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AN INVESTIGATION OF COMBINED THERMAL WEAKENING AND MECHANICAL DISINTEGRATION OF HARD ROCK

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Semi-Annual Report

by

G.B. Clark, T.F. Lehnhoff, V. Allen, M. Patel
Rock Mechanics & Explosives Research Center
University of Missouri-Rolla

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SUMMARY

The research under modified Contract No. H0220068 has been devoted to experimental thermal-mechanical fragmentation of Missouri red granite in place, and to supporting theoretical analyses. The results of the previous year's experimental work showed that thermal stresses are several times more effective in fragmenting hard rock when they are created within the rock rather than upon the surface. Also, large blocks (4-foot cubes) are not adequate to simulate the response of in situ rock.

Based upon laboratory tests an experimental round was designed analogous to an explosive blasting round with coiled wire heating elements placed in drill holes. Three displacement relief faces were required for effective fracture at a 5 kw power level for a 10 inch burden. However, the heaters clogged and failed, and although the rock was effectively fractured, the fragments required considerable mechanical effort to remove them. Electric arcs at 12 kw, utilizing carbon electrodes were employed to create thermal inclusions, and in holes 14 inches in depth with equal burden. The rock was fractured and easily removed, as was also the case with 20 inches depth and overburden. Experiments are in progress to optimize round geometry and energy levels. Major problems are the brittleness of the carbon electrodes, and maintaining of a stable arc as the heating is begun. Both of these problems are being solved.

Theoretical analyses of temperature and thermal stress distribution are progressing well and procedures are being refined for use of more accurate boundary conditions, temperature-dependent rock properties, and other input parameters. Laboratory experiments are being conducted to determine stress and temperature distribution for a cylindrical geometry for basalt. Calculations of projected rates of advance and excavation costs indicate that for a slot type round the process is technically and economically feasible.

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INTRODUCTION

Thermal stresses have been employed since antiquity in the fragmentation of rock. The most active use of heat in recent and current operations has been that of the flame jet for drilling, and the cutting and facing of spallable monument stone. Its successful employment led to a research project (1) on the feasibility of a flame jet tunneling machine, i.e., the utilization of flame jets for weakening hard rock to make it more susceptible to roller cone cutting. Slot cutting with heat and wedging of ridges between kerfs was also suggested as a possible excavation process. Large amounts of excess heat and combustion generated gas, inefficiency of heat transfer from a flame jet to rock, and other factors appeared to mitigate against its use, as well as the moderate increase of rock removal efficiency achieved by roller cones.

The advantages of tunnel boring machines in soft to medium hard rock, which they can excavate economically, and the disadvantages of drill and blast methods (cyclic character, overbreak into walls, and vibration and noise problems) have led to an intensive search for novel methods which will increase tunneling capabilities in hard rock. Of the several methods recently investigated, the use of heat has been the subject of considerable research, some fourteen techniques for drilling and fragmentation having been proposed and investigated. Flame jets have been in use for several decades, but have only limited application for drilling and quarrying. Various types of heat drills investigated to date have not been applied extensively because of nonadaptability of of equipment to underground conditions, environmental problems created by the excavation device, high energy consumption, or because results obtained in the laboratory could not be applied to rock in place.

Because it was found that thermal energy is much more effective in fragmenting rock when it is applied internally, the research described in this report was designed to evaluate the basic engineering factors in the development of a thermal round (of the same concept as a high explosive blasting round) for fragmentation of hard rock for use in a tunnel excavation system. The total concept includes a study of heat sources, hole placement and geometry, pertinent mineral and rock properties, heat transfer, temperature distribution, thermal stress distribution, fracture initiation and propagation, required rock displacement relief, methods of slot cutting, and related factors. Based upon these findings, existing mining equipment will be modified, or new equipment designed to accomplish the operation of the fragmentation process. Three years of research (as of June 1973) will have been completed on thermal fragmentation. The next phase will require a joint effort with a mining machinery manufacturing company, and the research will be phased over into full equipment and system development as soon as practical.

It should be noted that, while most recent related technical literature has emphasized the specific energy of drilling, breakage and other types of rock removal, the absolute value of this factor for a given rock and process combination is seldom a deciding factor by itself unless a critical value for specific energy is exceeded. The most critical operational factor, assuming specific energy requirements are not near or above maximum permissible values, is the rate of advance, for both drilling and excavation.

An evaluation of a method of thermal rock drilling and excavation can be made by assessing the following factors:

1. Current status
    a. Theory
    b. Research
    c. Development
2. Energy and fracture characteristics
    a. Specific energy requirements
    b. Efficiency of energy transfer
    c. Availability of energy
    d. Control of energy source
3. Application characteristics
    a. Control of energy within the rock
    b. Preservation or strengthening walls and roof
    c. Smoothness of opening excavated
    d. Efficiency of energy utilization
    e. Environmental factors
    f. Adaptability to variable rock properties and conditions
    g. Feasibility of equipment design and construction
    h. Continuity of method - down time
    i. R & D required
    j. Time to develop and apply new method
    k. Rate of advance
4. Cost factors
    a. R & D
    b. Capital equipment
    c. Operating: labor, materials, etc.
    d. Overhead

Many of the above factors have been studied in detail in relation to this research project. Theoretical and experimental studies are in advanced stages on heat transfer, thermal stress analysis, and effects of thermal properties of minerals and rocks. Extensive field tests of thermal fragmentation of granite have reached a stage which indicates a high probability of successful application. Rate of advance and cost analysis studies are in progress.

SCIENTIFIC AND ENGINEERING BACKGROUND

While there have been comprehensive studies made of thermal properties of minerals and rocks, only a limited number of investigations have been made of the specific scientific and engineering factors which are directly related to the problems posed by this investigation. There is a large fund of information from ceramics studies of heating and melting of synthetic silicates and selected clays, studies of the calcination of carbonates in their sintering for manufacture of Portland cement, and the physical chemistry of various types of rock in geologic studies of igneous action and metamorphic processes. Several experimental programs have been carried out on thermal stresses and fracture in rock, but there are few data available on rock properties as functions of temperature, or of melt properties.

Thermal Rock Drilling and Fracture

Twelve methods of drilling or breaking rock by thermal means were reviewed by Maurer in 1968 (2). These included flame jet (jet piercing), electric disintegration by low frequency current, cyclic heating and cooling with superheated steam and liquid nitrogen, high frequency currents, microwaves, induction, fusion and vaporization, nuclear heat (penetration), electric arc (drill), plasma drill, electron beam, and lasers. Carstens (3) reviewed several of these methods again in 1972, and described an additional method of forming an internal thermal inclusion and fracturing rock (4). Considerable research has been accomplished in the past four years, particularly on electron beams (5), lasers (6 and 7), with flame jets (1,8,9 and 10), high temperature penetrators (11), plasma jets (12), resistance wire and electric arc heaters(13).

Coiled wire resistance heaters made of Kanthal wire at 1000°C were found (UMR) to fracture hard granite when they were placed in pneumatically drilled holes, but heaters failed after short term usage. However, electric arcs from carbon electrodes generate an effective thermal inclusion in solid granite and multiple holes create thermal stress fields which will fracture over distances of 2 feet or more at reasonable electrical energy levels. Tests to date have yielded promising results for application.

Several approaches have been suggested in the last decade for the possible use of heat application within the rock mass to cause fragmentation. The fracture of rock by internal heating by means of electrical conduction through the rock has been the subject of several patents by Sarapu (14), the first issued in 1965. In a study of laser effects on rock Zar (6) proposed that a heated annulus on the surface of a hard rock face would cause the rupture of a section of the rock face. However, this assumes that the rock is free from fractures, joints, etc.

Thirumalai (15) was the first to report in 1970 on a method of formation of a controlled internal thermal inclusion, in this instance by dielectric heating. Laboratory test blocks of granite and basalt, somewhat larger than one foot on a side were fragmented without melting by localized heating below 600°C, the heated volume being less than 2 percent of the total rock volume. As a first approximation, a thermal inclusion was considered to exert a pressure on the inside of a cylindrical hole in an infinitely thick cylinder. However, quartzite blocks could not be fragmented by dielectric heating because of its electrical resistance.

The total electrical energy required to fracture Dresser basalt blocks varied from 0.067 to 0.100 kwhr, and the volume to thermal inclusion from 105 to 206 cc. For granite the electrical energy was 0.10 kwhr and the volume of the thermal inclusion was 206 to 350 cc. Time for fracture was less than 2 minutes. In a recent test (December 1972) at UMR a 2 foot cube of Missouri red granite was fractured by means of a rock (partially fused) melt created in a drill hole in the center of the rock with carbon electrodes. The total electrical energy was approximately 1 kwhr and the volume of the melt about 380 cc, the total heated volume of rock being larger. This represents about 0.2 percent of the total volume of the block. Similar results were obtained in granite in situ. (See Research Results).

The amounts of electrical energy per unit volume of rock broken are in the ratio of 1.6:1 for Missouri red granite cubes as compared to the basalt and granite cubes fractured by Thirumalai. The time for fracture and the total energy applied vary approximately as the volume of the block, indicating that the cube root law for energy usage may apply for similar rocks and test geometries.

In each of the above experiments, as in investigations reported by Nixon (5) with electron beams, radial cracks as well as cracks normal to the axis of the hole or inclusion were formed. Nixon (5) reports that temperature distributions were calculated by empirical formulas, with the assumption of a 1700°C melting temperature at the boundary of an advancing cylindrical cavity. Stresses were calculated by means of a finite element program utilizing values of Young's modulus, Poisson's ratio and thermal coefficient of expansion as functions of temperature. Both tangential and radial stresses near the cavity were found to be compressive, while in the cold zone the radial stresses were tensile.

Nixon also came to the conclusion that for transient penetration and heating the compressive stresses and gradients are typically larger by an order of magnitude than the tensile stresses and gradients. The expansion of the cavity along its axis and the radial growth of the heated region cause tensile stresses in the axis-radius plane and in the tangential direction. At depths equal to the melt cavity and below, the tensile stresses in the r-axis plane are larger than the tangential stresses, creating favorable conditioning for a crack normal to the axis. The calculations were confirmed only by the behavior of blocks of quartzite, however, but not with other types of rock. Similar stress patterns occur in rock for quasi-static cylindrical heat sources.

