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Robert T. Avery, Denis Keefe,
Tor L. Brekke, and Iain Finnie

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Use of Intense Sub-Microsecond Electron Bursts to Produce Rock Shattering

Robert T. Avery and Denis Keefe
Lawrence Berkeley Laboratory
University of California
Berkeley, California

and

Tor L. Brekke and Iain Finnie
College of Engineering
University of California
Berkeley, California

SUMMARY - It has been demonstrated that intense sub-microsecond bursts of very-high-energy ($\geq$ 1 MV) electrons cause significant pulverization and surface spalling of a variety of rock types, both wet and dry, and even moist clay. In general, for the same energy input, soft rocks show greater spall volume than hard rocks and wet rocks exhibit greater spall volume than dry rocks. The spall debris is of fine nature, being either dust, sand or small flakes. Selected test results are presented together with discussion of the fracture mechanisms occuring on this very short time-scale. Possible applications in tunneling and mining are briefly described.

RÉSUMÉ - Il a été prouvé qu'avec des jets intenses d'électrons sous très haute tension ($\geq$ 1 MV) d'une durée de moins d'une microseconde, on pulvérise en quantité significative et on fissure en surface toutes sortes de roches sèches ou humides et même l'argile mouillée. En général, pour la même quantité d'énergie conférée, on trouve un volume fissuré plus grand dans les roches tendres que dans les roches dures, dans les roches humides que dans les roches sèches. Les déchets sont fins, sous forme de poussière, de sable ou de petits flocons. Cet article donne les résultats de certains tests et discute les mécanismes de fracture se produisant pendant des temps très courts. Il décrit brièvement les applications possibles au forage de tunnels et de mines.

ZUSAMMENFASSUNG - Wir haben experimentell nachgewiesen, dass submicrosecunden lange Electronenpulse von hoher Electronenenergie ($\geq$ 1 MV) bedeutende Desintegration der Oberfläche von verschiedenen Gesteinstypen in nassem und trockenem Zustand hervorrufen, sogar feuchter Lehm zeigt solche Erscheinungen. Im Allgemeinen ist das Desintegrationsvolumen bei gleichem Arbeitsaufwand grösser für weiches und nasses Gestein als für hartes und trockenes. Das abgespaltene Material ist sehr fein, Staub Sand oder kleine Flocken. Ausgewählte Test-Resultate werden vorgetragen zusammen mit einer Diskussion über den Abspaltmechanismus wie er in dieser kurzen Zeitspanne abläuft. Mögliche Anwendungsgebiete im Tunnel- und Mienenbau werden kurz beschrieben.

INTRODUCTION

The technology of electron accelerators capable of pulse currents of many kiloamperes has rapidly expanded in recent years. While designing such a kiloampere pulsed electron accelerator, it became clear that the high-current electron beam had significant damage potential which might usefully fracture rock. The most promising damage mechanism, called shock spalling,[1] is based on delivering a modest amount of energy in a sub-microsecond pulse to produce intense tensile stresses underneath the surface of a rock face. This method takes advantage of the low tensile strength relative to compressive strength of rocks. It differs fundamentally from alternative methods using electron or laser beams to produce rock removal by melting, vaporization or sublimation and for which very much greater amounts of energy are needed because of the phase changes involved.

[1] The term "shock spalling" was selected to describe impulsive thermo-mechanical rock spalling due to very-short-duration energy deposition and to distinguish it from the more conventional static and quasi-static thermal spalling mechanisms. The stresswaves produced are believed to be elastic and should not be confused with the hydrodynamic type of shockwave.

* Work has been performed under the auspices of the U.S. Atomic Energy Commission with the financial support of the National Science Foundation.

