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Project 6.9

MEASUREMENT OF MATERIAL DENSITY WITH BETA DENSITOMETER

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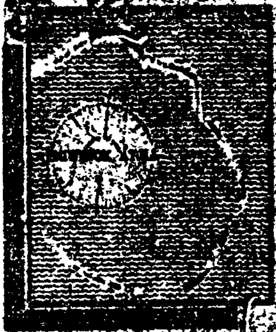

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Report to the Scientific Director

MEASUREMENT OF MATERIAL DENSITY WITH BETA DENSITOMETER

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ABSTRACT

The objective of beta-densitometer instrumentation at Ivy Mike shot was, primarily, to measure material density near ground surface as a function of time and, secondarily, to test the latest modifications to previous densitometer models.

The results showed (1) that thermal or preshock dust is absent at a ground range of about 23,000 ft (Station 690.02), (2) that it is possible to calculate the overpressure due to air shock alone from the measured density change, provided that preshock turbulence is not excessive, and (3) that the modifications to the densitometer proved to be satisfactory. The calibration and electronic engineering of the Ivy model densitometer were considerably improved over previous models.

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CHAPTER 1

OBJECTIVE

The objective of beta-densitometer instrumentation at Ivy Mike shot was, primarily, to measure material density near the ground surface as a function of time and, secondarily, to test the latest modifications to previous densitometer models.

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CHAPTER 2

BACKGROUND

2.1 PRINCIPLE OF OPERATION

A detailed explanation of the working principle and descriptions of the working parts of the densitometer appear in previous reports.[1,2]

Briefly, the densitometer consists of a fixed source of beta rays, a detector which responds to changes in beta-ray intensity, and a recording instrument which converts the detector output into an oscilloscope-beam deflection that is photographed by a strip camera for permanent record. The attenuation of the beta rays, and hence the detector output, is a function only of the density of material between source and detector. Densitometer components are shown in Figs. 2.1 to 2.3.

Three 1-curie amounts of Sr^{90} were used as beta sources in each station, except at Station 690.02, where two 1-curie amounts were used.

2.2 PROBLEMS IN DENSITOMETER DESIGN

2.2.1 Greenhouse Model

The Greenhouse densitometer used 6 curies of Sr^{90} at 50 cm from the detector. The amplifier was a balanced d-c type, designed to receive the total-gamma and total-beta signal from one RCA 5819 multiplier phototube at one grid input and the total-gamma signal only from a second phototube at another grid input. The subtracted outputs of the two plates of the amplifier were to give only the beta signal with all gamma or background signal canceled out.

Disregarding for the moment the difficulty of balancing a d-c amplifier and the variation of each photomultiplier gain with fatigue, the limitation of the design itself presented a formidable obstacle against obtaining a beta record in the presence of any appreciable background (mainly gamma) radiation. This obstacle arises from the fact that the grid input signal must be limited between the saturation value (usually a value of plus 4 or 5 volts) and the cutoff value (usually a value of minus 10 to 15 volts). If linearity of amplifier output with grid input is desired, an even smaller spread of grid input must be adhered to. Consequently, to get any usable beta-signal component in the output, the combined gamma and beta signal must be restricted to the usable portion of the amplifier characteristics. For practical reasons this means that the magnitude of the gamma signal must be comparable to the magnitude of the beta signal. Large gamma background will saturate both halves of an amplifier designed to accomodate a relatively small beta signal. With such an input system, therefore, only weak gamma backgrounds will be subtracted. Moreover, because of the difficulty of maintaining a balanced output, subtraction may not necessarily give zero gamma signal.

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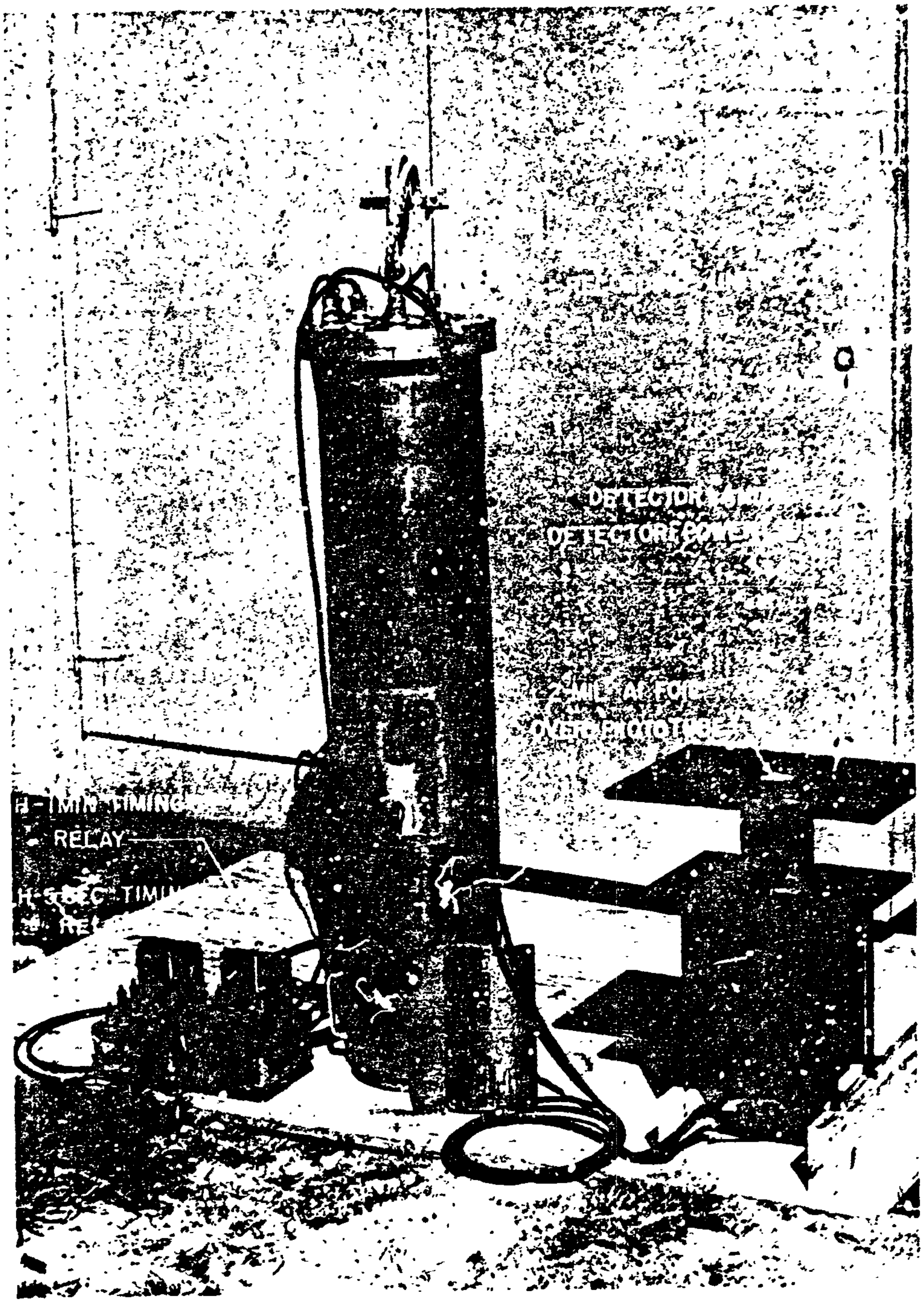

Fig. 2.1—Beta-densitometer components.