Thirumalai proposed an application of dielectric internal heating of ore and rock in stopes where two free faces exist for displacement relief. However, the feasibility of breakage by this means was not tested. Thirumalai (16) also suggested two types of tunnel rounds using thermal inclusions, one with a cut at the bottom of the face, and a V-cut type round with no strain relief other than the tunnel face. The feasibility of such tunnel rounds also was not investigated.

Investigators at LASL (17) have proposed a somewhat similar approach to hard rock tunneling utilizing a heating head which forces heated rods into the face by melting which, it is postulated, will cause local thermal stresses to spall rock fragments from the face. However, for effective spallation it has been found in experiments at UMR that effective fractures (two or three directions) are not caused by internal heating unless sufficient displacement relief is provided so that cracks can be initiated and propagated. "No cut" rounds of similar design have proven usable with explosives, but the fracture process in the latter case depends upon high order stress waves.

The specific energy of rock removal by drilling and other methods has received much attention in the literature. As pointed out earlier in this report the energy of breakage or of other type of rock removal by itself is not a sufficient criterion for evaluating the economic feasibility of a method. Many of the costs per foot of drilling and of costs per foot of advance of tunnel face are determined largely by the rate of advance.

A more meaningful measure of the energy effectiveness of a given method of rock breakage is the rate of advance per unit of specific energy, i.e., the (cm/min)/(joules/cc). Calculated values obtained from drilling data given by Maurer (2) are:

	Diam hole cm	(cm/min)/(joules/cc) x 10^3 Hard rock	Very hard rock
Pneumatic			
Jack hammer	3.8	2.85	1.35
Drifter	4.8	6.66	2.64
Blast hole	7.6	3.33	1.49
Rotary (mining)			
Roller	20	95.2	5.95
Diamond	5	17.8	1.11
Rotary (oil field)			
Roller drag	20	5.95	0.952
Diamond	20	1.42	0.357
Jet piercing	20	--	10.0

The lower rate-high energy methods appear to be usable only in special applications such as exploratory drilling, and not in operations where rapid rate of advance and removal of large volumes of rock are required.

A comparison of the rates of advance per unit of absorption of energy in drill penetration (Fig. 1) shows that for their particular application pneumatic drills have the highest rate of advance for energy input into the rock. Their actual rate of penetration is also the most favorable, i.e., three to six times faster than diamond drills of the same diameter, and 120 times faster than drilling by melting the rock. As shown elsewhere herein even though the energy consumption may be high, critical variable costs per foot are determined largely by the rate of advance.

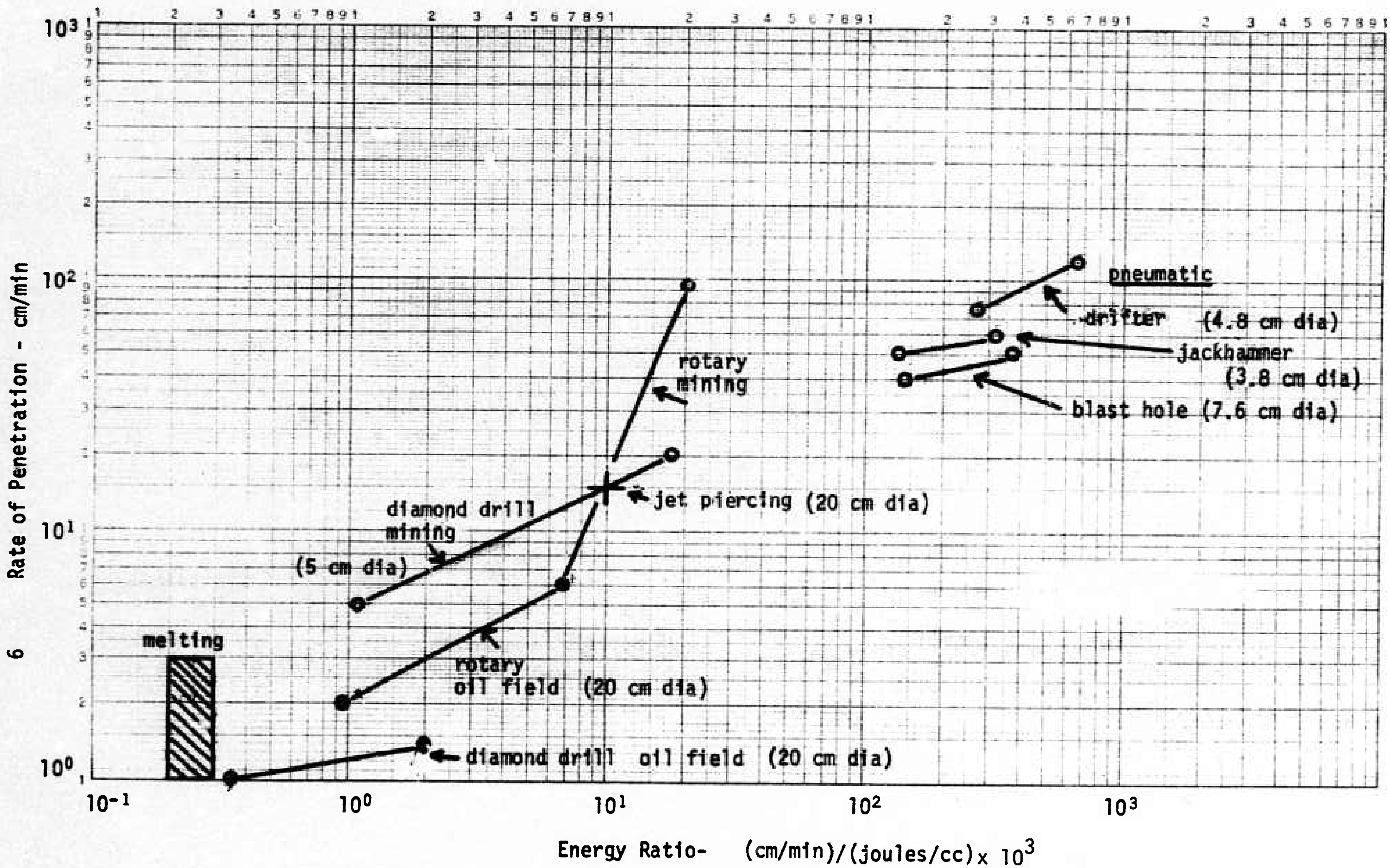

Fig. 1. Specific energy - rate of penetration for drilling methods.

Displacement Relief

If one considers a section of a heated cylindrical hole near the corner of a quadrant of an infinite elastic body, after the heat has been applied for a certain time there is a biaxial compressive stress immediately around the hole which changes to (tangential) tension with increase in distance from the hole. With increase in time the compressive zone increases as does the tensile zone, the magnitude of the latter decreasing with constant hole diameter. If the medium were infinite, radial cracks would form, their orientation depending upon imperfections in the medium. However, if there is one free face within a distance b such that the magnitude of the tensile stress is affected by the free surface, a crack will propagate from the hole normal to the free surface, but it will not widen because of the constraining effect of the mass. If two free surfaces exist within a critical distance b of the stressed hole, then two cracks will propagate from the hole normal to the two free surfaces. One of the objectives of the proposed experimentation is to determine the value of b for given rock properties, hole size, and energy level.

For three dimensions an octant of an infinite mass (the corner of a large cube) is considered, with multiple holes drilled parallel to one face. The problem becomes as indicated above one of determining the optimum distance from a free surface (burden), the spacing, plus depth of the hole. The holes act as loci for stress concentration and fracture guides. However, three planes within critical distances of the thermal inclusion are required for controlled fracture.

Theory of Thermal Fracture of Rock

It is a well established principle of blasting that a cylindrical column of explosive must have a free face to which to break. With stress waves generated by explosives the free face provides a means for spallation by reflected waves to occur and subsequent fracture to the explosive will take place in a properly designed round. Each hole is placed so that it will provide the necessary free faces to which other holes may break. The expanding explosive gases also assist in breaking the rock.

The process of fracture from thermal inclusions is different in several ways from fracturing by explosives. When a heater is placed in a hole in the rock a thermal stress is generated around the hole. The immediate periphery of the hole is in biaxial compression with a tensile stress beyond. The magnitude of the tensile stress depends upon the properties of the rock, the temperature and the radius of the hole.

The nonstationary state of stress due to a constant temperature suddenly applied to a spherical cavity in an infinite medium was analyzed theoretically by Sternberg (18). The radial displacement of the cavity surface is zero for all time. The temperature drops rapidly with distance away from the cavity surface (Fig. 2) and does not penetrate beyond 3 cavity radii (a) for $\tau = 3$ ($\tau = \frac{\kappa t}{a^2}$, t = time, κ = diffusivity). Radial displacement increases with time as does the radial stress, which is always compressive.

The tangential stress at a given r/a greater than one is compressive, becomes tensile and then compressive again with increase in time. The magnitude of the tensile stress decreases with r/a.

For constant diffusivity, the magnitude of the tangential tensile stresses is largest for small values of r/a, or for large values of the cavity radius, and increases linearly with the cavity temperature.

