Presented at the First IUPAP International
Conference on Physics Industry, Dublin,
Ireland, March 9 - 13, 1976

ROCK EXCAVATION BY PULSED ELECTRON BEAMS

R. T. Avery, D. Keefe, T. L. Brekke and I. Finnie

March 1976

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48
with the financial support of the National Science
Foundation (RANN) under NSF Grant AG-393

ROCK EXCAVATION BY PULSED ELECTRON BEAMS

Robert T. Avery and Denis Keefe
Lawrence Berkeley Laboratory, Berkeley, California
and
Tor L. Brekke and Iain Finnie
University of California, Berkeley, California

ABSTRACT

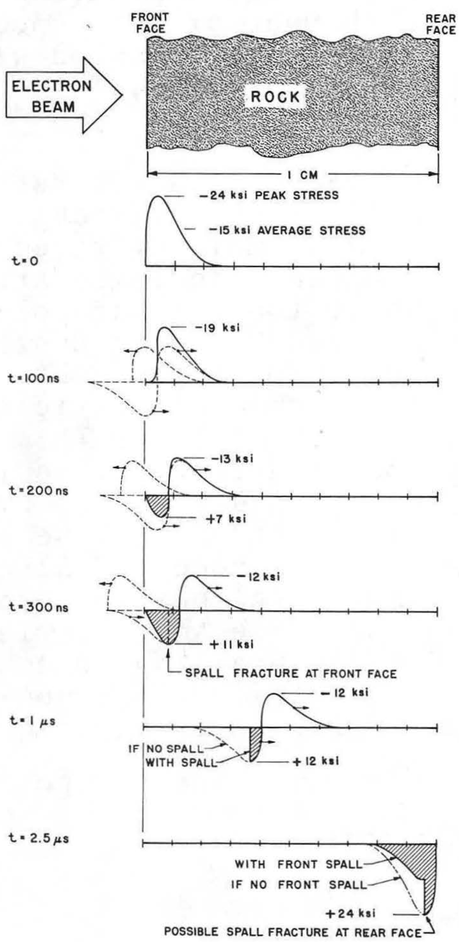
If an intense short pulse of megavolt electrons is deposited in a brittle solid, dynamic spalling can be made to occur with removal of material. Experiments have been made on several types of hard rock; results are reproducible and well-described theoretically. An accelerator with a rapidly-pulsed scanning electron-beam has been designed that could tunnel in hard rock about ten times faster than conventional drill/blast methods.

INTRODUCTION

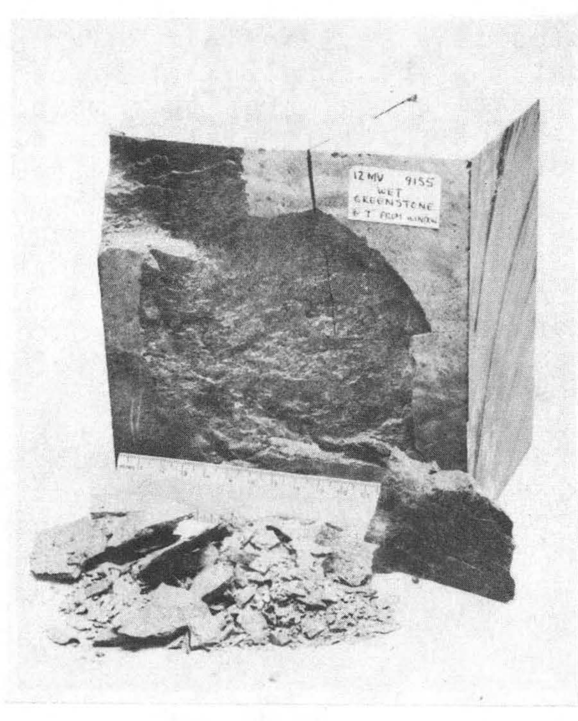
This report describes a new technique for excavation of hard rock (1). Present-day drill/blast methods are slow, with advance rates seldom exceeding 2.5-3.0 m per 8-hour shift. Our method uses a scanning electron beam with two essential properties: high particle-energy (megavolts) to ensure penetration of $\sim$ 1 cm, and pulses short in time so that material is removed by dynamic spalling. The energetic electrons can be thought of as a special kind of heater for a volume below the surface as contrasted with other types of heaters (laser, flame, heated metal pad, low energy beams) which heat the surface.

