB. #	TEST #	SAMPLE #	TREATMENT COMBINATION PRESSURE P	RATE F	STANOOFF S	NOZZLE N	SPECIFIC ENERGY FT.-LB./CU.IN.	JOULES/CU.CM.
322	251	5	65000	100	1.0	.0120	736994.77	60973.79
			65000	100	1.0	.0120	782505.05	64738.99
323	264	23	80000	100	1.0	.0120	1095941.50	90670.53
			80000	100	1.0	.0120	1150062.10	95148.09
324	269	26	50000	150	1.0	.0120	483743.12	40021.52
			50000	150	1.0	.0120	443778.11	36715.09
325	271	5	65000	150	1.0	.0120	598954.48	49553.30
			65000	150	1.0	.0120	561519.83	46456.22
326	287	25	80000	150	1.0	.0120	732632.16	60612.86
			80000	150	1.0	.0120	676275.84	55950.33
327	262	25	50000	50	1.5	.0120	1553223.40	128502.83
			50000	50	1.5	.0120	1451229.40	120064.56
328	246	26	65000	50	1.5	.0120	1471773.00	121764.20
			65000	50	1.5	.0120	1511550.70	125055.12
329	280	9	80000	50	1.5	.0120	1640088.60	135689.45
			80000	50	1.5	.0120	1450847.60	120032.97
330	282	15	50000	100	1.5	.0120	947067.43	78355.38
			50000	100	1.5	.0120	1002798.50	82964.52
331	253	17	65000	100	1.5	.0120	1049610.10	86837.39
			65000	100	1.5	.0120	1137077.60	94073.84
332	270	24	80000	100	1.5	.0120	1041821.09	86192.97
			80000	100	1.5	.0120	1121310.60	92769.39
333	242	23	50000	150	1.5	.0120	621289.35	51401.13
			50000	150	1.5	.0120	698740.06	57808.86
334	284	21	65000	150	1.5	.0120	701899.78	58070.27
			65000	150	1.5	.0120	585584.96	48447.20
335	289	22	80000	150	1.5	.0120	766708.03	63432.06
			80000	150	1.5	.0120	743474.50	61509.88
336	65	5	50000	50	.5	.0136	1042698.20	86265.55
337	326	17	65000	50	.5	.0136	1373493.80	113633.26
			65000	50	.5	.0136	1428057.20	118147.46
338	88	13	80000	50	.5	.0136	3939175.70	325899.83
			80000	50	.5	.0136	3692977.20	305531.09
339	312	25	50000	100	.5	.0136	907147.41	75051.03
			50000	100	.5	.0136	729888.72	60385.88
340	294	24	65000	100	.5	.0136	1159137.40	95898.91
			65000	100	.5	.0136	1128227.00	93341.61
341	317	22	80000	100	.5	.0136	957219.70	79193.66
			80000	100	.5	.0136	920403.56	76147.75
342	73	1	50000	150	.5	.0136	468345.26	38747.61
			50000	150	.5	.0136	555287.89	45940.61
343	320	24	65000	150	.5	.0136	925592.64	76577.06
			65000	150	.5	.0136	832201.18	68850.50
344	126	12	80000	50	.5	.0136	4181586.60	345955.20
			80000	50	.5	.0136	5436062.50	449741.76
345	293	26	50000	50	1.0	.0136	1590654.00	131599.58
			50000	50	1.0	.0136	1584901.20	131123.63
346	[illegible]	26	65000	50	1.0	.0136	1460513.10	120832.63
			65000	50	1.0	.0136	1442482.00	119340.87
347	307	9	80000	50	1.0	.0136	1772629.10	146654.92
			80000	50	1.0	.0136	1838282.00	152086.59
348	306	14	50000	100	1.0	.0136	855012.50	70737.75
			50000	100	1.0	.0136	798011.66	66021.90
349	327	14	65000	100	1.0	.0136	1132348.40	93682.58
			65000	100	1.0	.0136	1258164.90	104091.76
350	310	21	80000	100	1.0	.0136	1048805.50	86770.83
			80000	100	1.0	.0136	1012930.90	83802.81
351	305	17	50000	150	1.0	.0136	606369.09	50166.73
			50000	150	1.0	.0136	656899.84	54347.29
352	308	19	65000	150	1.0	.0136	596225.91	49327.56
			65000	150	1.0	.0136	605842.46	50123.16
353	330	19	80000	150	1.0	.0136	807531.03	66809.46
			80000	150	1.0	.0136	807531.03	66809.46
354	83	6	50000	50	1.5	.0136	1362458.90	112720.32
			50000	50	1.5	.0136	1129740.80	93466.85
355	303	5	65000	50	1.5	.0136	1658854.40	137242.00
			65000	50	1.5	.0136	1658854.40	137242.00
356	71	17	80000	50	1.5	.0136	1636273.00	135373.77
357	309	15	50000	100	1.5	.0136	1138626.40	94201.98
			50000	100	1.5	.0136	1109430.80	91786.54
358	314	23	65000	100	1.5	.0136	1381454.00	114291.83
			65000	100	1.5	.0136	1514606.10	125307.91
359	325	5	80000	100	1.5	.0136	1378711.50	114064.94
