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APPLICATION OF PARTICLE BEAMS
TO GEOTHERMAL WELL DRILLING

Final Report

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PARTICLE BEAM DRILLING

Introduction

Between 1971 and 1974 Lawrence Berkeley Laboratory performed experiments with electron beams that indicated such beams could be useful for excavating rock. This paper considers whether particle beams, proton or electron, might be useful for drilling vertical holes. The question originated at a 1975 meeting of the Geothermal Coordinating Group which considered novel drilling techniques. At that time, the energy efficiency (i.e, joules of energy deposited in the rock ÷ volume of rock broken up) of the Sandia spark drill, and the efficiency of the shock spalling mechanism, as then understood, appeared to be approximately 100 times as great as with conventional drilling. At that time, it did not seem to be possible to use electrons because the energy required in each pulse was so high that no conceivable electron pulse generator could fit in a geothermal well. On the other hand, by using protons, with their much smaller range, it seemed that the energy per pulse could be made much smaller, and it might then be possible to develop an accelerator that would fit in a geothermal well.

Description of Experiments

In the experiments (see Table 1) intense pulses of electrons were directed against rock samples. The electrons had energies of 1-9 million electron volts, depending on the particular machine used to produce the pulses. The electrons in the pulse are bunched together so that the pulse passes a given point in 80-160 nanoseconds, and the pulse is dense enough so that the electrons in it have a combined kinetic energy of 100-1000 joules per square centimeter of pulse area.

When the moving pulses of electrons collide with the rock samples, craters are formed. The debris from the craters is finely divided, and hard rocks crater almost as readily as soft rocks. Generally, the depth of the crater is roughly proportional to the voltage, and the volume removed is proportional to the total energy of the pulse. For example, a 9 Mev, 64 kJ pulse "9 cm in diameter" produces a crater 13 cm in diameter and 1 cm deep (maximum) in Sierra granite. The volume removed is about 75 cm³.

The cratering mechanism is a variety of shock spalling, and it is explained as follows: the electrons in the pulse are deflected by the atoms in the rock until they come to a stop, about .4 - 2.5 cm deep in the rock, depending on voltage. This heats the rock in the irradiated volume very rapidly, but only about 250°K. The heated volume expands

thermomechanically, and the time scale is so short that a stresswave is created that propagates from the compressed zone with a velocity of about 4 km/sec, the speed of sound in the rock, or perhaps faster. When this stresswave passes a point in the rock it produces a stress of around 12,000 lbs/in², or greater. This stress, acting on preexisting flaws in the rock, breaks it up, forming a crater at the surface bombarded by the beam. (If a relatively thin sample of rock is bombarded the traveling stresswave also excavates a crater in the rear surface.)

The electron accelerators used in the experiments had relatively fixed pulse characteristics such as voltage, current and pulse length, and hence it was not possible to determine the optimum pulse parameters to produce shock spalling. Specifically, it is not clear whether longer pulses (10^{-6} sec) would cause spalling. Also, since only a portion of the irradiated and stressed volume spalls, it is possible that repetitive pulses would excavate rock much more efficiently than single pulses.

The essential characteristics of shock spalling seem to be: the volume represented by the range of the electrons in the rock and the beam diameter will spall if irradiated with about 500 J/cm³ of energy. About 1/4 of the irradiated volume spalls away. The deposition of energy must be in a time similar to the shock travel time across the range, so that the heating produces a stress wave.

Application of Electron Beams to the Excavation of Rock Tunnels

Since shock spalling of rock seemed to be energy efficient and the debris was finely divided, it appeared that electron beams could be useful for tunneling rock. Lawrence Berkeley Laboratory made a conceptual design of an accelerator and tunneling system. The accelerator and muck removal system were so large that they would barely fit in a 21 ft diameter tunnel. However, it was in concept possible to condense the system a little.