FUNDAMENTALS OF SHOCK SPALLING

Consider a rock face struck by an intense burst of energetic electrons of 50ns duration with pulse current density of 14 MA/m^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 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 and the density-normalized electron range R (kg/m^2). The average temperature rise is

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

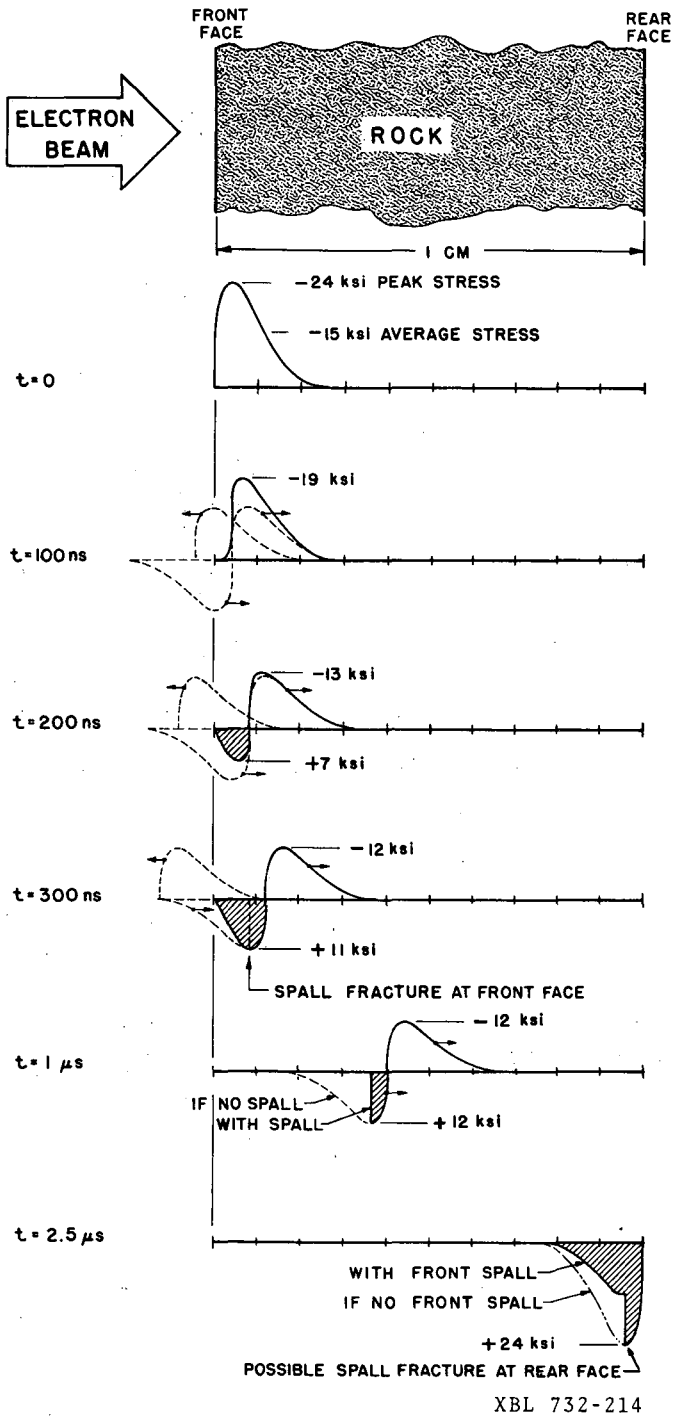


Fig. 1 - Idealized stresswave propagation within a 1-cm thick rock with wave velocity = 4 km/s. Stress is compressive above baseline and tensile (cross-hatched) below baseline. Wave at t = 0 represents initial energy deposition. Dashed lines represent travelling stresswaves whose algebraic sum is the 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.

where W is total energy absorbed in joules per pulse and c_v is specific heat. This temperature rise produces an initial compressive stress of

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

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

For a granite with mechanical properties as given in Table 1, an average temperature rise of 155K and a corresponding average initial compressive stress of 100 MN/m^2 (~ 15 ksi) are produced in the bombarded zone. The energy deposition is not uniform with depth, as mentioned earlier, so the values will vary from the average values accordingly and the peak temperature rise is ~ 250K and the peak compressive stress is ~ 160 MN/m^2(24ksi).

