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C. E. Ragan
M. G. Silbert
A. N. Ellis
E. E. Robinson
M. J. Daddario*

*Lawrence Livermore Laboratory, Livermore, CA 94550.

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

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PERFORMANCE OF ELECTRICAL CONTACT PINS NEAR A NUCLEAR EXPLOSION

by

C. E. Ragan, M. G. Silbert, A. N. Ellis, E. E. Robinson, and M. J. Daddario

ABSTRACT

The pressures attainable in equation-of-state studies using nuclear-explosion-driven shock waves greatly exceed those that can be reached in normal laboratory conditions. However, the diagnostic instrumentation must survive in the high-radiation environment present near such an explosion. Therefore, a set of experiments were fielded on the Redmud event to test the feasibility of using electrical contact pins in this environment. In these experiments a 60-cm-high shield of boron-lead was placed on the rack lid ∿ 1 m from the device. A sample consisting of slabs of molybdenum and ^{238}U was placed on top of the shield, and twelve electrical contact pins were embedded to five different depths in the materials. Five different multiplexing-charging circuits were used for the pins, and a piezoelectric quartz gauge was placed on top of the uranium to obtain an estimate of the fission-energy deposition. All of the charged pins survived the radiation and produced signals indicating shock arrival. The uncertainty in determining the pin-closure time was ∿ 3 ns. The signal from the quartz gauge corresponded to a pressure that was consistent with the calculated neutron fluence.

I. INTRODUCTION

High-pressure-equation-of-state (EOS) data are obtained mainly from shock-loading experiments in which measurements of two shock parameters are used to define a point on the Hugoniot. Usually, the shock velocity and particle velocity are determined using either direct or indirect techniques, and conservation relations are then used to calculate the pressure, density, and specific internal energy. Various theoretical arguments can be used to extend the EOS away from the Hugoniot to neighboring areas of the P-V-E surface. Once the Hugoniot for a "standard" material has been determined, Hugoniot data for other samples can be determined in "impedance-matching" experiments in which only the shock velocities in the standard and in the sample are measured. This greatly simplifies the experiment since shock-velocity measurements are rather straightforward.

In a recent add-on experiment[1] conducted at the NTS, we determined a point on the molybdenum Hugoniot at 2.0 TPa by simultaneous, direct measurements of both the shock velocity and the particle velocity. The results are in good agreement with the best theoretical estimates of the molybdenum Hugoniot and provide experimental data to test calculations in a pressure region where no data were heretofore available. (Previously molybdenum had been well studied[2] at pressures below 0.21 TPa, with some data available[3] up to 1 TPa.) After completing this experiment in which an experimental basis was provided for the Hugoniot of a standard (molybdenum), we began to explore techniques for performing impedance-matching experiments in this pressure region.

Under normal laboratory conditions, impedance-matching experiments are straightforward, and a number of techniques have been devised for measuring shock velocities. However, previous experiments have been limited to the pressure region below one TPa, with most facilities capable of pressures of only a few tenths TPa. Nuclear explosions are capable of producing pressures of many tens TPa, but the high-radiation environment in the vicinity of such an explosion severely limits the types of experiments that can be performed.

Electrical and optical means are the most commonly used laboratory methods for determining shock-arrival times, from which shock velocities can be calculated. One advantage of electrical contact pins, which close and produce a pulse when the shock arrives, is the inherent simplicity compared with most optical techniques. Pins are also capable of providing nanosecond timing accuracy, and because of their small size many pins can be used to map the shape of the shock front at a given depth. However, a number of questions about pin performance in a high-radiation environment needed to be answered before we could proceed with a full-scale set of impedance-matching experiments. We therefore fielded a set of experiments on the Redmud event to test the feasibility of using electrical contact pins to obtain high-pressure EOS data. The main problem areas addressed in this experiment are discussed in the next section.

II. DESIGN CONSIDERATIONS

While our measurements of the molybdenum EOS were under way, workers at the Lawrence Livermore Laboratory (LLL) fielded an experiment[4] on the Edam event to study the behavior of pins located within approximately 2 m of a nuclear explosion. Three types of pin insulator materials were tested: Al_2O_3, quartz, and Lexan. In this experiment, the pins were optimally shielded by layers of polyethylene, lead, and boron carbide. While the shock transmitted through such a shield was expected to be distorted by shock reflections at interfaces, the shielding did limit the radiation to a rather low level. All three types of pins survived the radiation and provided signals upon shock arrival. In addition, quartz-insulated pins used on the Husky Pup event[5] survived at a distance $\sim$ 1 m from the device.