The electron accelerators used to demonstrate shock spalling were of the high current pulse power technology type (see Figure 2). These machines were designed for research and are unsuitable for excavation purposes where reliable operation for billions of pulses is required. Also they are huge in size, 6 ft in diameter, 40 ft long with a capacitor bank 20 ft x 20 ft x 30 ft.

Lawrence Berkeley Laboratory suggested the use of a different type of accelerator, the linear induction accelerator, which in principle could provide the repetitive operation required (but which was also very large). At the time of the experiments there was no induction accelerator with pulse characteristics suitable for rock spalling, but now such an accelerator is being built at Lawrence Livermore Laboratory. The Livermore Experimental Test Accelerator will have a 5 Mev, 10 kilo-amp, 50 nanosecond pulse of electrons which can be repeated at a rate of 5 pulses per second, and will fit on a railroad flatcar.

Characteristics of Particle Beams for Rock Spalling

Before trying to answer the question of whether a practical drilling system could be built using proton or electron beams, it is necessary to examine the characteristics particle pulses must have to be useful for spalling rock.

Approximately speaking, the range of a particle beam in matter is the average depth the particles penetrate into the matter before they lose their initial kinetic energy. Table 2 shows rough estimates of the ranges of protons and electrons in rock. They are derived from values of the range given in grams per square centimeter from experiments with various materials. At 5 Mev, the range of an electron in rock is about 1 cm, and for a proton is .02 cm.

The experiments performed by Lawrence Berkeley Laboratory, and theoretical understanding of the shock spalling mechanism indicate that shock spalling rock requires that the beam lose about 500 J/cm^3 in the rock volume defined by the particle range and the beam diameter, and that this energy is deposited in a time short with respect to the time it takes a shock wave to traverse the range. A shock wave travels about $4 \times 10^5 \text{ cm/sec}$ in rock (or faster). Thus, if R is the range, a shock traverses the range in $2.5 \times 10^{-6} R$ sec, which is about 2.5×10^{-6} sec for 5 Mev electrons, and 5×10^{-8} sec for 5 Mev protons. It is believed that shock spalling occurs if enough energy is deposited in about 1/10th of

this time, or 2.5×10^{-7} sec for 5 Mev electrons and 5×10^{-9} sec for 5 Mev protons. Further experimentation is necessary to nail down the pulse lengths and energy density required more precisely. In particular, it has not been demonstrated that protons will shock spall rock, though at the present level of understanding it seems likely that they will. Experimentation might show that the pulses can be longer and that energy density can be smaller, particularly with repetitive pulses, which would simplify some problems in conceiving of excavation systems based on particle beams.

From the voltage, pulse length, and energy density we can derive some of the other requirements proton and electron beams must satisfy to be useful for drilling. In Table 3 these characteristics are shown per unit of beam area for 5 Mev particles. (This particle energy is taken as an example. For protons, at about 6 Mev there will be short-lived radioactive products formed in the rock. For electrons, radioactive products will be formed above about 12 Mev. As seen below, the amount of rock broken up by a pulse is related to the energy of the particles in the pulse. Thus, for drilling systems based on particle beams, the energy of the particles is bounded below by the repetition rate that can be achieved and above by the radioactivity problem. A reasonable compromise seems to be 5 Mev, for both electrons and protons, but specific cases where particles of other energies might serve a useful purpose are

pointed out later.

Note that a 5 Mev pulse of protons moves only a tenth as fast as a 5 Mev pulse of electrons. But the required proton pulse is only 5 nsec long, compared with 250 nsec for electrons. Thus the length in space of the proton cloud is only 1/500 that of the electron cloud. The result is that the charge density of the proton pulse is 10 times the charge density of the electron pulse. This charge density, and the fact that 5 Mev protons only move 1/10th as fast as 5 MeV electrons leads to the conclusion that the magnetic field required to keep the proton pulse bunched in a vacuum tube is 1000 times as intense as would be required with electrons, though a more exact statement would require the use of a modern beam calculation code. Also, since protons have a range a hundredth that of electrons, the vacuum requirements are much greater for protons in any transport tube. These two characteristics of the proton beam, the charge density and range, must be kept in mind when thinking about drilling systems. Specifically, for protons they imply that it would not be possible to place an accelerator outside of the well and transport the beam to the bottom of the hole by means of a vacuum tube. Thus for protons it is necessary to produce the beam down-hole. Furthermore, the range of the protons is so short that there can be very little matter between the beam source and the rock.