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 penetration depth (R/ρ) the stresswave can be treated as planar and it will propagate in the depth direction as shown in Figure 1 (neglecting attenuation and dispersion). The initially-stressed region can be thought to create two oppositely-travelling waves, each of half-magnitude as shown by the dashed curves. The front-going compressive wave is reflected at the free rock face into a rear-going tensile wave. As the waves propagate, a region of the rock at a depth of ~ 1 mm is subjected to a tensile stress of ~ 80 MN/m^2(12 ksi) peak magnitude for a fraction of a microsecond. This stress level greatly exceeds the static tensile stress and likely will result in spalling of the surface layer, even though the very-short-time 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, additional spalling may occur as indicated in the lower waveform of Figure 1. This description fits the primary spalling mechanism for a dry brittle material. The effects due to water are discussed later.

Table 1 - Properties of a competent granite

Density, ρ	2.7 kg/liter
Thermal coefficient of Expansion, α,	7×10^{-6}/K
Specific heat, c_v,	840 J/kg·K (0.2 BTU/lb-°F)
Modulus of elasticity, E,	55 GN/m^2 (8×10^6 psi)
Poisson's ratio, ν	0.2
Sonic velocity, $c = \sqrt{E/\rho}$	4 km/sec
Compressive strength, σ_c,	207 MN/m^2 (30,000 psi)
Tensile strength, σ_t,	6.2 MN/m^2 (900 psi)

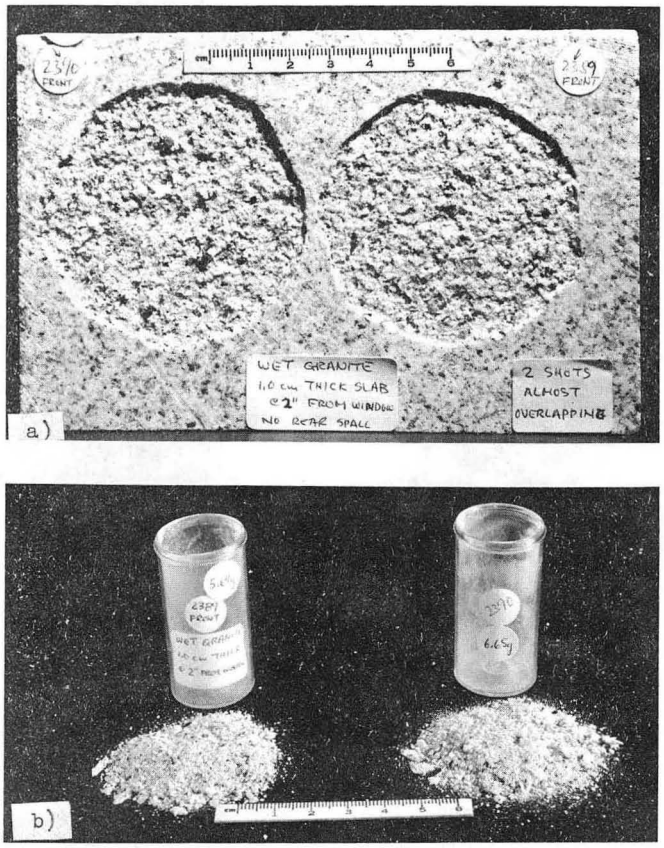


Fig. 2 - a) Sierra granite subjected to two separate 1.1 MV electron pulses. b) The spall debris therefrom.