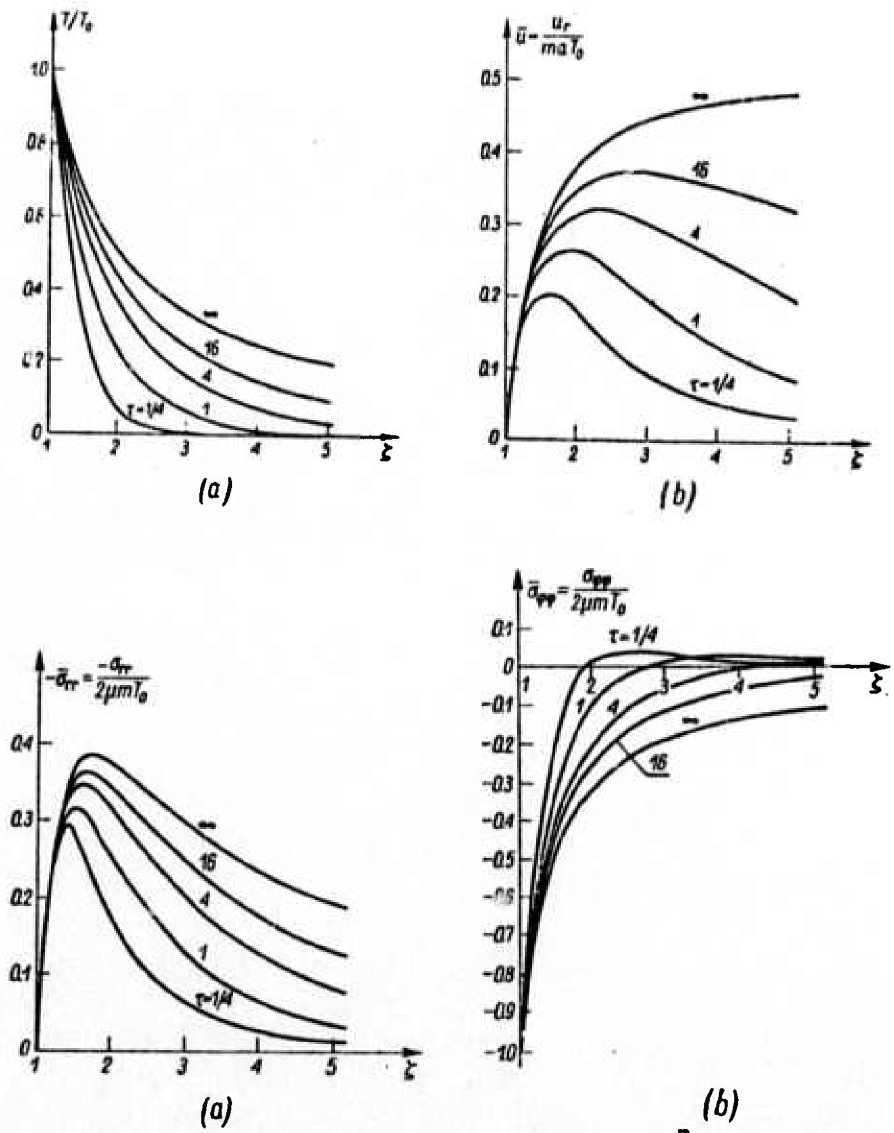

Fig. 2. Temperature distribution, displacement and thermal stresses around a spherical cavity in an infinite medium ($\zeta = r/a$). (18)

The curves in Figure 2 may serve as approximate guides to the thermal stress history around the thermal inclusion created by carbon electrodes in a hole in solid granite face. However, the cavity in granite increases in size with time and some of the rock properties are temperature dependent. Also, the stress pattern is altered by the presence of the drill hole.

The analysis by Sternberg (18) agrees qualitatively with that by Nixon (5), the latter being the (cylindrical) finite element thermal stress analysis for electron beam penetration. That is, the magnitudes of compressive stresses are ten times those of the tensile stresses, and for longer heating times the zone of tension extends considerably beyond the heated zone.

The initiation and propagation of fractures in rock in the configurations used herein due to internal thermal stresses are controlled by two important factors, (1) the magnitude and direction of the tensile stresses, and (2) strain relief due to compressibility of the rock or nearby traction-free surfaces. Computations are based upon the classicial fracture theories.

<u>Displacement Relief and Fracture</u>

When a high temperature source is placed in a cylindrical or spherical cavity in an infinite (rock) medium, thermal stresses are induced in patterns as indicated above (18). This may be shown graphically (Fig. 2) for a given time after a temperature T_0 has been applied to the surface of the cavity.

When the tensile stress exceeds the strength of the material a crack normal to the stress direction will form. However, the distance it will propagate and the amount it will widen depends upon displacement relief. In nonporous hard granite it has been found that the rock cannot move normal to the crack unless there are three planes or faces of strain relief within critical distances. (In this respect thermal stresses function differently than explosively induced stresses which will create craters with only one free face). With less than minimum displacement relief only hairline fractures are formed, extending into the cavity and a short distance into the rock. However, where free faces are present and multiple heater holes furnish stress fields which reinforce each other, cracks propagate for longer distances and widen to 1/4 inch or more due to the expansion of the rock around the cavities. The blocks of rock formed by the fracture are easily removed. That is, thermal forces have demonstrated a significant amount of follow-through in dislodging the fractured blocks in experimental tests. (See below).

Electric Arcs

A review of some of the important characteristics of electric arcs was made (19) in relation to an investigation of the feasibility of their use in drilling oil wells. Their performance in air and water was of direct interest in these studies, and much of this information is of basic interest in the rock fragmentation research with which this project is concerned.

The low voltage required for arcs may be advantageous for rock breakage, i.e., it is generally easier and safer to use in underground environments. McMaster (19) reports that the voltage drop (dc) at the cathode is of the order of the least ionization potential of the gas or vapor in which it burns. The arcs employed in drilling experiments were subject to severe transients and rapid fluctuations in length, position, current and voltage so that the average characteristics might not correspond to a steady state operating condition. The temperature of the arc column in air has been measured and varied from 4330°C to 7330°C at atmospheric pressure, and as high as 10,760°C in the center of the arc column for high current arcs. It is noted that the temperature of the surrounding gas just a few hundredths of an inch from the boundary of the arc is nearly ambient. Also, the temperature of the electrodes cannot exceed their boiling temperature, and hence, very large temperature gradients exist at the ends of the arc and at its boundaries. Conduction, convection, and ionization potential affect the voltage gradient and arc-column diameter. If the ionization potential is lowered by the presence of easily ionized substances, the voltage gradient and temperature are reduced.

Heat is lost from the arc-column by conduction, convection, and diffusion through the surrounding gas. It is estimated that about 15 percent of the heat is lost by radiation. Most chemical compounds, particularly gases, are completely dissociated at arc temperatures, and contribute to transfer of heat. That is, dissociated atoms, ions and electrons diffuse from the arc column, and when they recombine in the cold surroundings they give up their energy of dissociation.

The voltage gradient of the arc is related to the current by

$$E = B/i^n$$

where

E = voltage gradient

i = current

n and B = constants

For nitrogen and air, n = 0.60, and for steam n = 0.59. Its value for the material in the arc-column in molten rock is not known, but for basalt, granite, and quartzite the arc becomes stable after a melt is formed. The above is an opposite effect than that described by Ohm's law. This negative characteristic requires a series resistance to maintain a stable arc.

The current density in high current arcs may be as high as 20,000 amps/in^2. An amount of heat, approximately equal to the voltage drop at the electrode times the arc current, is produced at each electrode, and an additional amount from the recombination of dissociated molecules.

Arc stability, or its ability to reignite after short circuit, or after each reversal of alternating current is determined by the arc characteristics and the recovery-voltage capabilities of the power source. It has been found that superposition of high frequency voltages may add to the stability of arcs. An arc is usually started by bringing the electrodes in contact, or by "striking the arc", preferred voltages for dc being 60 to 150 volts and for ac, 80 to 200 volts.

Cost Analysis

The direct costs for excavation are usually considered under the categories of fixed costs, or those which are constant per foot of advance, and variable costs, which are constant per day charges, and consequently vary with the rate of advance. Examples of fixed costs are power and bit wear, and variable costs are equipment and labor costs. Overhead costs also fall into the last category.

It is not possible to make a simple comparison by category of the direct costs of rock breaking or removal by such methods as tunnel boring machines, drill and blast, and excavation utilizing heating processes, because of differences in the operational characteristics of each. Also, each method has different types of trade-off costs. For example, the smooth walls created by tunnel boring machines may reduce the cost of tunnel support, and one method may require less ventilation than another, or incur higher muck removal costs.

Hence, a fair comparison of methods would need to include cost factors in all categories which are affected by the overall operation.

Costs for Rock Breaking and Drilling

In a study of excavation costs in rocks in the NE Corridor by Harza Engineering Company in 1968 (20) rock breaking costs were given for four general types of rock:

X. Rocks assumed to be mineable with boring machines with relative drillability factors between 5 and 7, average unconfined compressive strength 4000 to 32,000 psi.

Y. Same as X with higher average compressive strengths, 18,000 to 32,000 psi, 65 percent of rock type is mineable with boring machines. Relative drillability factor of 1 to 4.

Z. Rocks of somewhat the same strength as Y, but requiring conventional drill and blast methods.

D.G. Difficult ground associated with faults, gouge, susceptible to squeezing.

The representative direct rock breaking costs were categorized as follows by percentage distribution:

Unit	X	Y	Z	DG
Labor	33	39	50	30
Equipment	62	54	38	65
Materials	5	7	12	5

It is notable that labor costs are the highest for drill and blast (Z) partly due to the cyclic nature of this method. It is notable also that costs per foot increase almost linearly with the excavated diameter (Fig. 3).