Under ideal conditions, in which a large fraction of a sphere is available for shielding, it should be possible to design a shield that will transmit a smooth-profile shock front, while limiting the transmitted radiation to a low level. In this case, a homogeneous shield is needed to eliminate the reflections present in an optimum shield composed of layers of material. With this consideration in mind, as well as the information from the Edam and Husky Pup experiments, we began to design an experiment to test the behavior of contact pins in a high-radiation environment. The main objective of this experiment was to obtain enough information on pin behavior to allow a full-scale, impedance-matching experiment to be designed. In designing such an experiment, we needed to know what level of radiation the pins could withstand, what timing accuracy the pins could provide, and what degree of pin multiplexing was possible. In addition, calculations on various shields were needed to determine their neutronic properties, as well as the characteristics of the transmitted shock. A number of homogeneous shields were studied using Monte Carlo calculations; mixtures of both lead-boron and lead-B_4C (1.81 boron atoms per lead atom) were found to be equally effective. With about 1 m of either shield, the energy deposition in a sample with a fission threshold such as ^{242}Pu would cause a temperature rise of < 300K.

Hydrodynamic calculations[6] were performed by Group TD-3 to determine both the pressure and the shock position as a function of time in the shielding material, whose EOS was provided by Group T-4. Preliminary calculations performed in a one-dimensional, planar geometry indicated that with a driving temperature of 0.5 keV, a 0.4-TPa shock would be produced 50 cm into the shield. Later, 1-D calculations (DITTO and MCRAD) using a 3-cm slab of B_4C below a lead-boron shield (ρ = 8.32g/cm^3) and a temperature profile provided by Group TD-2 indicated that the pressure transmitted through 60 cm of shielding to a molybdenum sample would be 3-4 TPa. The calculated shock arrival time was $\sim$ 16 μs after nuclear time. These results were used in setting up the data recording system.

III. EXPERIMENTAL SETUP

Figure 1 shows a schematic of the experimental setup used on the Redmud event. A 30-cm-diam by 60-cm-high shield of lead plus boron (fabricated in five layers by CMB-6) was positioned on the rack lid approximately 1 m from the device. An additional slab of the shield filled a 25.4-cm-diam hole in the lid; a 3-cm-thick layer of pressed B_4C (ρ = 2.5g/cm^3) was supported below the lid by a 1.5-mm-thick sheet of aluminum. The molybdenum sample was positioned on top of the shield near the back edge to provide as much direct shielding as possible. A slab of ^{238}U was mounted on top of the molybdenum with a quartz piezoelectric gauge located on top of the ^{238}U. Figure 2 shows a schematic of the sample assembly and gives detailed information on the location of the pins. The pressure imparted to the quartz gauge by the heated uranium was used to provide information about the neutron flux at the sample position. The twelve pins were encased in an aluminum tube filled with Sylgard-184 epoxy (Fig. 1). In order to shield the pins from the side, this aluminum tube was surrounded by lead, B_4C powder, and boron-loaded polyethylene.

Figure 3 shows a schematic of the pin construction: both stylan (a polycarbonate) and Lexan insulators (both supplied by LLL) were used with a 25-μm layer of copper electroplated on the outside. In addition, 1-mm-thick $LiNbO_3$ piezoelectric crystals requiring no applied high voltage were mounted on the center electrodes of the two pins labeled E and E' in Fig. 2. The expected pressure on this shot was well above that at which these crystals would be expected to operate properly; however, they were included because of their simplicity.