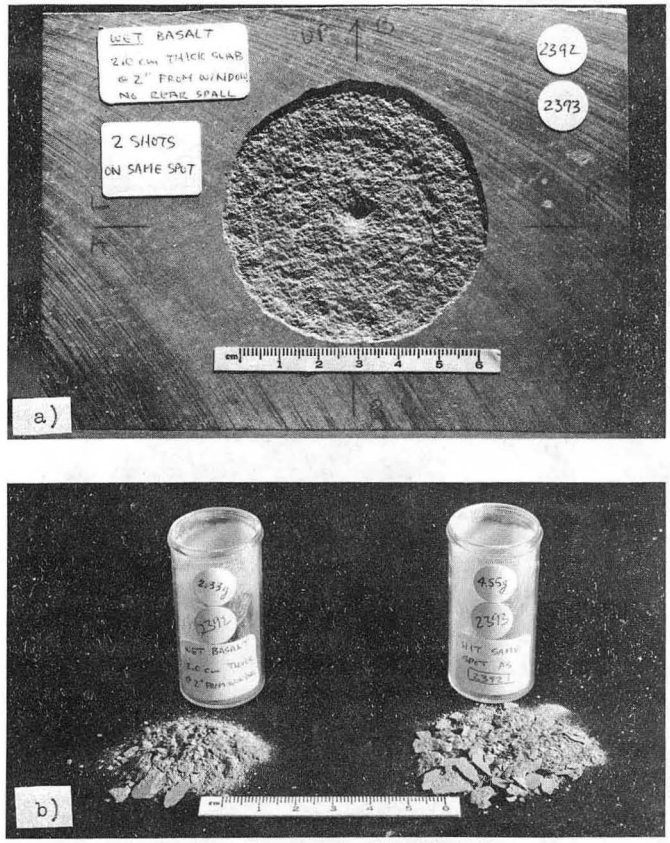


Fig. 3 - a) Napa basalt bombarded by two 1.1 MV electron pulses on same spot. b) The spall debris therefrom.

EXPERIMENTAL RESULTS

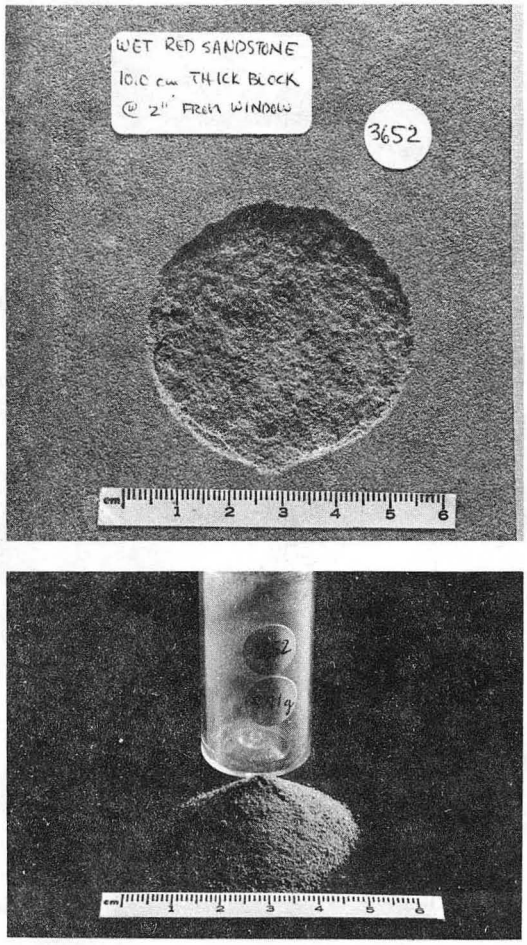
Experimental verification of the shock spalling technique was reported in an earlier paper (Avery, et. al., 1973) for some igneous, sedimentary and metamorphic rock types including granite, sandstone, basalt, white limestone (marble) and a very tough greenstone. These early tests also verified, at least for 1.0 cm thick slabs of granite subjected to a single pulse, that shock spalling can occur not only at the front face, but also at a rear face as predicted in Figure 1.

Further tests have been performed using the Pulserad #422 accelerator[2] at the Lawrence Livermore Laboratory. A granite slab subjected to two almost-overlapping "shots" is shown in Figure 2 together with the sandy debris produced. Shot #2390 removed ~ 20% more rock than Shot #2389, possibly indicating that the earlier shot enhanced the spall volume on the second shot. A slab of hard basalt subjected to two shots at the same spot and the associated debris are shown in Figure 3. Compared to Shot #2393, the earlier Shot #2392 produced a spall ~ 2/3 as large - the approximate outline of which can be seen within the later spall. This again possibly indicates spall enhancement on subsequent shots.

[2] Manufactured by Physics International Co., San Leandro, Calif., USA.

Another series of tests were performed using the Pulserad 422 accelerator, but with mean acceleration potential of ~ 2.0 MV instead of the ~ 1.0 MV of the earlier tests. The energy delivered per shot was 3-4 kJ as for the earlier tests. At the higher voltage, the electrons penetrate more deeply into the rock and consequently produce a deeper spall. Successful shock spalling of hard rocks having been demonstrated, it was of interest whether it also would work on softer materials. A weak sandstone bombarded with a single shot produced the spall and the sandy debris shown in Figure 4. Single-shot bombardment of a shale produced the spall shown in Figure 5. The debris (not shown) was a fine dusty powder. Single-shot bombardment of a moist plastic adobe clay produced the spall shown in Figure 6. Successful spalling has been achieved at various standoff distances up to 0.15 meter from the accelerator exit port. High-speed movies were taken of several tests at framing times from 5 to 250 microsecond per frame with observed spall velocities as high as 580 meters per second. Significant movement of the front surface was observed at 5 microseconds (first frame) after bombardment.

