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SHATTERING ROCK WITH INTENSE BURSTS OF ENERGETIC ELECTRONS*

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Summary

It has been successfully demonstrated that intense bursts of energetic electrons cause significant rock spalling for modest energy inputs. The corresponding temperature rise per pulse in the bombarded volume of rock is only ~ 200° C, or so. Some analytical predictions and experimental evidence of this novel accelerator application are presented. The promise of this technique for more rapid and economical tunneling through rock is also examined.

1. Introduction

Of recent and considerable interest, are novel methods that might significantly reduce the cost and increase the speed of underground excavation and tunneling, particularly through hard rock. If successful, such methods could increase the economic feasibility of underground location of many types of facilities, such as nuclear power plants, urban transit, fuel depots, factories, inter-city high-speed railways, warehouses, and utility lines. The consequent improvement in the earth's surface environment would be readily apparent.

The technology of electron accelerators capable of pulse currents of many kiloamperes has rapidly expanded in recent years. While designing the kiloampere ERA injector accelerator (Ref. 1), the damage potential of the high-current electron beam was noted. This prompted the possibility of turning these effects to good use in quite different applications. The following two mechanisms for rock damage by electron beams were predicted (Ref. 2):

a) Thermal cratering based on quasi-static thermal stresses for sub-second pulses.
b) Shock spalling (Ref. 3) based on intense stresses caused by submicrosecond pulses.

These are based on delivering modest amounts of energy to the rock and achieving damage by taking advantage of the low tensile strengths of brittle materials (typically 1 - 10% of compressive strength). This is sharply to be contrasted with other published methods of using electron or laser beams to effect rock removal by melting or vaporization in which very much greater amounts of energy would need to be supplied to produce the phase changes.

The thermal cratering mechanism has been studied computationally and experimentally and judged to be of less immediate importance than shock spalling, to which the rest of this paper is primarily devoted.

2. Fundamentals of Shock Spalling

Consider a rock face being struck by an intense burst of energetic electrons of 50ns duration with pulse current density of 1400 A/cm^2, mean voltage of 1.0 MV and peak voltage of 1.25 MV. The electrons deposit energy in the rock with a depth dependence approximately as shown in the initial waveform of Figure 1. The electron penetration depth varies with electron voltage and is ~ 2 mm for this example.

The following simple analysis elucidates the main features of the phenomenon. The energy is assumed to be deposited uniformly and instantaneously within the volume defined by the beam diameter 2a (cm) and the electron range R (g/cm^2). The assumption of "instantaneous" energy deposition simply means that the beam pulse duration is so short that stresswaves cannot travel significant distances compared with the dimensions of the stressed volume which is essentially valid for the assumed 50 nsec pulse duration. The initial temperature rise is

$$T_o = \frac{U}{\pi a^2 R c_v} \qquad (1)$$

where U is total energy absorbed in calories per pulse, ρ is density in grams per cubic centimeter and c_v is specific heat. This temperature rise produces an initial compressive stress in the heated portion of the rock of

$$\sigma_o = \frac{\alpha T_o E}{1-2\nu} = \frac{\alpha E U}{(1-2\nu)\pi a^2 R c_v} \qquad (2)$$

where α is the thermal coefficient of expansion, E is Young's modulus of elasticity, and ν is Poisson's ratio.

The example is continued for one of the sample rock types studied, the mechanical properties of which are given in Table I below.

Table I - Properties of a competent granite

Density, ρ,	2.7 gm/cm3
Thermal coefficient of expansion, α,	7 x 10^{-6}/°C
Specific heat, c_v,	0.2 cal/gm -°C
Modulus of elasticity, E,	8 x 10^6 psi (550 kbar)
Poisson's ratio, ν,	0.2
Sonic velocity, $v = \sqrt{E/\rho}$	0.4 cm/μsec
Compressive strength, σ_c,	30,000 psi (2.1 kbar)
Tensile strength, σ_t,	900 psi (62 bar)

The assumed electron beam has an energy density of 70 joules/cm^2 (17 calories/cm^2) which produces an average temperature rise of 155° C in the bombarded zone of the granite and a corresponding average initial compressive stress of ~ 15 ksi (1.0 kbar). The energy deposition is not uniform, as mentioned earlier and the values will vary from the average values accordingly so the peak temperature is ~ 250° C and the peak compressive stress is ~ 24 ksi (1.6 kbar).