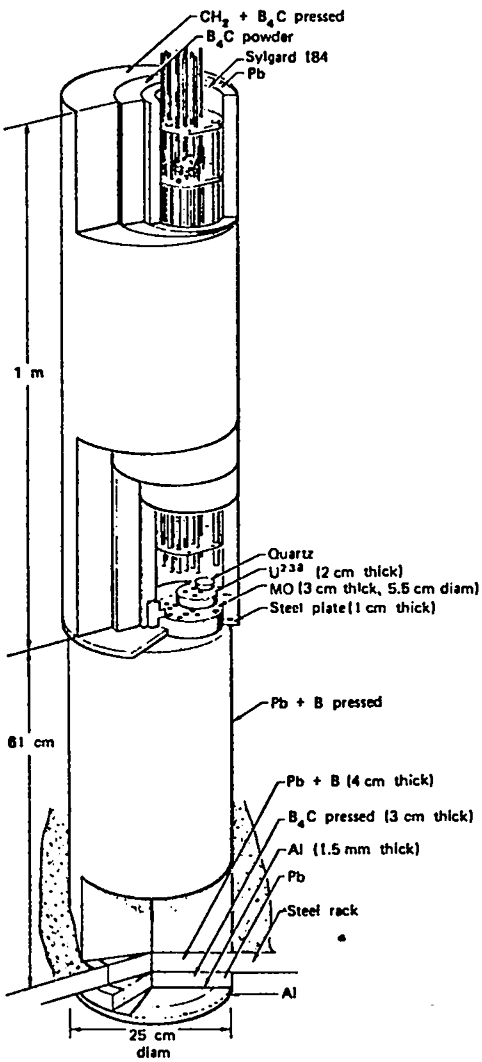

Fig. 1.

Sketch of overall experimental setup. The 60-cm-high, pressed Pb-B shield was mounted on the rack lid, while a 3-cm-thick slab of B_4C was located below the lid. The molybdenum-^{238}U sample was positioned on top of the shield. The contact pins (∿1 m long) were embedded to different depths in the samples, and a quartz piezoelectric gauge was mounted on top of the uranium. The pins were shielded for ∿1 m with layers of boron-loaded polyethylene, B_4C powder, and lead. At this point, the pins were connected to the rack cables, which in turn were shielded with 5 cm of lead for ∿18 m. The volume around the shield and the sample was filled with a mixture of B_4C powder and iron pellets.

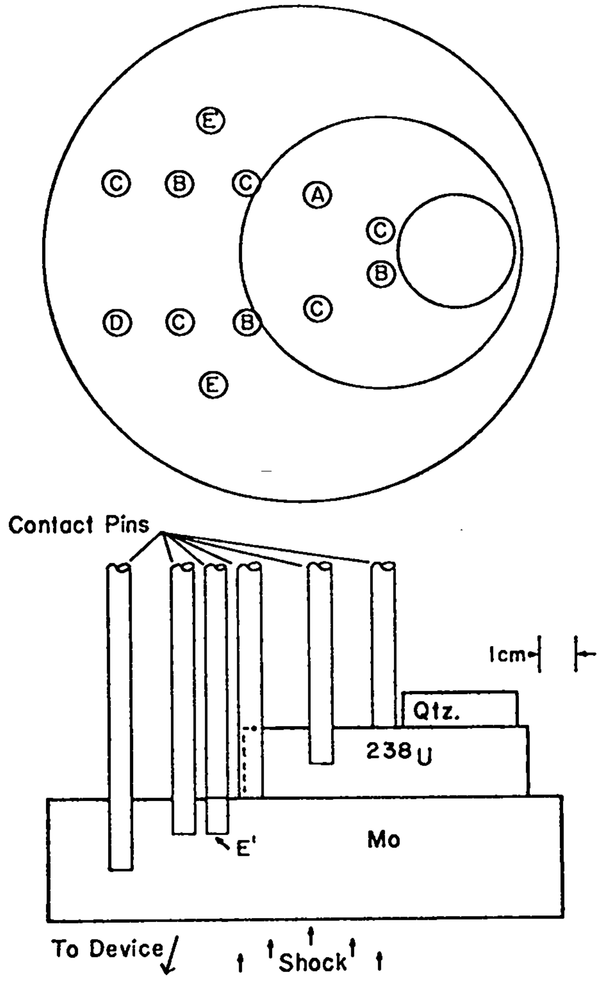

Fig. 2.

Drawing of the sample assembly showing the locations of the twelve pins. The labeling corresponds to that used in Fig. 8. The five pins labeled C were multiplexed onto a single cable at the top of the rack using the circuit shown in Fig. 4. These pins were dc charged prior to the shot. The three pins labeled B were multiplexed onto a single cable using the circuit shown in Fig. 5. A pulse from the recording station was used to fire the SCR's, which applied voltage to the pins after nuclear time. The single pins labeled A and D were powered from uphole using the circuits shown in Figs. 6a and 6b, with pin A being dc charged and pin D being pulse charged. The piezoelectric $LiNbO_3$ pins labeled E and E' were multiplexed using a diode adder.

Five pins at different depths (labeled C in Fig. 2) were multiplexed on one cable using the circuit shown in Fig. 4. The voltage was applied to these pins well in advance of shot time (dc charging). However, this meant that these pins would be exposed to the high radiation in the charged condition. Three other pins (labeled B in Fig. 2) were multiplexed onto one cable (see circuit in Fig. 5) but were not charged to full voltage until after nuclear time. This was possible because of the long transit time of the shock through the shield. Two other pins (labeled A and D in Fig. 2), each using a single cable, were used as back-ups with one charged well in advance and one charged by the pulsing technique described above. The circuits used for these single pins are shown in Fig. 6. The outputs from the two self-powered piezoelectric pins (labeled E in Fig. 2) were multiplexed using a diode adder.

