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Operation IVY

PACIFIC PROVING GROUNDS

November 1952

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Project 6.11

FREE-AIR ATOMIC BLAST PRESSURE AND THERMAL MEASUREMENTS

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Report to the Scientific Director

FREE-AIR ATOMIC BLAST PRESSURE AND THERMAL MEASUREMENTS

By

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Agency to:

Geophysics Research Directorate
Air Force Cambridge Research Center
Cambridge, Massachusetts
August 1953

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ABSTRACT

Measurements of blast overpressure and thermal-radiation flux were carried out at high altitudes during both Mike and King shots of Operation Ivy by means of parachute-borne telemetering canisters. For each shot six canisters were dropped from each of two B-29 aircraft. Telemetered data were recorded from 10 of the 12 canisters at Mike shot and from 8 of the 12 canisters at King shot.

When corrected for known altitude effects, the peak overpressures observed at high altitudes agree well with those measured on the ground except at extreme ranges, where the ground overpressure is relatively low. It is believed that this is due to upward refraction of the blast wave, which is to be expected at very low overpressures. The observed peak overpressures also agree reasonably well with a peak overpressure vs slant range curve scaled up from Operation Tumbler-Snapper results, but, to obtain agreement with the reported energy yields, the blast efficiency of Mike shot appears to have been about 23 per cent and of King shot about 44 per cent greater than the average of the Tumbler-Snapper shots.

The interpretation of the thermal-radiation data is questionable since the observed values are very low as compared to other measurements. It is believed that this is due to cooling of the hot thermocouple junction by ventilation. If similar measurements are made in future tests, it is suggested that a shielded thermocouple be used.

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CHAPTER 1

INTRODUCTION

1.1 OBJECTIVES

Since measurements of blast overpressures at and near the surface of the ground are subject to various boundary-layer effects that are difficult to predict theoretically, it was considered desirable to supplement the surface-pressure measurements in Operation Ivy with measurements made at altitudes far above the range of influence of boundary-layer irregularities. Previous tests, Operation Tumbler-Snapper in particular, were considered to have confirmed current methods of taking into account the effect of the varying ambient conditions of the atmosphere with altitude; therefore it was thought that overpressure measurements at high altitudes, when suitably corrected for such effects, would provide a significant test of the extension to extremely large detonations of the scaling law relating peak overpressure to bomb yield.

Another objective was the measurement of the intensity of thermal radiation received over a wide range of altitudes and distances. Whereas the instrumentation and operating procedures for the measurement of blast overpressures by means of parachute-borne telemetering gauges had been brought to a state of comparatively high reliability in previous tests, the thermal-measurement phase was added at a late date and must be regarded primarily as a test of instrumentation rather than as a definitive test of thermal scaling at very high yields.

1.2 HISTORICAL

The military requirements for an experimental test of the Fuchs theory of the effect of varying ambient atmospheric conditions on peak blast overpressure were brought to the attention of the Terrestrial Sciences Laboratory early in 1950. At that time a proposal was prepared for participation in Operation Greenhouse. However, there was insufficient time for the preparation of such an extensive project, and no action was taken.

In December 1950 the proposal was reinstated under Operation Windstorm, and in February 1951 the project was officially included. After Operation Windstorm was cancelled, the project was tentatively included in Operation Buster, but, because of conflicting radio-frequency requirements, the project was diverted to Operation Jangle. Conclusions from the results of this operation were considered tentative since the actual positions attained by the air-borne instrumentation differed greatly from the intended positions and did not provide a clear-cut test of the Fuchs altitude correction. There was justification, however, for concluding that the data obtained supported the Fuchs theory within the probable accuracy of the observations out to overpressures of about 0.1 psi.

Project plans were included in Operation Tumbler-Snapper. The operation consisted in the measurement of peak blast overpressures by deploying 16 parachute-borne canisters from two B-29 aircraft in both Shots 5 and 8. The observed peak overpressures covering the range from about 0.1 to 3.0 psi confirmed the Fuchs theory to within practical accuracy requirements and supplemented other free-air peak-overpressure measurements made at higher overpressures by other methods.

CHAPTER 2

EXPERIMENTAL PROCEDURES

2.1 INSTRUMENTATION

The instrumentation involved in Operation Ivy was designed to accomplish four objectives: (1) to suspend pressure and thermal-radiation probes in the blast field by deploying parachute-borne canisters from two B-29 aircraft, (2) to receive the radio telemetry signal (data intelligence) from the parachute-borne canisters, (3) to record the arrival time of the peak blast overpressure at each canister, and (4) to record the pressure and thermal data.

A general description of the instrumentation for pressure and altitude determinations and thermal measurements and of the radio telemetry system is presented in this section. For a detailed description of the basic design of the canister instrumentation and the radio telemetry system, reference should be made to Operation Jangle Report, Project 1.3c;[1] Bendix Aviation Corp. reports, the operation and maintenance instructions;[2] and the Y-11600 telemetering canister instruction manual.[3]

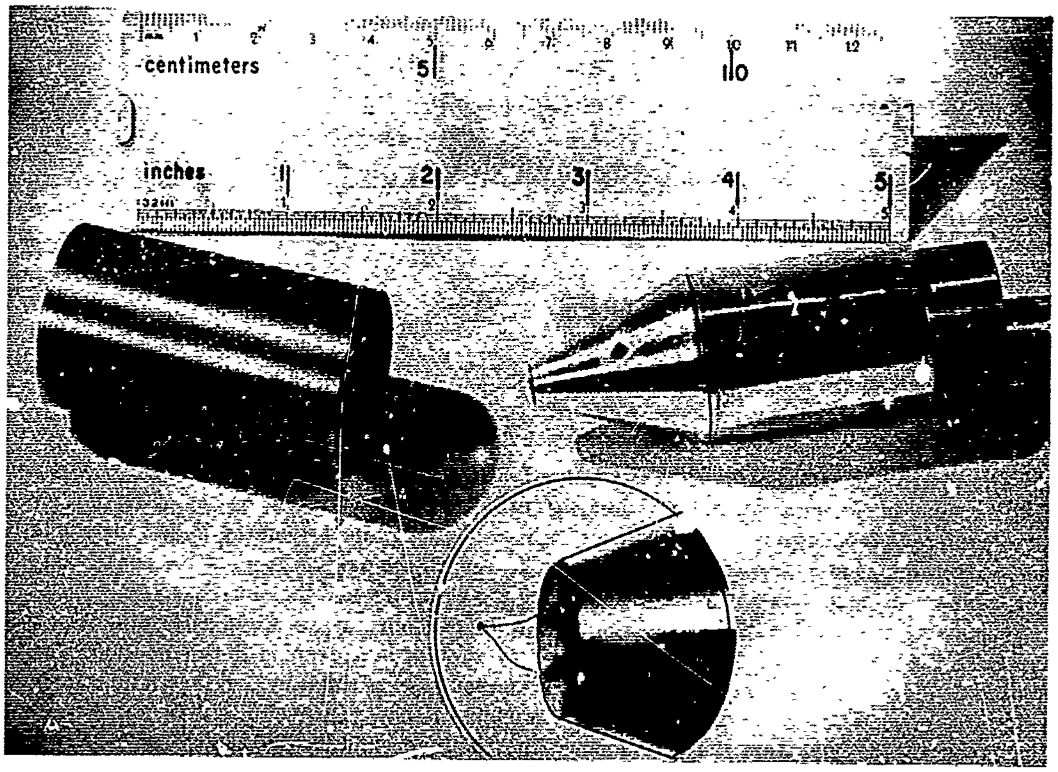
2.1.1 Pressure and Thermal Transducers

The pressure transducers are a diaphragm type in which the displacement of the diaphragm produced by a difference in pressure on opposite sides changes the air gap in a magnetic circuit. The resulting variation of inductance causes a variation in the frequency of the oscillator channel to which it is connected.

In the case of the differential-pressure transducers, one side of the diaphragm is vented to the atmosphere through a probe about 2 ft long mounted on the nose of the canister. The other side of the diaphragm is connected to a reference chamber with a volume of about 125 cu in., which in turn is vented to the atmosphere through a slow leak consisting of a 7-ft length of 1/8-in.-O.D. copper tubing. This provides a means of equalizing the pressure on both sides of the diaphragm during parachute descent, but it allows differential pressures of short duration to be measured before appreciable equalization of pressures takes place. In order to obtain the full pressure-time curve of the blast pulse, the reference chamber vent is sealed by a solenoid-operated valve, which is activated by the initial blast overpressure. When this valve fails to operate, an accurate pressure-time curve is not obtained, but the indicated peak overpressure is not affected (Sec. 3.1.1).

The altimeter pressure transducer is similar to the differential-pressure gauges except that the case body on one side of the diaphragm is evacuated and sealed and the other side is vented to the atmosphere in the open afterbody of the canister.