Hypothetical Drilling Systems Based on Particle Beams

In order to imagine how particle beams might be used for drilling it is necessary to solve the problems of how to get the pulses to the bottom of a hole and how to remove the rock fragments (Figures 3 & 4). For the first problem, there seem to be three possibilities: (1) put the particle source, including the power conditioning equipment, in the well; (2) put the particle source in the well, but put the power conditioning equipment outside the well; (3) place the particle source outside the hole and transport the pulses into the hole by means of a vacuum tube and focusing magnets. There are two possible types of accelerators that can be considered: the pulse power diode type (Figure 1) and the linear induction accelerator (Figure 2). It would not be possible to place a linear induction proton accelerator in the hole, because either the beam diameter would be too large or the focusing coils would be too large. Although it seems that there is no physical reason that a 2 ft diameter linear induction electron accelerator could not be built, the practical problems appear to be very great, and with electrons it seems easier to place the accelerator outside the hole anyway.

Consider (1) first, using electrons. In order to spall, the rock must gain about 500 J/cm^3 of irradiated volume, in a time interval

short, 1/10th as long, as the time required for a stress wave to traverse the volume. Moreover, the beam diameter must be large, say 5 times the range of the particles, in order that the stresses are not dissipated in the radial direction. Considering 5 Mev electrons with a range of 1 cm, an electron pulse 5 cm in diameter must carry $\pi \times (2.5\text{cm})^2 \times 1\text{cm} \times 500 \text{ J/cm}^3 = 10,000 \text{ J}$ of energy to spall the rock. Typically, these 10,000 Joules would remove about 1/4 of the irradiated volume, or $1/4 \times \pi \times (2.5\text{cm})^2 \times 1\text{cm} = 5\text{cm}^3$. Since the pulse must traverse the the range in about 1/10th of the time a sonic signal traverses the range, and the speed of sound in rock is about 400,000 cm/sec, the entire pulse is condensed to a duration of 250 nsec. Thus, the peak power is $10,000\text{J} \div 2.5 \times 10^{-7} \text{sec} = 4 \times 10^{10} \text{ watts}$, which means the peak current is $4 \times 10^{10} \text{ watts} \div 5 \times 10^6 \text{ volts} = 8000 \text{ amps}$.

The size of the machinery necessary to generate an 8000 amp peak current of electrons at 5 million volts and condense it to a 5 cm diameter beam makes it difficult to imagine a pulse power electron accelerator compact enough to be placed in the hole. There is presently no Marx generator 1 ft in diameter with the capability of storing 10,000 Joules that can be discharged in 250 nsec at 5 million volts and which will operate for billions of cycles at 2 cycles per second. Nonetheless, a well-size diode type electron accelerator capable of repeated pulses that could spall rock could probably be developed with considerable effort.

Consider the same scheme with protons. A 5 Mev proton has a range in rock of about .02 cm. Thus, to get the planar geometry that seems to be required, the pulse would only need a diameter of about .1 cm. Assuming that for spalling the volume defined by the range and beam diameter must receive 500 Joules per cubic centimeter, the pulse must carry only .08 Joule. The pulse duration is hypothesized to be 5 nsec.