Photographs of oscilloscope traces were the primary means of data recording, and a magnetic video disk provided a back-up recording system. Basically two types of triggering techniques were used for the oscilloscopes. The fast-sweep scopes (200 ns/cm), which were expected to give the best quality data, were self-triggered. That is, pick-offs on the cables from the two deepest pins provided signals that were mixed with an OR-gate to generate a trigger pulse. The signals from the pins were then delayed approximately 300 ns before being presented to the scopes. The initial radiation burst induced a large signal on all of the cables, and to prevent this signal from triggering the scopes, the pick-off pulses were sent through a discriminator that was gated off until ∿ 7 μs after nuclear time. This allowed the initial radiation-induced signal to decrease to a level below the discriminator threshold before the discriminator was turned on. For each signal, several fast-sweep scopes were triggered ∿ 1.8 μs apart providing a coverage, depending upon the number of scopes, of between 4 and 8 μs. Slower sweep scopes (∿ 1 μs/cm) were triggered by a delayed fiducial timing signal from the nuclear device. The amount of delay was determined from the calculations of the expected shock transit time through the shield. Best estimates from 1-D calculations of this transit time were ∿ 16 μs. Since any 2-D effects should decrease the velocity and delay the shock arrival, these scopes covering ∿ 20 μs were triggered ∿ 15 μs after expected nuclear time.

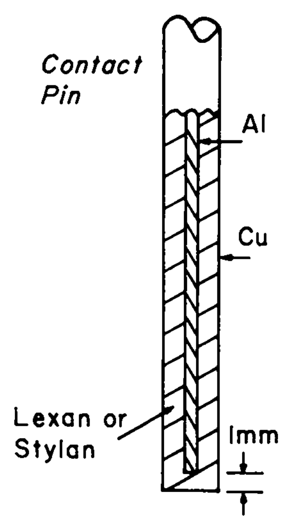

Fig. 3.
Typical pin construction. The center conductor was fabricated in place for the stylan pins; for the Lexan pins an aluminum wire was placed in a hollow Lexan rod and epoxy was used to fill the void around the wire. A 1-mm insulating plug was epoxied onto the tip of the pin after which a 25-μm layer of copper was electroplated onto the outside of the entire insulator.

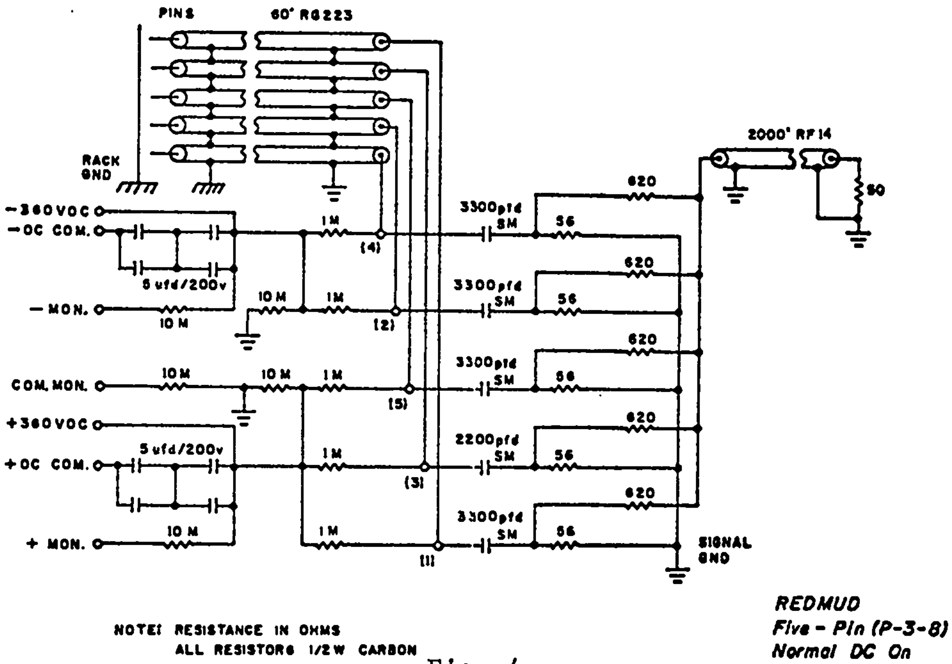

Fig. 4.