A further set of tests were performed using the Pulserad 1140 accelerator at the Physics International Co. factory. This accelerator delivered an electron pulse of ~ 4 MV mean voltage and ~ 9-10 kJ per shot. At this voltage the electrons penetrate even more deeply, which was verified. A block of basalt bom-



a)

b)

Fig. 4 - a) Colorado red sandstone bombarded by single 2 MV electron pulse. b) The spall debris therefrom.

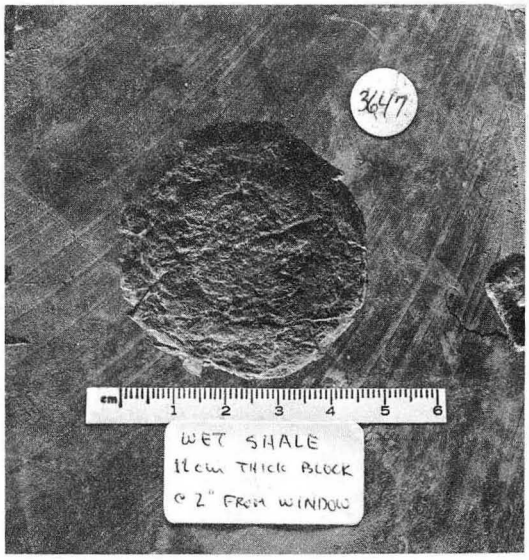


Fig. 5 - Shale subjected to single 2 MV electron pulse.

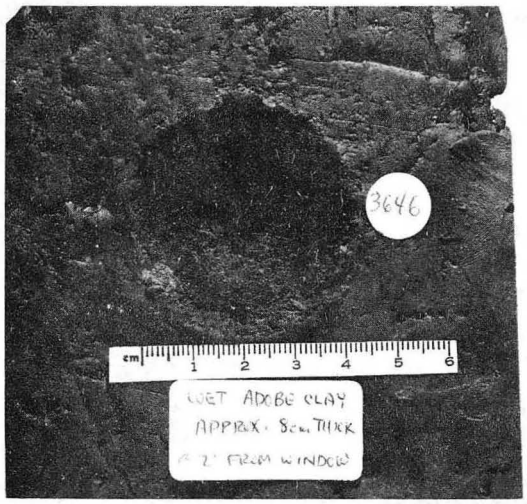
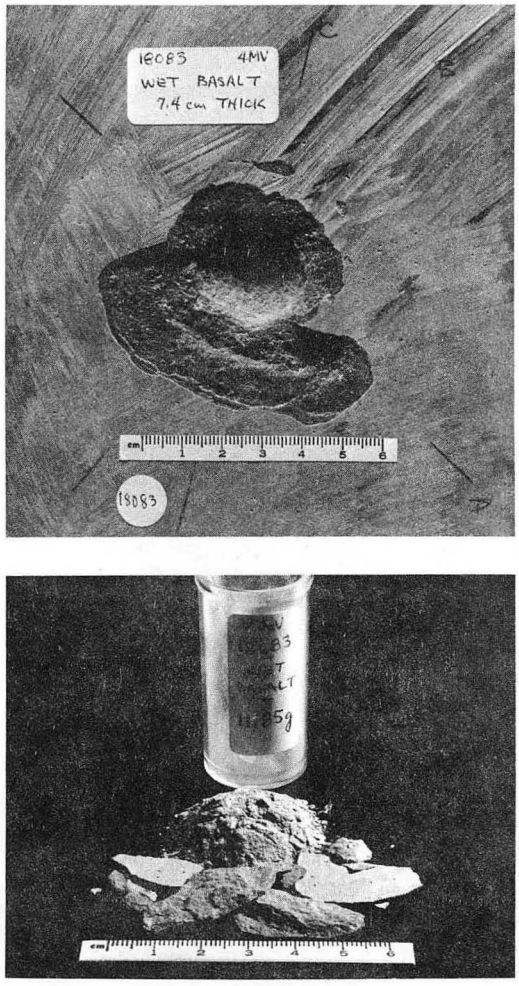