The thermal transducer is a thermocouple which has been designated as type K-2 by the manufacturer, The Eppley Laboratory, Inc., of Newport, R. I. The construction is shown in Fig. 2.1. A couple of platinum-rhodium alloy and gold-palladium wires, 1.5 mils in diameter, was formed with the exposed hot junction in an approximately spherical bead 10 mils in diam-



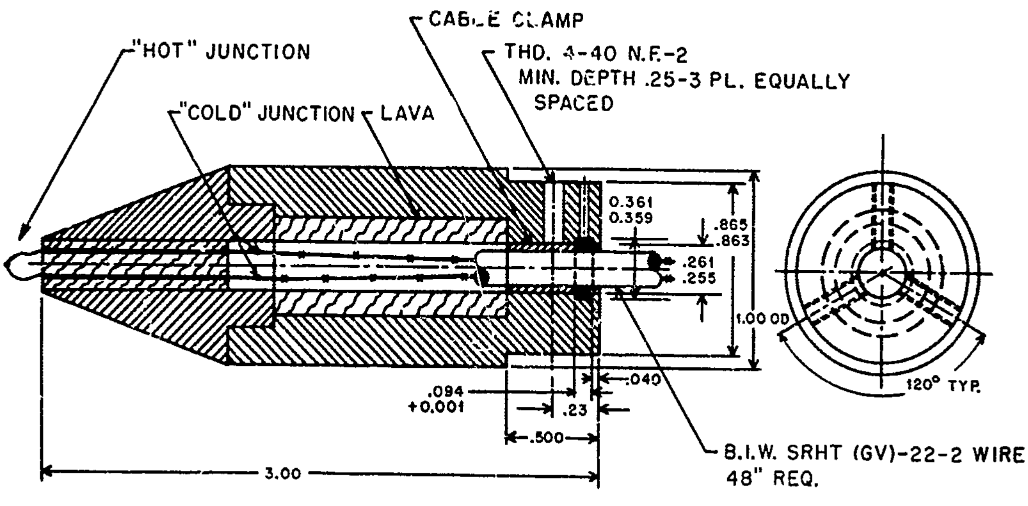


Fig. 2.1—Thermocouple housing.

eter. The hot junctions were variously coated to give a range of sensitivities; thus there were three types: aluminized (A), natural or uncoated (O), and blackened (B). The range in sensitivity was less than expected, as explained in slightly more detail in Sec. 2.2.1. To obtain an output of 1 mv, the irradiation intensities were, respectively, in gram calories per square centimeter per second, A, 1.49; O, 1.43; and B, 0.69. The cold junction was shielded in a cavity mostly enclosed by the lava through which the wires passed; the whole was surrounded by a massive brass cylinder.

2.1.2 Radio Telemetry Instrumentation

Each parachute-borne canister contained an altimeter pressure transducer, two differential pressure transducers (one having a scale ratio of approximately 3 with respect to the other), a thermocouple transducer, and a radio telemetry transmitter. Pressure and thermal stimuli caused each transducer in the canister to frequency-modulate a subcarrier frequency; the three subcarrier frequencies were mixed, and subsequently they frequency-modulated the radio-frequency (RF) carrier which was the multiplexing link between the canister and the recording ground station. The ground station contained a separate receiving and recording system for each parachute-borne canister RF carrier frequency. The output of each receiver, which was a mixture of the three frequency-modulated subcarriers, was separated by filter networks. Each frequency was channeled to a discriminator which produced an electrical current proportional to the original stimulus. These currents actuated galvanometers in the recording oscillograph.

The radio telemetry system, measuring equipment, and parachute-borne canisters were developed and fabricated by the Pacific Division Laboratories, Bendix Aviation Corp., Burbank, Calif., under Contract AF 19(122)-459. Incorporated in the telemetry ground stations were the important factors of high mobility in rough terrain, self-sufficient field operation, and accuracy of calibration under difficult field conditions.

2.1.3 Aircraft Instrumentation

The air-borne APQ-13 radar system was used to position the two B-29 aircraft, both in reference to time and course position. Various islands in the Eniwetok Atoll were excellent target points for the radar system. Twelve parachute-borne canisters, six from each B-29 aircraft, were deployed in both Mike and King shots.

The aircraft bomb bays were wired to furnish aircraft electrical power to each canister. This power was used to preheat the canisters internally during high-altitude operation prior to canister deployment. The technique of preheating the canisters was necessary to increase battery efficiency and to stabilize the operation of the electronic equipment. The temperature inside the canisters was controlled within the range of 70 to 80°F by the use of thermostats and electric heating strips installed in each subsection of the canister. Heat losses were minimized by lining the inner frame of the canister with a 1-in. layer of insulating material.

2.1.4 Canister Instrumentation

The telemetry instrumentation in the canister is described in Sec. 2.1.2 as part of the radio telemetry system. Two canister parachute systems were designed. The first system, a dual-parachute assembly, consisted of a 6-ft fist ribbon parachute and a 28-ft-square semiribbon parachute. The latter parachute was designed for the project at Wright Air Development Center for the specific purpose of minimizing parachute oscillation during canister descent in order to hold the transmitting antenna as nearly vertical as possible and thus minimize oscillations in the RF signal strength. Immediately after canister deployment from the aircraft, the 6-ft ribbon parachute was released by the static line attached to the aircraft. The time of canister descent on the 6-ft ribbon parachute was determined by the canister array position and ballistic data. An internal timer, set for a predetermined time after canister deployment, fired a squib-cutting mechanism which detached the 6-ft ribbon parachute and released the 28-ft-square parachute.

The second system consisted of three parachutes, a 6-ft fist ribbon parachute and two 28-ft-square parachutes. The operation of the 6-ft ribbon and the first 28-ft parachute was identical to the previously described dual system. If the first 28-ft parachute happened to be destroyed by radiation, resulting in a free fall of the canister, a second 28-ft parachute would be released by a second squib-cutting mechanism. A pressure differential between a reference chamber in the canister and the ambient pressure occurs during the canister free fall because of the pressure time lag of the reference chamber. The value of this pressure differential, after approximately 10 sec of canister free fall, is sufficient to activate a pressure switch. When this pressure switch closes, it activates the second squib-cutting mechanism, thereby releasing the second 28-ft parachute. The 10-sec delay was very desirable to prevent thermal damage to the latter 28-ft parachute, assuming that damaging thermal effects would exist for only 10 sec after detonation. In each test six of the canisters were supplied with the triple-parachute system since they were expected to be within the range of possible thermal damage. The remaining six canisters, located at longer slant ranges, contained the dual-parachute system. The parachute-borne canister was 86 in. in over-all length, 14 in. in diameter, and weighed 300 lb.

2.2 CALIBRATION PROCEDURE

Reference is made to Operation Jangle Report, Project 1.3c,[1] for a detailed description of blast-pressure calibration procedure.

2.2.1 Calibration of Transducers

The thermocouples were calibrated through the courtesy of the Material Laboratory of the Brooklyn Naval Shipyard. The following description of the calibration method is quoted from their report (Laboratory Project 5046-2, Part 6; dated 24 March 1953).

> The three type K-2 thermocouple radiometers have been calibrated by the Laboratory. This investigation was conducted at the request of the Air Force Cambridge Research Center and as part of the Thermal Radiation Program sponsored by the Armed Forces Special Weapons Project.
>
> The radiometers were calibrated by means of a high-intensity carbon-arc source which produces 4 per cent of its energy in the ultraviolet region, 36 per cent in the visible, and 60 per cent in the infrared. This source provides an irradiance of 18 cal/cm^2 sec^{-1} over approximately a 0.5-cm diameter area. In order to obtain lower irradiances, perforated metal attenuating screens with transmittances of 0.087, 0.17, 0.21, 0.41, and 0.50 were used. The response of the radiometers was measured with a calibrated recording potentiometer. An open-ended box with 8-inch-square cross section was used to protect the radiometers from air draughts. Each radiometer at each irradiance was given a series of three 3-second exposures. The response remained constant during the 3-second period, except for some variation due to fluctuation of the carbon-arc and cooling of the radiometer thermojunction by air currents. There was seldom as much as 10 per cent difference between the three response readings in one series.
>
> In the table (Table 1—Response of K-2 Radiometers) is the average response for each irradiance. It is to be noted that the uncoated (No. 2563) and the aluminized (No. 2567) radiometers have a linear response, whereas a smooth curve drawn through the experimental points of the blackened (No. 2565) radiometer shows some saturation effect. This is explained by the fact that the blackened thermojunction at the temperature of interest loses a large part of its absorbed heat to reradiation according to the fourth-power law, while the other thermojunctions have much too low an emissivity for this effect to be important.
>
> The time constants (0.63 of the maximum deflection for continuous illumination) of the radiometers were determined with a galvanometer oscillograph with a frequency response, measured under the conditions of use, flat up to 80 cps. An irradiance of 9 cal/cm^2 sec^{-1} was used on the blackened radiometer, and 18 cal/cm^2 sec^{-1} on the others. All of the rise or fall time constants measured were within 15 per cent of 0.21 sec.

Table 1—RESPONSE OF K-2 RADIOMETERS

Irradiance ($g\ cal\ cm^{-2}\ sec^{-1}$)	Radiometer No.: Coating:	E.M.F. (millivolts) 2567 Aluminized	2563 Uncoated	2565 Blackened
1.6		1.1	1.2	2.6
3.1		2.0	2.5	4.7
3.8		2.8	2.7	5.9
7.4		4.9	5.1	10.3
9.0		6.4	6.6	12.2
18		12.1	12.7	21.7

From the data given in the table, the least-mean-square values for response were determined. For the aluminized and uncoated thermocouples an output of 1 mv is obtained with, respectively, in gram calories per square centimeter per second, 1.49 and 1.43. For the blackened thermocouple only the lower values of irradiance were used in the computation, and a response of 0.69 resulted.

An output of 1 mv indicated a temperature rise of 30°C.