Schematic of the circuit used to multiplex the five pins onto a single uphole cable. The pins were located near the bottom of the rack, with the batteries and other components located near the top of the rack. A relay was used to turn on the pin voltage at minus 30 seconds.

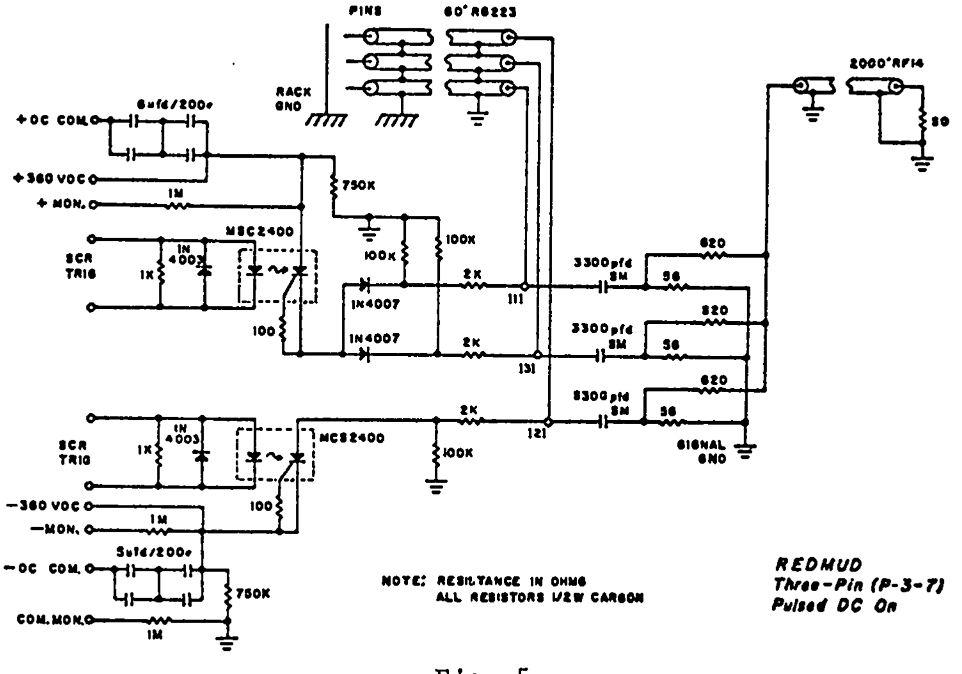

Fig. 5.

Schematic of the circuit used to multiplex the three pins onto a single uphole cable. The pins were located near the bottom of the rack, with the batteries and other components located near the top. The SCR trigger was provided by a pulse down a twisted-cable pair, which applied voltage to the pins starting at ∿ 1 μs after nuclear time.

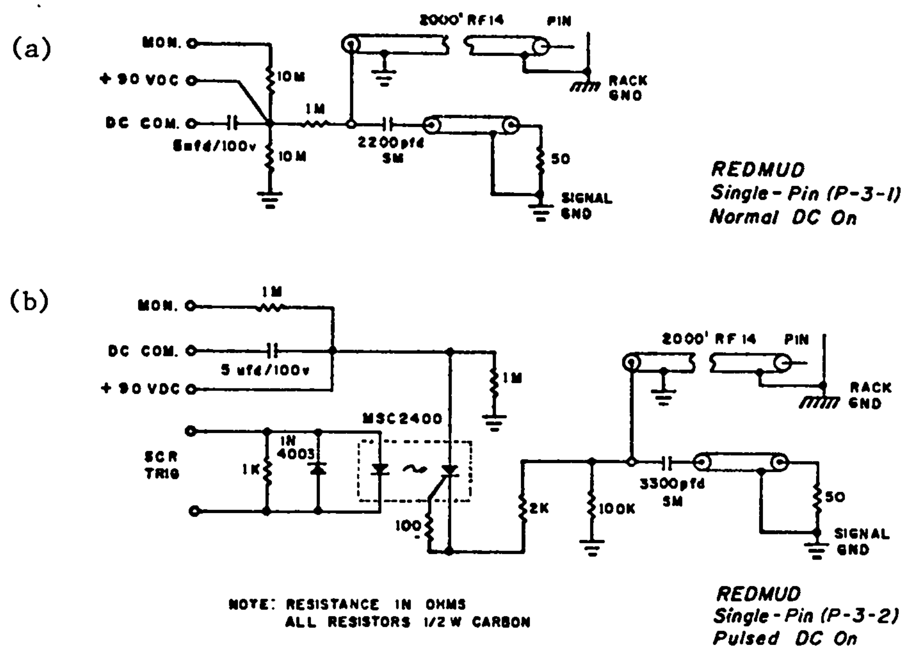

Fig. 6.
Schematic of the circuits used to power the single pins. The pins were located near the bottom of the rack and the charging networks were located uphole in the recording stations. The circuit in (a) was used for the dc-charged pin, and the circuit in (b) was used to pulse charge its pin after nuclear time.