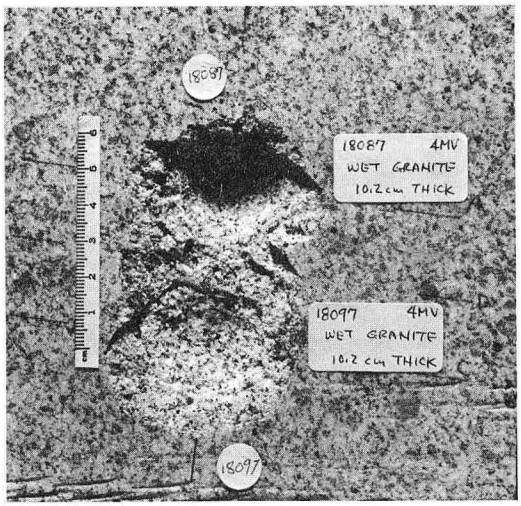
Fig. 6 - Moist adobe clay subjected to single 2 MV electron pulse.



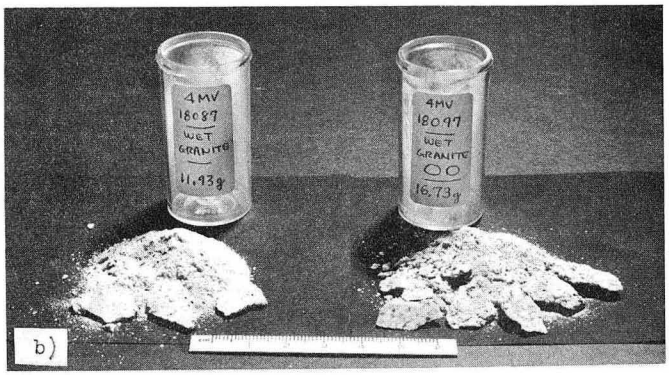
a)

b)

Fig. 7 - a) Napa basalt bombarded by single 4 MV electron pulse. b) The spall debris therefrom.



a)



b)

Fig. 8 - a) Sierra granite bombarded by two adjacent 4 MV electron pulses. b) The spall debris therefrom.

barded with a single shot produced the results shown in Figure 7. A block of granite was similarly bombarded by shot #18095 followed some minutes later by an adjacent shot #18096. The resulting spalls and debris are shown in Figure 8. Shot #18096 produced ~ 50% more spall volume than shot #18095, primarily due to easy removal of the partially fractured material located between the two spalls. The large flakes in the rock debris of these shots comes from the periphery, not the central core, of the spall. The spalls produced by the 4 MV Pulserad 1140 accelerator appear significantly different than those at 1 and 2 MV produced by the Pulserad 422 accelerator. This is attributed to the relatively greater penetration depth relative to beam diameter which causes the primary ejected spall to peel off flakes of adjacent material by shear action. Further study is needed to determine if this type of spalling is more efficient than that obtained using the 422 accelerator.

Nearly one hundred test shots have been conducted. These have demonstrated the following characteristics of the shock spalling mechanism.

1) It produces spalls on a variety of rock types and even clay.

2) It is reproducible, as shown by repeatable front and rear spalls on 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 primarily a function of rock type and moisture content.

5) Spalling can occur at rear free surfaces as well as at front face.