Since the proton pulse only requires .08 Joule, electrical energy storage could be confined to a much smaller volume. With pulse power technology, the 5 nsec pulse length might not be possible, but this pulse length is hypothetical. It is possible that a 20 nsec pulse would spall, and this pulse length can be achieved. (A 20 nsec pulse could be made to spall if its particle density was made the same as the 5 nsec pulse in Table 3. It would be a factor of 4 less energy efficient.) In order to achieve the same drilling rate with this 5 Mev, .1 cm diameter, .08 J/pulse proton beam as could be achieved with the 5 Mev, 5 cm diameter, 10,000 J/pulse electron beam, the proton pulse repetition rate would have to be 125,000 times the repetition rate with electrons, or at least 125,000 pulses per second for a drilling system that would advance a 12 in diameter hole 3 ft/hr. The 5 nsec pulse length and the 125,000 pulse per second repetition rate are far beyond what current pulse power proton accelerators can do. A 20 nsec pulse and 1 pulse per second are presently possible.

The second scheme (2), placing the particle source in the hole and the power source outside the hole is possible, assuming that a high power diode is used as the particle source. For a 5 Mev, 5 cm diameter, 10,000 J electron pulse, the line transmission from the top of the hole to the diode would have to be less than two ft in diameter and transmit an 8000 peak amp, 250 nsec, 5 million volt pulse thousands of feet without spreading the pulse or short circuiting, and this is impossible. The same thing can be said about the 3 peak amp, 5 nsec, 5 million volt pulse required for a 5 Mev, .1 cm diameter, .08 J proton pulse.

This brings us to the third scheme (3), and figure 3 shows what we believe is the most practical proposed scheme for drilling with particle beams. A linear induction electron accelerator is placed near the hole to be drilled. As shown in Figure 4, a linear induction accelerator consists of a sequence of toroidal magnetic cores. An electric pulse in the winding of the core causes a change in the magnetic field within the toroid. This induces an electric field in the axial direction, which is used to accelerate the electrons (or protons). The beam voltage is the sum of the voltages of the individual cores. The accelerator is most economical if the frequency is in the range of 60-360 cycles per second, and the voltage per core is in the 100-250 kilovolt range. The experimental test accelerator being built at Lawrence Livermore Laboratory, which will be the only such accelerator with rock spalling capability,

produces 5 Mev, 10 kA, 50 nsec pulses and can be operated at 5 pulses per second. It will fit on a railroad flatcar, and cost around \$5 million. For drilling operations a power plant would be required. The advantages of a linear induction accelerator are that parts do not need to be replaced between pulses, the maximum potential to ground is 100-250 kV, it can produce a very short pulse, perhaps 10 nsec, and it can be built for repetitive operation.

The accelerator in this scheme produces 5-25 MeV electrons. At the higher voltages, there is an advantage that focusing is easier, so the beam can be smaller in diameter and the standoff distance from the rock can be greater, and individual pulses can be more powerful. On the other hand, at above 8 MeV there is a problem with induced radioactivity. After leaving the accelerator the beam is turned by magnets and directed down a vacuum tube that extends into the hole. Roughly, the tube would be 4-6 in. in diameter, and each 10 ft or so there would be a 50-100 gauss quadrupole focusing magnet. Surrounding the inner tube and magnets would be an outer tube. In some way this tube would have to be extended into the hole as drilling proceeded. The tube must be good enough to hold a 10^{-2} Torr vacuum. At the bottom of the hole would be a scanning and shutter device. This is perhaps the most difficult portion of the machine to imagine, since it must protect the approximately 10^{-2} Torr vacuum in the tube from the downhole environment, spall, X-rays, and

mucking at the face, let the pulses reach the rock face at preselected instants, and allow the beam to be scanned across the face. The advantage of the high voltage beams (25 Mev) is that they can be pinched easily to pass through the shutter and the pulse could be made sufficiently energetic so that after passing through the shutter it would expand to the full diameter of the hole (18 inches) and still retain enough energy density to spall the rock.