IV. PRESHOT TEST

In order to test the overall response of the entire electronic package after installation in the rack, circuits to simulate the shorting actions of the pins were attached to the rack cables. For each pin, a fast SCR was triggered at the expected arrival time of the shock. Thus for the multiplexed pins, a series of pulses were transmitted to the recording station, which was in shot configuration. These records were used to ensure that the multiplexing systems worked as expected, that one pin signal did not interfere with another, and that the triggering for the recording station was working properly.

Figure 7 shows a photograph of the test signal for the multiplexed cable containing three pins. The SCR's were fired in the sequence expected from the pin depths, and the scopes were triggered by a simulated signal from the pin at the lowest depth in the molybdenum. The rise times of $\sim$ 10 ns are due mainly to the closure times of the SCR's.

V. RESULTS

A. Pin Data

Pin-closure signals were obtained for each cable containing active pins except for the single, pulsed pin. However, this failure was due to a scope-triggering problem and not due to any malfunction of the pin itself. Thus, all of the active pins survived the radiation blast and were apparently not destroyed by the resulting heating. The passive pins ($LiNbO_3$) acted as piezoelectric gauges producing a very large radiation-induced signal lasting for many

Fig. 7.
Photograph of the test signal from the multiplexed system with three pins. An SCR was used to simulate the shorting action of each pin with the entire setup installed in the rack in shot configuration. The square waves provide a time base with a 100-ns period. The initial deflection is a time-tie pulse used to relate one scope to another. The SCR's were fired at the expected arrival times of the shock. The observed rise times are due mainly to the closure time of the SCR's.

microseconds. There is some indication that they recovered slightly from the initial radiation and produced a small additional output at shock arrival time. However, their time resolution was too poor to be useful for shock velocity measurements.

Figure 8 shows the three active pin signals from the self-triggered scopes. The top sweep shows the signal from the single dc-charged pin. The middle sweep shows the signal from the triply multiplexed, pulse-charged series of pins. The lower sweep was obtained from the series of five pins multiplexed on one cable using a dc-charging system. For each sweep the initial negative blip is an electronically produced time-tie that occurred ∿ 8.5 μs after nuclear time. The time-ties occurred a few nanoseconds apart at the scopes due to different cable lengths, and this was taken into account in comparing one signal to another. The square waves are electronically generated time-marks with a 100-ns period. Table I gives the times of the points labeled in the figure relative to a common time-tie. Several general points should be noted: 1) about 5 μs after the time-tie, a fast-rising, negative voltage was observed on each sweep (near the right-hand side of the figure); 2) for the single pin (top) only one dip was observed; 3) for the three-pin case (middle) two large dips and one smaller dip were observed; 4) for the five-pin case (bottom) a number of dips (⩾ 4 were observed at ∿ 5 μs with an additional dip at ∿ 1 μs.

The uncertainty in determining the closure time varies from one pin to another, but with careful digitizing of the film record an accuracy of ∿ 3 ns can be obtained. A timing accuracy of 3 ns, a shock velocity of 2 cm/μs, and pin separations of 1 cm lead to an uncertainty in the shock velocity of ± 0.6%. This approaches the accuracy with which measurements can be made under normal laboratory conditions and would probably not be the dominant source of error in an NTS experiment.