To put the process of spalling in perspective, consider three mechanisms of rock failure when heat is applied at different rates to a semi-infinite slab of rock. For (A) Melting to occur heat must be supplied at a fast enough rate that the temperature derivative continues to remain positive up to the melting point. The energy for removal of a unit volume (called Specific Energy) must be enough to raise the temperature to the melting point ($\sim$ 1000° C) and to supply the latent heat. A characteristic time for this process can be several seconds or minutes. For (B) Thermal Cratering to occur heat is supplied at a faster rate (on a one second or less scale) so that thermal stresses set up by a sharp temperature gradient exceed the material strength. We have examined this with a finite element 3-D computer code and also does occur with lower Specific Energy than for (A) but the cracks are predominantly at right angles to the rock face and material is not spontaneously ejected. For (C) Dynamic Spalling to occur it is vital that energy deposition occur quickly and in a non-zero volume. This volume of material in trying to expand creates a compressive stress that can be called instantaneous if the duration of the pulse is less than the smallest dimension (x) of the volume divided by the speed of sound (c). Since we shall be dealing with disc-shaped volumes we can treat the process simply as one-dimensional. The local instantaneous stress results in two half-amplitude compressional stress waves propagating to both left and right, at the speed of sound. The left-going stress pulse however encounters the free face and is reflected with inversion to a tensile wave now travelling to the right. Figure 1 is an illustration of the evolution in time of the compressive pulse and succeeding tensile pulse travelling to the right, as a result of the sudden energy deposition of a 1 MV electron beam. Being a brittle solid the rock is much weaker in tension than compression and if the energy input is adequate the rock will fail under tension. Because of the sign of the stress at failure the broken material is accelerated away from the rock face, which is favorable for excavation. One can estimate for typical hard rock properties the threshold energy input needed for spalling should lead to an instantaneous temperature rise of about 100-200° C, much less than that needed to produce melting.

Note that mechanisms (A) and (B) can be considered as quasi-static and depend on the bulk transport of heat at a rate determined by the thermal conductivity. Spalling on the other hand is a dynamic effect and independent of the heat conductivity; in essence the beam is used just to create a sudden stress in a localized volume.



XBL 732-214



CBB 741-344

Fig. 1. Stress wave propagation. Fig. 2. Example one-shot spall.

EXPERIMENTAL RESULTS

We chose five different rock-types for tests of spalling (Sandstone, Limestone, Granite, Greenstone, and Basalt). They varied widely in compressive strength from moderately hard to extremely tough (6.2 kpsi to 46 kpsi) and in other properties such as porosity. These types were chosen because they were relatively uniform in composition; thus results on different specimens of the same type were expected to be reproducible. Clay and shale were also bombarded just to verify that spalling is successful in soft materials that might be encountered in seams during hard-rock excavation.

Tests were carried out at a variety of high current accelerators that had voltages ranging from 1 to 9 MV, and currents in the range 2 to 50 kA. The pulse length in all cases was about 0.1 μsec and the energy content per pulse ranged from 0.2 to 64 kJ. These machines were all of the common type in which a Marx generator developing the full voltage is used to charge up a coaxial or tri-axial line which serves as a pulse-shaping device that is switched across a vacuum cold-cathode diode. These accelerators tend to be bulky - 3 to 6 meters in diameter - because of the need to stand off multi-megavolt voltages. Single shot tests were performed on the rock samples under various conditions (Fig. 2) and the results can be summarized as follows:

- Spalling occurred in a highly reproducible way, i.e., with a sharp threshold in charge-density for a given rock type.
- The debris was ejected from the rock in the form of flakes and finely-divided debris.
- The effect of water - a common ingredient in underground rocks - is to enhance the spalling in certain cases. While the electrons may heat the rock by 200° C the water rises in temperature only by 50° C because of the difference in specific heats. In rocks that contain moderate amounts of water in interstices microns in dimensions (e.g., Granite) rapid heat transfer occurs and the increased water pressure enhances the tensile stress. In rocks tnat absorb no water (Greenstone) or absorb a lot of water (Sandstone) there is no such enhancement.
- The volume removed is in first order proportional to the energy per pulse and the specific energy varied from 0.78 to 1.25 kJ/cc for the different rock types. This is a surprisingly small spread for rocks with such widely-varying properties.
- The specific energy depends somewhat on the electron beam voltage, higher voltages being more efficient.
- When a rock sample just a few centimeters thick is bombarded, spalls at both front and rear faces are observed (c.f. Fig. 1). This verifies the travelling stress wave explanation and rules out that spalling arises from the charge or heat deposition at the front face.
- Spalling was observed at distances in air up to ∿ 20 cm from the exit window of the accelerator.

THEORETICAL UNDERSTANDING

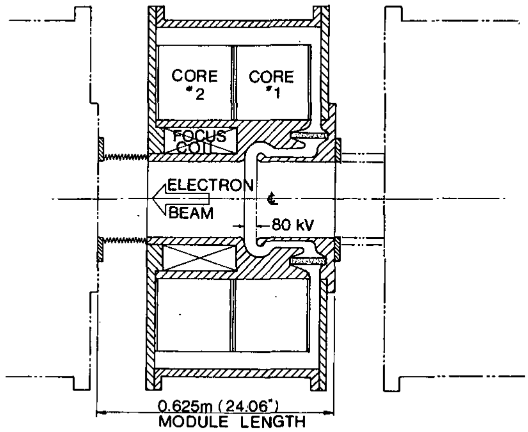
The mechanism of fracture on this short time scale has been pursued theoretically and our results seem now to have a satisfactory description. If there are many incipient flaws in the material from which cracks can propagate, only a short time is needed before cracks coalesce and fracture occurs; alternatively, if there are few such sites more time is needed for the cracks to grow to coalescence. Thus the stress duration, τ, is important: where $\tau \approx x/c \propto$ Beam voltage/c. The other important ingredient is the statistical distribution of crack sizes normally described in terms of a Weibull distribution. The three Weibull parameters for each of the five rock types have been determined by Vardar (2) by means of 3-point bending tests, and fracture criteria developed which agree well with the experimental results for all rock types. In particular, the dependence of failure on τ, and hence voltage, is well explained.