Following creation of the impulsively stressed volume, elastic stresswaves propagate from the compressed zone. If the electron beam diameter is large compared with the electron range (R/ρ) the stresswave can be treated as planar and it will propagate in the depth direction as shown in Figure 1 (neglecting attentuation and dispersion). This is analogous to an electrical transmission line short-circuited at the end. The initially-stressed region can be thought to create two oppositely-travelling waves, each of half-magnitude as shown by the dashed curves. As the wave propagates, a region of the rock at a depth of ~ 1 mm is subjected to a tensile stress of ~ 12 ksi (0.6 kbar) peak magni-

tude for a fraction of a microsecond. This stress level considerably exceeds the static tensile stress of 900 psi and likely will result in spalling of the surface layer, even though the very-short-term tensile strength may be several times the static tensile strength. If there should happen to be another free surface at moderate depth into the rock face, then the right-going stresswave may be reflected and cause additional spalling as indicated in the lower waveform of Figure 1. Thus, with only a single pulse, one might observe spalling of a rear surface as well as a front surface.

This description fits the primary spalling mechanism for a dry brittle material. For wet rock, secondary effects due to the presence of water must be considered in addition.

3. Experimental Results

Shock spalling was verified experimentally for a variety of rock types of igneous, sedimentary and metamorphic origin including several granites, two sandstones, schist, basalt, white limestone (marble) and a very tough greenstone. These rocks had compressive strengths ranging from well below 10 ksi up to 46 ksi. The tests were conducted with electron beams from two Febetron #705 accelerators (Ref. 4) and one Pulserad #422 accelerator (Ref. 5) all located at the Lawrence Livermore Laboratory. These accelerators have output beam characteristics very similar to those given at the start of Section 2 with an effective beam diameter of ~ 2 cm for the Febetrons and ~ 7.5 cm for the Pulserad 422.

In one series of tests, 10 cm-thick blocks of wet rock were each subjected to a single pulse from the Pulserad 422 while each was located in air at 5 cm from the output window. The resulting surface spalls are in excellent agreement with predictions of Section 2 and are shown in Figure 2 and characterized in Table II for three different rocks. While, the volume removed may seem small, it should be remembered that the energy input is also small and that some of the intact material is partially damaged. Other beam voltages or operating parameters not yet explored may well produce even more favorable results.

Table II - Measured Spalls for Several Wet Rocks Subjected to a Single Burst from Pulserad 422 Accelerator.

Rock Type		Sierra Granite	White Lime-Stone	Napa Basalt
Compressive strength	ksi	26	8	46
Spall area	cm^2	29	34	21
Spall depth, max.	mm	1.1	0.8	0.7
Volume removed	cm^3	1.6	1.9	0.7
Total energy deposited,	kcals.	0.6	0.6	0.6
	kjoules	2.5	2.5	2.5
Specific energy (Energy deposited/volume removed)	kJ/cm^3	1.5	1.3	3.2

Perhaps the most interesting test was one in which a 1.0 cm thick slab of wet granite was located in air at 2.5 cm from the output window of the Pulserad 422 and also subjected to a single pulse. As predicted, spalling occurred at both front and rear faces as shown in Figure 3. Figure 4 presents several frames from a high-speed movie which shows the rather-violent spalling at the front surface facing the accelerator and a slower, flake-like spalling at the rear face. The greater violence of the front spalling is not yet fully understood but is thought to be due to water thermal expansion and/or gas generation acting in addition to the tensile stresswave. Since the rock is ~ 5 electron ranges thick, the rear spall appears clearly to be due to the travelling stresswave unassisted by other phenomena.

These and other tests have demonstrated (at least tentatively) the following characteristics of the shock spalling mechanism.

1) It is successful for a wide variety of rock types.
2) It is reproducible, as shown by repeatable front and rear spalls on four successive identical tests.
3) Stronger and tougher rocks show less spalling for same energy input.
4) There is a threshold energy input below which spalling does not occur. Threshold value is function of rock types, moisture, etc.
5) Spalling can occur at rear free surfaces as well as at front face.
6) Stresswaves appear to be a dominant fracture mechanism as evidenced by rear-face spalling and relative uniformity of spall depth.
7) Wet rocks generally show significantly more spalling than dry rocks for same energy input (fortunately, since tunnels are usually wet). Phenomena other than stresswaves are apparently contributing.
8) Rocks bombarded in vacuum (~1 torr) spall similarly to those in air.
9) Energy threshold is increased if the electron penetration depth (range) is comparable to or greater than the beam diameter.
10) Spall debris is small flakes, sand and dust (which should facilitate debris removal).