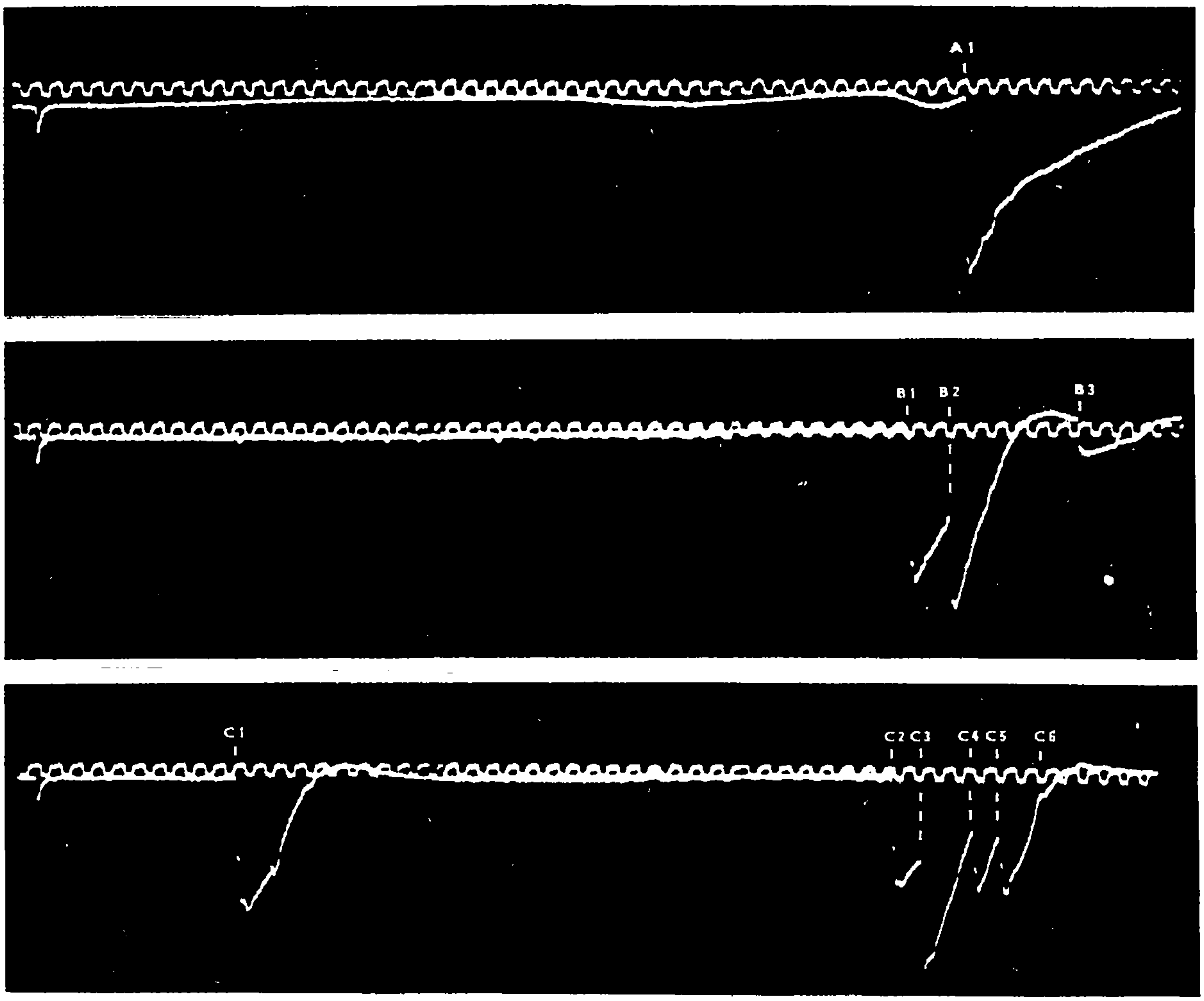

Fig. 8.

Photograph of the actual signals from three of the pin cables. The square waves provide a time base with a 100-ns period. The initial negative spike on each sweep is a time-tie, which allows all of the signals to be referenced to a common time. The top sweep is from the single, dc-charged pin labeled A in Fig. 2. The middle sweep is from the pulse-charged system with three pins (labeled B in Fig. 2) multiplexed onto a single cable. The bottom sweep is from the system of five pins (labeled C in Fig. 2) multiplexed onto a single cable. The obvious deflections from the baseline are labeled, with the times of these breaks given in Table I. For further discussion of these signals see text. The vertical voltage scale is such that the pulse A-1 corresponds to 136 V on the pin, B-1 to 650 V on the pin, and C-1 to 660 V on the pin.

TABLE I

TIME-TIE TO SIGNAL

Label	Time from Time-Tie (ns)
A-1	4513
B-1	4242
B-2	4435
B-3	5101
C-1	972
C-2	4158
C-3	4311
C-4	4566
C-5	4691
C-6	4896

We have no explanation for the 1-μs dip on the bottom sweep. It could be that one of the five pins fired at this time for some spurious reason. The single, dc-charged pin (D), located at the same depth as the lowest pin in this group of five, showed no signal at this time. Thus, we feel that this dip was not shock induced. The signals at 5 μs on all sweeps are rather difficult to understand in detail. However, it appears that the negatively charged pins did not produce a signal, which should have been positive. However, the initial radiation may have discharged this polarity and increased the charge on the other. In fact, this phenomenon may have produced the same polarity charge (positive) for all the pins, but at different levels. The negative-signal amplitudes are larger than expected by as much as 85%, indicating that some such extraneous charging probably occurred.