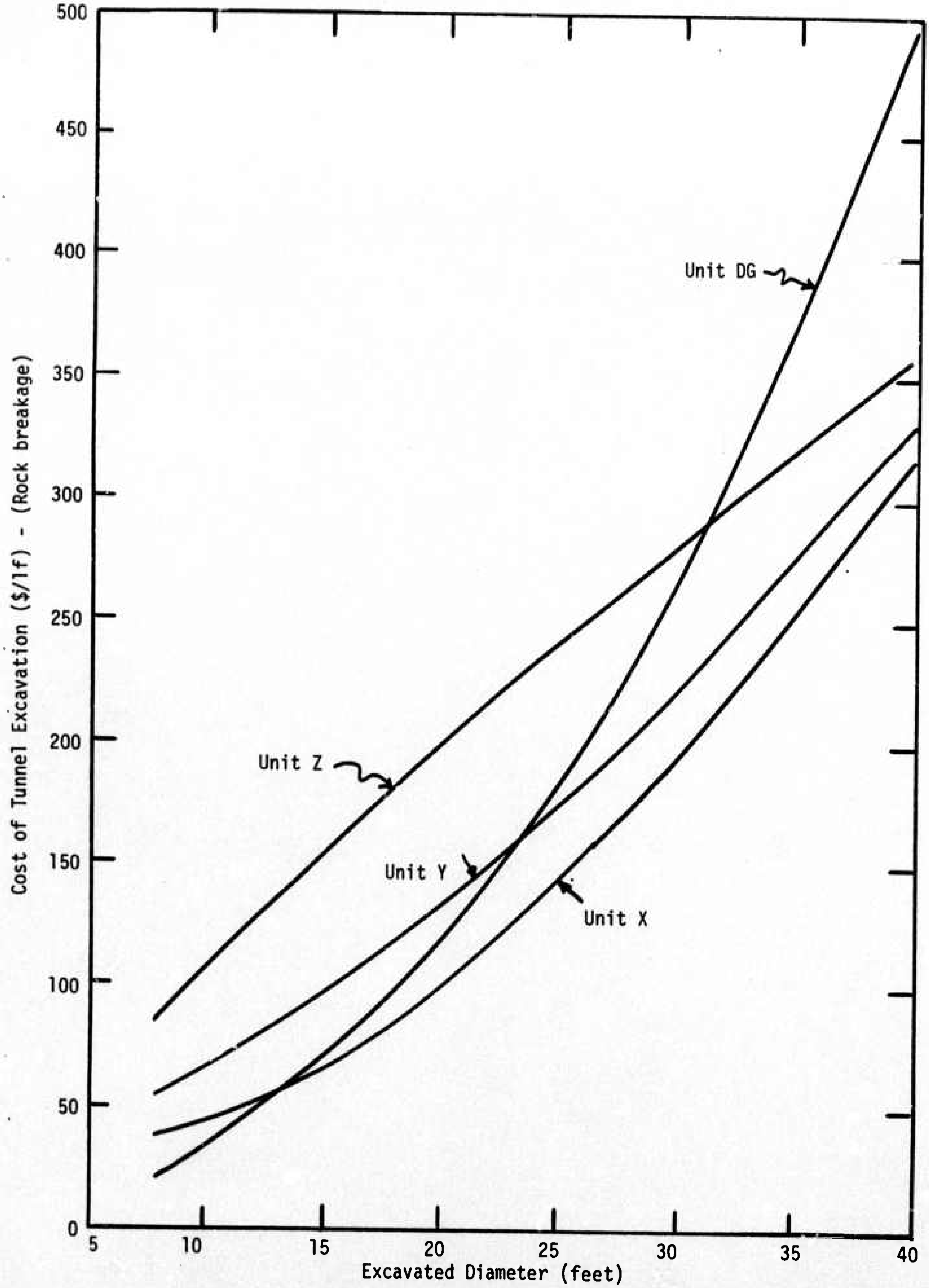

Fig. 3. Tunnel Excavation Costs (20)

Because of the high labor costs of drill and blast, novel methods of breaking hard rock have a considerable margin of capital which can be expended for additional energy and equipment if the method is automated and has other requisite cost advantages similar to boring machines.

Thus, for a tunnel driven by a thermal fragmentation method, possible trade-offs for increased drilling costs will be labor reduction, reduction in cost of breakage energy, higher rate of advance and other factors yet to be defined.

In analyses of pneumatic drilling costs it has been found that the factors of greatest cost are for labor, equipment, and maintenance (21). Amortization or rental charges per foot for equipment are less for two or three shift operation.

For a single 2 in. pneumatic drill the costs are approximately as follows:

	Per hr		
Compressor	$ 3.75	Bit Cost	$25.00
Drill	4.25	Life	2000 ft
Labor (2 men)	7.00	Reconditioning	$15.00
Fuel (4 gal)	0.60	Rod cost/ft	$ 0.03
2" carbide bit and rod	3.00		
	$18.60		

Rate of drilling in hard granite (overall) 60 ft/hr

Cost/ft = $0.31

A method of excavation employing thermal fragmentation may be semi-continuous or ultimately continuous in operation. One procedure would permit simultaneous drilling of heater holes and slots, or another the cutting of a slot first and simultaneous drilling of heater holes and fragmentation. Also, after the rock is fractured, rock removal is accomplished by rock splitter or impact tool. Direct costs may be estimated as follows:

Example:	10 x 10 tunnel
Hole spacing:	2 ft centers
Depth of round:	2 ft
Number of heater holes:	36 - 2-1/4" - 72 ft total

Slots: 2 - 2" x 2' x 10' 240 ft of 2" diam hole

Advance: 16 ft/shift = 576+
1920
2496 ft of hole

Equipment Costs:

	Cost/hr	Total/hr	3 Shift
10 small drifter drills 150 cfm	3.50 ea	35.00	11.67
4 large drifter drills 400 cfm	4.75 ea	19.00	6.33
1 compressor 3000 cfm	4.50/drill	63.00	21.00
Jumbo	5.00	5.00	1.66
Fuel (compressor 5 gal/drill)	10.50	10.50	10.50
Rods	0.40	5.60	5.60
Bits .40/drill	0.40	5.60	5.60
Maintenance and miscellaneous	0.50	2.00	2.00
Labor (3 men)	9.00	9.00	9.00
		$154.70	$73.36
Cost per ft of hole		0.49	0.24
Drilling costs/ft of tunnel	$37.00		

Drilling costs will be reduced if the hole spacing can be increased as expected.

THERMAL FRAGMENTATION RESEARCH

Research was begun at UMR on thermal fragmentation of hard rock in 1969 and has been carried out in three phases:

1. Heat weakening and surface chipping.
2. Mechanical slot cutting and thermal kerf removal.
3. Investigation of a thermal round similar in design to an explosive round.

In phase one the surface of blocks of selected igneous and metamorphic rock was subjected to heat from a small flame jet torch causing shallow fractures. The rock was then chipped off with a traversing jackhammer. It was found that while the surface of most of the rocks tested was weakened by heat, rock removal by impact was not enhanced by the heating process.

In phase two slots 1-3/4 inches wide by six inches deep were cut in the surface of three-foot cubes of granite, quartzite and basalt, with six-inch ridges in between the slots. When heat was applied to the bottom of the slots the ridges between were readily fractured off from the rock face.

Phase three has been devoted to the investigation of the feasibility of developing a thermal round which will function in principle in a manner similar to an explosive round. The application of heat at the bottom of deep slots within the rock in phase two demonstrated clearly that the rock is much more effectively fractured if the heat energy is deposited within the rock.

Thirumalai (4) had shown earlier that thermal inclusions generated by dielectric current would readily fracture small blocks of basalt but not quartzite. Thus, a positive method of heating was desired which is independent of the electrical properties of the rock. In the first experiments coiled nichrome wire was wrapped in a spiral on alundum cores and placed in pneumatically drilled holes in three-foot cubes of quartzite and granite. The heaters successfully fractured the rock parallel and perpendicular to the heater holes, but the nichrome wire burned out at sustained temperatures of 600° to 700°C. Kanthal wire resistance heaters were employed at temperatures of 900° to 1200°C. These fractured the rock more readily, but also burned out in heater holes in granite at sustained temperatures of 1000°C. They were employed successfully to fracture granite in place with nine-inch burden on the holes and with three directions of strain relief.

Experimental Results - Thermal Fracture

It has been found that coiled wire electric resistance heaters one foot long and 1-3/4 inches in diameter will generate from 3.5 to 4.5 kw at temperatures from 900°C to 1200°C. They will successfully fracture a strong granite in place with 10-inch burden and spacing to a depth of 15 inches where three free faces are present. However, there is a little follow-through by radial compression and fractured blocks are sometimes difficult to remove. Also, in spallable rocks such as granite, flakes of minerals spall off from the cavity walls and clog up the heater coils, causing them to burn out after 15 to 20 minutes of use.

The results obtained with coiled wire heaters indicated that higher temperatures were desirable, and that the heater should be of an economical type that could furnish high temperatures in a hole in rock without breaking down. Refractory metal heaters of a type similar to those used for the LASL melting drill (11) were considered, but the cost was too high ($750 each) for funds available.

Electric arcs with carbon electrodes were suggested and tested. Depending upon the size of electrodes and other factors, from 10 kw to 20 kw of power are easily obtainable in a 2-inch drill hole. Temperature of the arc is in the neighborhood of 10,000°C. While carbon electrodes are brittle, with reasonable care they can be used under difficult working conditions.

In an initial test two 1/2-inch electrodes were placed in a 2-1/4 inch diameter hole in a granite block with about 5 to 6 kw power from an arc welder. The block broke with a loud noise in 6 minutes, using about 0.6 kwhr, and producing a fracture completely through the block parallel to the heater hole, as well as breaking the top half of the block into three large segments. The heat developed a hollow, bulb-shaped thermal inclusion about eight inches long and a four-inch maximum diameter. The mass of the inclusion was made up of partially fused granite and mineral flakes, of 380 cc volume, representing 0.2 percent of the volume of the rock. The time and energy requirements for tests at UMR and those of Thirumalai (4) indicate that the cube root law of energy scaling may apply. The upper limit to the amount of heat energy which can be deposited usefully in a drill hole remains to be determined. Similar tests were conducted on 30-inch blocks of quartzite and basalt with the following results:

Block Breakage

Type of Rock	Dimensions	Power (kw)	Fracture Time
Mo. red granite	24 x 24 x 20	6	9 min
Mo. red granite	24 x 24 x 24	5	6 min
Sioux quartzite	16 x 30 x 30	5	2½ min
Dresser basalt	30 x 30 x 24	6	3 min

The Missouri red granite is less brittle and stronger than the quartzite, which broke easily, probably due to the high coefficient of thermal expansion of quartz and its change from α to β quartz as its temperature is increased. Basalt fractured readily even though it contains little or no free quartz, its lava being very liquid.

As indicated above, coiled wire heaters fractured granite in place with 10-inch burden and spacing, but blocks were difficult to dislodge and heaters burned out after 20 minutes service. Separated blocks were removed quite easily by mechanical means.

Field tests with electric arc heating were also performed in solid granite in place with three face displacement relief. In the first test the burden and spacing were 12 inches, the power about 12 kw and the time to first fracture about 4 minutes, or about 0.8 kwhr per hole. The heaters were left on several minutes and the cracks widened to $\sim$1/4 inches. In the second test the burden, spacing and depth were increased to ±16 inches and fracturing at the same power level occurred in about 5 minutes. Three minutes continued heating widened the cracks as before. No additional major cracks were formed, however. (See Fig. 4).