			80000	100	1.5	.0136	1292542.00	106935.88
360	93	11	50000	150	1.5	.0136	1313799.70	108694.59
			50000	150	1.5	.0136	1167821.90	96617.41
361	329	9	65000	150	1.5	.0136	932065.32	77112.56
			65000	150	1.5	.0136	865489.22	71604.52
362	98	16	80000	150	1.5	.0136	2127154.90	175985.91
			80000	150	1.5	.0136	2127154.90	175985.91

```
ØRIAL FRAGMENTATIØN TEST DATA, RØCK TYPE NUMBER:   6

TEST  SAMPLE        TREATMENT CØMBINATIØN                               SPECIFIC ENERGY
  #      #     PRESSURE    RATE   STANØØFF   NØZZLE
                  P          F        S         N        FT.-LB./CU.IN.        JØULES/CU.CM.

   6     9      50000       50       .5      .0080         306953.47            25395.18
                50000       50       .5      .0080         275199.66            22768.09
  53    13      80000       50       .5      .0080         209697.94            17348.94
                80000       50       .5      .0080         215216.30            17805.49
  55     4      50000      150       .5      .0080          67348.44             5571.94
                50000      150       .5      .0080          67348.44             5571.94
  14    17      80000      150       .5      .0080         106904.83             8844.56
                80000      150       .5      .0080         102870.69             8510.80
   1    18      50000       50      1.5      .0080         252556.65            20894.77
                50000       50      1.5      .0080         212679.28            17595.60
   2    14      80000       50      1.5      .0080         218085.85            18042.90
                80000       50      1.5      .0080         209697.94            17348.94
  10     2      50000      150      1.5      .0080         108430.99             8970.82
                50000      150      1.5      .0080         100399.06             8306.32
  61     1      80000      150      1.5      .0080         116728.13             9657.27
                80000      150      1.5      .0080         121916.05            10086.48
 110    11      50000       50       .5      .0136         729888.72            60385.88
                50000       50       .5      .0136         648789.97            53676.34
 118    10      80000       50       .5      .0136         656529.29            54316.64
                80000       50       .5      .0136         738595.45            61106.22
 103     5      50000      150       .5      .0136         324394.99            26838.17
                50000      150       .5      .0136         299441.52            24773.70
  80    12      80000      150       .5      .0136          76595.08             6336.94
                80000      150       .5      .0136          87597.69             7247.22
 107    16      50000       50      1.5      .0136         686954.09            56833.77
                50000       50      1.5      .0136         729888.72            60385.88
  97    15      80000       50      1.5      .0136         854084.92            70661.01
                80000       50      1.5      .0136         869901.31            71969.54
  99     3      50000      150      1.5      .0136         311419.19            25764.64
                50000      150      1.5      .0136         283108.35            23422.40
  84     6      80000      150      1.5      .0136          88026.27             7282.68
                80000      150      1.5      .0136         101004.51             8356.41


          ANALYSIS ØF VARIANCE TABLE