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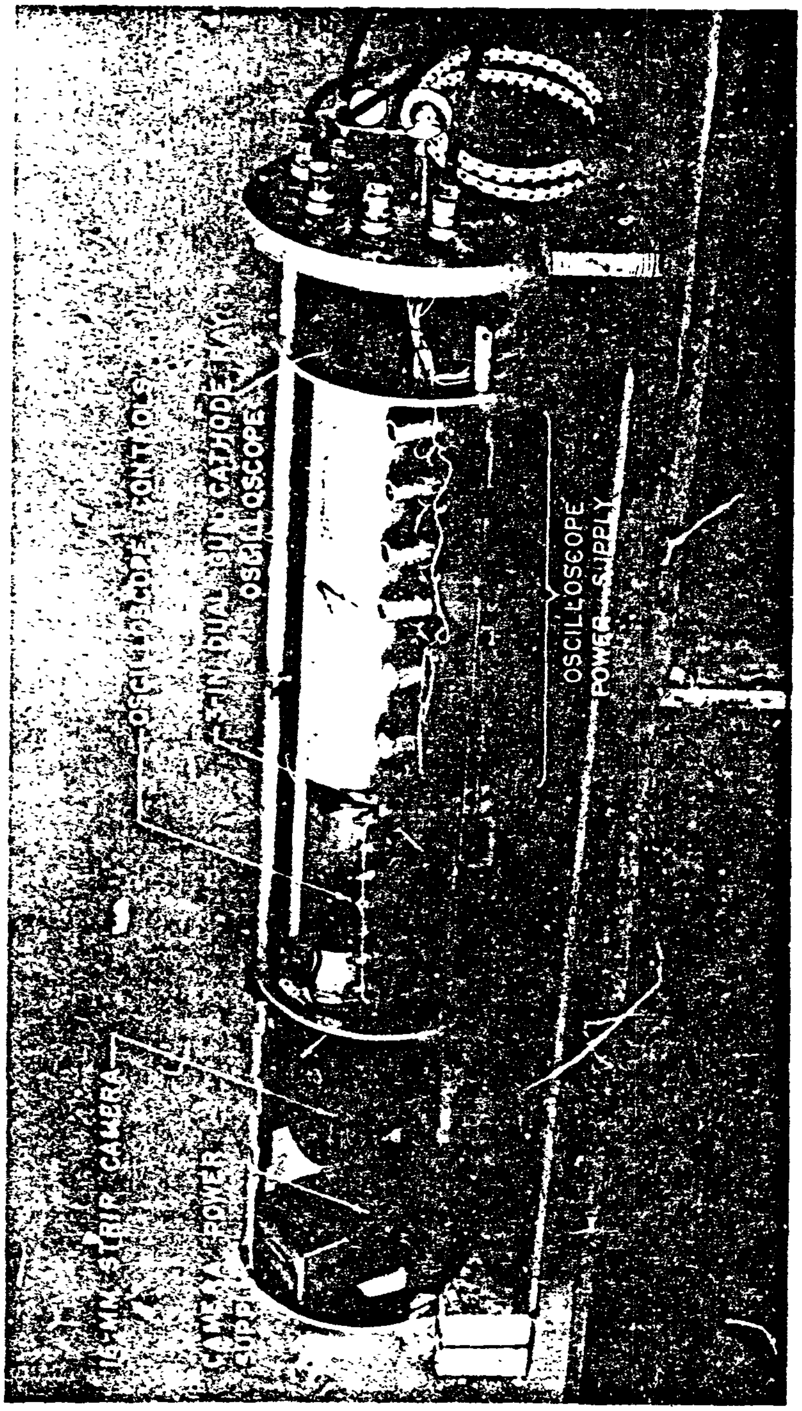

Fig. 2.2—Recording unit.

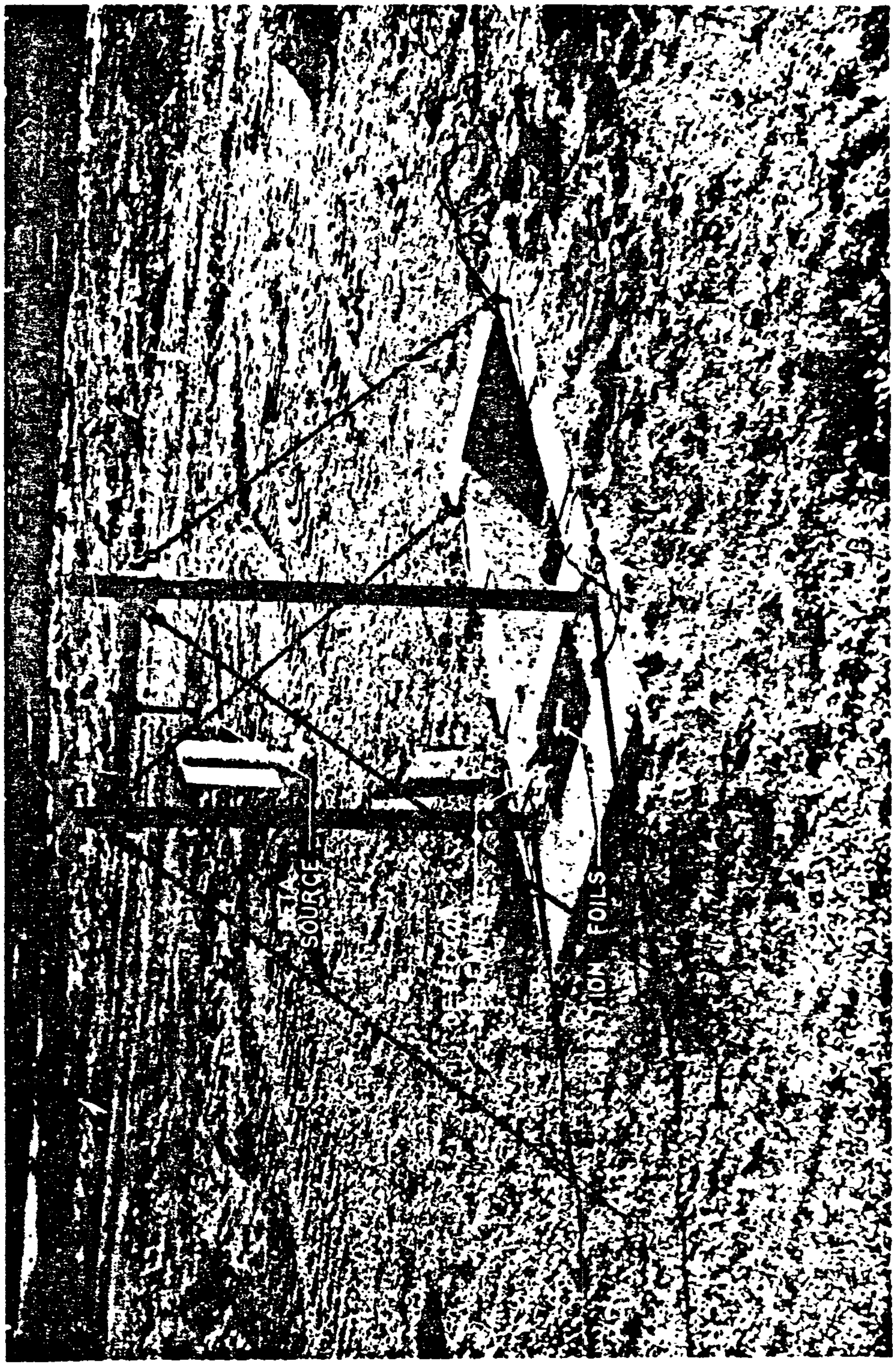

Fig. 2.3—Densitometer station, Operation Ivy.

Another serious source of difficulty in subtracting the gamma signal with the amplifier used at Greenhouse was the fact that the 5819 photomultipliers were turned on and were fatiguing several hours prior to shot time. The gain of two photomultipliers, carefully selected as they may be, could vary considerably after several hours of fatigue. Of the two records obtained at Greenhouse, one was a pure gamma (background) record without superimposed beta signal. The other was the net output of the balancing system.

2.2.2 Buster Model

In the Buster model a mechanical chopper cutting off the beta flux 400 times per second was used with a single 1P21 photomultiplier. A band-pass filter and amplifer displayed the 400-cps variation of the beta signal and the superimposed noise. This was a sound design that could have worked, except for the high spurious noise picked up that made the record unreadable. The amplifier was noisy when disturbed by shock, but otherwise it operated satisfactorily. The excessively long leads, about 20-ft loops, between successive dynodes and photomultiplier-power supply picked up and amplified spurious signals of magnitude comparable to that of the detected beta signal.

As in Greenhouse no system of field calibration was incorporated in the instrument. Laboratory calibration with a pressure tank was relied upon to relate detected beta signal to material density along the beta path.

2.2.3 Tumbler Model

Both the Greenhouse d-c model and the Buster a-c model with completely redesigned electronic systems were used at Tumbler with the idea of:

1. Eliminating deficiencies from both systems.
2. Testing a field calibration method using removable foils in the beta path.
3. Comparing the systems for best results.
4. Determining feasibility of use at Ivy.
5. Obtaining density-time measurement for Tumbler.

Both the d-c and the a-c systems, described in the Tumbler report, worked satisfactorily. The d-c system is favored over the a-c system for the following reasons:

1. It smoothes out statistics and therefore produces a cleaner record.
2. The d-c system requires simpler instrumentation, eliminating the mechanical chopper and band-pass circuits.

The amplifier was used in the linear and nonlinear range; this required accurate knowledge of the amplifier characteristic in the interpretation of results. A completely linear reproduction of the beta signal would have been preferable, especially because the variation of beta signal with material density was logarithmic. An amplifier with a larger voltage variation could be used, but this would require more batteries and more circuitry. A more attractive solution, achieving both linear response and simplified circuitry, is to use a high-sensitivity fast-response phosphor with the photomultiplier.

REFERENCES

1. F. B. Porzel and J-7 Blast Measurement Group, Measurement of Air Density in a Shock Wave, Greenhouse Preoperational Report, Project 6.4.1.
2. P. R. FlorCruz, C. G. Young, Jr., and A. T. Brousseau, Beta-Densitometer Feasibility Test, Tumbler-Snapper Project 19.2c Report, Part II, WT-556.