Table 2 - Single-shot Spalls and Specific Energies for Several Materials Tested

		Moist Adobe Clay	Colorado Red Sandstone	Shale	White Limestone (Marble)	Sierra Granite	Napa Basalt	Green-stone
Compressive strength	MN/m^2 ksi	Not Meas.	43 6	Not Meas.	58 8	180 26	320 46	270 40
Young's modulus of elasticity	GN/m^2 10^6 psi	Not Meas.	13 1.9	Not Meas.	41 6	55 8	72 10	99 14
Shot Ident. No.		3646	3652	3647	2069	2390	3634	2373
Mean accelerating voltage	MV	2	2	2	1.0	1.0	2	1.1
Total energy deposited	kjoules	3.1	3.1	3.1	3.1	3.7	3.1	3.7
Spall area	cm^2	16	20	17	34	35	15	11
Spall depth, max	cm	1.0	0.26	0.29	0.08	0.13	0.19	0.13
Volume removed	cm^3	6.8	3.4	3.2	2.6	3.1	1.8	1.0
Specific energy (Energy deposited/volume removed)	kJ/cm^3	0.46	0.9	1.0	1.2	1.2	1.7	3.7

6) Stresswaves appear to be a dominant fracture mechanism.

7) Wet rocks generally show more spalling than dry rocks for same energy input. Phenomena other than stresswaves apparently are contributing.

8) Rocks bombarded in vacuum also spall.

9) Spall debris is small flakes, sand and dust which should facilitate debris removal by hydraulic slurry or pneumatic means.

10) Greater accelerating voltage produces deeper spalls.

11) Successive nearby pulses may enhance the spalling process.

Single-shot spall measurements and the associated specific energy values for several materials tested are given in Table 2.

DISCUSSION OF THE FRACTURE PROCESS

When a rock or other brittle material is subjected to static tension, failure typically is characterized by growth of a single crack from a pre-existing major flaw, followed by propagation of the crack over the cross section. The rate of crack propagation approaches a terminal velocity somewhat less than half of sonic velocity in the material. In a sense, the weakest point within the rock determines the static tensile strength of the rock.

The shock spalling fracture process is significantly different. As indicated in Figure 1, the travelling stresswaves produce tension at a given location within the rock for only a few tenths of a microsecond. Even if a crack were to start at the onset of the tensile stresswave and travel at terminal velocity, it could propagate only ~ 1 mm before the wave is passed. This suggests that each small area on the spall surface is fractured substantially independently. A multitude of bonds must be broken simultaneously to free the spall from the rock face. The data in Figure 1 and in Table 1 indicate that the peak value of the tensile stresswave is approximately an order of magnitude greater than the static tensile strength. In other words, the dynamic tensile strength of rock subjected to sub-microsecond tensile pulses is an order of magnitude greater than the static tensile strength. This and the physical appearance of the spalled surface are qualitatively consistent with achieving simultaneous fracture at a multitude of nucleation centers across the spall face.

As noted earlier, wet rocks generally show more spalling than dry rocks. The somewhat-limited data indicate virtually no difference for the greenstone which has porosity of 0.22% but a marked difference for granite (0.88% porosity), for limestone (0.85% porosity) and for basalt (0.48% porosity). However, sandstone with a very high porosity of 17.8% exhibited virtually no enhancement. Under electron bombardment, the energy deposition per unit weight within a water volume is essentially the same as for rock. However, the specific heats are such that if the rock temperature rises 250 K, the intergranular water rises only ~ 50 K during bombardment. After bombardment, significant heat can be transferred by thermal diffusion from the rock to the water on a microsecond time scale, particularly if the intergranular water layers are only a few micrometers thick as may be the case for the rocks showing the greatest spall enhancement by water. Thus, the intergranular water temperature may be approaching the rock temperature. The thermal expansion coefficient of water is an order of magnitude greater than for many rocks. Consequently, the intergranular water expands more than the surrounding rock and the hydraulic impedance of the internal water paths may be sufficient on this time scale for such water expansion to account for the greater spalling of certain wet rocks. Steam generation may be enhancing the greater spall velocity observed and also may be contributing to the greater spall volume.

POSSIBLE APPLICATIONS

Tunneling, mining and other excavation in rock are promising applications for the shock spalling technique although it is clear that additional research and engineering are needed. The specific energy levels reported may be low enough for economic feasibility, but even lower values appear likely. Beam parameters not yet tested may produce more efficient spalling. Lateral compressive stresses due to residual heat during high-rep-rate bombardment as well as those generally prevailing in in-situ rock may enhance the shock spalling efficiency. 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 mechanical means. A conceptual design of a tunneling system based on this method is under preparation. The prospects for technical and economic feasibility appear promising. 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.

ACKNOWLEDGMENTS

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