The conclusion drawn from the arc heater tests is that thermal fracturing is technically feasible with proper strain relief provided

<u>Thermal Round Concepts</u>

There appear to be several concepts of thermal rounds which will function to break the rock. The primary problem is providing strain relief. The possible "cut" portion of a round may be patterned after explosive tunnel rounds, which use draw, V, pyramid, and burn cuts. These are discussed below. (Fig. 5).

In the first experimental field test at a granite quarry two perpendicular slots 2 inches wide by 30 inches deep were cut in the granite

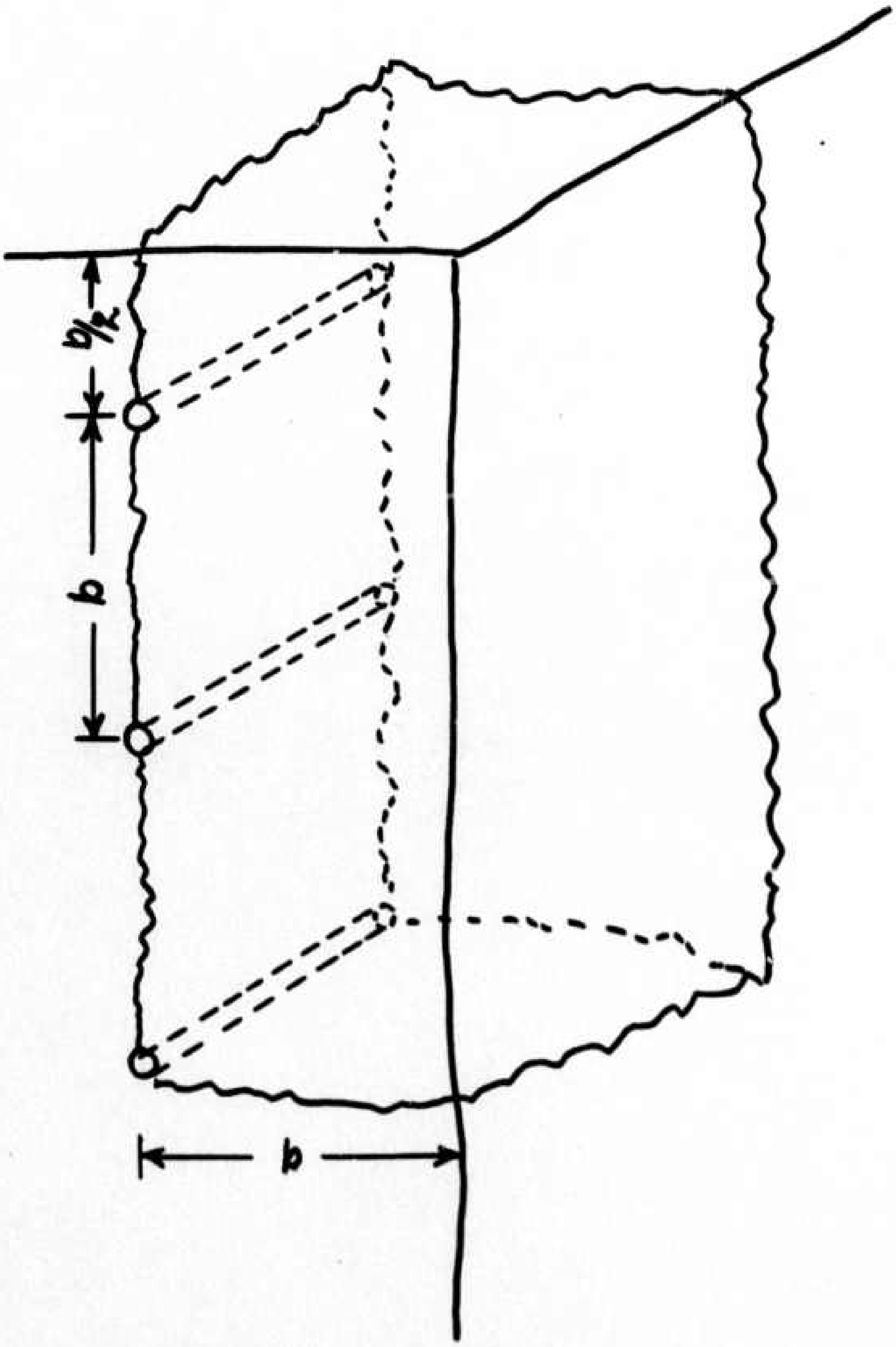

Fig. 4. Fracture pattern for three heater holes at slot intersection in thermal round

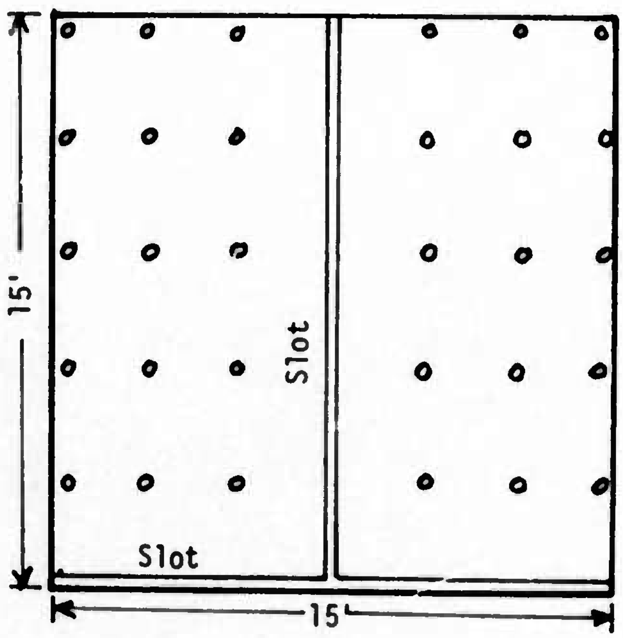

Fig. 5. Suggested thermal slot round for square 15 foot tunnel

in the center of the tunnel face with a pneumatic (drifter) drill. Such a slot requires about five times as much drilling as an explosive round. At an estimated cost of 30¢/foot of drill hole the total cost of drilling for a 15 x 15 foot tunnel 216 feet of drill hole is required or $64.80/ft of tunnel. Assuming for illustration that half of the work time is used for drilling at a rate of 24 inches/min, 15 drills would be required for 100 foot/day tunnel advance. The total energy for breakage is estimated at a maximum of 2 kwhr per foot length of heater hole (36 holes) to be 72 kwhr. At 3¢/kwhr the energy cost for breakage would be $2.16/foot of tunnel.

The initial hole size required is determined largely by the space required for insertion of the heater, although for carbon electrodes, two small diameter holes intersecting at the desired depth may be drilled. Two holes may furnish better loci for crack formation, and the melt would conceivably be formed more readily and efficiently.

The most effective temperature for inducing stresses in the rock is theoretically the highest that can be applied because higher temperatures result in greater heat flow and sharper stress increases at large distances. Carbon electrodes first create an arc (10,000°C), causing the rock to spall, melt, and change chemical and physical form. After a melt is formed most of the heat generated still comes from the arc, but is transferred by several complex processes. Hence, the effective temperature in the cavity is the melting temperature of the rock, which is usually lower than 1700°C for silicate rocks. With any type of heater that causes the rock to melt the cavity is being continually enlarged, which is advantageous. That is, the larger the cavity the greater the stresses are at larger distances from the cavity.

Results of tests performed to date at UMR indicate that thermal fragmentation by heat deposition in holes drilled by pneumatic drills requires from 1 to 2 kwhr per ft of hole for breakage. A hole spacing of 2 feet, which may be about optimum for 12 kw carbon electrode heaters, is similar to hole spacing required for explosives. Explosive energy equivalent varies from 0.4 to 0.6 kwhr/lb for 40 percent to 75 percent dynamites, with about 1 lb per ft of hole for strong rocks.

While electrical breakage energy requirements, based upon tentative information, are about 3 times greater for explosives than for thermal fragmentation, electricity costs about 2 to 3¢/kwhr, dynamites at 50¢/lb range from $0.83 to $1.25/kwhr. Most inexpensive ammonium nitrate-fuel explosives are not suitable for breaking hard rocks.

The time required for automated insertion of heaters such as carbon electrodes in a hole is a very small fraction of that required for loading explosives. More important is that the operational characteristics of the proposed system will permit simultaneous drilling, fragmentation and mucking. That is, the operation as planned will be semi-continuous or continuous.

Although for single short slots of 2-foot length it was not possible to obtain effective fracture of rock on the sides of the slot, it may be that a single long slot in the face will be sufficient to provide displacement relief for breakage. Also, V, pyramid, and burn cut type relief offer possibilities for successful application. The more promising of these may be investigated in the remaining six months of Contract No. USDI H-0220068 after tests are completed for optimizing parameters for the three face relief configurations.

Characteristics of Thermal Fragmentation Method of Excavation:

Drilling required:	1 ft of hole/cu ft of rock removed
Drilling energy:	200 to 390 j/cc
Percent of face drilled:	5%
Breakage energy:	0.2 kwhr/cu ft
Rock melted:	Maximum of 0.3%
Labor at face:	4 men in 15 x 15 tunnel
Character of muck:	Small fragments to 3 ft cubes
Continuity:	Semicyclic to continuous
Down time:	Minimal
Heat developed:	Negligible
Noise and vibration:	From pneumatic drilling only
Gases created:	Small amounts - easily removed
Environmental problems:	Minimal
Equipment costs	Nominal, for drills, jumbos, etc., costs for modification and redesign
Services:	Electrical power
	Compressed air, assists ventilation
Tunnel wall stability:	Some slight fracturing of surrounding rock
Equipment required:	Standard drilling equipment - modified
	Mountings for electrodes
	Improved electrodes
Estimated time to prototype:	1 year
Estimated time to full operation:	3 to 4 years

Theory and Computation

The computational analyses which involve the determination of the optimum spacing, hole depth, hole size and slot configuration, uses a package of finite element and related computer codes. These codes are as follows:

1. GRDCHK, To check the input data and to plot the finite element grid,
2. S70, Finite element conduction code for the solution of the transient temperature problem,
3. TCP, Temperature contour plotter,
4. TTST, Finite element code for the solution of transient thermal stress problems with temperature distributions given for different times,
5. SRPLT, To plot various stress regions,
6. FRACTR, To check for the fractured elements and to plot the probable fracture contours,
7. 1DNLSS, One-dimensional finite element program for the solution of steady state heat conduction problems where element conductivity can be expressed as $K(T) = K_0 + K_2T + K_2T^2 + K_3T^3$
8. 1DNLT, One-dimensional finite element program for solution of transient heat conduction problems where element conductivity can be expressed as $K(T) = K_0 + K_1T + K_2T^2 + K_3T^3$ and the product of density and heat capacity as $\rho(T)C(T) = C_0 + C_1T + C_2T^2 + C_3T^3$,
9. 2DNLSS, Two-dimensional version of 1DNLSS,
10. 2DNLT, Two-dimensional version of 1DNLT.