CHAPTER 3

INSTRUMENTATION

3.1 GENERAL

The densitometer used at Ivy Mike shot was the d-c type. Aside from having the desirable features of previous models, it had an added simplification in that it did not use a second photomultiplier for balancing the background gamma signal. This simplification was made possible by the special situation expected to prevail at Mike shot. Calculations by F. B. Porzel predicted negligible background radiation at the instrument stations at the times of blast-wave arrival.

With only one photomultiplier to receive both the beta and the background signal, background radiation (mainly gamma) would increase the total signal and could, if sufficiently strong, drive the electron beam, which is supposed to respond to the beta signal only, off the face of the oscilloscope. Any thermal* or preshock dust, on the other hand, would diminish the signal. Miscalculation of the gamma-radiation rate could lead to confusion in the interpretation of the beta trace, even if the beta trace between zero time and time of blast arrival appears comparable to the preshot trace. It could mean that there was no detectable gamma nor preshock dust. It could also mean that the effects of gamma background and preshock dust neutralized each other. Tumbler records showed that the first possibility is more likely than the second, especially if the trace returns to its preshot level rapidly. Preshock dust raises the beta trace to a fairly steady level. Decaying gamma, on the other hand, brings the trace down continuously. As it turned out, calculations of gamma-radiation rate and prediction on the behavior of the beta trace were correct.

3.2 BETA SOURCES

Three 1-curie Sr^{90} beta sources were used at each station, except at Station 690.02, where two 1-curie sources were used. Sources were 100 cm from the 2-mil aluminum foil which covered the detector.

Each 1-curie source of Sr^{90} was contained in a cylindrical stainless steel shell, 1.0 in. in diameter and 0.3 in. deep. The active face was sealed with a 1-mil stainless steel foil. Details of the source holder are shown in Fig. 3.1.

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*When a nuclear bomb is detonated over a dry ground surface, dust is literally exploded from the surface shortly after detonation and usually before the arrival of the blast wave. The exact mechanism of this phenomenon is complex and is believed to be due to the intense burst of thermal energy released by the bomb, hence the term thermal dust.

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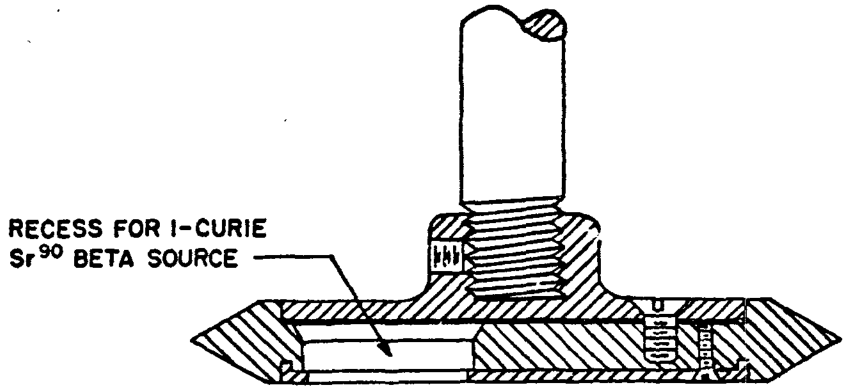

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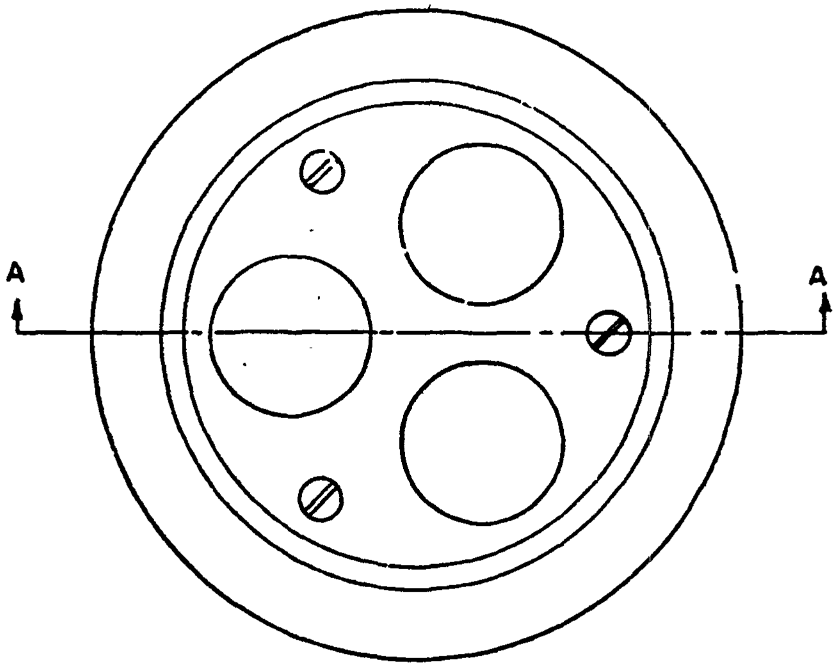

BOTTOM VIEW

Fig. 3.1—Beta-source holder (full scale).

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3.3 DETECTOR

The detector consists of an RCA 5819 photomultiplier and a phosphor glued to the cathode end of the tube. The phosphor is made up of 5-mil transtilbene crystal glued on top of a ¼-in. lucite disk. The disk is formed to fit the contour of the tube face.

The phosphor, being far more effective in attenuating beta than gamma radiation, is therefore more sensitive to beta than to gamma radiation. The phosphor was effective in increasing detector output to such an extent that it was possible to eliminate the d-c amplifier (i.e., to feed the detector output directly to the oscilloscope) and also to double the distance between source and detector. Doubling the beta path meant doubling the material sample whose density was measured.

The detector circuit is shown in Fig. 3.2. The power supply is made up from the 30-volt cells of 300-volt Eveready No. 493 batteries. Each power supply consists of duplicate 1260-volt banks of batteries, paralleled for greater reliability. Construction of the power supply in this manner resulted in very short leads, which is an essential requirement for minimizing or eliminating spurious signals.

The voltages applied to the various pins are as follows:

1. Cathode to dynode No. 1: 180 volts.
2. Between dynodes (No. 1 to No. 10): 90 volts each.
3. Dynode No. 10 to plate (across load): 270 volts.

The plate load was variable between 200,000 and 400,000 ohms with the center of the load grounded. This point was selected as ground to permit a balanced-line output to the recording unit.

The photomultiplier power was turned off by relays which opened to remove voltage from dynodes No. 2 and No. 4. This method was effective. When the power was turned off in this manner, there was no photomultiplier output nor fatigue. This method was particularly convenient in that no high-voltage circuits had to be turned on or off.

The photomultiplier was made light tight by housing it in a steel tube (Fig. 3.3), which also afforded magnetic shielding. The cathode end was sealed with a 1.5-mil aluminum foil.

3.4 RECORDING UNIT

The recording unit consisted of a dual-trace cathode-ray tube, a strip camera, timing lights and oscillators, control and delay circuits, and associated power supplies (Fig. 2.2).

The entire assembly was housed in a watertight aluminum cylinder (Fig. 2.1).

The output (current) of the photomultiplier was fed to a variable (resistance) load, balanced about ground and located in the recording unit (Fig. 3.4). The voltage drop across this load was displayed directly on the screen of a dual-gun cathode-ray tube.

Any spurious noise picked up by the beta-signal leads in cable D would also be picked up by an additional pair of leads terminated across a 600,000-ohm load in the battery box (Fig. 3.2) between terminals d and e. In this way spurious signals that might be mistaken for beta-signal variations would be displayed in greater amplitude by the second or noise-monitoring trace of the cathode-ray tube.

The cathode-ray tube was a 3U2P11 manufactured by the Electronic Tube Corporation. The power supply was made up of dry batteries as follows:

Ground: anodes No. 2 and No. 3, unused deflection plates, and center taps of signal leads.
−600 to −900 volts: focusing or anode No. 1.
−1170 to −1200 volts: control grids (30-volt batteries).
6 volts: across filaments (at −1200 volts).
180 and 120 volts: positioning voltages.