No data were obtained from the slow-sweep, fiducially triggered scopes. These scopes were triggered at ∿ 15 μs after nuclear time, and as it turned out, this was well after shock arrival. It was fortuitous that the self-triggered scopes worked as well as they did. The discriminator units, which were gated off for 7 μs, were overloaded by the large initial radiation-induced signal, and these units provided an output pulse to trigger the scopes shortly after the blocking pulse was removed. This problem can be easily corrected by grounding the discriminator input signal through a switching circuit for the first few microseconds.

B. Quartz Gauge

Figure 9 shows a photograph of the magnetic disk recording of the signal from the quartz gauge. The fission energy dumped into the ^{238}U caused it to expand and drive a pressure pulse into the quartz. At the observed voltage level, the quartz gauge output is very nonlinear, and it is surprising that the gauge behaved as well as it did. Estimates of the energy deposition in the uranium, corresponding to this signal from the quartz, range from 1.0 to 1.5 MJ/kg. Monte Carlo calculations using the postshot yield predicted an energy deposition of ∿ 0.75 MJ/kg in the uranium. These values are in reasonable agreement considering both the uncertainties in the measurement and the calculation. Most of the neutrons arriving at the uranium do not come through the shield itself, but rather through the iron shot and B_4C powder in the volume around the shield. Thus any voids in the actual geometry would have a significant effect.

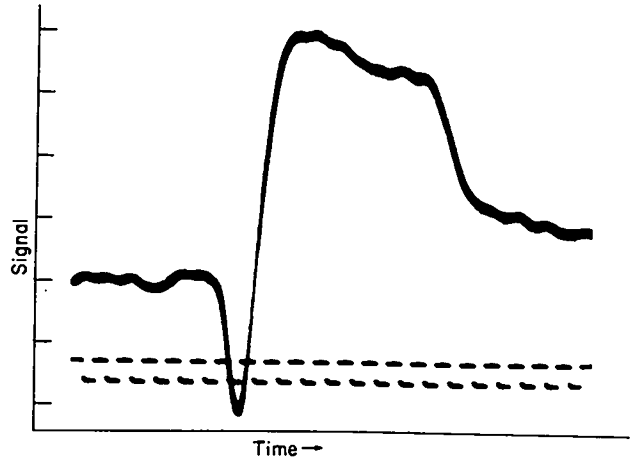

Fig. 9.
Photograph of the signal from the quartz gauge, recorded on the magnetic video disk. The square wave is a 5-MHz time base. The initial negative pulse is due to gamma-ray irradiation of the cable-gauge assembly. This is followed by a positive-going signal induced by neutron bombardment. During the initial positive rise, the quartz starts to behave as a piezoelectric gauge and produces a rather flat-topped signal that lasts for ∿ 1.7 μs, the transit time of the gauge. On the vertical scale, one division corresponds to 62 V (into 50 Ω) of quartz gauge output. The fact that the signal did not return to the baseline after the initial pulse increased the uncertainty in determining the energy deposition in the uranium.

VI. SUMMARY AND CONCLUSIONS

The results of this experiment demonstrate that pins can be used to obtain shock arrival data with an accuracy of a few nanoseconds in a high-radiation environment. The pins can survive in the charged condition, and it is not necessary to use pulsed-charging techniques. Multiplexing appears to work, but more information is needed to determine if the radiation discharges one polarity. A modification of the triggering method should provide a reliable technique for triggering the scopes just prior to the shock arrival signal without relying on a calculation of the shock transit time through the shield.

The Monte Carlo techniques presently used appear to be adequate for predicting heating levels in both the pins and the samples. In a more ideal geometry with the combined shield/shock transmitter covering a large fraction of a sphere, Monte Carlo calculations should be even more reliable. In the geometry used on Redmud, with nearby pipes as possible sources of radiation, shielding calculations were very difficult. In addition, these pipes may have served as sources of unexpected shock waves. This may be one explanation for the early closure time of the pins. A diagnostic pipe passing ∿ 25 cm from the pins may have been the source of a shock. This pipe was not covered with lead, and a shock originating near the pins would have arrived quickly from the side rather than from the bottom. The pin data do not rule out such a possibility.

Whatever the shock direction, however, the pins appear to have responded to its arrival.

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