Codes GRDCHK and SRPLT were developed by the Engineering Mechanics Department at the University of Missouri-Rolla. The conduction code S70 was originally developed by Wilson (22). Code FRACTR is based on the equations and analysis given by Lauriello (23). All codes have been modified and codes TCP and TTST are specially developed for this analysis. The transient thermal stress analysis code can be used for plane or axisymmetric bodies with temperature dependent material properties. Theoretical development of equations for this code has been given by Jones and Crose (24). Nonlinear steady state solutions are obtained by iterations (1DNLSS and 2DNLSS). Nonlinear transient solutions are obtained by incremental loading and iteration within each increment (1DNLT and 2DNLT). All one-dimensional programs can handle constant temperature, constant flux or convection boundary conditions. 1DNLT has the added capability of allowing a radiation boundary condition.

The computer codes (1-10) have been developed or they are being developed for application to three models which represent the fracture conditions for hard rock tunneling via the semi-continuous thermal round method. The models Have been derived from three views of the actual hole-slot configuration. The two-dimensional models selected describe the significant thermal stress and fracture areas. A one-dimensional model is also being used to study such basic phenomena as the type of thermal boundary condition that most accurately describes experimentally observed phenomena, temperature dependent thermal and elastic properties, etc.

The geometry and temperature field make the conduction, thermal stress, and fracture problems three-dimensional. The thermal round configuration is a semi-infinite region with vertical and horizontal relief slots cut to facilitate fracture. The slots are cut using overlapping holes from pneumatic drills. Other methods may prove desirable in future research. Heater holes are drilled to slightly more than the desired depth of fracture. The heaters, carbon arc, etc. are placed in the bottom of the holes forming a thermal inclusion. The nature of the temperature and resulting thermal stress field is such that the rock is first fractured (cracked) along the line of a series of holes either horizontal or vertical. A second and very important fracture occurs on a plane perpendicular to the hole axes passing through the center of the thermal inclusion. This fracture is parallel to the work face and makes possible the removal of a layer equal to the depth of the thermal inclusions.

The first type of experimentally observed fracture suggests that the significant process parameters could be studied using a two-dimensional model containing the hole diameter and spacing parameters (Fig. 6).

The second type of fracture suggests that some important parameters relative to the process development could be studied using another two-dimensional model. This model is obtained by passing a cutting plane along a series of holes and observing the geometry that is projected on the cutting plane (Fig. 7).

The stress state in the elastic rock surrounding the heater and molten rock inclusion results primarily from the temperature field (thermoelastic stresses). The thermoelastic stresses can be determined from finite element models of the heater and melt geometry as previously described. The program package has been modified to solve the stress problem with variable (temperature-dependent) thermal and elastic properties.

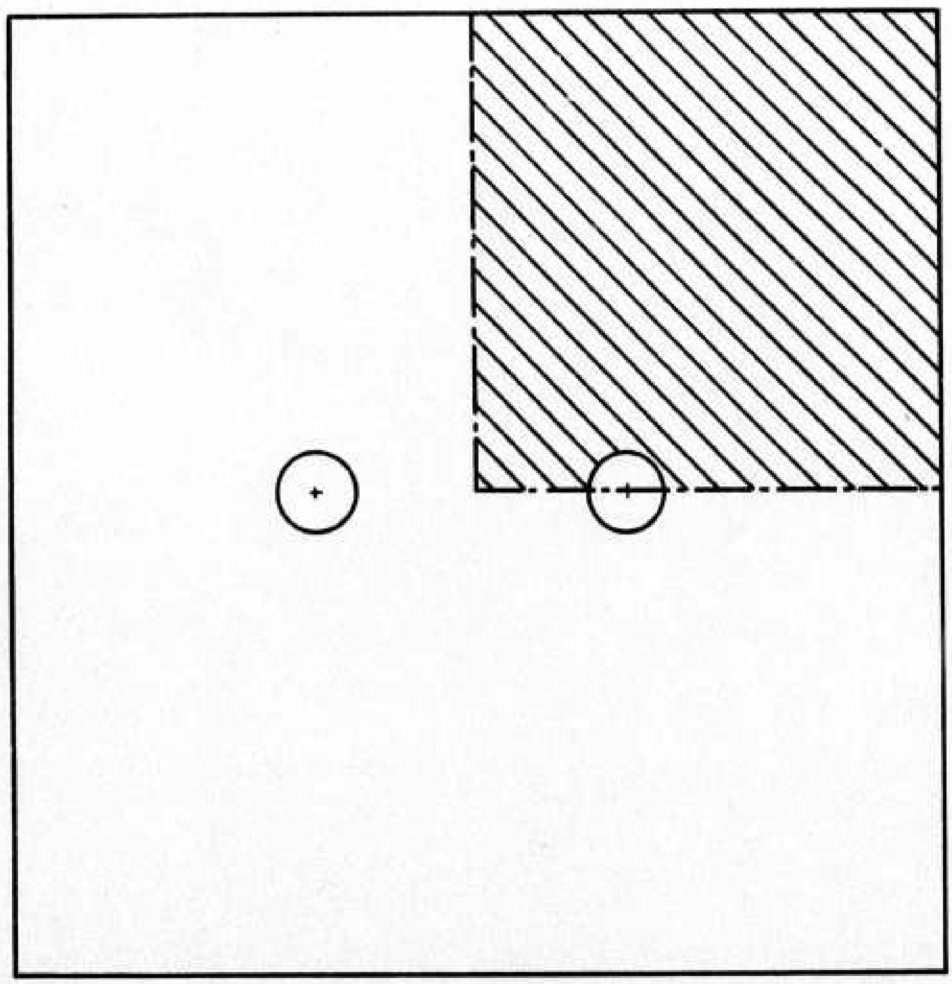

Fig. 6. Multiple hold model showing typical section for analysis

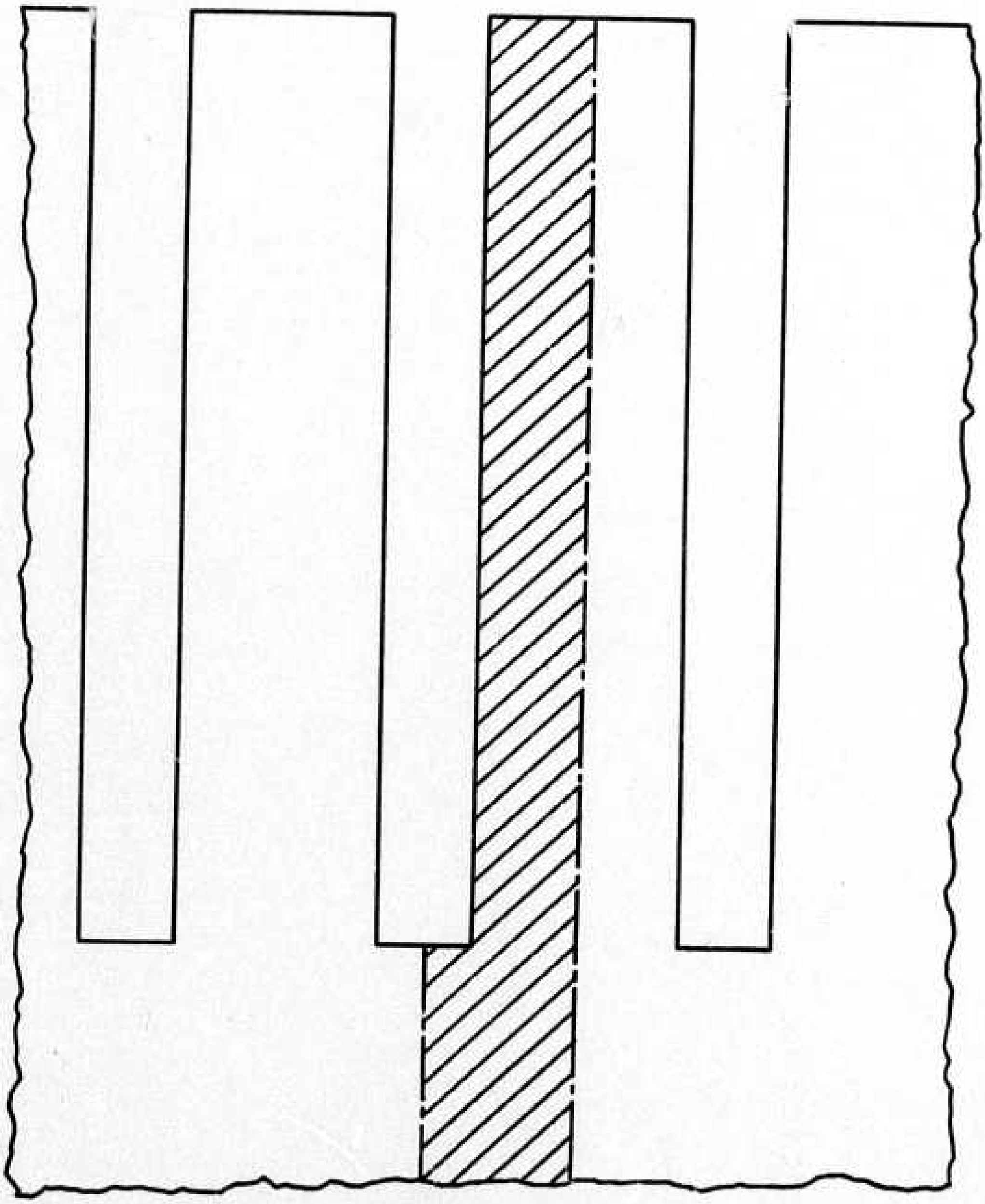

Fig. 7. Multiple slot model showing typical section for analysis

Two-dimensional finite element programs for the study of fracture propagation in rock are also available. The stress from the finite element stress analysis can be used via the Griffith and McClintock-Walsh theory (24) to predict whether cracks will propagate in hard rock and the extent to which they will propagate. From the crack geometry the controlling parameters (hole spacing, size, depth, etc.) can be optimized and the feasibility of the proposed technique for hard rock tunneling can be postulated.