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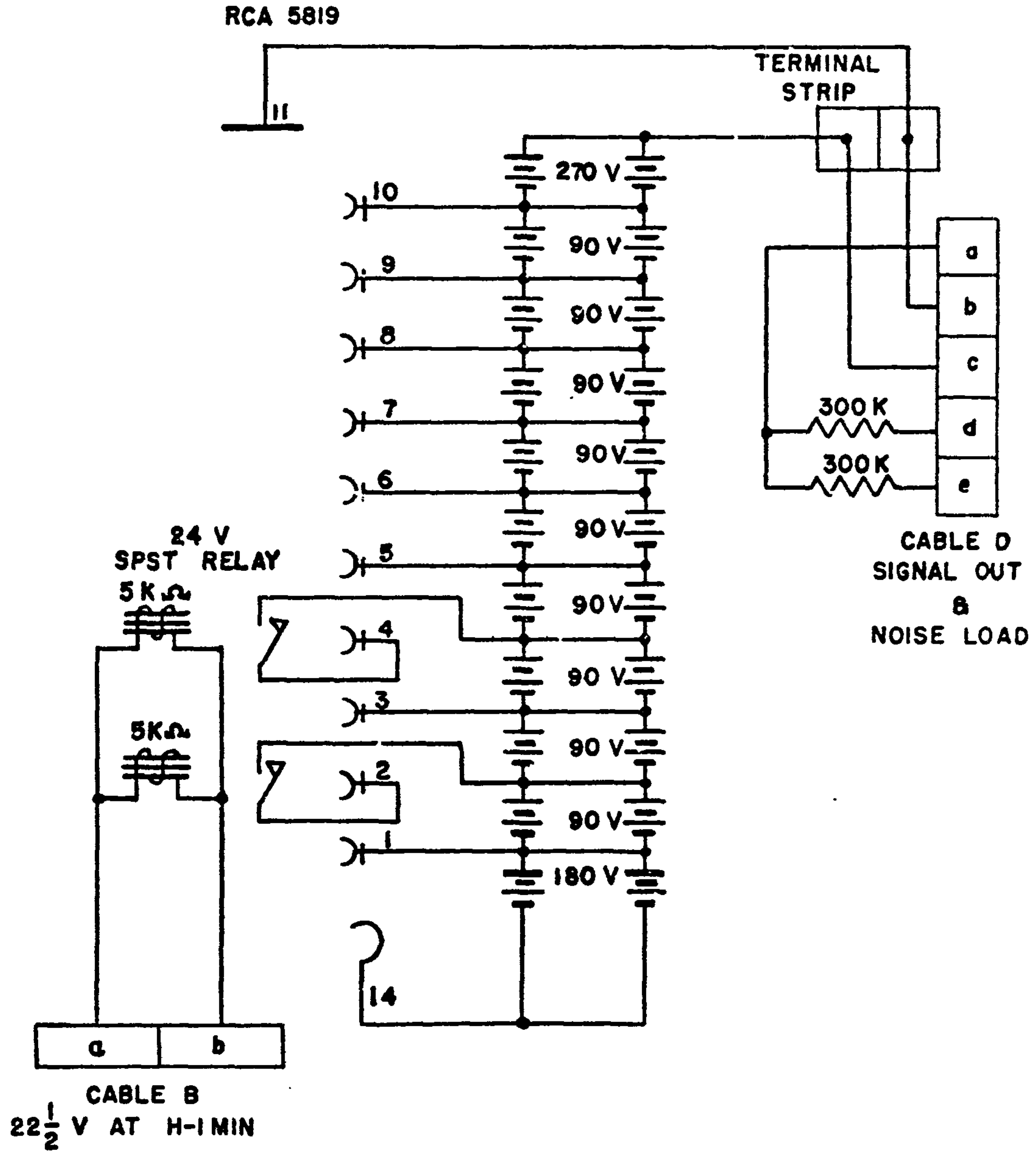

Fig. 3.2—Detector circuit.

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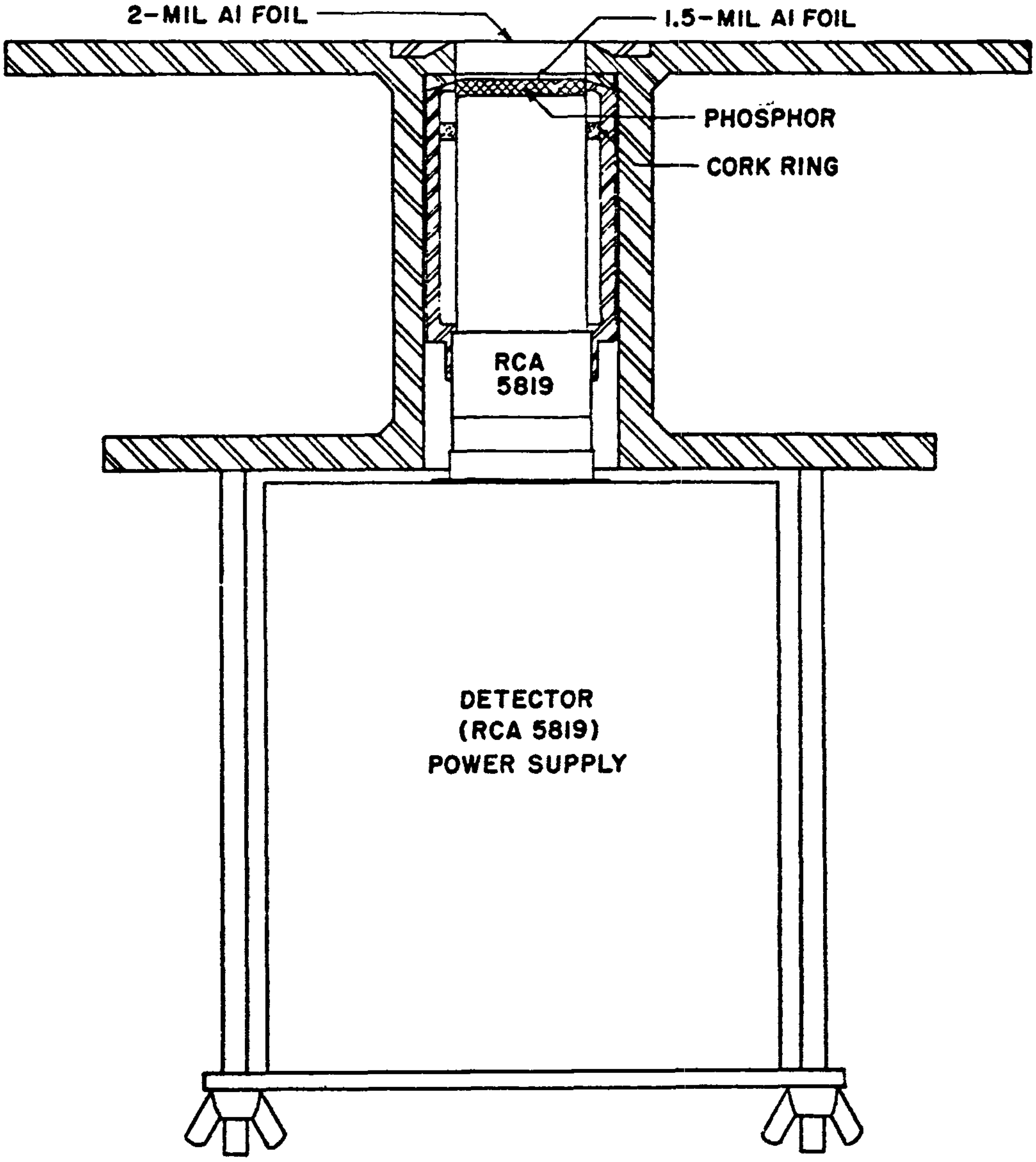

Fig. 3.3—Detector assembly.