2.2.2 Calibration of Telemetry System

Thermal calibration of the receiving stations was accomplished by measuring oscillograph galvanometer deflections as a function of frequency input to the discriminators. The manufacturer of the K-2 thermocouple performed a calibration of the temperature rise vs thermocouple output. After installation of transducers in the canisters, it was necessary to determine subcarrier oscillator-output frequency as a function of thermocouple output. This calibration was made by applying known voltages to the transducer and subcarrier oscillator-input circuit and recording the subcarrier oscillator-frequency deviation. The impedance of the K-2 thermocouples varied from 3.6 to 4.7 ohms, and a resistance was added to each circuit to make the impedance, as seen by the control coil, 5 ohms in all cases. Ten calibration voltages from 0 to 90 mv were applied to the circuit which caused known currents to flow through the control winding of the subcarrier oscillator. As the voltage was applied in step functions of 10 mv to the circuit, galvanometer deflections as a function of subcarrier oscillation frequencies were recorded by the receiving stations.

This calibration was performed on all canisters used in each test prior to loading the canisters in the aircraft bomb bays. At approximately H−3 hr this calibration was repeated while the aircraft was flown in a prescribed pattern over the receiving telemetry station located aboard the USS Oakhill. The air-borne calibrations were received and recorded by this station. The calibration performed prior to loading the canisters aboard the aircraft was made to prevent loss of calibration if operational difficulties had prevented the air-borne calibration from being made. Successful air-borne calibrations were made on each test and were used in all cases to obtain final data.

2.3 MIKE SHOT

The operational problems consisted of five phases: (1) the positioning of two B-29 aircraft over a drop point both in reference to time and course position, (2) the positioning of canisters in space by correcting the aircraft drop point for the integrated horizontal wind drift of the parachute-borne canisters, (3) the deployment of 12 parachute-borne canisters from the aircraft, (4) the installation of the recording telemetry station on the deck of a Landing Ship Dock (LSD), and (5) the recording of telemetered blast-pressure and thermal data from each canister.

Figure 2.2 shows the location of the radio telemetry ground station in relation to Ground Zero.

2.3.1 Aircraft Operation

Overcast cloud conditions prevented aircraft flight in close formation except for the last flight pattern. The B-29 aircraft were flown at 30,000 ft MSL on a bearing from Ground Zero to the telemetry ground station based on the USS Oakhill. The correction of the target point for parachute-borne-canister wind drift was 4000 ft. At H−540 sec both B-29 aircraft were 1 sec ahead of scheduled time and were approximately 1000 ft east of the planned course line. Both aircraft deployed a payload of six canisters. Each payload was a backup for the other to prevent loss of data if (1) one aircraft had to abort or (2) telemetering equipment failed either in the canister or at the ground station. Both aircraft commanders reported the following interesting effects: (1) the free-air temperature rose 2°C by H+5 sec at a range of approximately 30 nautical miles from Ground Zero and (2) both aircraft were approximately 55 nautical miles from Ground Zero when the blast wave passed the aircraft at H+295 sec. The rate-of-climb indicator showed an apparent rate of descent of 1000 ft/sec, and the altimeter showed an apparent decrease in altitude of 500 ft. Both instruments settled to normal conditions 15 sec after the passage of the blast wave. No turbulence was observed by any of the aircraft crew.

Figure 2.3 shows the canister array and the intended canister positions compared with the attained positions.

2.3.2 Canister Operation

Pressure data were recorded from all canisters except Nos. 1 and 6. The large parachutes failed to open on canister No. 1, and the RF carrier failed in canister No. 6. Thermal data were recorded from the five canisters having the shortest slant range from Ground Zero.

The operation of the dual-parachute assemblies was very successful since only canister No. 1 incurred a free fall. The operation of the triple-parachute assemblies could not be determined; however, no loss of data could be attributed to these assemblies.

The laboratory for canister maintenance and calibration at Kwajalein was installed with air conditioning and dehumidification equipment for protection against corrosive effects to instrumentation. Corrosion due to high humidity and salt particles in the air was extremely damaging to relay contacts and other components which contained electrical switching contacts. Two of the thirty canisters taken to the test site eventually became corroded beyond repair. It is emphasized that air conditioning and dehumidification were invaluable in controlling corrosion of instrumentation.

2.3.3 Radio Telemetry Operation

The radio telemetry ground station was based on the aftersection of the USS Oakhill, LSD, located 30.4 nautical miles southeast of Ground Zero. The facilities on the LSD were exceptionally satisfactory, especially with regard to parking space for the ground station and to the forward position of the LSD superstructure. The radio telemetry equipment was housed in two type K-35 trailers. Laboratory work space and photographic facilities were housed in a third trailer. Electrical power was obtained from four PE-95 power units. Corrosive effects of high humidity and salt particles in the air were minimized by operating the electronic equipment almost continuously so that the dissipation of the heat from transformers and electronic tubes kept the equipment hot and dry.

The LSD, during the operation, established a course of 180° so that the directional antennas mounted on the telemetry trailers faced the direction toward Ground Zero and were not affected by intervening superstructure. The canister RF carriers were recorded from the time of deployment from the aircraft to approximately H+5 min.

2.4 KING SHOT

The operational problems in King shot were identical to those in Mike shot.

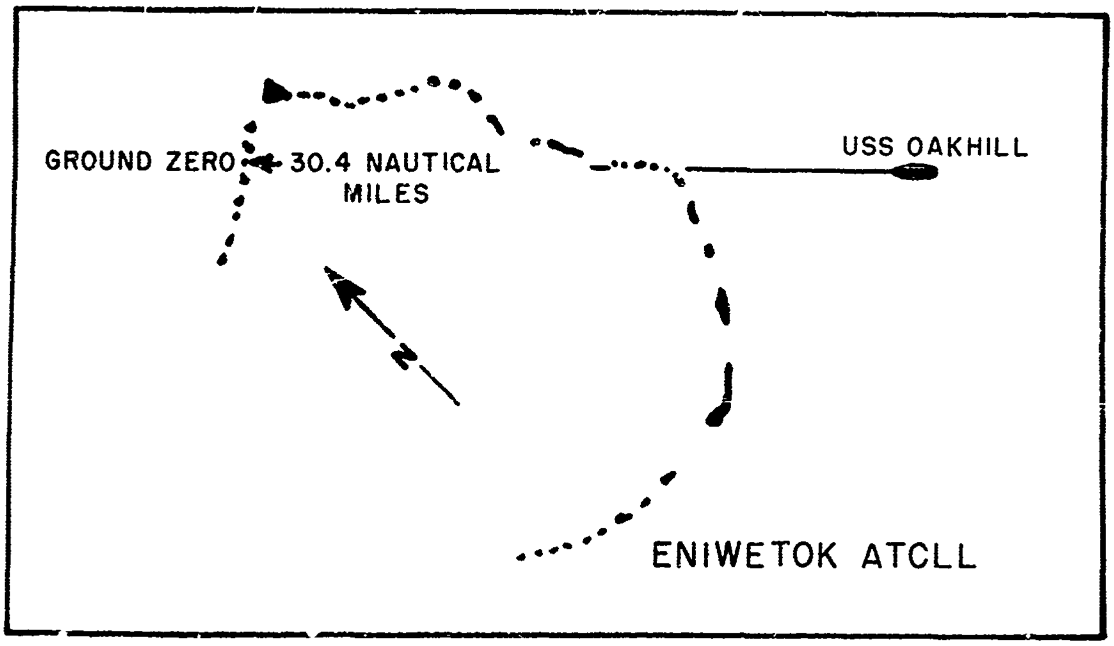


Fig. 2.2—Plan of array and radio telemetry station with respect to Ground Zero, Mike shot.

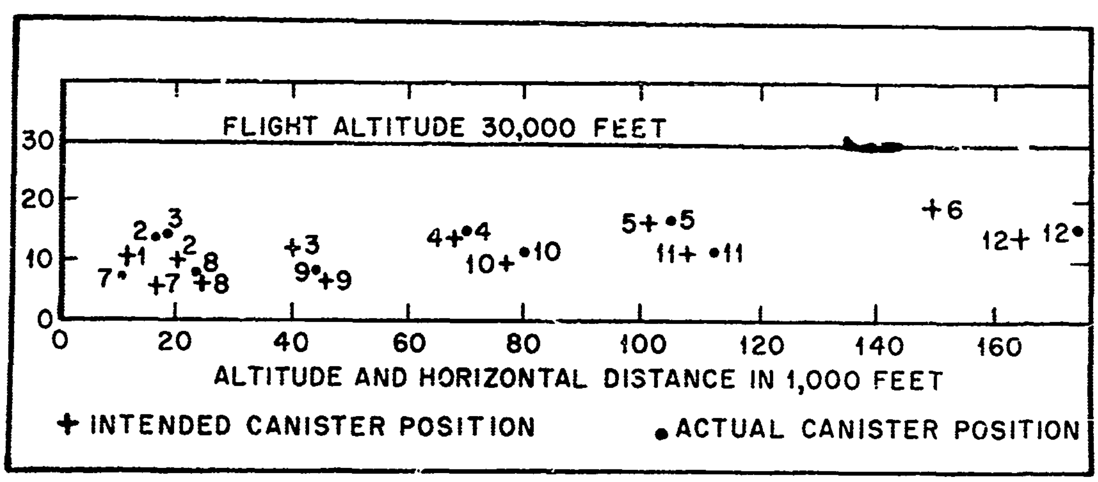


Fig. 2.3—Intended and actual canister positions, Mike shot.