Theoretical modeling of the type described in this section should augment and accelerate a future experimental prototype program. Final optimization studies could be made as a part of the prototype program. These would utilize information obtained from the most recent field and laboratory tests.

Typical results from the two-dimensional model for temperature and stress are shown in Figures 8 and 9.

Typical results from the one-dimensional model for temperature using nontemperature-dependent and temperature-dependent properties are shown in Figures 10 and 11.

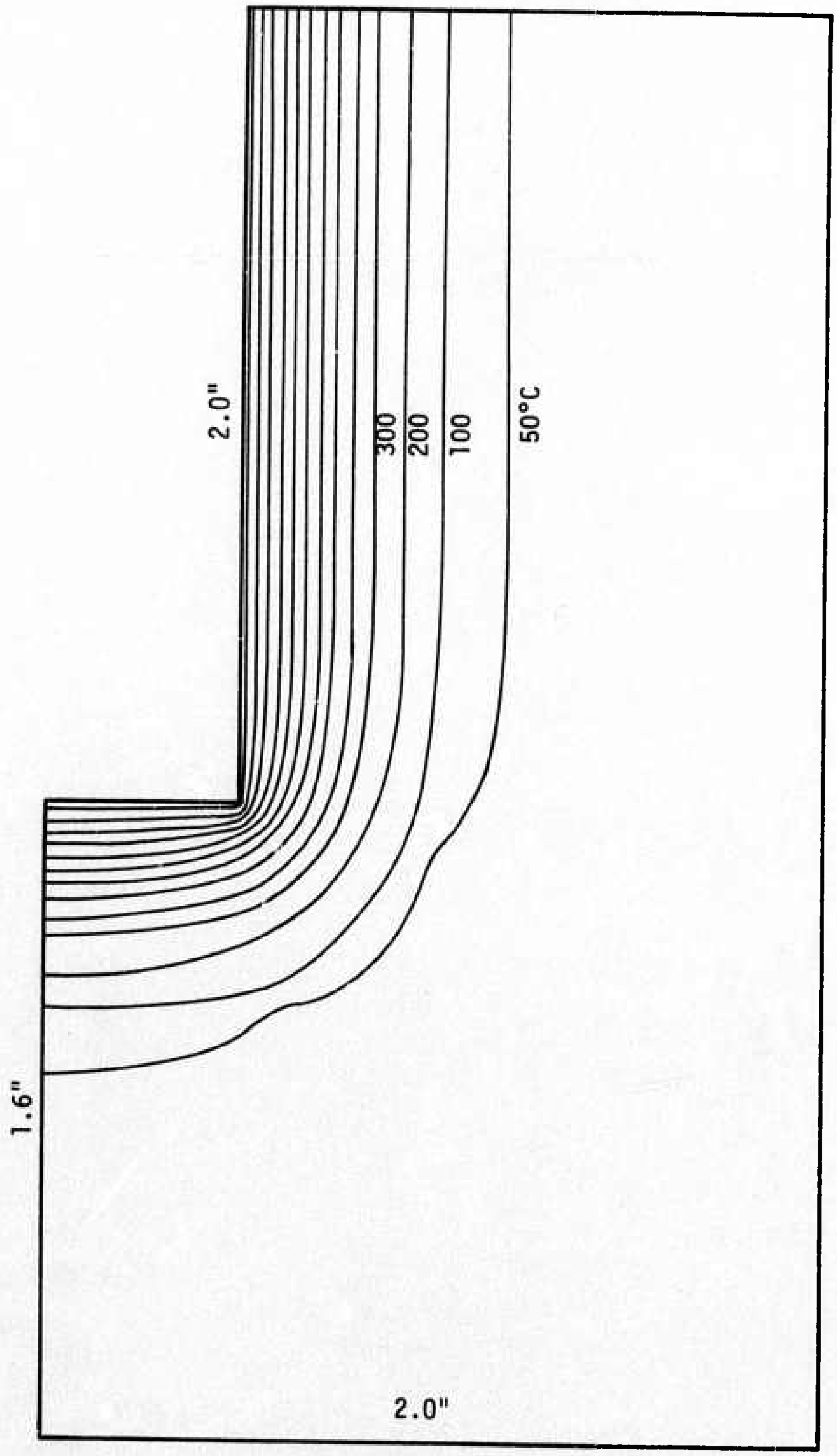

Fig. 8. Temperature distribution, case 1, t = 60 sec

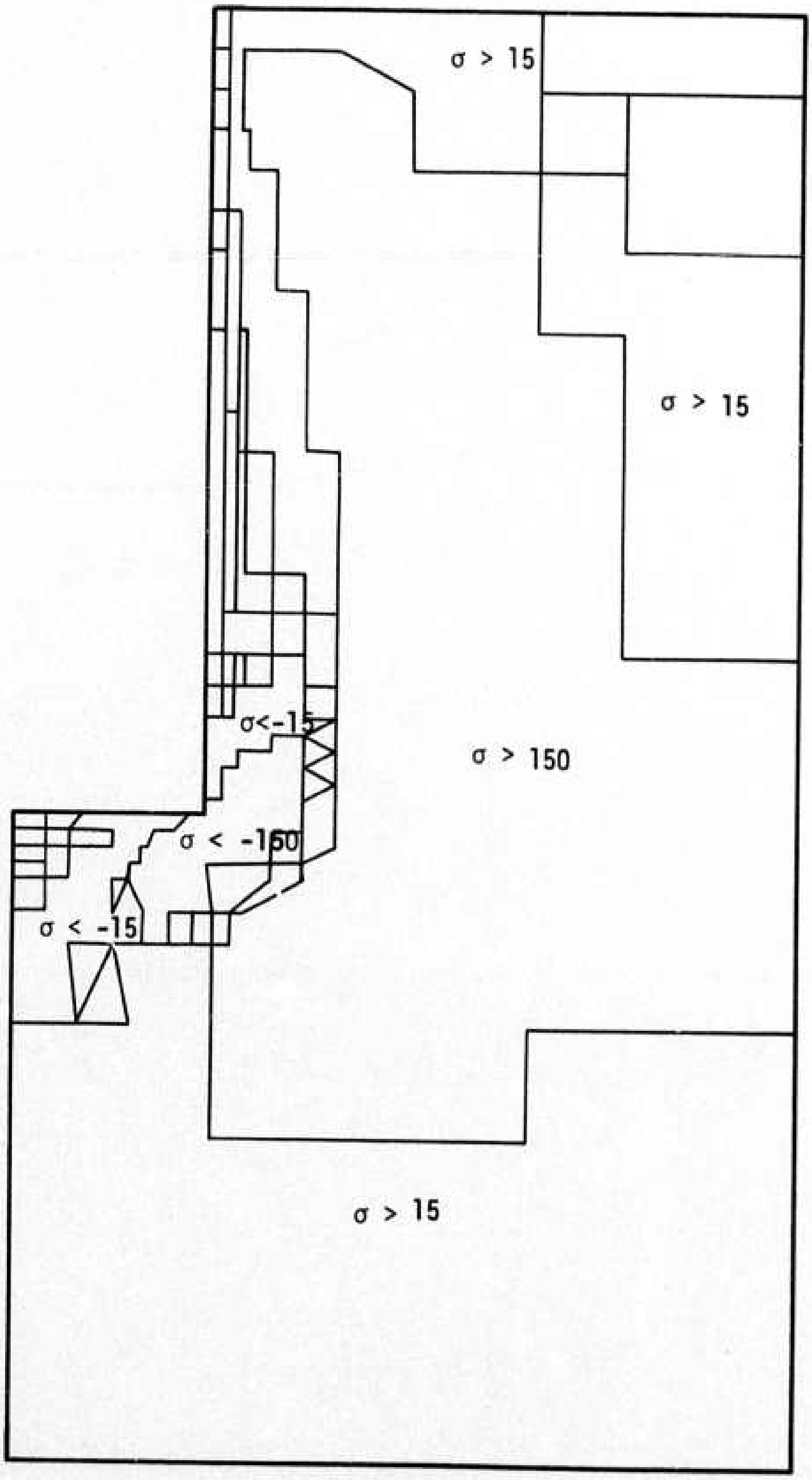

Fig. 9. Maximum principal stress in KSI, case 1, t = 60 sec

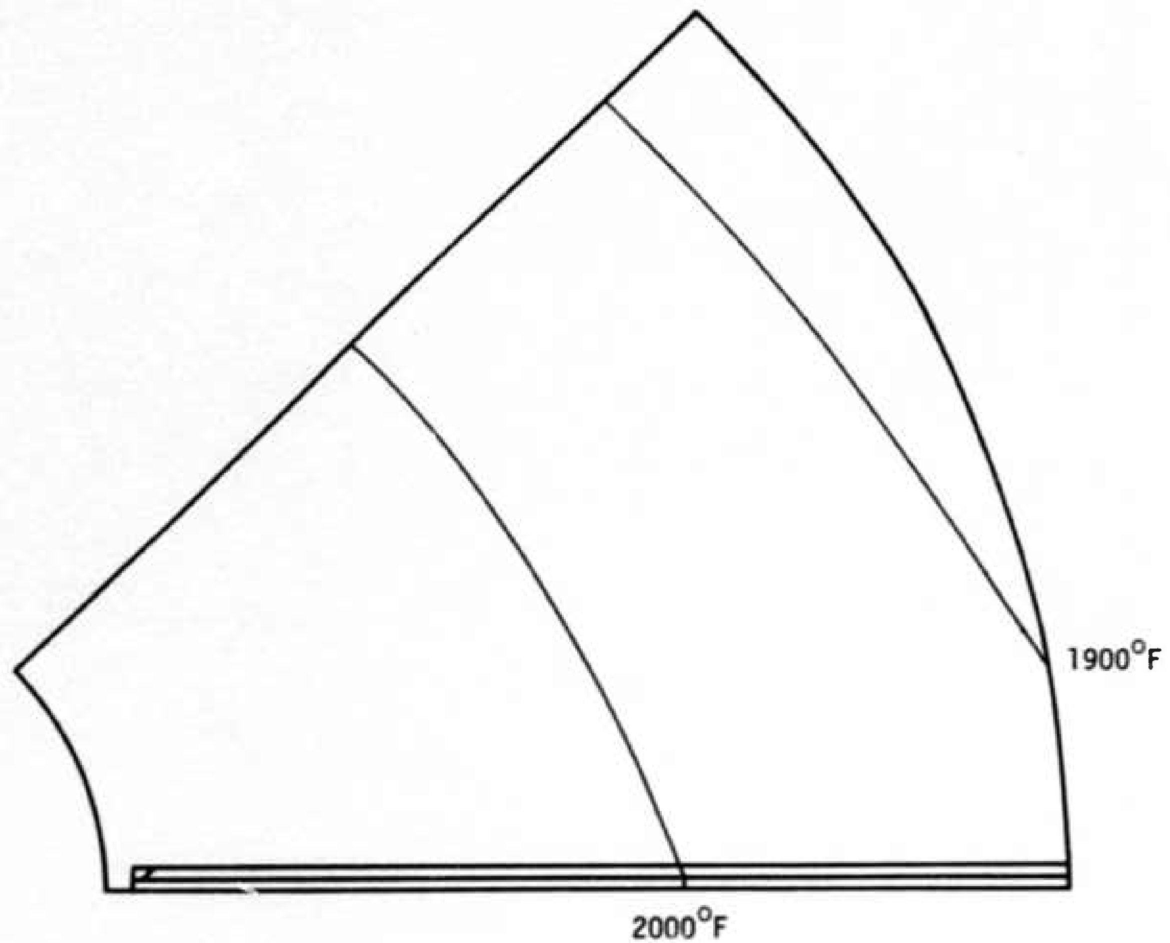

Fig. 10. Isotherms for constant conductivity and thermocouple 1 mm from surface

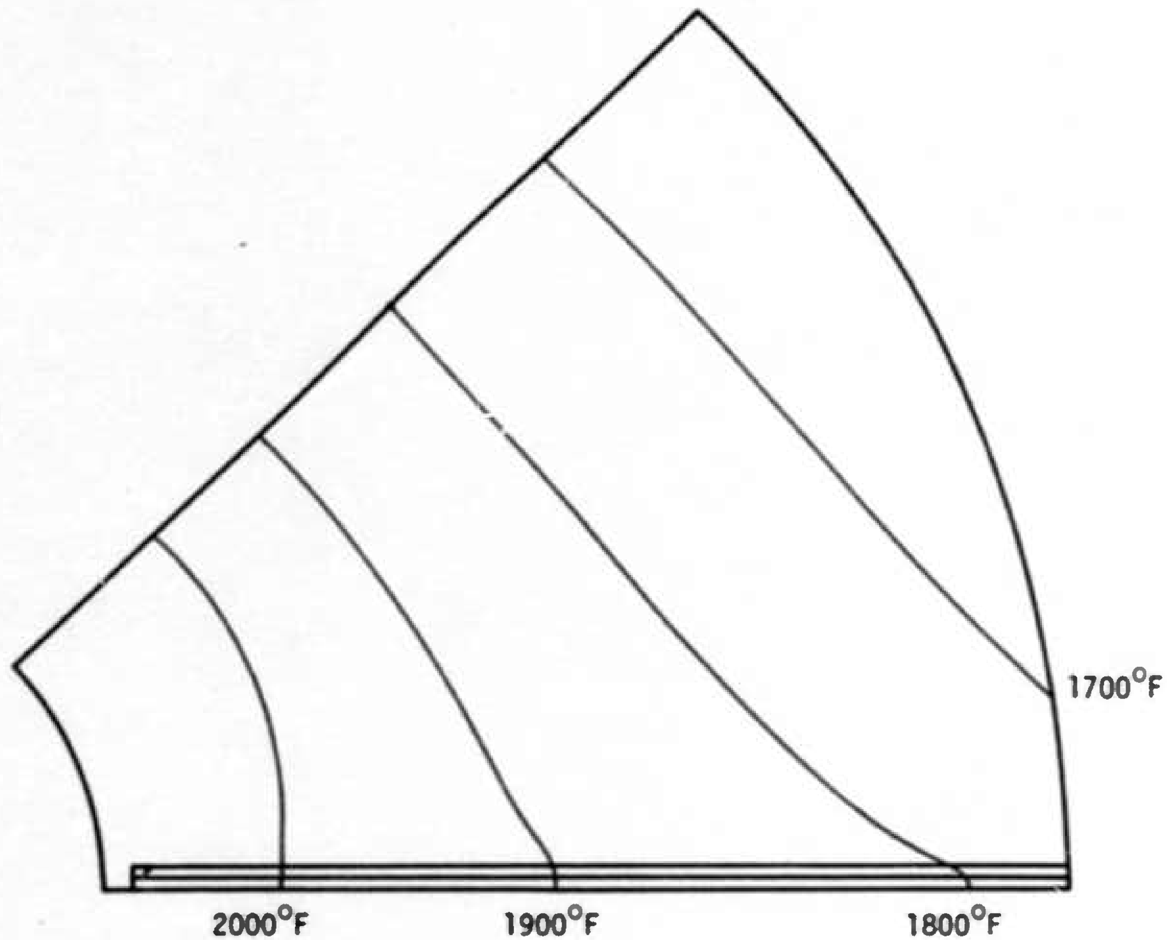

Fig. 11. Isotherms for variable conductivity and thermocouple 1 mm from surface

REFERENCES

1. Carstens, J.P., et al., "Feasibility of Flame-Jet Tunneling", UARL Rept. G-910560-10, May 1968.

2. Maurer, W.C., Novel Drilling Techniques, Pergamon Press, London, 1968.

3. Carstens, J.P., et al., "Thermal Fracture of Rock - A Review of Experimental Results," 1st. No. Amer. Rapid Excav. and Tunneling Conf., June 1972.

4. Thirumalai, L., "Rock Fragmentation by Creating a Thermal Inclusion with Dielectric Heating," Bur. of Mines RI 7424, 1970.

5. Nixon, D.R., and Schumacher, B.W., "Use of an Electron Beam Gun for Hard Rock Excavation," Western Electric Corp., Repts. R71-35, R71-32, 1971.

6. Zar, J., "The Use of a Laser for ARPA Military Geophysics Program " (Rock Mechanics and Rapid Excavation), AVCO. Semi-annual Tech. Rept. Bur. of Mines, Contract No. H-210039, December 1971.

7. Carstens, J.P., and Brown, C.O., "Rock Cutting by Laser," SPE Paper 3529, October 1971.

8. Carstens, J.P., et al., "Heat Assisted Tunnel Boring Machines," UARL Rept. No. J-970802-12, September 1970.

9. Thirumalai, K., and Chueng, J.B., "A Study of a New Concept of Thermal Hard Rock Crushing," 14th Symp. on Rock Mech., June 1972.

10. Clark, G.B., et al., "Combined Thermal Weakening and Mechanical Disintegration of Hard Rock," U. of Mo. RMERC, Annual Rept., July 1972.