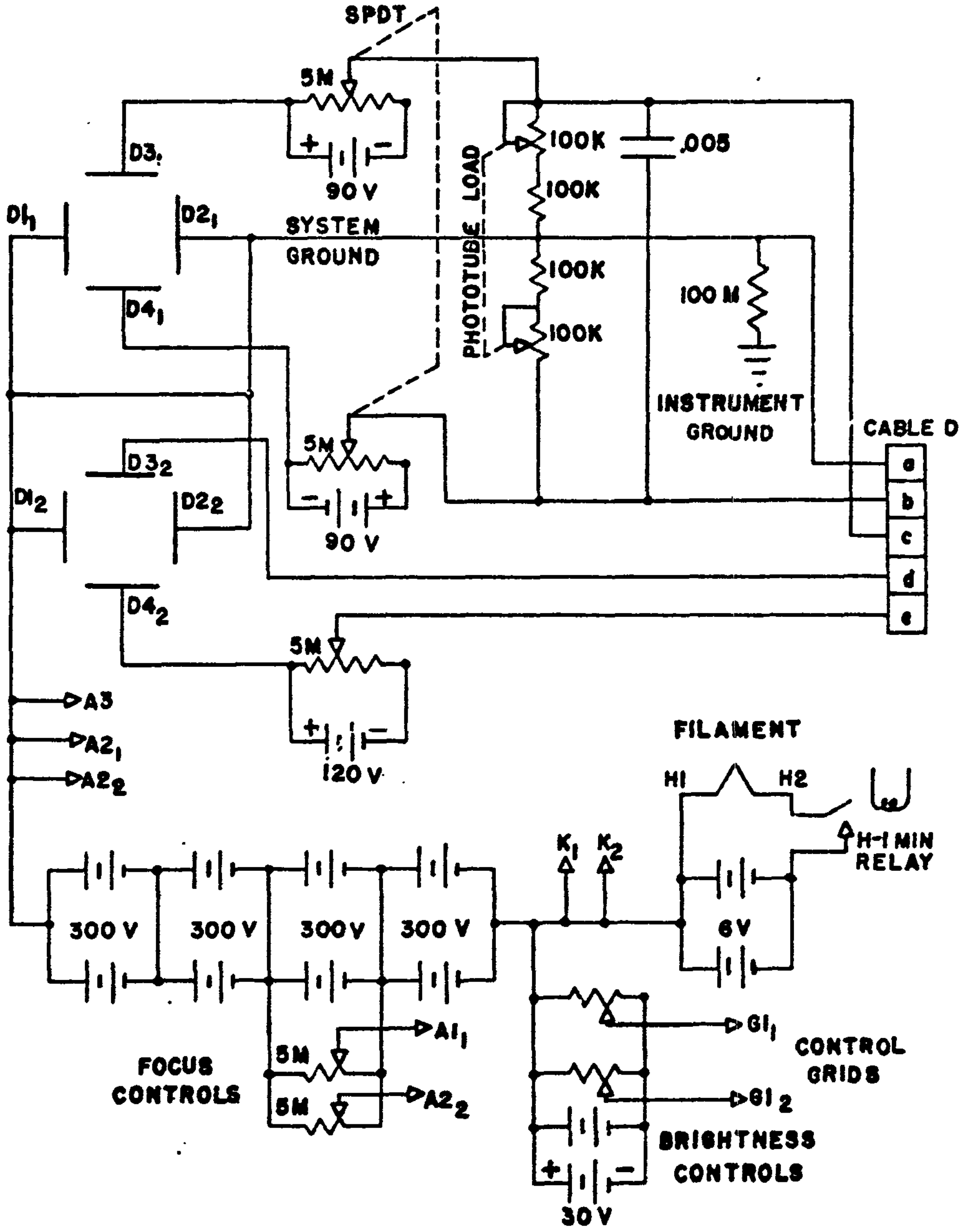

Fig. 3.4—Cathode-ray oscilloscope and detector (phototube) output circuit.

All batteries making up these voltages were in duplicate and connected in parallel as insurance against failure.

NT6 Willard 6-volt wet cells were used for filament power in lieu of dry cells because of the greater current requirement which these cells could furnish.

The cathode-ray tube was mounted inside a Mu-metal cylinder to shield it from the earth's magnetic field.

The ground points of the beta-signal circuit and of the cathode-ray tube were connected to the recording unit case through a 100-megohm resistor to drain any static charges and to provide a high impedance to any possible short to the case from any part of the recording-unit circuit.

A 16-mm Kodak Cine E strip camera photographed the variation of the signals on the cathode-ray-tube screen and generated a time base proportional to the film speed. Since the speed of the camera varies noticeably, accurate time intervals could not be determined by measuring film lengths. Oscillator circuits were used to generate 5- and 100-cycle pulses to neon bulbs mounted on the oscilloscope screen. Thus a series of 0.20- and 0.01-sec timing marks were included in the film record, directly below the beta-signal trace. The 0.20-sec timing marks were included merely as an aid in counting the 0.01-sec marks.

The camera was powered by a bank of 22½-volt dry batteries. With approximately a 2-amp drain, the batteries were reliable only for two to three runs of about 1 min each. However, for the measurement time involved the power was sufficient. For repeated trial runs the camera was powered by external batteries connected through monitoring cable C (Fig. 3.5).

A timing-oscillator circuit is shown in Fig. 3.6. Each timing light oscillator consisted of a Weinbridge oscillator and peaking circuit. The oscillator output was a voltage spike great enough to flash the GE51 neon bulb and sufficient to give sharp timing marks on the recording film. Filament and plate voltages were supplied by duplicated dry batteries.

3.5 CONTROL SYSTEM

The control system consisted of two external master Edgerton, Germeshausen & Grier, Inc. (EG&G) relays and nine sealed-type relays mounted in the recording unit and in the photomultiplier battery box. The master relays, normally open, closed to give timing signals at H−1 min and H−5 sec, respectively.

The H−1 min relay activated the circuits of a hold-down relay and five switch relays (Fig. 3.7), which turned on the power supplies to the photomultiplier and the filaments of the cathode-ray tube and timing oscillators. The H−5 sec relay activated a hold-down relay, a switch relay for the camera-motor power, the foil calibration circuit, and the power for the delay relay. After a predetermined time the delay relay closed and burned out a fuse which turned off power to all internal relays and to the camera motor.

Although the relays were rated at 24 volts, 45 volts was used to give them a greater closing force and prevent the contacts from chattering when hit by a shock.

The heater voltage for the delay relay (Amperite 6N060) was obtained from the oscillator-filament 6-volt battery (Fig. 3.5).

To facilitate calibration and last-minute adjustments in the field, an access window (Fig. 2.1), covered by a removable plate, was cut on the side of the aluminum cylinder which housed the recording unit. The following checks and adjustments could be accomplished through the window:

1. Check functioning of timing light.
2. Check camera-lens settings.
3. Insert or replace control fuse.
4. Adjust electron beams on CRT screen for focus, brightness, and position.
5. Set photomultiplier load to locate output-signal level at desired point on screen (final field calibration adjustment).

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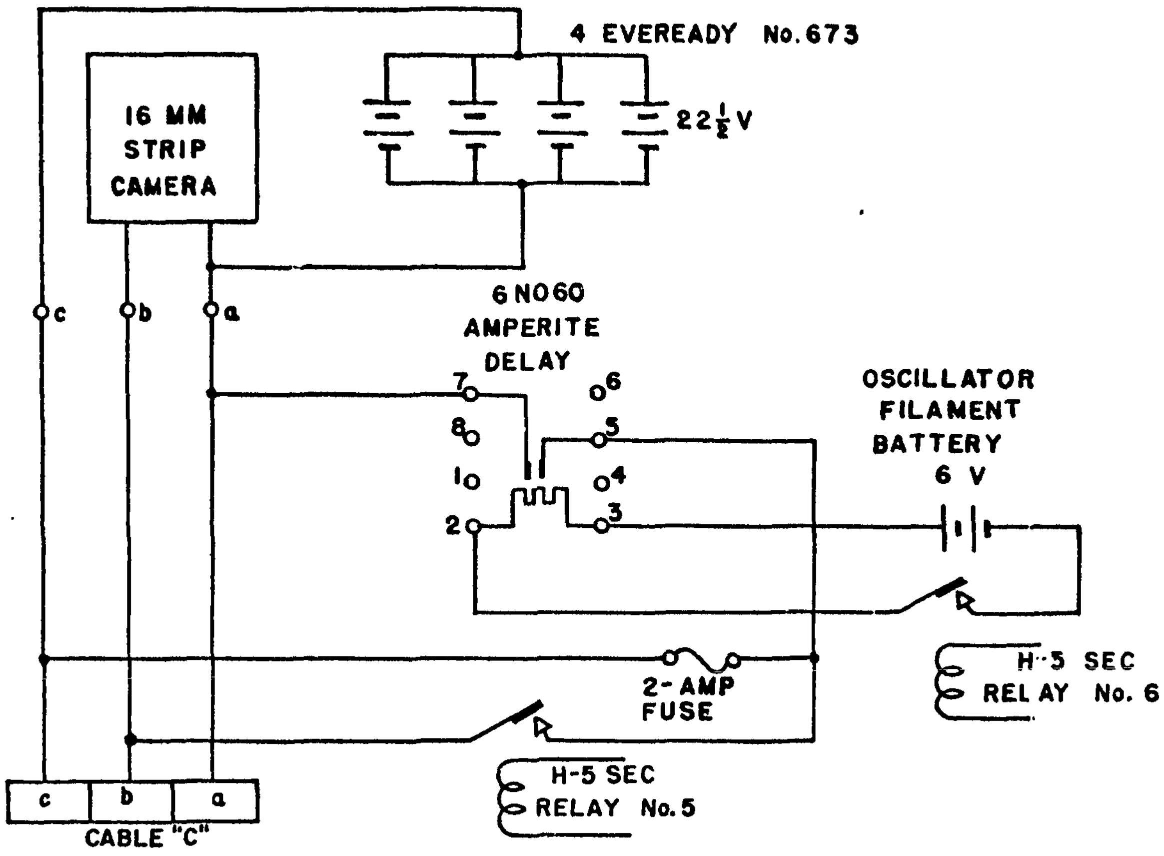

Fig. 3.5—Camera-control circuit.