F        SUMS ØF          DF                F RATIØ         TREATMENT
N        SQUARES                                            EFFECTS
          1.24563 E 10    I                  18.9077        -39459.3
          9.28607 E 11    1                  1409.55        -340699.
          2.47057 E 10    1                  37.5012        -55571.6
          3.86120 E 9     1                  5.86099         21969.3
          5.49589 E 9     1                  8.34231         26210.4
          745434495       1                  1.13151        -9652.94
          5.04012 E 9     1                  7.6505         -25100.1
          7.18257 E 11    1                  1090.26         299637.
          6.37752 E 9     1                  9.68056        -28234.5
          3.27019 E 11    1                  496.388        -202182.
          6.92812 E 10    1                  105.072        -93019.6
          4.36179 E 9     1                  6.62085         23350.
          2.28356 E 9     1                  3.46627         16895.1
          1.08246 E 10    1                  16.4308        -36784.1
          159753947       1                  .242494        -4468.7

E         81092608         1                 .123092

          9.88195 E 9      15

          2.12938 E 12     31

AN SQUARE=                658796407
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3*2 FACTØRIAL FRAGMENTATIØN TEST OATA, RØC

CØMB.    TEST   SAMPLE       TREATMENT CØMBIN
  #        #       #      PRESSURE    RATE  STA
                              P         F

 167       53      13       80000       50
                            80000       50
 168      140       8       80000      100
                            80000      100
 169       14      17       80000      150
                            80000      150
 170      163       7       80000       50
                            80000       50
 171      158      20       80000      100
                            80000      100
 172      159      19       80000      150
                            80000      150
 173      118      10       80000       50
                            80000       50
 174      168      18       80000      100
                            80000      100
 175       80      12       80000      150
                            80000      150


ADDITIØNAL FRAGMENTATIØN TEST DATA, RØCK T

CØMB.    TEST   SAMPLE       TREATMENT CØMBIN
  #        #       #      PRESSURE    RATE  STA
                              P         F

 383      396       9       50000      450
                            50000      450
 384      395       9       80000      450
                            80000      450
 385      393      14       50000      900
                            50000      900
 386      392      14       80000      900
                            80000      900


                   MEAN SPECIFIC ENERGY VAL

CØMBINATIØN #   MEAN SPECIFIC ENERGY (FT.-L
 383             52382.1
 384             58934.7
 385             35976.7
 386             47958.7


                   ANALYSIS ØF VARIANCE TAB

SØURCE ØF        SUMS ØF          DF
VARIATIØN        SQUARES
P                 1.71765 E 8     1
F                 3.74871 E 8     1
PF                1.47390 E 7     1

REPLICATE         7094880          1

ERRØR             426097850        3

TØTAL             994567456        7

ERRØR MEAN SQUARE=                1.42033 E 8
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ATA, RØCK TYPE NUMBER:    6

 CØMBINATIØN                                   SPECIFIC ENERGY
ATE  STANDØFF  NØZZLE
        S         N        FT.-LB./CU.IN.          JØULES/CU.CM.