EXAMPLE PULSED ELECTRON TUNNEL EXCAVATOR

The experiments described were carried out at available accelerators under limited conditions. In particular, the beam profiles tended to be sharply peaked - a more uniform distribution could result in reducing the specific energy by a factor of as much as three. Also if a rapidly-pulsed scanning beam were used enhanced spalling would be expected because of heating and incipient cracking produced by preceding pulses. Thus we expect under real operating conditions a lower specific energy than the $\approx$ 1 kJ/cc observed in the tests; we choose as a reasonable design value 250 J/cc. We specify the example excavator to be capable of removing 104 cu. m (136 cu. yds.) of rock per hour, i.e., to advance a 6.4 m (21 ft.) diameter tunnel at a rate of 3.2 m (10.6 ft.) per hour. This is an order-of-magnitude greater advance rate than by present-day drill/blast techniques.

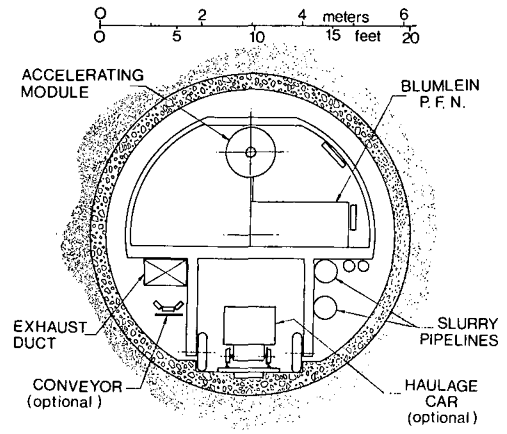
The average beam power required is 9 MW and at present we envisage using a linear induction accelerator producing 25 kJ pulses at a 360 Hz rate. This can be achieved with a 5 kA pulse 1 μsec long, with an electron beam voltage of 5 MV. The induction accelerator is composed of many separate ferro-magnetic cores through which the electron beam passes. By pulsing a primary winding an increment of energy is supplied by each core through transformer action to the beam which acts as the secondary circuit. This type of accelerator seems to have several advantages over other types considered (coaxial pulseline, transformer or Marx generator types) for the following reasons:

- Its modular construction allows continued operation near full output should one or a few modules fail.
- Only modest voltages (< 100 kV) to ground exist at any point.
- The stored energy that would be released by an arc-over in a module is not large and would cause little damage.
- The total beam voltage can be very well-regulated as needed for scanning.
- The overall electrical efficiency (mains to beam) can be greater than 50%.



XBL 753-555

Fig. 3. Schematic of one of the 64 accelerator modules.



XBL 753-535

Fig. 4. Section at accelerator unit.

The accelerator will require 64 modules each producing 80 kV pulsed voltage (see Fig. 3). Construction of such modules seems reasonably straightforward and by suitable de-rating of components they can be made highly reliable. It is hoped that ignitrons will work successfully at the 360 Hz rate; if not, more expensive thyratrons would be needed. The electron beam scanning could be in a raster-pattern by means of fast electromagnetic deflection in combination with a slow mechanical movement of the scanning pattern. The vacuum window is a serious problem; several potential solutions have been conceived of, but more engineering development is needed on this item.

The accelerator proper is only one part of the overall excavator which is designed to operate on a continuous rather than batch basis. The engineering details of the systems required are treated in (1) and Fig. 4 gives an indication of how they are incorporated within the tunnel. The debris is handled by combined pneumatic and slurry techniques; a continuously advancing combination of slipform and concrete extrusion creates the tunnel lining. The ozone and x-ray problems can be handled satisfactorily and induced activity is not a problem. The accelerator and ancillary control systems and materials handling systems are mounted on nine articulated units (1)

The authors thank the NSF (RANN) for funding this work and U. S. ERDA for the use of LBL facilities.

REFERENCES

(1) R. Avery, D. Keefe, T. L. Brekke, and I. Finnie: IEEE Trans. Nucl. Sci. NS-22, 3 (1975), and References quoted herein.

(2) O. Vardar: "Fracture of Brittle Solids under Multi-Axial and Dynamic Loading," Ph.D. Thesis, University of California (1975).

0 0 0 0 4 5 0 1 0 3 1

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720