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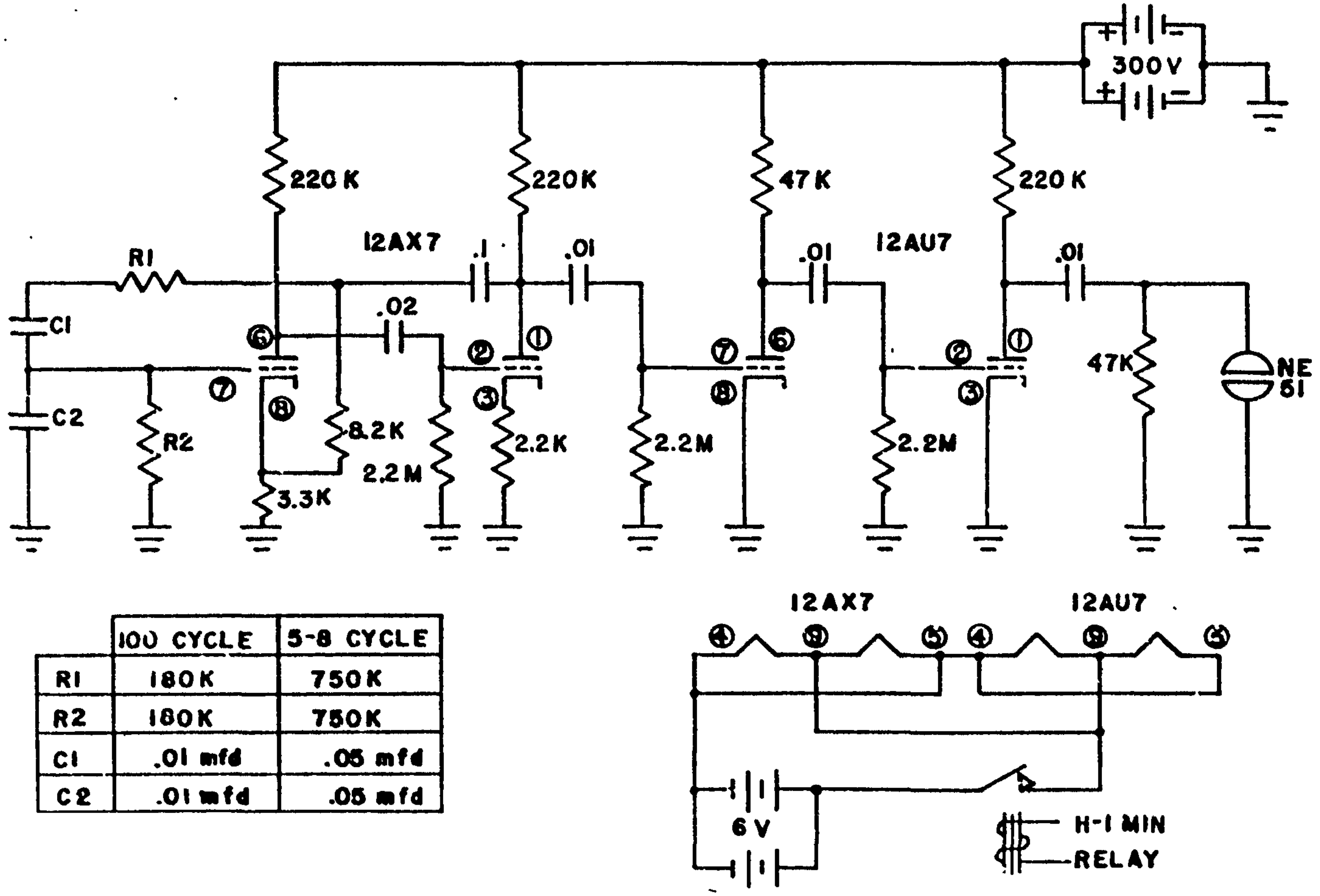

	100 CYCLE	5-8 CYCLE
R1	180 K	750 K
R2	180 K	750 K
C1	.01 mfd	.05 mfd
C2	.01 mfd	.05 mfd

Fig. 3.6—Timing-oscillator circuit.

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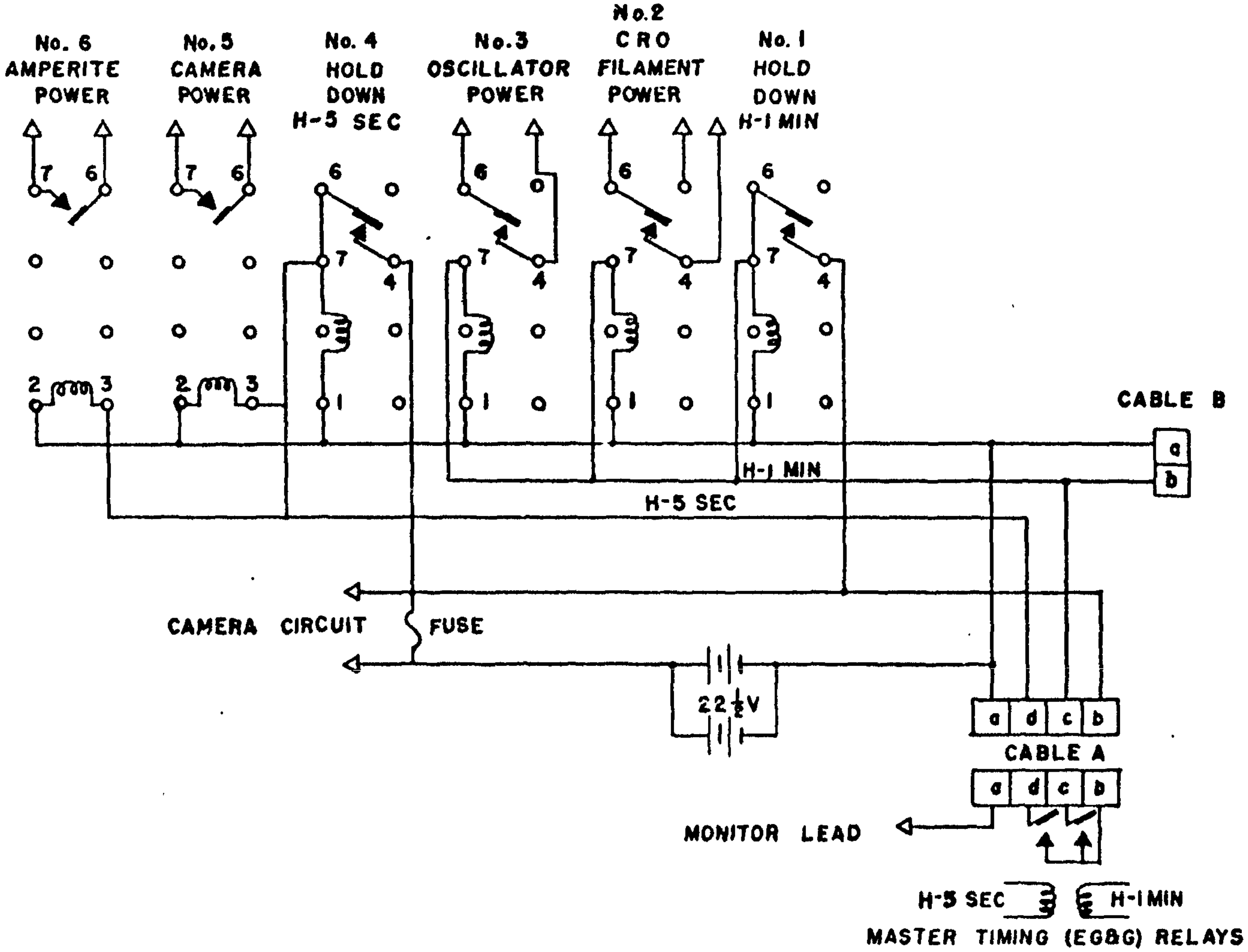

Fig. 3.7—Control relays and shut-off circuit.

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3.6 CALIBRATION

Calibration consisted, essentially, in determining electron-beam deflection of the cathode-ray tube corresponding to material density along the beta path. Since the deflection sensitivity of the cathode-ray tube was constant, calibration could also be done by measuring the deflection voltages corresponding to known values of material density along the beta path.

In the field, calibration was accomplished by:

1. Recording on film, just prior to installing each instrument station, electron-beam deflections corresponding to several known values of deflection voltages.
2. Recording the electron-beam deflections corresponding to known thicknesses of two aluminum foils over the receiver. The aluminum foils are released one at a time between H−5 sec and zero time. Thus, a calibration trace obtained just prior to shot time appears on the same film with the density record.

The information from field calibration when checked against laboratory measurements of deflection voltages and beam deflections corresponding to known values of material density in the beta path enables one to convert the record of beam deflection into material density. The calibration foil-release circuit is shown in Fig. 3.8.

3.7 INSTRUMENT STATIONS

Densitometers were located at four stations:

Station No.	Site	Distance from ground zero, ft
690.01	Engebi	10,166
690.02	Kirinian	23,219
690.03	Bokonaarappu	30,501
690.04	Aomon	47,897

A detail drawing of the instrument station is given in Fig. 3.9.