It has just come to our attention that independently Shea (Ref. 6) has studied rock spalling and has bombarded dry rocks in a vacuum with a single 4MV, 15kJ pulse of electrons and obtained correspondingly larger spalls that appear to be in substantial agreement with the data herein.

4. Future Prospects

Tunneling and other underground excavation through rock are very promising applications for these new fracture mechanisms although it is clear that additional research and engineering results are needed. Rock-tunneling rates are limited at present primarily by the fundamental power limitations of existing rock drilling methods (e.g., only limited horsepower can be transmitted by a rock drill). Rates are also limited by the time required for removing the rock debris and for supporting and lining of the tunnel, if required. The shock spalling approach offers the possibility of breaking through these limitations. In constrast with most rock penetration techniques, shock spalling delivers the fracturing energy directly within the rock volume rather than at the surface. Pulse rates up to hundreds per second can be considered, each producing a miniblast which further erodes the rock face. Thereby, tunnel advancement might no longer be limited by the role of rock removal at the tunnel face. The debris is essentially sand and dust which can be removed easily by suction or hydraulic slurry piping or by mechanical conveyors. Little damage is done to the rock surrounding the tunnel so support and lining requirements are minimized. All of these factors

could contribute to improved rates of tunnel advance.

The specific energy levels reported above may be low enough for economic feasibility, but even lower values appear likely. Beam parameters not yet tested may produce more efficient spalling. The prevailing compressive stress in underground rock due to the earth and rock overburden should facilitate spalling (as evidenced by "rock bursts" at free surfaces of deep tunnels and massive rock faces). The residual heat during high-rep-rate electron bombardment should cause surface compressive stresses which may further enhance the shock spalling. In addition, a variety of strategies for using shock spalling in combination with other methods can be considered, such as cutting a pattern of grooves by shock spalling followed by removal of intermediate material by electron beam heating or by mechanical means.

In mining, the fine nature of the shock spalling debris may facilitate ore dressing. On a much smaller scale, shock spalling might be used for "machining" of ceramic turbine blades and other brittle materials. As an immediate application, these very-short duration stress pulses can provide information on the fundamental nature of fracture initiation and crack propagation in brittle materials.

5. Conclusions

It has been demonstrated that shock spalling produces effective rock removal by producing mini-explosions within the rock. This technique may produce the much-needed breakthrough in the speed and cost of tunneling and underground excavation through rock. It offers sufficient promise to merit further study.

Acknowledgments

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References

1. R. Avery, et al. "The ERA 4 MeV Injector, "IEEE Trans. Nucl. Sci., NS-18, No. 3 (June 1971).

2. R.T. Avery, "On the Possibility of Rock Fracture by Intense Bursts of Energetic Electrons", UCID-3522 (1971).

3. The term "shock spalling" was selected to describe rock spalling due to very-short-duration energy deposition and to distinguish it from the more conventional static and quasi-static spalling mechanisms. The stresswaves produced are believed to be elastic and not possess the wavefront characteristics of shockwaves, with which they should not be confused.