For a lower voltage beam the aperture and shutter must be moved as the beam is scanned on the face. The actual scanning is not a problem. The problem is the aperture which must protect the vacuum in the transmission tube from the downhole environment. This shutter-aperture and scanning apparatus appears to be the most difficult engineering (vs. economic) obstacle to this drilling machine. Obviously, devising a scheme for removing the cuttings, extending apparatus down the hole, and integrating all this machinery in the hole and at the well head challenges the engineering imagination. On the other hand, if cost was no object, it could probably be done.

With protons, the above scheme would be much more difficult. As has been said, the proton beam is hard to focus because the protons aren't moving very fast and the space charge density in the pulses may need to be 100 times as high as with electrons. This presents unsolved problems for the low energy end of an induction accelerator. Also, a 5

nsec pulse is at the lower end of what is possible for single cores with special magnetic materials. The vacuum in the transport tube must be much better, the magnets more closely spaced and powerful, the distance between the shutter and the rock much shorter, and to get a drilling rate comparable to electrons, the shutter must have a higher repetition rate. All of these things indicate to us that the scheme is much more workable with electrons.

In any of these schemes, cutting removal (mucking) is more difficult than with conventional drilling. The space at the bottom of the hole between the output window of the accelerator or transport tube and the rock must be kept relatively free of matter. As can be seen from Table 2, 2.5 gm/cm^2 of matter between the window and rock will absorb essentially all the energy of a 5 Mev electron beam, and $.05 \text{ gm/cm}^2$ of matter will absorb essentially all the energy of a 5 Mev proton beam. Furthermore, any pressure in this space would tend to force material through the window into the accelerator or vacuum tube, creating problems for the vacuum system. Blowing the cuttings away with air seems to be the most plausible alternative, but we cannot at present give a plausible mechanism.

Potential Economics of Particle Beam Drilling

The relative energy efficiency of particle beam drilling and conventional drilling can now be determined. Assume that a conventional rig can advance a 12 in diameter hole 100 ft/day at an average of 100 HP. (This would be typical at 100 RPM at 10,000 ft depth). Then the power required is about 75 kw. It should be noted that the specific energy required to excavate holes by rotary drilling in medium strength rock is estimated to be 200-500 J/cm³ (which lies within the range of estimates for particle beam drilling). This indicates that for conventional drilling at 10,000 ft only about 10% of the power applied to the drill stem actually is used to excavate rock. The remainder is used to overcome friction between the drill pipe and the hole.

For particle beams, we can speculate that when optimum beam parameters are determined, (as explained on p.) then cratering efficiency might be improved to 100 J/cm³. Thus, the power required to advance a 12 in diameter hole 100 ft/day using particle beams would be

$$(100 \text{ J/cm}^3) \times \pi \times (6 \text{ in} \times 2.54 \text{ cm/in})^2 \times (100 \text{ ft} \times 12 \text{ in/ft} \times 2.54 \text{ cm/in}) \div (24 \text{ hr/day} \times 60 \text{ min/hr} \times 60 \text{ sec/min}) = 2574 \text{ J/sec} = 2.6 \text{ kw.}$$

If the accelerator is about 50% efficient, then particle beam drilling will advance a 12 in diameter hole 100 ft/day at an average power of 5.2 kw. Thus being optimistic about particle beam drilling

indicates the method is about 14 times as efficient as a rotary rig at 10,000 ft. Using the demonstrated excavation efficiency of 2000 J/cm^3 and a 25% efficiency for getting electricity into particle beams into the rock the rotary drilling method would be 3 times as efficient as the particle beams. In general, for conventional rotary drilling fuel represents less than 4% of the cost of drilling a well. Even in the best case for particle beams, the energy efficiency is not an important economic consideration. Particle beam drilling probably would not be significantly more energy-efficient than conventional drilling. (This does not consider the energy used in mucking.)