 50      .5      .0080       209697.94             17348.94
 50      .5      .0080       215216.30             17805.49
100      .5      .0080       181738.21             15035.75
100      .5      .0080       204455.49             16915.22
150      .5      .0080       106904.83              8844.56
150      .5      .0080       102870.69              8510.80
 50      .5      .0120       223361.46             18479.36
 50      .5      .0120       195147.38             16145.13
100      .5      .0120       106935.60              8847.10
100      .5      .0120       104491.36              8644.88
150      .5      .0120       100749.24              8335.29
150      .5      .0120       117217.87              9697.79
 50      .5      .0136       656529.29             54316.64
 50      .5      .0136       738595.45             61106.22
100      .5      .0136       113086.38              9355.98
100      .5      .0136       125053.20             10346.03
150      .5      .0136        76595.08              6336.94
150      .5      .0136        87597.69              7247.22
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. RØCK TYPE NUMBER:    6

T CØMBINATIØN                                  SPECIFIC ENERGY
ATE  STANDØFF  NØZZLE
F       S         N        FT.-LB./CU.IN.          JØULES/CU.CM.

450      .5      .0080        44898.96              3714.63
450      .5      .0080        59865.28              4952.83
450      .5      .0080        71269.89              5896.37
450      .5      .0080        46599.54              3855.32
900      .5      .0080        37415.80              3095.52
900      .5      .0080        34537.66              2857.40
900      .5      .0080        45434.55              3758.94
900      .5      .0080        50482.84              4176.60

ERGY VALUES

Y [FT.-LB./CU.IN.]


 ANCE TABLE

                  F RATIØ        TREATMENT
                                 EFFECTS
                  1.20933         9267.28
                  2.63933        -13690.7
                  .103772         2714.69

                  4.99525 E-2


42033 E 8
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APPENDIX H

TEST RESULTS - BEREA SANDSTONE (NO. 6)

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KERFING FRAGMENTATIØN TEST DATA, RØCK TYPE NUMBER:    6

         PRESSURE = 50000 PSI = 34483.00 NEWTØNS/SQ.CM.
         FEEDRATE =   900 IPM = 38.10 CM./SEC.
         STANDØFF =    .5 IN. = 1.270 CM.
         NØZZLE   = .0080 IN. = .20320 MM.

         SPACING BETWEEN CUTS = .093 IN. = .236 CM.

CØMB.    TEST    SAMPLE    NUMBER            SPECIFIC ENERGY
  #        #        #      ØF CUTS   FT.LB./CU.IN.          JØULES/CU.CM.

 385      393      14         1        37415.80               3095.52
                   14         1        34537.66               2857.40
 426      426       2         2        22449.48               1857.31
                    8         2        20153.51               1667.36
                   20         2        23966.34               1982.81
 426      426       2         3        17990.34               1488.39
                    8         3        17501.73               1447.97
                   20         3        19001.88               1572.08

      CUT NUMBER            AVERAGE SPECIFIC ENERGY PER CUT
                          FT.LB./CU.IN.        JØULES/CU.CM.

          1                 35976.73              2976.46

          2                 16042.13              1327.21

          3                 13329.01              1102.75

       AVERAGE              14685.57              1214.98
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CTØRIAL FRAGMENTATIØN TEST OATA, RØCK TYPE NUMBER:    7

 TEST   SAMPLE        TREATMENT CØMBINATIØN                          SPECIFIC ENERGY
   #       #    PRESSURE    RATE  STANOØFF  NØZZLE
                    P          F        S          N      FT.-LB./CU.IN.        JØULES/CU.CM.