4. Made by Field Emission Corp., McMinnville, Oregon.

5. Made by Physics International Co., San Leandro, Calif.

6. J.H. Shea, Physics International Co., private communication (Feb. 1973).

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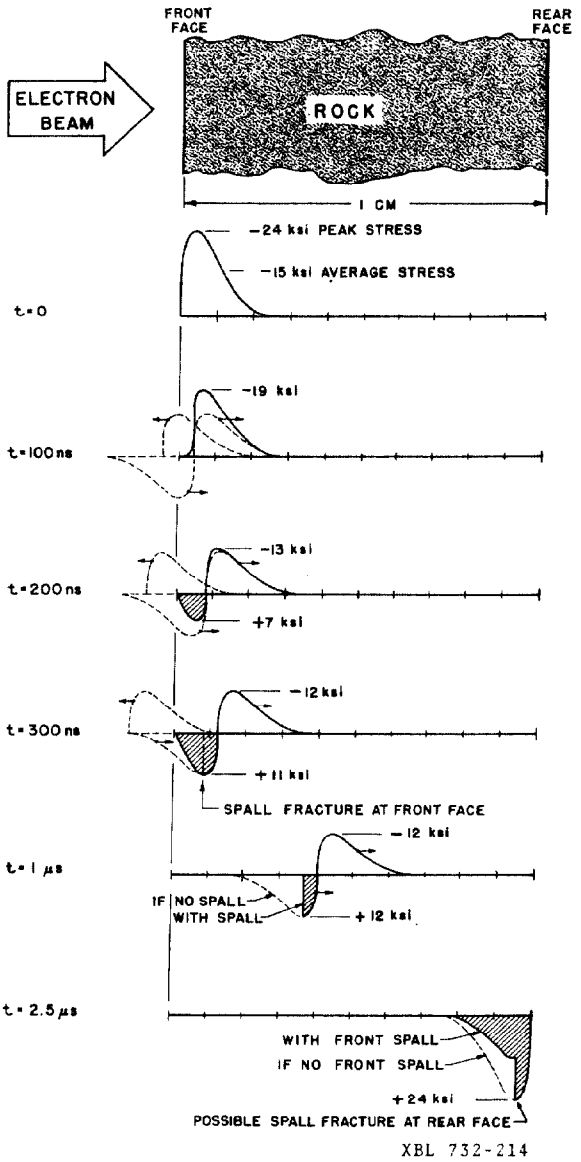
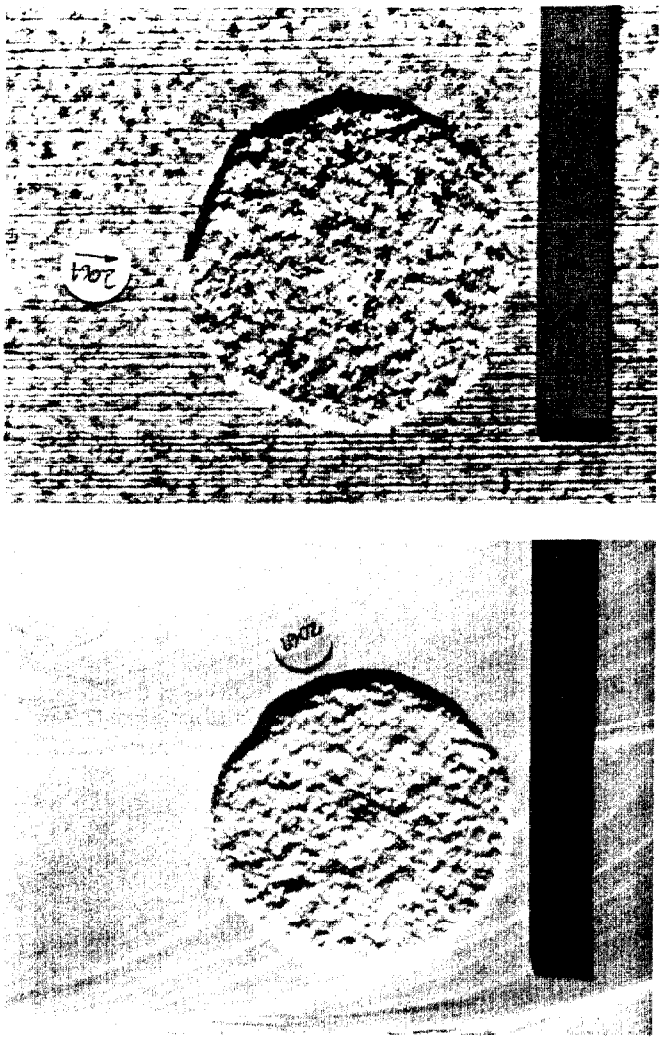


Fig. 1 - Idealized stresswave propagation within a 1-cm thick rock with wave velocity = 4 mm/μs. Stress is compressive above baseline and tensile (cross-hatched) below baseline. Wave at t = 0 represents initial energy deposition. Dashed lines represent travelling stresswaves whose algebraic sum is the actual stress shown by solid curve. Note the possibility for both a rear spall and a front spall resulting from a single burst of electrons.



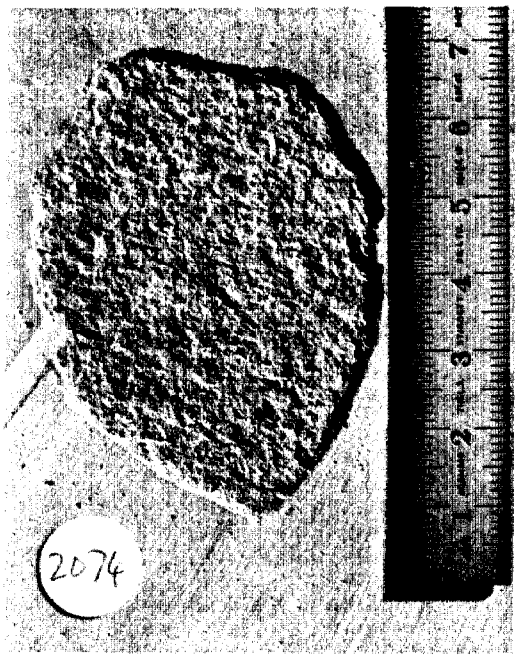


Fig. 2 - Wet rocks each bombarded in air with single electron burst (< 1 MV >, 2.5 kJ, 50 ns) from Pulserad 422 accelerator. Rocks are granite (upper left), white limestone (lower left) and basalt (above).