Conventional costs of making a well run \$67-\$134/ft in hard rock, of which about a third is the cost of the drilling (i.e, cost of renting the machinery and the labor to turn the bit and circulate the fluids). The other two thirds of the cost is supervision, site preparation, mobilization and demobilization, casing (hardware and services) cement (hardware and services), drilling fluids, chemicals, logging, air compressors, bits, transportation, pipe inspection, drill pipe charges, well head, and other supplies and services. Only bit costs and drill pipe charges, amounting to less than 10% of the cost of the well, are eliminated by particle beam drilling, at least if removing the cuttings and holding the hole is at least as costly as with conventional rigs, which seems likely. Thus at most 50% of the cost of drilling a well is

affected by a change in drilling method from rotary drilling to particle beams, or any other type rock drill.

Assume the accelerator costs around \$5 million. The size of the power plant is determined by drilling speed. For a 12 in diameter hole and drilling rate S (ft/hr) the power plant size C (kw) is $C = .052S$, where an optimistic excavation efficiency of 100 J/cm^3 and an optimistic accelerator efficiency of 50% have been assumed. If the power plant costs \$500/kw, then the power plant cost is $26S$ (\$).

Hence, as a function of drilling rate, the rig cost is $\$6 \times 10^6 + 26S$. Assume that the rig spends about 1/5 of its time (during a year) actually drilling a hole, and that 1/3 of the rig cost is paid in one year. Then in one year it will drill $1752S$ feet of hole. Thus the cost of the rig per foot of hole is $1/3 \times (6 \times 10^6 + 26S) \div 1752S = 1141/S + .005$ (\$).

To achieve a cost of \$25/ft to provide for the cost of the rig itself, the rig must drill at a minimum rate of 46 ft/hr, 20% of the year. This rate would be easily possible with known accelerator technology.

To sum up these economic considerations, there is no indication that particle beam drilling will be less expensive than conventional drilling.

SUMMARY AND CONCLUSIONS

1. Since particle beam drilling affects only about 40% of the cost of making a well, and guesses at the cost of particle beam drilling appear to be similar to conventional costs, it is not likely to contribute significantly to the Division of Geothermal Energy's goal of demonstrating by 1986 the technology to reduce well costs by 50%. In fact, no change in drilling technique that does not affect the costs of removing cuttings and holding the hole can reduce well costs by 50%.
2. It appears that a several-man-year effort would have about a 50% chance of producing a convincing concept for a workable drilling method using particle beams.
3. Further experiments should be done to elucidate the mechanism of shock spalling, as a contribution to engineering science.
  - a. How does excavation efficiency vary with pulse length for electrons and protons?
  - b. Do repeated pulses improve the efficiency?
  - c. Can spalling be done with protons?
4. The development of inertial confinement fusion technology is relevant to particle beam drilling. Studies of the transport of particle beams are also relevant to their use in drilling.
  - a. Beam codes are available for determining vacuum and focusing requirements for particle beam transport schemes.
  - b. Practical reactors for deriving energy from the implosion of deuterium-tritium pellets by means of particle beams seem to require the development of apertures that allow the beam to pass but protect the accelerator from the environment in the reactor vessel.
  - c. Present schemes for imploding deuterium-tritium pellets for fusion with particle beams require the development of compact accelerators with very short, repeatable pulses. (But at power levels far greater than what is necessary for rock drilling.)
  - d. The means of producing and transporting high power particle pulses are being studied at several laboratories.

TABLE 1

LAWRENCE BERKELEY LABORATORY SHOCK SPALLING EXPERIMENTS WITH ELECTRON BEAMS

Source: Reference 1

Typical operating parameters of electron accelerators during rock bombardment experiments.