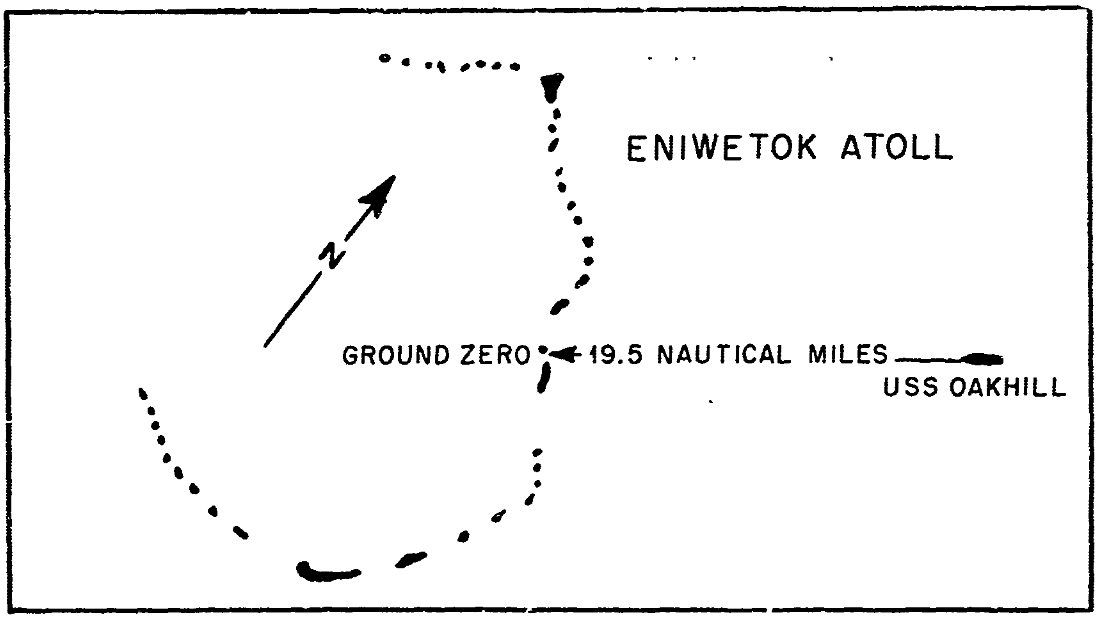


Fig. 2.4—Plan of array and radio telemetry station with respect to Ground Zero, King shot.

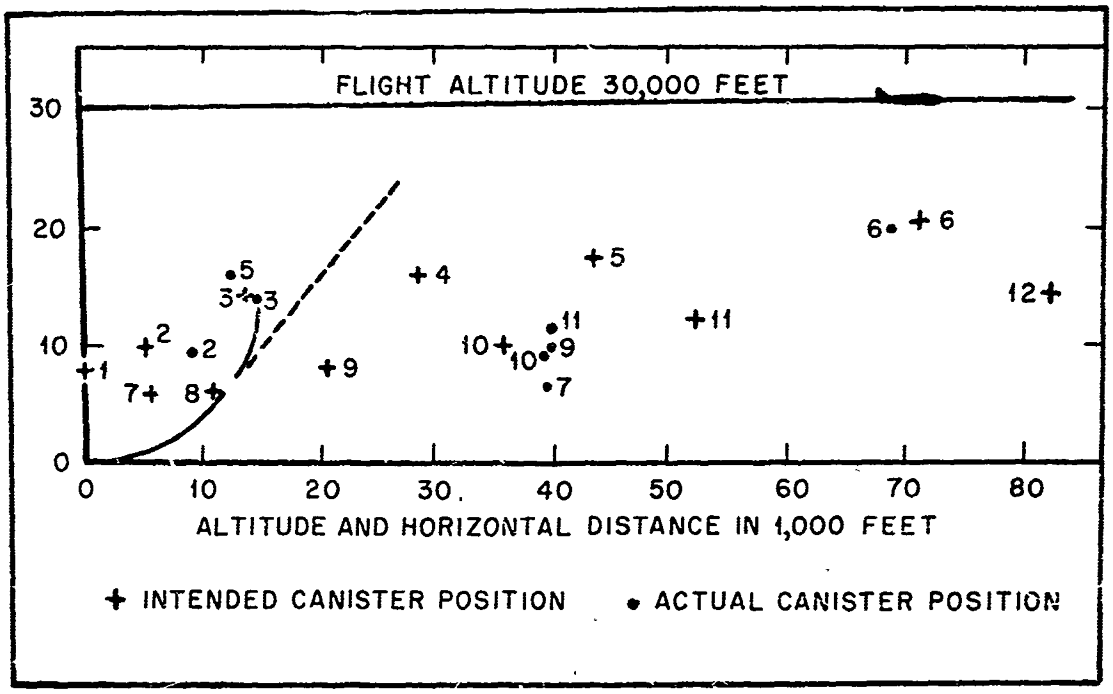


Fig. 2.5—Intended and actual canister positions, King shot.

Figure 2.4 shows the location of the radio telemetry ground station in relation to Ground Zero.

2.4.1 Aircraft Operation

The two B-29 aircraft were flown in close formation during the entire mission at 30,000 ft MSL on a bearing from Ground Zero to the telemetry ground station based on the USS Oakhill.

Neither parachute-borne canisters nor the two aircraft were permitted to enter a cylindrical zone of 5000 ft radius established above Ground Zero. This zone was established because of important safety factors involved in an atomic air drop. Since the computed canister wind drift resulted in a target point within the prohibited zone, a drop point 6500 ft southeast of Ground Zero was determined in order to minimize the slant range to Ground Zero of canisters Nos. 1 and 2.

Each B-29 aircraft deployed a payload of six canisters. Aircraft 4035 was early by 27 sec and aircraft 1833 was early by 20 sec over the target point. Canisters Nos. 1 through 6 were each deployed 18 sec early. Because of a malfunction of the bomb-bay system, canisters Nos. 3 and 5 were deployed at the time No. 3 was released. Canisters Nos. 7 through 12 were deployed by the salvo switch at H−178 sec owing to the failure of the bomb-bay system.

Figure 2.5 shows the canister array, indicating the intended canister positions compared with the attained positions.

2.4.2 Canister Operation

Pressure data were recorded from all canisters except Nos. 1, 4, 8, and 12. Thermal data were recorded from all the canisters except Nos. 1, 4, 8, 10, and 12.

The first 28-ft parachute of canisters Nos. 1 and 12 failed to open. All other canister dual-parachute assemblies were satisfactory. No RF signal was received from canisters Nos. 4 and 8, probably owing to canister power-supply failure. The thermocouple on canister No. 12 was damaged during deployment. The operation of the triple-parachute assemblies in the six canisters nearest Ground Zero could not be determined; however, no loss of data could be attributed to these assemblies.

2.4.3 Radio Telemetry Operation

The radio telemetry ground station was based on the aftersection of the USS Oakhill, LSD, located 19.5 nautical miles northeast of Ground Zero.

The canister RF carriers were recorded from the time of deployment from the aircraft to approximately H+3 min.

REFERENCES

1. N. A. Haskell and J. O. Vann, The Measurement of Free-air Atomic Blast Pressures, Operation Jangle, Project 1.3c, Air Force Cambridge Research Center, April 1952 (reprinted in Blast and Shock Measurements II, Operation Jangle Report, WT-367).
2. Bendix Aviation Corp., Operation and Maintenance Instructions for Portable Telemetering Receiving Station, Report DLM-14, February 1952.
3. Bendix Aviation Corp., Instruction Manual, Y-11600 Telemetering Canister, Report DLM-4.

CHAPTER 3

TEST RESULTS

3.1 MIKE SHOT

3.1.1 Blast-overpressure Data

The basic peak-overpressure, time, altitude, and slant-range data for Mike shot are given in Table 3.1. Sample oscillograph traces are shown in Fig. 3.1, and the overpressure vs time curves, as scaled from the original records and calibration curves, are plotted in Fig. 3.2. In canisters Nos. 7 and 12 the blast-actuated switch, which is intended to seal the pressure reference chamber, failed to operate. This does not affect the peak-pressure readings since the reference chambers are vented to the atmosphere through a sufficiently high acoustic impedance to give a time constant of several seconds. It does mean, however, that the later parts of the overpressure vs time curves are referenced to a slowly varying, rather than a constant, back pressure. At canister No. 7 the duration of the positive overpressure phase is short enough that the apparent duration should not be greatly in error, but, because of the very long duration at canister No. 12, no quantitative estimate can be given in this case.

Table 3.1 — PEAK-OVERPRESSURE, TIME, AND POSITION DATA, MIKE SHOT

Canister No.	Peak overpressure (ΔP), psi: High-range gauge	Low-range gauge	Mean	Arrival time (T), sec	Duration of positive overpressure (ΔT), sec	Altitude (z), ft	Slant range (R), ft
2	8.50	8.65	8.575	7.93	6.07	12,950	21,130
3	7.80	Off scale	7.80	8.84	7.57	13,440	22,790
4	1.17	1.14	1.155	48.43	11.15	15,500	72,110
5	0.78	0.75	0.765	74.51	11.49	17,450	103,640
7	22.0	21.95	21.975	3.63	3.21(?)	7,050	13,180
8	6.20	6.10	6.15	11.15	7.69	7,950	24,740
9	2.40	2.40	2.40	29.61	10.46	7,300	49,180
10	1.05	1.08	1.065	56.29	14.06	11,900	80,760
11	0.67	0.59	0.63	85.06	7.56	11,850	112,450
12	0.30	0.26	0.28	142.46	(?)	16,000	174,230