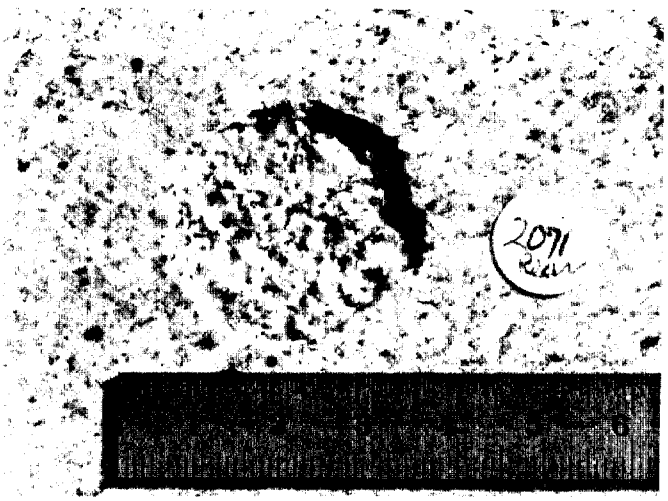


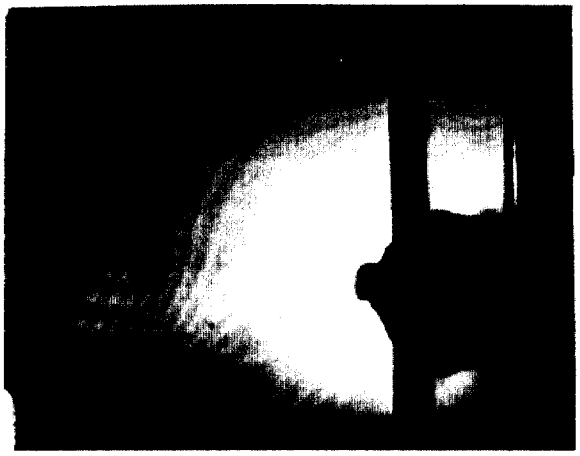
Fig. 3 - Granite slab 1 cm thick bombarded in air with single electron burst (< 1 MV >, 2.5 kJ, 50ns) from Pulserad 422 accelerator. Front surface spall is shown left and rear surface spall is shown at right.



t = 0



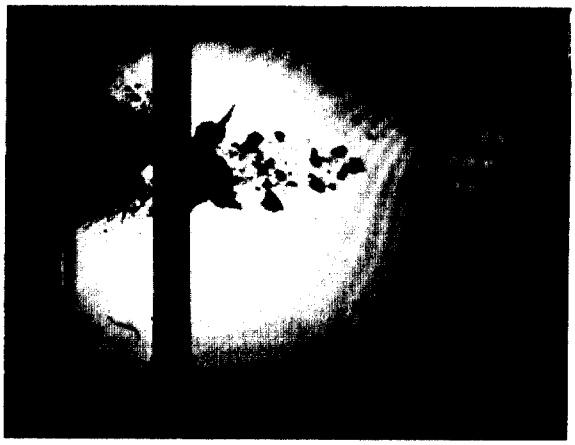
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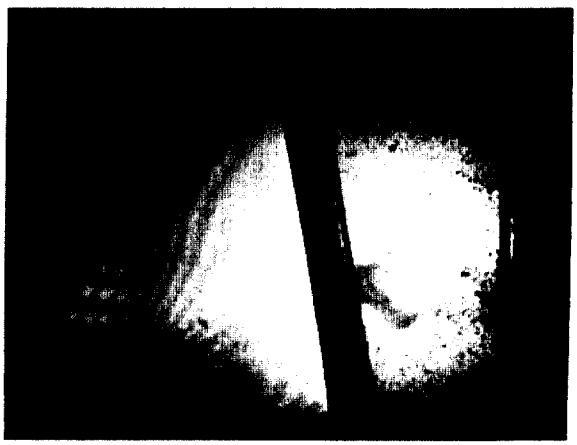
t = 0.25 ms



t = 25 ms



t = 2 ms



t = 75 ms

Fig. 4 - Frames from hi-speed movie showing spalling at both front and rear surfaces of same rock as Figure 3. Note that front spall is sandy and rapid while rear spall is flaky and slower.