  59       6      50000       50       .5      .0080      621677.90            51433.28
                  50000       50       .5      .0080      673484.40            55719.38
  47      20      80000       50       .5      .0080     1258187.60           104093.64
                  80000       50       .5      .0080     1258187.60           104093.64
  64      11      50000      150       .5      .0080      316933.83            26220.89
                  50000      150       .5      .0080      316933.83            26220.89
  12       1      80000      150       .5      .0080      685777.78            56736.45
                  80000      150       .5      .0080      783746.03            64841.66
  63       4      50000       50      1.5      .0080      425358.57            35191.19
                  50000       50      1.5      .0080      621677.90            51433.28
  49       7      80000       50      1.5      .0080     2044554.90           169152.16
                  80000       50      1.5      .0080     1635643.90           135321.73
  39       3      50000      150      1.5      .0080      340951.47            28207.94
                  50000      150      1.5      .0080      170475.74            14103.97
  62      18      80000      150      1.5      .0080      613366.46            50745.65
                  80000      150      1.5      .0080      788614.02            65244.40
 108      13      50000       50       .5      .0136     4671287.80           386469.65
                  50000       50       .5      .0136     2335643.90           193234.83
  79      19      80000       50       .5      .0136     1543902.70           127731.71
                  80000       50       .5      .0136     1650378.80           136540.79
  66       9      50000      150       .5      .0136      606369.09            50166.73
                  50000      150       .5      .0136      437933.23            36231.53
 125       8      80000      150       .5      .0136     1750744.80           144844.37
                  80000      150       .5      .0136     1750744.80           144844.37
 112      10      50000       50      1.5      .0136     1459777.40           120771.77
                  50000       50      1.5      .0136     1167821.90            96617.41
 119      17      80000       50      1.5      .0136     3889936.00           321826.08
                  80000       50      1.5      .0136     4243566.60           351082.99
 122       2      50000      150      1.5      .0136      515788.03            42672.69
                  50000      150      1.5      .0136      429823.36            35560.58
 127      15      80000      150      1.5      .0136     2279094.50           188556.33
                  80000      150      1.5      .0136     2279094.50           188556.33


               ANALYSIS ØF VARIANCE TABLE

 ØF         SUMS ØF           DF              F RATIØ           TREATMENT
TIØN        SQUARES                                             EFFECTS
              5.56410 E 12    1                29.7754           833974.
              7.44470 E 12    1                39.8391          -964670.
              1.57968 E 11    1                .845338           140520.
              1.57306 E 11    1                .841796           140226.
              4.45570 E 12    1                23.8439           746299.
              1.56450 E 10    1                8.37216 E-2      -44222.4
              2.83232 E 12    1                15.1567          -595013.
              1.06449 E 13    1                56.9643           1.15352 E 6
              1.48843 E 11    1                .79651            136402.
              1.27631 E 12    1                6.82998          -399424.
              1.32220 E 12    1                7.07555           406541.
              1.96123 E 10    1                .104952           49513.
              2.53526 E 12    1                13.567            562945.
              7.06670 E 10    1                .378163           93986.1
              1.44761 E 12    1                7.74663          -425383.

CATE          1.92191 E 11     1               1.02848

              2.80304 E 12    15

              4.10883 E 13    31

 MEAN SQUARE=                1.86869 E 11
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3*2 FACTØRIAL FRAGMENTATIØN TEST OATA, R

CØMB.    TEST   SAMPLE       TREATMENT CØMB
  #        #       #    PRESSURE    RATE  S
                            P          F

 176      47      20      80000       50
                          80000       50
 177     142       5      80000      100
                          80000      100
 178      12       1      80000      150
                          80000      150
 179     155      12      80000       50
                          80000       50
 180     147      16      80000      100
                          80000      100
 181     146      14      80000      150
                          80000      150
 182      79      19      (0000       50
                          (0000       50
 183     169       1      80000      100
                          80000      100
 184     125       8      80000      150
                          80000      150


ADDITIØNAL FRAGMENTATIØN TEST DATA, RØCK

CØMB.    TEST   SAMPLE       TREATMENT CØMB
  #        #       #    PRESSURE    RATE  S
                            P          F

 387     388       3      50000      450
                          50000      450
 388     387       3      80000      450
                          80000      450
 389     400      20      50000      900
                          50000      900
 390     399      20      80000      900
                          80000      900


                        MEAN SPECIFIC ENERGY V

CØMBINATIØN #  MEAN SPECIFIC ENERGY (FT.
 387           86961.6
 388           346955.
 389           62003.3
 390           160768.