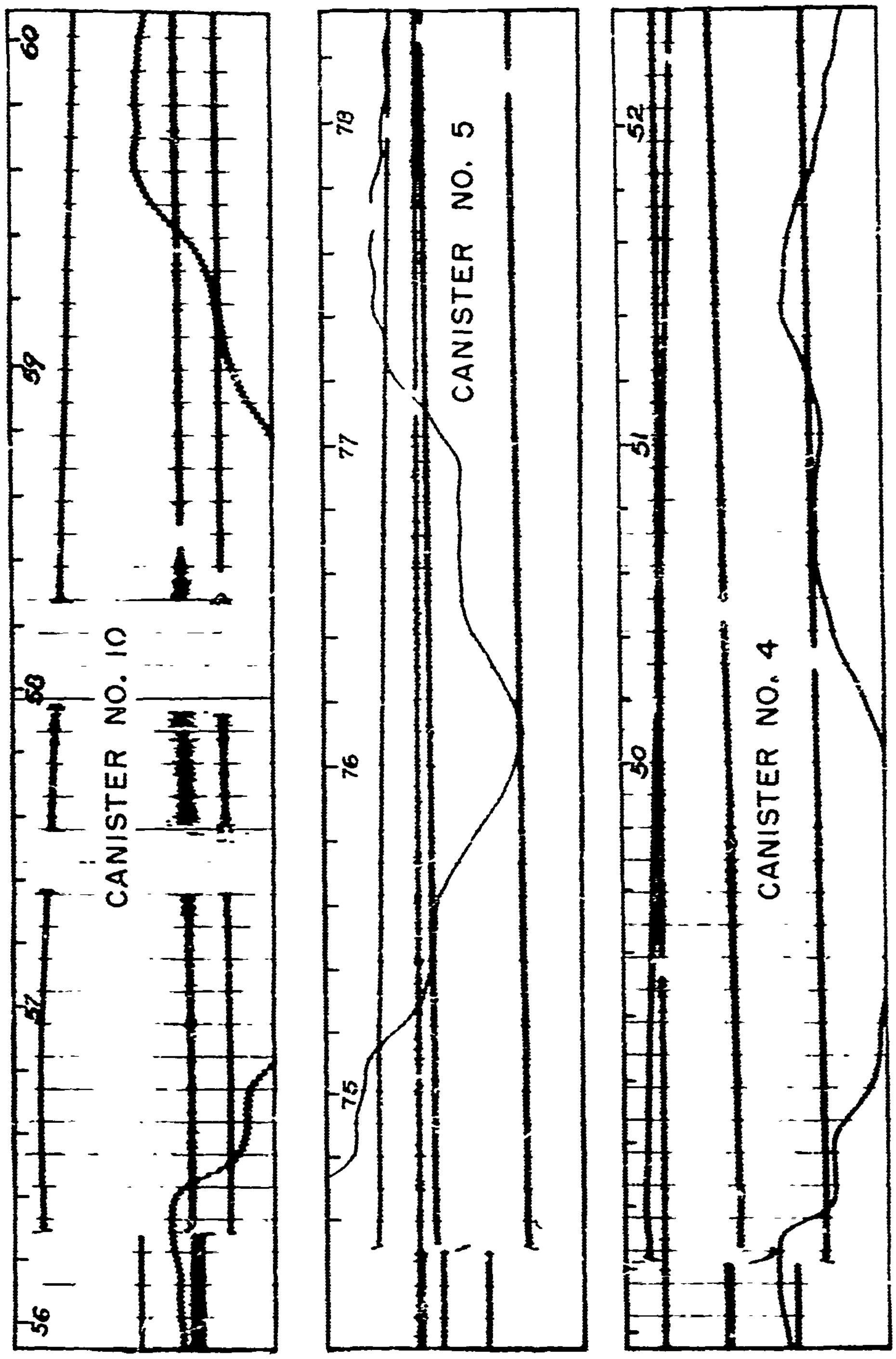


Fig. 3.1—Sample telemetered pressure records, Mike shot.

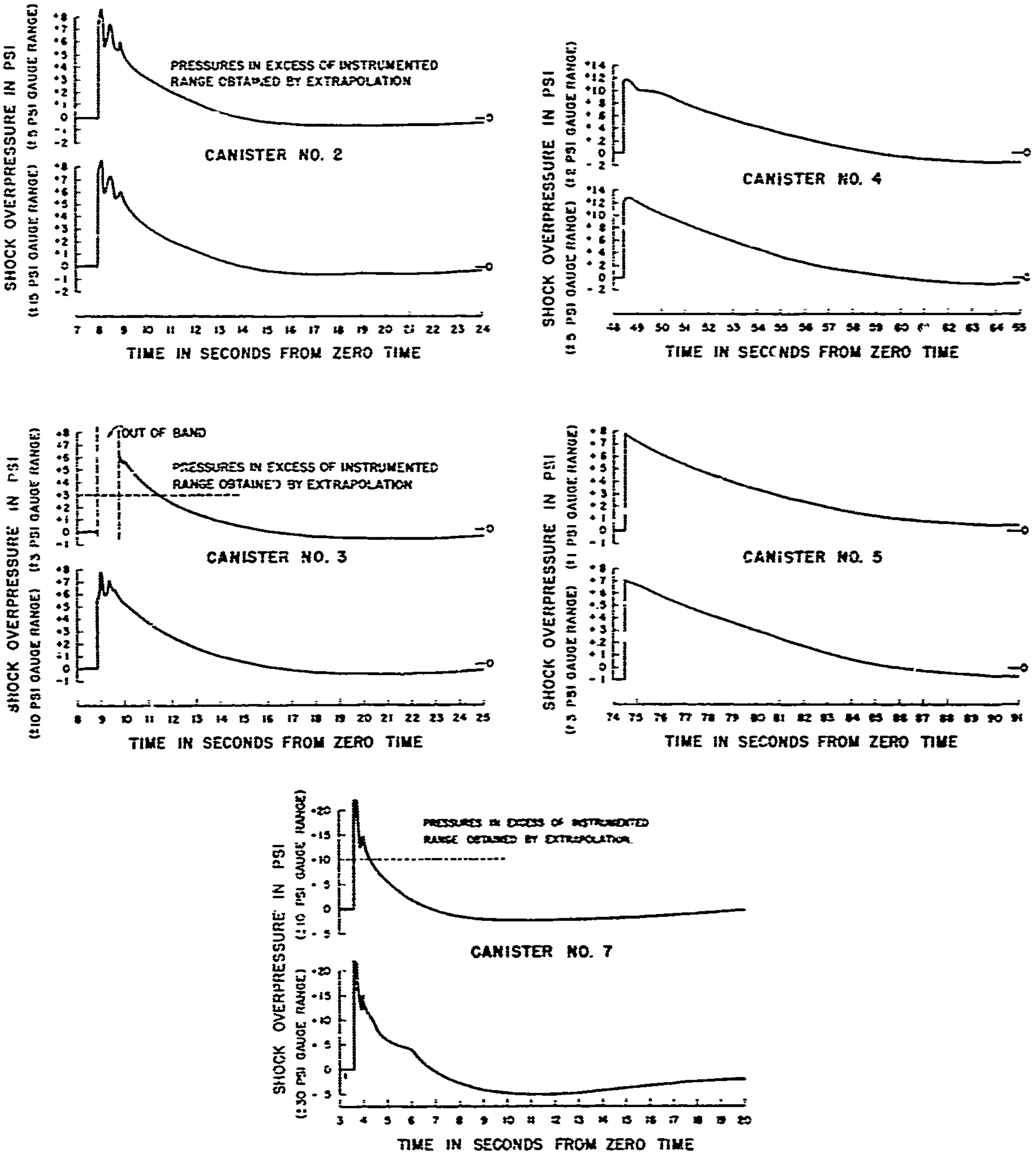


Fig. 3.2—Shock overpressure vs time, Mike shot.