Test dates	Accelerator used	Location	Beam voltage E (MV)		Calc. max. penetration depth for $\rho=2.7$ h (cm)	Approx. beam diameter D (cm)	Approx. bombarded volume $V=\frac{\pi}{4}D^2h$ (cm ³)	Pulse rep. rate f (Hz)	Pulse duration t (10 ⁻⁹ s)	Pulse current, mean I (kA)	Energy delivered $U = EIt$ (J)	Per pulse		Remarks
			Mean	Max								Typical central energy fluence $u_0 = 4U/\pi D^2$ (kJ/cm ²)	Typical central electron fluence $q = u_0/E$ (μ C/cm ²)	
May 1971	Febatron 705	LLL Bldg. 255	1.4	2.2	0.39	1.7	0.8	Single pulse	100	2.0	2.8×10^2	0.13	91	Values at 0.6 cm from accelerator output window.
Oct 1972	Microwave Electron Linac	LBL Bldg. 25	- 7	- 7	1.33	1.2	1.5	up to 120	6000	1.4×10^{-4}	5.9	0.005	0.7	Values at 1 cm from accelerator output window.
Dec 1972	Astron Linac	LLL Bldg. 411	5.8	5.8	1.10	-1.0	-0.9	1	300	0.3	5.2×10^2	-0.66	-114	Values at 0.7 cm from accelerator output window.
Jan 1973	Febatron 705	LLL Bldg. 341	1.2	1.9	0.33	1.6	0.7	Single pulse	100	1.6	1.9×10^2	0.09	75	Values at 0.6 cm from accelerator output window.
Feb 1973	Pulsarad 422 (co-axial mode)	LLL Bldg. 169	1.0	1.3	0.22	4.8 (3.1)	4.0 (1.7)	Single pulse	80	39	3.1×10^3	0.17 (0.40)	170 (400)	Values at 5 cm (parenthetic values at 2.5 cm) from accel. output window.
Mar 1973	Pulsarad 422 (co-axial mode)	LLL Bldg. 169	1.1	1.4	0.24	6.3 (3.8)	7.4 (2.8)	Single pulse	90	37	3.7×10^3	0.12 (0.32)	110 (270)	Values at 5 cm (parenthetic values at 2.5 cm) from accel. output window.
Aug 1973	Pulsarad 422 (triaxial mode)	LLL Bldg. 169	2.0	3.1	0.57	3.6	5.9	Single pulse	70	22	3.1×10^3	0.10	150	Values at 5 cm from accel. output window.
Nov 1973	Pulsarad 1140	Physics Intl. Co. San Leandro	- 4.0	- 5.0	0.94	3.5	9.1	Single pulse	100	24	9.5×10^3	0.96	120	Values at 3 cm from window on partial atmosphere chamber.
Jan 1974	Hermes II	Sandia Corp. Albuquerque	- 9	12.5	2.41	9.9	221	Single pulse	160	45	6.4×10^4	1.00	78	Values at 18 cm from accelerator output window.

- Notes:
1. To convert joules to calories, multiply given value by 0.239.
  2. Fluence values given are on axis and are typical of conditions used for actual tests.
  3. Approximate beam diameter calculated such that beam area = energy delivered/central energy fluence. Some of the electron beam falls outside of the beam diameter so calculated.

TABLE 2

RANGE OF PROTONS AND ELECTRONS*

ENERGY	PROTON RANGE IN ALUMINUM	ELECTRON RANGE IN ALUMINUM	PROTON RANGE IN ROCK (2.75 gm/cm ³)	ELECTRON RANGE IN ROCK (2.75 gm/cm ³)
Mev	gm/cm ²	gm/cm ²	cm	cm
1	.0042	.409	.002	.15
2	.0117	.928	.004	.34
3	.0223	1.458	.008	.53
4	.0358	1.991	.013	.72
5	.0521	2.526	.019	.92
6	.0709	3.061	.026	1.11
7	.0922	3.598	.034	1.31
8	.1160	4.133	.042	1.50
9	.1421	4.670	.052	1.70

*Ranges in aluminum from American Institute of Physics Handbook.
Ranges in rock estimated.