                        ANALYSIS ØF VARIANCE T

SØURCE ØF      SUMS ØF          DF
VARIATIØN      SQUARES
P               6.43538 E 10    1
F               2.22910 E 10    1
PF              1.29973 E 10    1

REPLICATE       56201984         1

ERRØR           3.06352 E 9      3

TØTAL           1.02762 E 11     7

ERRØR MEAN SQUARE=               102117230
```

```
EST DATA, RØCK TYPE NUMBER:    7

ATMENT CØMBINATIØN                          SPECIFIC ENERGY
E   RATE  STANDØFF  NØZZLE
     F        S        N        FT.-L8./CU.IN.       JØULES/CU.CM.

    50       .5     .0080       1258187.60          104093.64
    50       .5     .0080       1258187.60          104093.64
   100       .5     .0080       1153713.10           95450.15
   100       .5     .0080        672999.31           55679.25
   150       .5     .0080        685777.78           56736.45
   150       .5     .0080        783746.03           64841.66
    50       .5     .0120       1520082.10          125760.95
    50       .5     .0120       1363036.60          112768.11
   100       .5     .0120        876237.81           72493.78
   100       .5     .0120       1082411.40           89551.14
   150       .5     .0120        532436.17           44050.04
   150       .5     .0120        621033.54           51379.97
    50       .5     .0136       1543902.70          127731.71
    50       .5     .0136       1650378.80          136540.79
   100       .5     .0136       1181752.70           97769.95
   100       .5     .0136       1074320.70           88881.77
   150       .5     .0136       1750744.80          144844.37
   150       .5     .0136       1750744.80          144844.37
```

```
 OATA, RØCK TYPE NUMBER:    7

ATMENT CØMBINATIØN                          SPECIFIC ENERGY
E   RATE  STANDØFF  NØZZLE
     F        S        N        FT.-L8./CU.IN.       JØULES/CU.CM.

   450       .5     .0080        115988.98            9596.12
   450       .5     .0080         57934.14            4793.07
   450       .5     .0080        330433.[illegible]          27337.72
   450       .5     .0080        363476.[illegible]          30071.49
   900       .5     .0080         59865.28            4952.83
   900       .5     .0080         64141.37            5306.61
   900       .5     .0080        139798.62           11565.96
   900       .5     .0080        181738.21           15035.75

IC ENERGY VALUES

ENERGY [FT.-L8./CU.IN.]



 VARIANCE TABLE


 OF                  F RATIØ          TREATMENT
                                      EFFECTS
 1                    63.0195          179379.
 1                    21.8289         -105572.
 1                    12.7278         -80614.1

  1                   5.50367 E-2

  3

  7

  1021172309
```

APPENDIX I

TEST RESULTS - TENNESSEE MARBLE (NO

```
KERFING FRAGMENTATIØN TEST DATA, RØCK TYPE NUMBER:    7

          PRESSURE = 50000 PSI = 34483.00 NEWTØNS/SQ.CM.
          FEEDRATE =   900 IPM = 38.10 CM./SEC.
          STANDØFF =    .5 IN. = 1.270 CM.
          NØZZLE   = .0080 IN. = .20320 MM.

          SPACING BETWEEN CUTS = .125 IN. = .317 CM.

CØMB.    TEST    SAMPLE    NUMBER          SPECIFIC ENERGY
  #        #        #      ØF CUTS   FT.LB./CU.IN.          JØULES/C
 389      400      20        1          59865.28               4952
                   20        1          64141.37               5306.
 427      427       S        2          46080.51               3812
                   14        2          44898.96               3714
                   16        2          47262.06               3910.
 427      427       S        3          43776.49               3621
                   14        3          46447.20               3842.
                   16        3          48106.03               3979.

     CUT NUMBER          AVERAGE SPECIFIC ENERGY PER CUT
                         FT.LB./CU.IN.        JØULES/CU.CM.

         1                 62003.33              5129.72

         2                 36664.78              3033.39

         3                 46168.80              3819.68

      AVERAGE              41416.79              3426.54
```