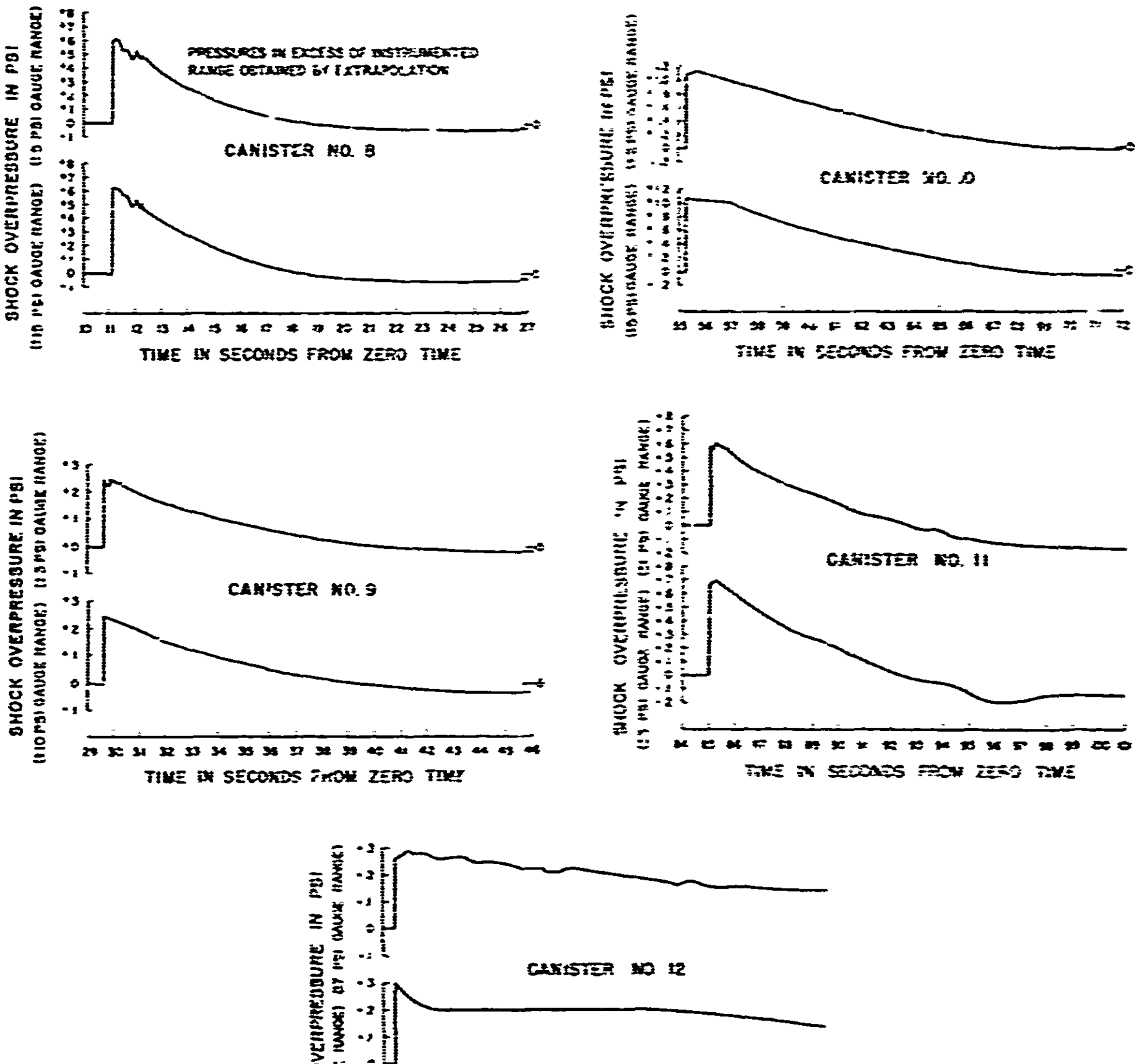


Fig. 3.2—(Continued)

The altitudes tabulated have been computed from the telemetered ambient-pressure records, using the meteorological data taken at Bikini (see Appendix B). The slant ranges have been computed from the observed blast-arrival times and peak overpressures by using a previously computed curve giving average blast-wave velocity as a function of peak overpressure, with corrections for the variation of sound velocity and wind component along the propagation path from shot to gauge. This method of computing the slant range is discussed in more detail in Appendix A.

All differential-pressure records show the blast-wave arrival as a true shock, that is, the rise times are less than the time-resolution capability of the system, but in most cases there are small departures from ideal shock-wave shape in the form of a slight rounding off of the peak or of superimposed oscillations immediately following the shock front. The periods of the oscillations (0.3 to 0.4 sec) are far too great to be attributed to any mechanical or electrical resonances in the measuring system, but they could coincide with some motion of the canister caused by the impact of the blast on the parachute. However, the recorded variations in RF carrier signal strength show that large oscillations of the canister may take place without any corresponding variation appearing on the pressure records. It is therefore considered probable that the pressure irregularities are not instrumental but are a real property of the blast wave. It is suggested that they are caused by small-scale inhomogeneities or turbulence in the atmosphere. The largest oscillations found in the present case (canister No. 2) have an amplitude of about 17 per cent of the peak overpressure. Attention is called to this fact because a pressure perturbation that develops immediately behind the shock front will propagate forward with a velocity greater than that of the shock front. This will result in a variation of pressure at the shock front as successive peaks and troughs of the perturbation overtake it. The possibility of an essentially random variation of this kind implies a limit to the reproducibility and predictability of peak blast overpressure as a function of distance.

3.1.2 Thermal-radiation Data

The total thermal radiation registered by the successful canisters, together with their respective slant ranges, are given in Table 3.2. The time-response curves, with ordinates in millivolts output as they were read, rather than in gram calories, are given in Fig. 3.3, but they are also labeled with the integrated thermal values as in Table 3.2. In Fig. 3.3 it is shown

Table 3.2—THERMAL VALUES FOR MIKE SHOT (REVISED 20 APRIL 1953)*

Array position	Slant range, ft	Total thermal, g cal cm^{-2}	Peak intensity, g cal cm^{-2} sec^{-1}	Rise in temperature of couple, °C	Coating†
2	21,130	32	17.0	350	O
		(18)	(10)	(210)	
3	2[illegible],790	32	12.0	260	O
		(22)	(10)	(210)	
7	13,180	112	62.0	1260	A
		(124)			
8	24,740	27	12.0	260	O
		(23)	(11)	(250)	
9	49,180	9	2.0	90	B

*Values in parentheses are those obtained assuming no change during exposure in the zero between cold and hot junctions.

†Coatings: O, natural, not coated; B, blackened; and A, aluminized.

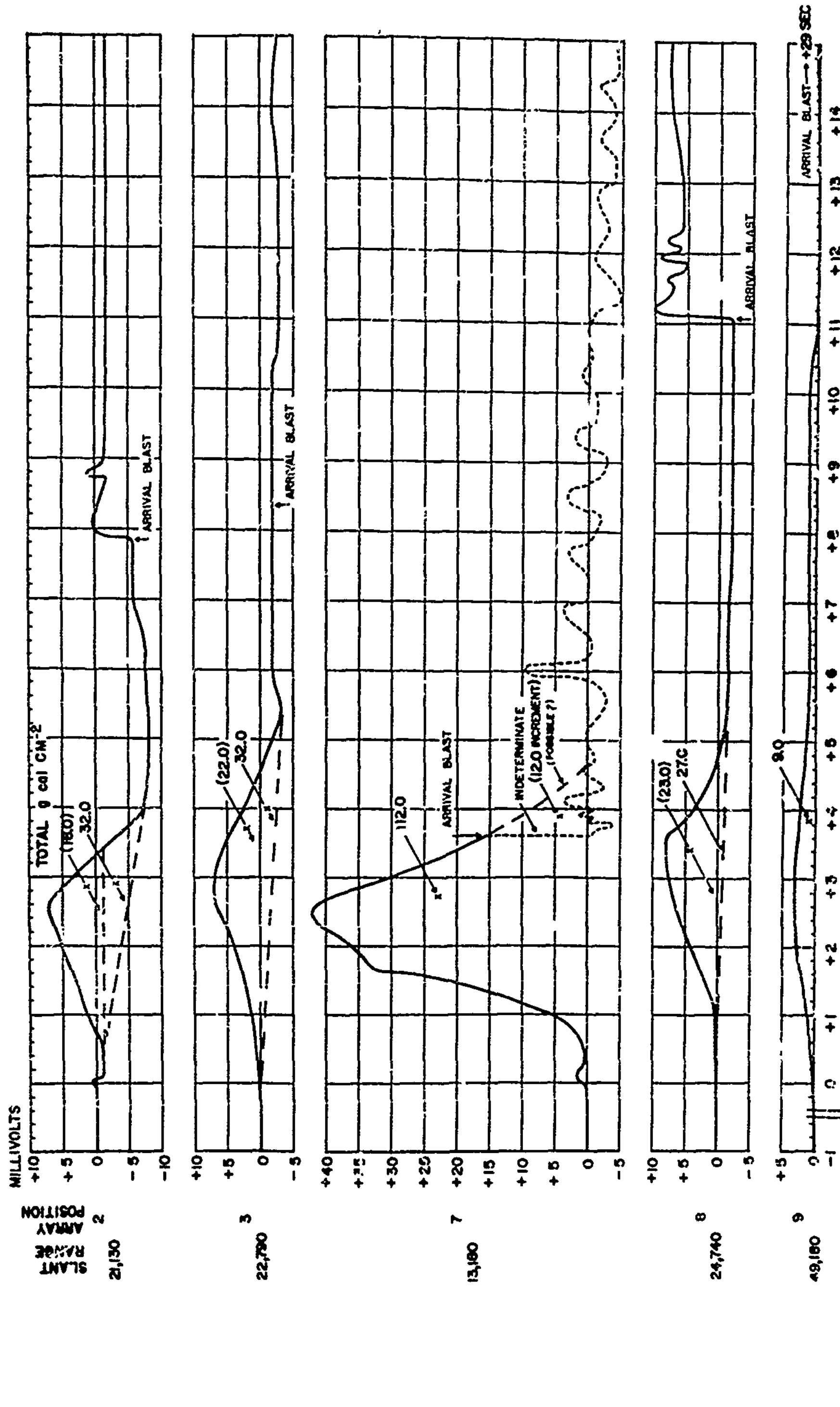


Fig. 3.3—Thermal intensity vs time, Mike shot.

that in the case of three observations, Nos. 2, 3, and 8, the couples did not return to the initial zero. They all showed negative voltages. The reason is not apparent. The possibility of a cooler environment of ambient air is not plausible. A higher temperature for the mass of brass and lava surrounding the cold junction, although possible, does not appear likely. Therefore two products (millivolts × time) were taken for each of these three radiometers. First, the area was measured using as a base the initial zero; this was assumed to hold. Second, the line connecting the first zero and the negative voltage was used as a base line (see Fig. 3.3). In Table 3.2 the latter, the "corrected" zero, values are given first; the second values, in parentheses, are those obtained assuming no change during exposure in the zero between cold and hot junctions. These alternate choices for zero result in alternate values for the data in the total-thermal column, the peak-intensity column, and the rise-in-temperature column, and they are distinguished by enclosing the "uncorrected zero" values in parentheses.

It is further to be noted that the blast arrived at Mike canister No. 7 before the radiation pulse had ceased. Apparently the shock injured the telemetering system within the canister. An estimate of the unrecorded remainder of the radiation pulse was attempted, as shown by the dashed line in Fig. 3.3. This increment would increase the total energy for No. 7 by about 10 per cent. This augmented value is given in parentheses in Table 3.2. The random output from the injured telemeter component is not taken as evidence of an injured thermocouple or of a zero shift.