11. Robinson, E.S., et al., "A Preliminary Study of the Nuclear Subterrene," Rept. LA-4547, LASL, 1971.

12. Ionarc Gets USBM Aid for Tunneling Research, E & MJ, July 1972.

13. Clark, G.B., Internal Reports on Research Contract No. USDI-H-022068, Bur. of Mines, (ARPA), 1972.

14. Sarapu, E., "Electrical Fragmentation of Magnetic Iron Ores," AIME Preprint 69-AO-52, 1969.

16. Thirumalai, K., "Potential of Internal Heating Method Rock Fragmentation," 12th Symp. on Rock Mech., U. of Mo.-Rolla, 1970.

16. Thirumalai, K., Private communication referencing research in 1969.

17. Neudecker, J.W., Fifty Foot Hole Melted by Two-inch Diameter Subterrene, Memo S-37, February 18, 1972.

18. Sternberg, E., "Transient Thermal Stresses in an Infinite Medium with Spherical Cavity," Proc. Kon. Akad. Wetensch, B, 1957.

19. McMaster, R.C., and Hecox, W., Drilling Oil Wells with Electric Arcs, Drilling Research Inc., Pt. IV, Collected Reports, 1949.

20. Harza, R.D., A Computer Program for Estimating Costs of Hard Rock Tunneling, 2 Vols., Final Rept., May 1970.

21. Phillips, E.H., and Kunan, A.F., "Percussion Drilling," Chapt. 6.2, Surface Mining, AIME, 1968.

22. Wilson, E.L., and Nickell, R.E., "Application of the Finite Element Method to Heat Conduction Analysis," Nuclear Engineering and Design, Vol. 4, pp. 276-286, 1966.

23. Lauriello, P.J.J., "Thermal Fracturing of Hard Crystalline Rock," Ph.D. Dissertation, Rutgers University, 1971.

24. Jones, R.N., and Crose, J.G., "SAAS II-Finite Element Stress Analysis of Axisymmetric Solids with Orthotropic, Temperature Dependent Material Properties," Aerospace Corporation, California, 1968.

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13. Abstract

A thermal round, analogous to an explosive blasting round, was designed and tested in situ for breaking of hard rock for rapid excavation. Electric arcs at 12kw energy level have proven effective in fracturing rock burdens up to two feet where three pre faces are present. Calculations show that the process is technically and economically feasible for application to tunnel excavation. Laboratory experimentation and theoretical analyses are being conducted to support field investigations.

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rock fragmentation						
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