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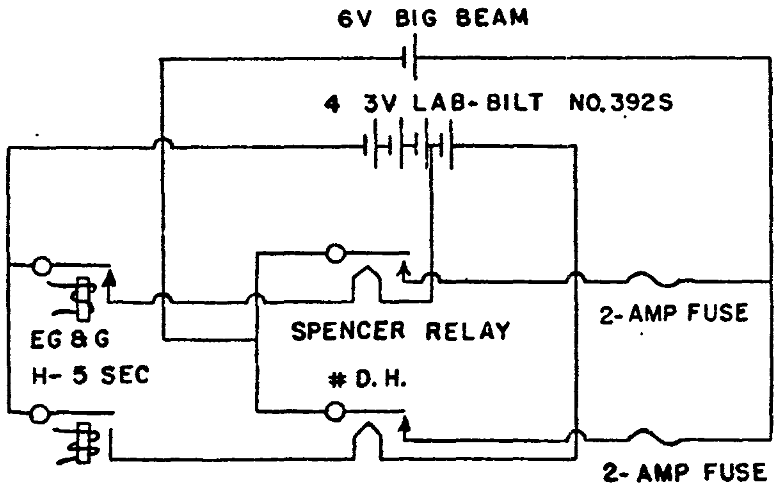

Fig. 3.8—Calibration foil release circuit.

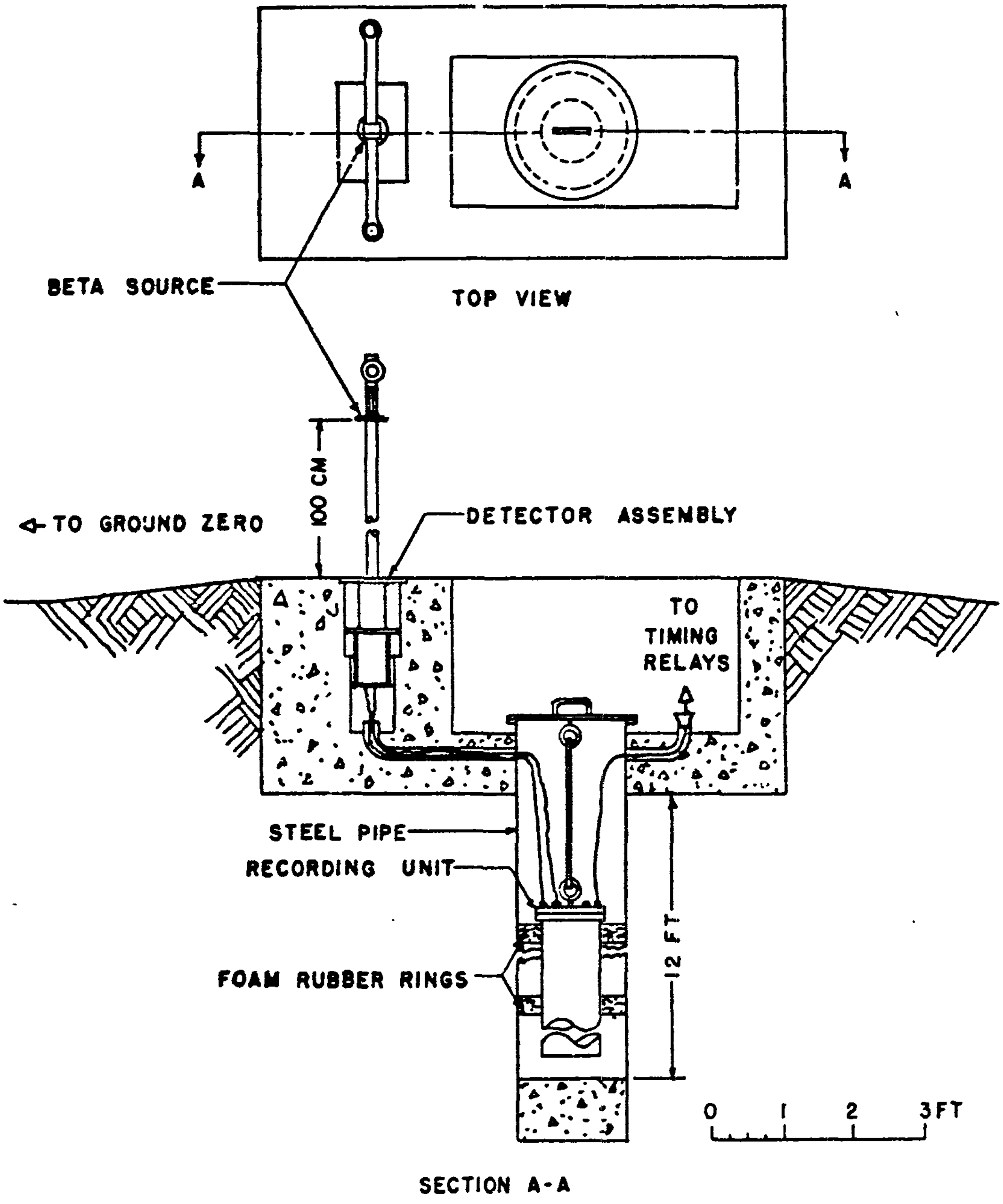

Fig. 3.9—Detail of beta-densitometer station.

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CHAPTER 4 .

RESULTS

The densitometer at Station 690.01 did not function properly. The recording camera did not run, as shown by the film footage indicator and the unexposed section of film following the record of voltage calibration made just prior to closing the station on M – 5 days.

The densitometer at Station 690.02 functioned successfully. The data obtained are given in a later paragraph.

At Station 690.03 the camera ran, but the timing oscillator and the oscilloscope were never turned on. At Station 690.04 all components operated, but in reversed timing sequence so that the camera power was turned off before the blast wave arrived.

The instruments and instrument stations withstood the stresses due to heat and blast. The only damaged parts were the two front guy wires in Station 690.01, which were snapped and bent. However, the source holder was undamaged and the relative position of the beta source and detector was unchanged. Stations 690.01 and 690.02 were washed over. Both were covered with coral rock and sand on recovery. Washing over, obviously, must have occurred long after blast arrival, or else the record at Station 690.02 could not have been obtained.

An enlargement of a portion of the densitometer film record at Station 690.02 is shown in Fig. 4.1. As was predicted, zero time, characterized by a burst of gamma radiations, was distinctly identified on the record by a discontinuity of the beta trace. The electron beam recording the beta signal was driven off the oscilloscope screen but came back to its preshot position in approximately 0.30 sec. It remained at this position until the blast arrival.

The noise-monitoring trace remained at the same level from the start to the finish of the record run, thus proving the relative immunity of the circuit components from electromagnetic disturbance and other spurious signals.

From the densitometer record at Station 690.02, the following data were obtained (Fig. 4.1):

Time of blast arrival, 9.86 sec
Density at H + 9.86 sec, 1.76 g/liter
ρ/ρ_0 at H + 9.86 sec, 1.53 ± 0.03

(where ρ_0 is the density of unshocked air and ρ is the density of the material along the beta path)

Maximum density measured (at H + 12.01 sec), 9.20 g/liter
Maximum ρ/ρ_0 measured (at H + 12.01 sec), 8.00

In general, during the period 0.1 to 3.5 sec after blast arrival, the material density varied randomly (suggesting swirling and turbulence) from about 2.5 to 4.3 times preshot atmospheric density. This indicates considerable loading of the air by dust, pebbles, coral, rock, and other debris.