3.2 KING SHOT

3.2.1 Blast-overpressure Data

The basic peak-overpressure, time, altitude, and slant-range data for King shot are given in Tables 3.3 and 3.4. Sample oscillograph traces are shown in Fig. 3.4, and the overpressure vs time curves as scaled from the original records and calibration curves are plotted in Fig. 3.5. The records from canisters Nos. 2, 3, and 5 show secondary shocks within 0.5 to 2 sec following the primary shock. It is very probable that these represent the reflection from the ground and that these canisters therefore lie within the region of regular reflection.* The records from the other canisters show a single main peak with only a very small secondary shock at around 6 sec after the primary shock. This is far too late an arrival to be attributed to ground reflection; hence all canisters except Nos. 2, 3, and 5 are assumed to lie within the region of Mach reflection.

From the time intervals between direct and reflected shocks at canisters Nos. 2, 3, and 5, a crude estimate of the path of the triple point can be obtained by assuming that this interval may be extrapolated linearly to zero with distance along straight lines drawn between the pairs 5-3 and 2-3. The locus shown by the dashed line in Fig. 2.5 is thus obtained. For comparison the path of the triple point has also been plotted as computed from the data derived from experiments with high explosives as summarized in The Effects of Impact and Explosion.[1] In the computations a burst height of 1500 ft, a yield of 550 Kt, and a blast efficiency of 40 per cent relative to TNT were assumed.

3.2.2 Thermal-radiation Data

For King shot the information similar to that for Mike shot given in Table 3.2 and Fig. 3.3 are presented in Table 3.5 and Fig. 3.6. The records do not show the anomalies found in Mike shot, as already discussed.

*This contradicts a statement made in a preliminary report on Operation Ivy, Project 6.11, which was written before the significance of the secondary shocks shown on the pressure-time records had been adequately considered in order to make the principal data on peak overpressure available to interested groups as quickly as possible.

Table 3.3—PEAK-OVERPRESSURE, TIME, AND POSITION DATA, (FIRST ARRIVAL) KING SHOT

Canister No.	Peak overpressure (ΔP), psi: High-range gauge	Low-range gauge	Mean	Arrival time (T), sec	Duration of positive overpressure (ΔT), sec*	Altitude (z), ft	Slant range (R), ft
2	2.40	2.45	2.425	8.31	3.58	9,350	14,030
3	1.39	1.31	1.35	13.75	3.65	14,050	20,890
5	1.26	1.30	1.28	13.82	3.76	16,300	21,130
6	0.30	0.24	0.27	58.62	5.35	19,550	71,400
7	0.85	0.90	0.875	29.93	3.16	7,050	40,380
9	0.76	0.85	0.805	30.48	4.51	10,000	41,090
10	0.80	0.81	0.805	30.36	3.76	9,700	40,860
11	0.76	0.68	0.72	31.33	4.06	11,400	41,760

*Data are questionable since there was an apparent drift in the base line during passage of the blast wave.

Table 3.4—OVERPRESSURE INCREMENT AND TIME INTERVAL OF GROUND REFLECTION, KING SHOT

Canister No.	Peak-overpressure increment, psi: High-range gauge	Low-range gauge	Mean	Time interval after direct shock, sec
2	0.46	0.51	0.485	1.03
3	0.34	0.29	0.315	0.56
5	0.26	0.26	0.26	1.79

Table 3.5—THERMAL VALUES FOR KING SHOT (REVISED 20 APRIL 1953)

Array position	Slant range, ft	Total thermal, g cal cm^{-2}	Peak intensity, g cal cm^{-2} sec^{-1}	Rise in temperature of couple, °C	Coating*
2	14,030	11	12	270	O
3	20,890	6	8	160	O
5	21,130	9	8	360	B
6	71,400	0.9	0.7	30	B
7	40,380†	1.0	1.6	30	A
9	41,090†	0.4	0.4	15	B
11	41,760†	1.0	1.0	45	B

*Coatings: O, natural, not coated; B, blackened; and A, aluminized.
†Salvoed.

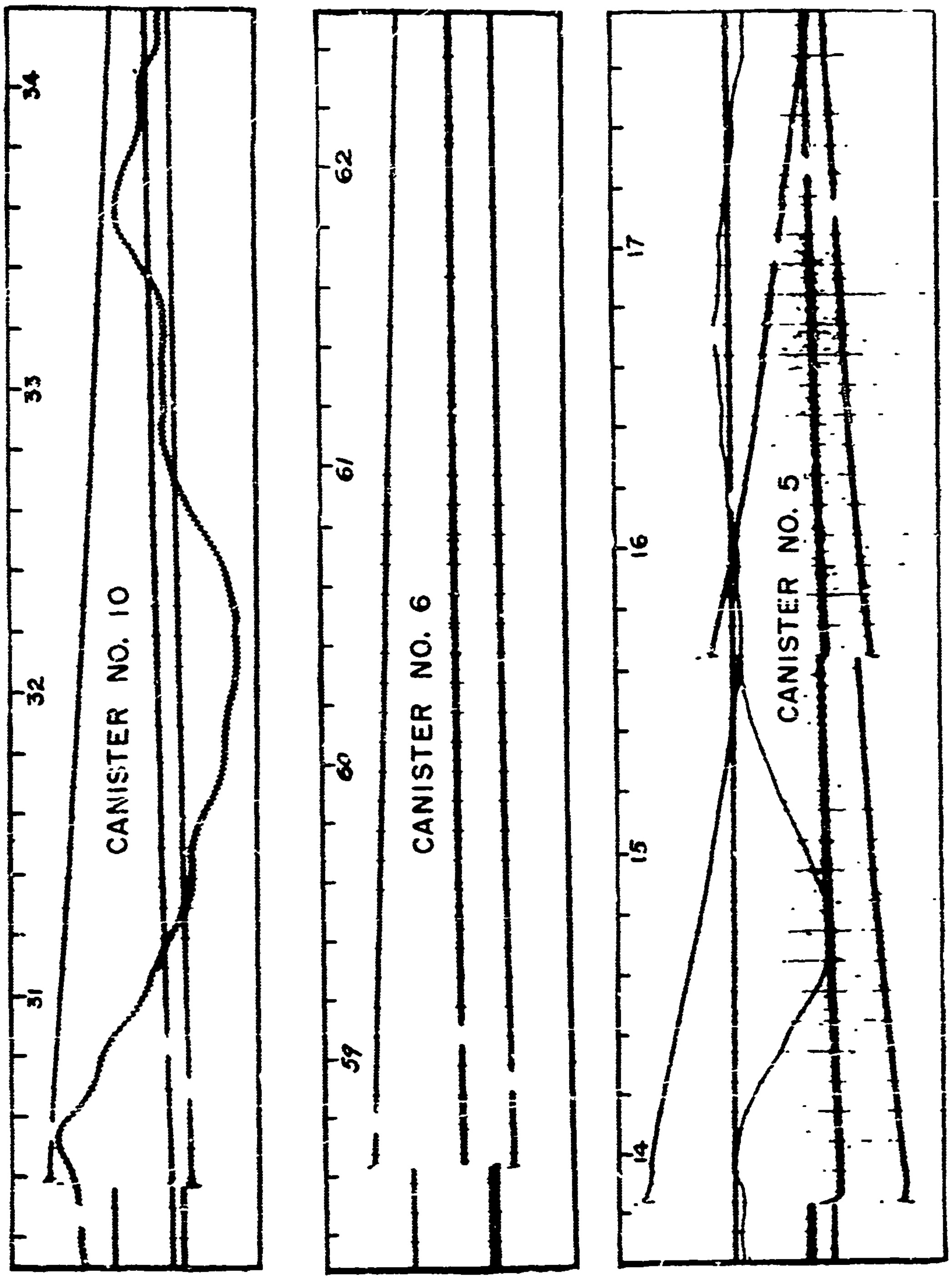


Fig. 3.4—Sample telemetered pressure records, King shot.