TABLE 3

PARTICLE BEAMS FOR ROCK SPALLING

PARAMETER	5 Mev ELECTRON BEAM	5 Mev PROTON BEAM
1. Range	1 cm	.02 cm
2. Energy Density Deposited	500 J/cm ³	500 J/cm ³
3. Energy/Pulse	500 J/cm ²	10 J/cm ²
4. Repetition rate for 20 m/hr	2.2222 pulses/sec	111 pulses/sec
5. Average Power	1110 watts/cm ²	1110 watts/cm ²
6. Beam Velocity (5 Mev)	2.99x10 ¹⁰ cm/sec	3.09x10 ⁹ cm/sec
7. Time for Sound to Traverse Range	2.5x10 ⁻⁶ sec	5x10 ⁻⁸ sec
8. Pulse Duration	2.5x10 ⁻⁷ sec	5x10 ⁻⁹ sec
9. Length of 5 Mev Pulse	7470 cm	15 cm
10. Peak Power	2x10 ⁹ watts/cm ²	2x10 ⁹ watts/cm ²
11. Peak Amps	400	400
12. Particles/Pulse	6.25x10 ¹⁴ /cm ²	1.25x10 ¹³ /cm ²
13. Charge/Pulse	1x10 ⁻⁴ coul/cm ²	2x10 ⁻⁶ coul/cm ²
14. Charge Density (5 Mev)	1.33x10 ⁻⁸ coul/cm ³	1.33x10 ⁻⁷ coul/cm ³

FIGURE 1

PULSE POWER
TYPE ACCELERATOR

When all of the switches S_i are open, the capacitors C_i are connected in parallel. In this configuration, the capacitors are charged to $q = c_o v_o$, where c_o is the capacitance of each capacitor and v_o is the charging voltage. The time constant for this is

$$T = (2\pi/c)(Lnc_o)^{1/2}.$$

The total charge on the network is $nc_o v_o$, where n is the number of stages. Next, the switches (spark gaps) S_i are closed connecting the capacitors in series, so that the voltage across the network is nv_o . The network is then discharged to the diode with time constant

$$T = (2\pi/c)(Lc_o/n)^{1/2}.$$

Thus, the Marx generator pictured here raises the voltage by a factor of 20 and gives a discharge time constant 1/20th of the charging value. The resulting voltage pulse strips electrons from the cathode and propels them through the anode foil and down the output tube.

FIGURE 2

INDUCTION ACCELERATOR

DIAGRAM OF ACCELERATING CAVITY

An initial pulse from the modulator (a blumlein charged by a Marx generator) establishes a magnetic field in the core (ferrite toroid). Following this, the accelerating pulse reverses the field in the core. The flux change in the core causes an accelerating voltage to appear across the accelerating gap. By passing the beam through enough such accelerating gaps of modest voltage the pulse is accelerated to the final voltage. The figure at above right is a cross-section of a core and accelerating cavity from the ERA 4 Mev Injector.

The figure below shows the 2.5 million volt electron gun for the Livermore Experimental Test Accelerator. Ten cores of 250 kv are stacked to produce a 2.5 million volt field that strips the electrons from the cathode and accelerates them down the hollow anode.

FIGURE 3

TWO HYPOTHETICAL DRILLING SCHEMES

(1) Pulse forming network and particle accelerator placed in the well

(2) Pulse forming network at surface, accelerator placed in the well

FIGURE 4
HYPOTHETICAL DRILLING SYSTEM

ABBREVIATIONS

J	joule
kJ	kilojoule
Mev	million electron volts = 1.6×10^{-13} joules
cm ³	cubic centimeter
km	kilometer
nsec	nanosecond = 10^{-9} second
in ²	square inch
kamp	kiloamp = 1000 amperes
kV	kilovolt = 1000 volts
Torr	pressure exerted by a 1 mm mercury column
kw	kilowatt = 1000 watts
HP	horsepower
c	speed of light

REFERENCES

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