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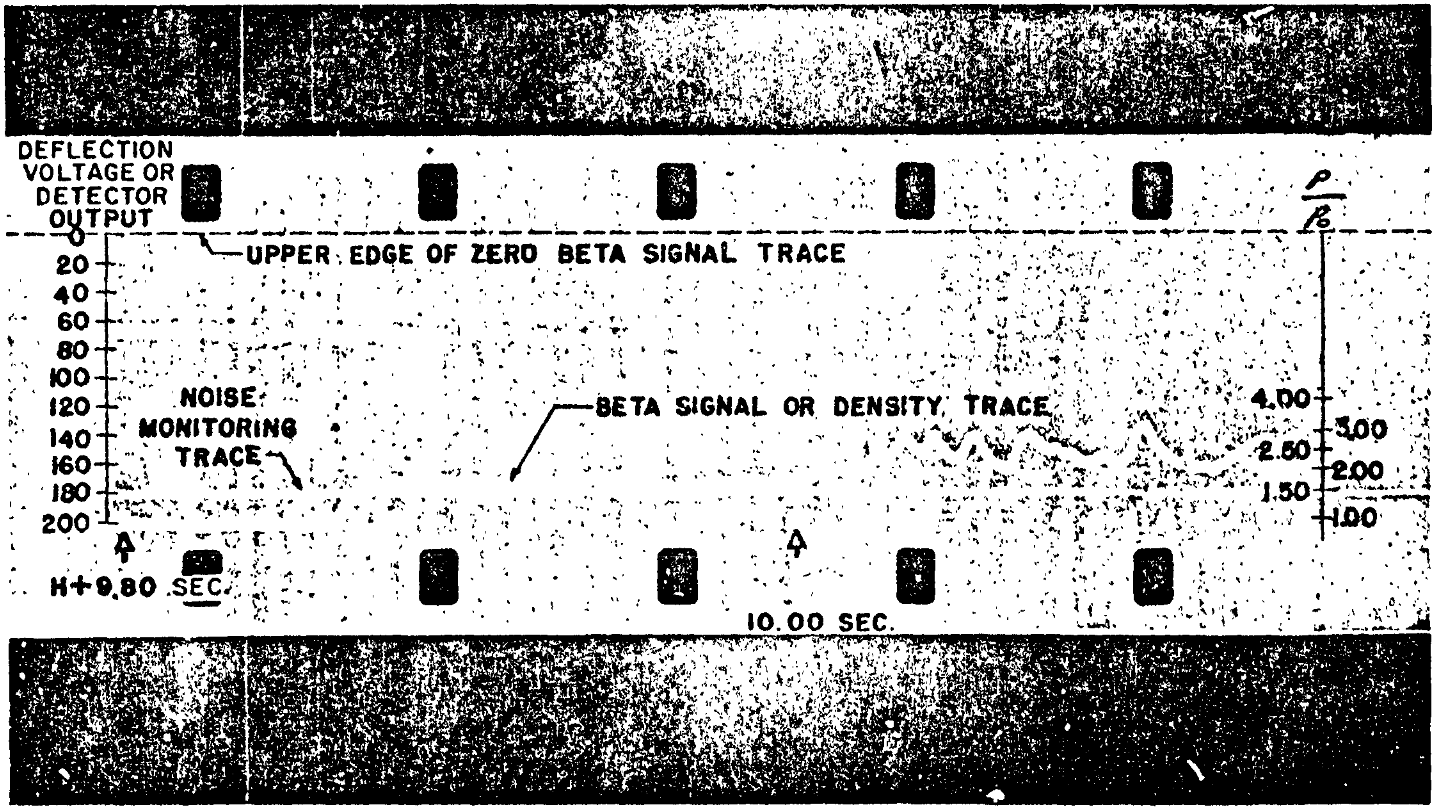

Fig. 4.1—Beta-densitometer record, Ivy Mike. Nov. 1, 1952; Station 690.02; 23,219 ft from ground zero. ρ = material density; ρ_0 = air density at zero time (1.15 g/liter).

CHAPTER 5

ANALYSIS OF RESULTS

The voltage-calibration trace and foil-calibration trace that were made just prior to closing each station showed that all densitometers were in satisfactory operating condition. These calibrations were made both as a final check on the serviceability of the densitometers and also to check the calibration during the record run.

The causes of the functional failures at Stations 690.01, 690.03, and 690.04 are not definitely known. However, there are several possible explanations. At Station 690.01 there may have been a faulty contact between the recording-unit outlet and the cable connected to the H−5 sec timing (EG&G) relay. Hence the control relay in the recording unit which was to close the camera power circuit was not actuated.

At Station 690.03 a situation opposite to that at Station 690.01 appeared to have occurred. The camera and all other circuits designed to close at H−5 sec were turned on. However, oscillator- and filament-battery voltages after recovery indicated that they were never turned on (at H−1 min). This time the control cable connected to the H−1 min timing relay may have made poor contact.

The densitometer at Station 690.04 operated well but with reversed timing sequence. The designed timing sequence was for the timing oscillators and oscilloscope-filament circuits to close at H−1 min. The camera power was to be turned on at H−5 sec. The film record showed that the camera had already been running about 58 sec when the timing marks appeared and the oscilloscope filaments were turned on. Since all the densitometers were connected in an identical manner, the timing relays at Station 690.04 could have been marked in reverse.

The record obtained at Station 690.02 agreed with predictions. The time of release of the last calibration foil had been measured in the laboratory to be about 2.9 sec after the master timing relay closed at H−5 sec. The break in the beta trace at about 1.1 sec after the release of the last foil was therefore taken as the zero-time mark. The break in the beta trace was believed to have been caused by a sudden burst of gamma radiation at the instant of explosion. This momentary large background gamma radiation superimposed on the beta signal was sufficient to deflect the electron beam off the face of the oscilloscope.

The quick recovery of the beta trace to its prezero-time level proved that the predicted low gamma radiation rate was indeed correct and that its consequence, namely, elimination of lead shielding and of a second phototube for subtracting background radiation, was justified.

Except for the short break (for about 0.30 sec) in the beta trace at zero time, the beta-trace level was essentially constant from H−1.03 sec (time of release of last calibration foil) until H + 9.86 sec (time of blast arrival). This was interpreted to mean not only negligible background radiation but also the absence of dust-loading in the air (thermal dust prior to blast arrival). It also indicated phototube fatigue was negligible during the period of measurement.

[redacted]

The complete absence of bumps and wiggles in the noise-monitoring trace showed that the instrument was well shielded from spurious signals, and therefore all variations in the beta trace could be attributed to bona fide material-density changes.

In view of the apparent absence of thermal dust, the initial rise in density (rise time = 0.003 sec) was interpreted as being caused only by an increase in density of shocked air. The measured density of shocked material (air) to unshocked material (air), $\rho/\rho_0 = 1.53$, would give, using the Rankine-Hugoniot relation

$$\frac{P}{P_0} = \frac{-(\gamma + 1)\frac{\rho}{\rho_0} + (\gamma - 1)}{(\gamma - 1)\frac{\rho}{\rho_0} - (\gamma + 1)}$$

and

$$\gamma = 1.40$$

a peak overpressure of $P - P_0 = 12.4$ psi at Station 690.02, which was 23,219 ft from ground zero.

Unless there is so much turbulence as to prevent positive identification of blast arrival, it appears possible to calculate ρ/ρ_0, and hence P/P_0, due to air shock alone by subtracting the increase in density due to thermal dust, which is recorded on the film.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Standardization of the beta densitometer was attained to a large degree at Ivy. All densitometers were built and installed alike. However, each had its characteristic calibration curve which is strongly dependent on the voltage sensitivity of the cathode-ray tube and especially on the phototube used. As available commercial phototubes become more standardized, so will densitometers. Densitometer accuracy, now reliable to 10 per cent or better, will be more accurate as better phototubes (high sensitivity, less fatigue, negligible dark current, etc.) become available. Calibration will be more accurate.

At Ivy a suitable phosphor (made by Earl Fullman, Group GMX-5, LASL) was finally made available for densitometer use. This phosphor eliminated the need for amplifier circuits and their power supplies. It appears that densitometers will continue to use phosphors.

Two of the simplifications incorporated in the densitometers at Ivy may not be applicable in densitometers to be used with smaller or nominal bombs. The elimination of shielding and of a second phototube to subtract background radiation was made possible by the low background radiation that was encountered at the Ivy Mike densitometer stations. This condition will not hold in smaller bombs (yields in the order of 100 kt or less) at ranges of interest. Unless advances in electronics make it unnecessary, densitometers for use with nominal or smaller bombs will require a second phototube and also lead shielding around the phototubes. Experience at Operation Tumbler showed that these are reasonable modifications to make.

The success of the d-c beta densitometer at Ivy makes the d-c beta densitometer a preferred choice over the a-c type. The densitometer instrumentation at Ivy also set a reliable pattern of densitometer circuitry so that emphasis on future improvements can be shifted from circuit design to a search for more rugged battery power supplies and circuit parts.

Specific improvements that can be made on the Ivy model beta densitometer are as follows:

1. Use double-pole double-throw relays to decrease current per pole and to increase reliability.
2. If relay contacts persist in sticking, use more rugged-type relays.
3. Use one pair of H−5 sec master relay terminals to close H−1 min circuits in the event H−1 min signals are faulty. This precaution will prevent losing the density record for times of arrival greater than 20 sec.
4. Use an internal delay circuit to operate on the H−1 min signal and to close the camera circuit in approximately 55 sec in the event that the H−5 sec signal is faulty.
5. Use photosensitive relays (Blue Box) to ensure that all circuits close and remain closed after zero time.
6. Inasmuch as the densitometer has proved to be relatively immune from spurious or noise signals, one trace of the oscilloscope may be used to record total background radiation

or gamma-tube output only in a dual-photomultiplier system.

7. Investigate the desirability of using heavier control cables and connections or of using additional parallel control lines.

8. Fabricate a junction box for preoperational connection to the EG&G relays, allowing subsequent control cables to be plugged in during operational installation. This will ensure connections that are identical to those used on tests, save time, and prevent accidental triggering of control circuits.

9. Check timing signals during dry runs by measuring the open and closed condition of plug pins at the recording-unit end of the control cables.

10. Install indicator lights for monitoring circuits.

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