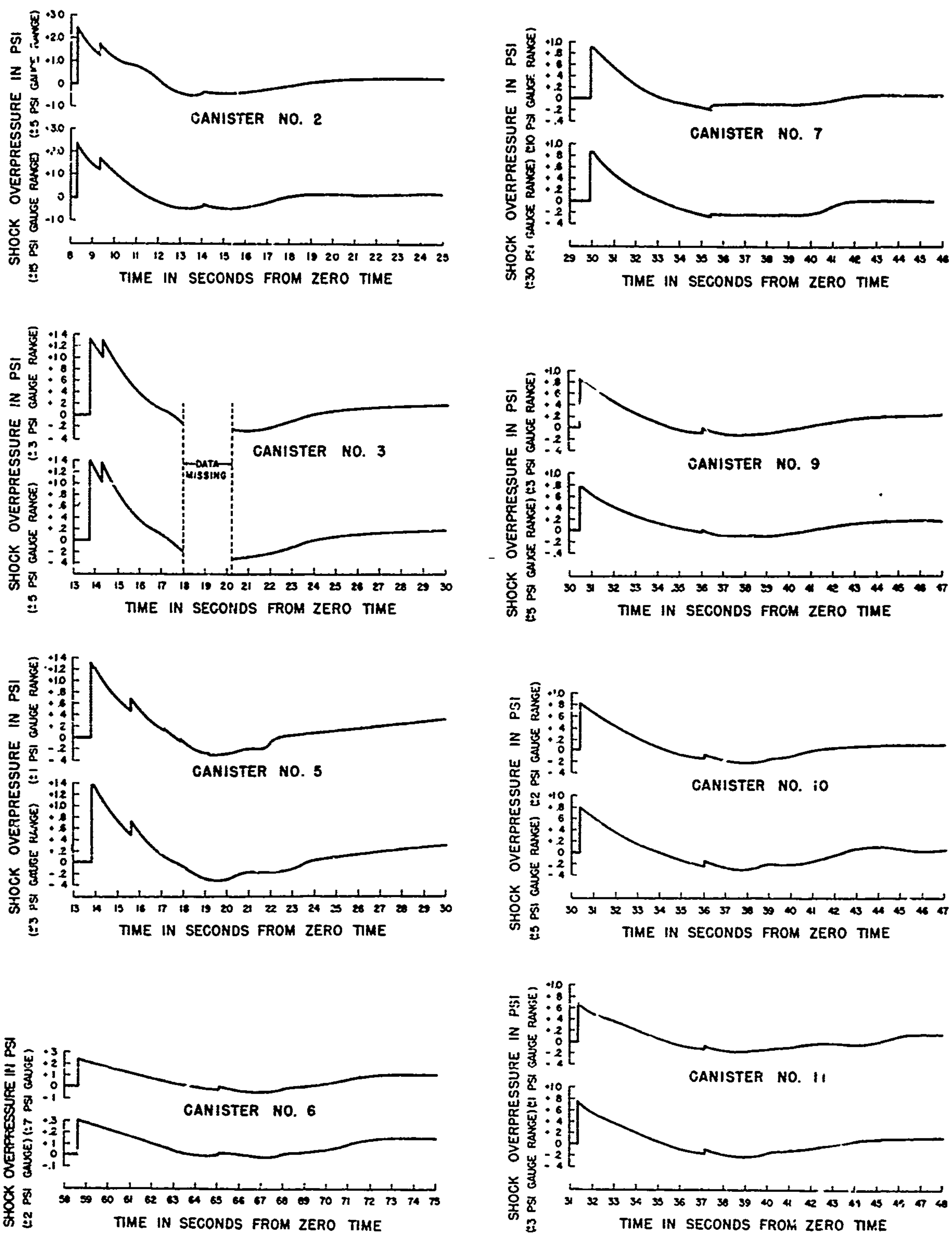


Fig. 3.5—Shock overpressure vs time, King shot.

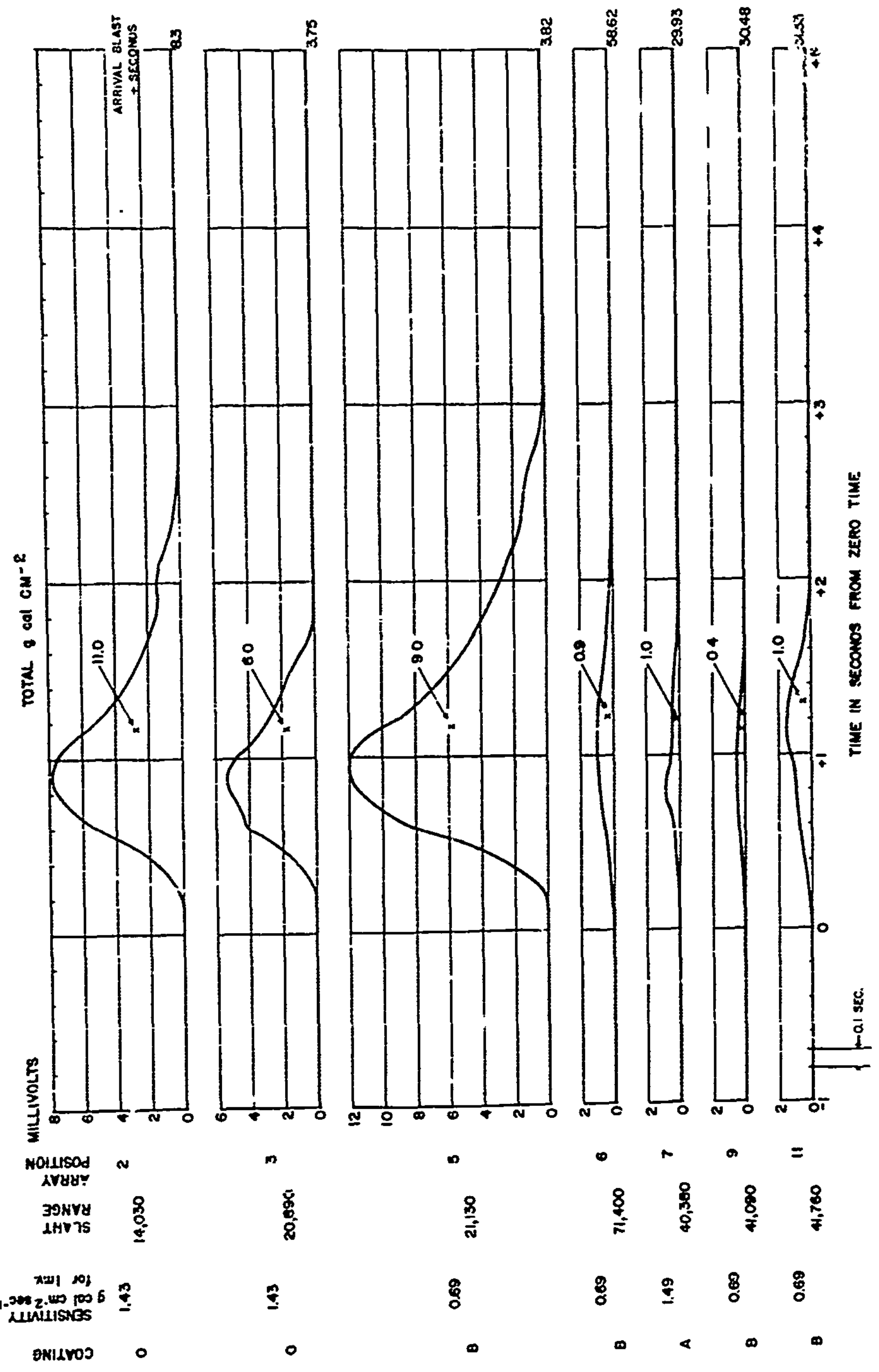


Fig. 3.6—Thermal intensity vs time, King shot.

3.3 DISCUSSION

3.3.1 Blast Overpressure

The measured peak overpressures and slant ranges have been reduced to equivalent values in a uniform atmosphere at sea-level pressure and temperature by applying the Fuchs[2] scale factors defined by

$$\lambda(z) = \exp \int_c^z \left\{ \left[\frac{T(0)}{T(z)}\right]^{3/4} \left[\frac{P_0(0)}{P_0(z)}\right]^{1/2} - 1 \right\} \frac{dz}{z} \tag{3.1}$$

$$\mu(z) = \lambda(z) \left[\frac{T(0)}{T(z)}\right]^{1/4} \left[\frac{P_0(z)}{P_0(0)}\right]^{1/2} \tag{3.2}$$

where $T(z)$ and $P_0(z)$ are the ambient absolute temperature and pressure, respectively. These factors have been computed as functions of altitude by numerical integration of the Bikini meteorological data for the time of Mike shot. Since the meteorological data for King shot differed only slightly from that for Mike shot, the same values of λ and μ have been used in both cases. The fact that King shot was fired at an altitude of 1500 ft instead of actually at sea level has been ignored since correction for this factor would be entirely negligible. The computed values of λ and μ used are given in Appendix C.

According to the Fuchs scaling law the peak overpressure at altitude z and slant range R due to a bomb burst at sea level is given by

$$\Delta P = \mu\, f(\lambda R) \tag{3.3}$$

If the reduced overpressure is defined as $\Delta P/\mu$ and the reduced range as λR, Eq. 3.3 states that the reduced overpressure is a function only of the reduced range. The values of $\Delta P/\mu$ and λR for Mike shot are listed in Table 3.6 and are plotted (circled points) in Fig. 3.7. The points indicated by triangles in Fig. 3.7 are preliminary readings of ground-pressure gauge measurements obtained by the Sandia Corporation and transmitted to the Air Force Cambridge Research Center (AFCRC) through the courtesy of E. F. Cox. The final results from Sandia Corporation on Project 6.1 are presented in WT-602.[3]

For comparison with previous results, the following analytic expressions have been derived to represent the free-air peak overpressure in a homogeneous atmosphere at sea-level ambient pressure:

$$f(r) = \frac{1.564}{r^3} + \frac{1.964}{r^2} + \frac{3.071}{r} \qquad r < 1.5 \tag{3.4}$$

$$f(r) = \frac{3.243}{r\sqrt{\log (r/0.5858)}} \qquad r > 1.5 \tag{3.5}$$

where $r = \lambda R/W^{1/3}$, R being the slant range in kilofeet and W the yield in kilotons. It will be noted that these expressions differ somewhat from similar analytic formulas that have been used in previous reports on air-borne pressure measurements during Operations Jangle[4] and Snapper.[5] The present forms give an improved fit to the Tumbler-Snapper results both in the region of high overpressures (Naval Ordnance Laboratory smoke-rocket photography) and at low overpressures (AFCRC parachute gauges). The curve plotted in Fig. 3.7 is computed from Eqs. 3.4 and 3.5 for an effective yield of 24 Mt. This figure for the effective yield is the cube of the arithmetic mean of $W^{1/3}$ computed separately for each parachute-gauge data point. The ground-pressure gauge data were not used in this determination. Since, for a ground burst,

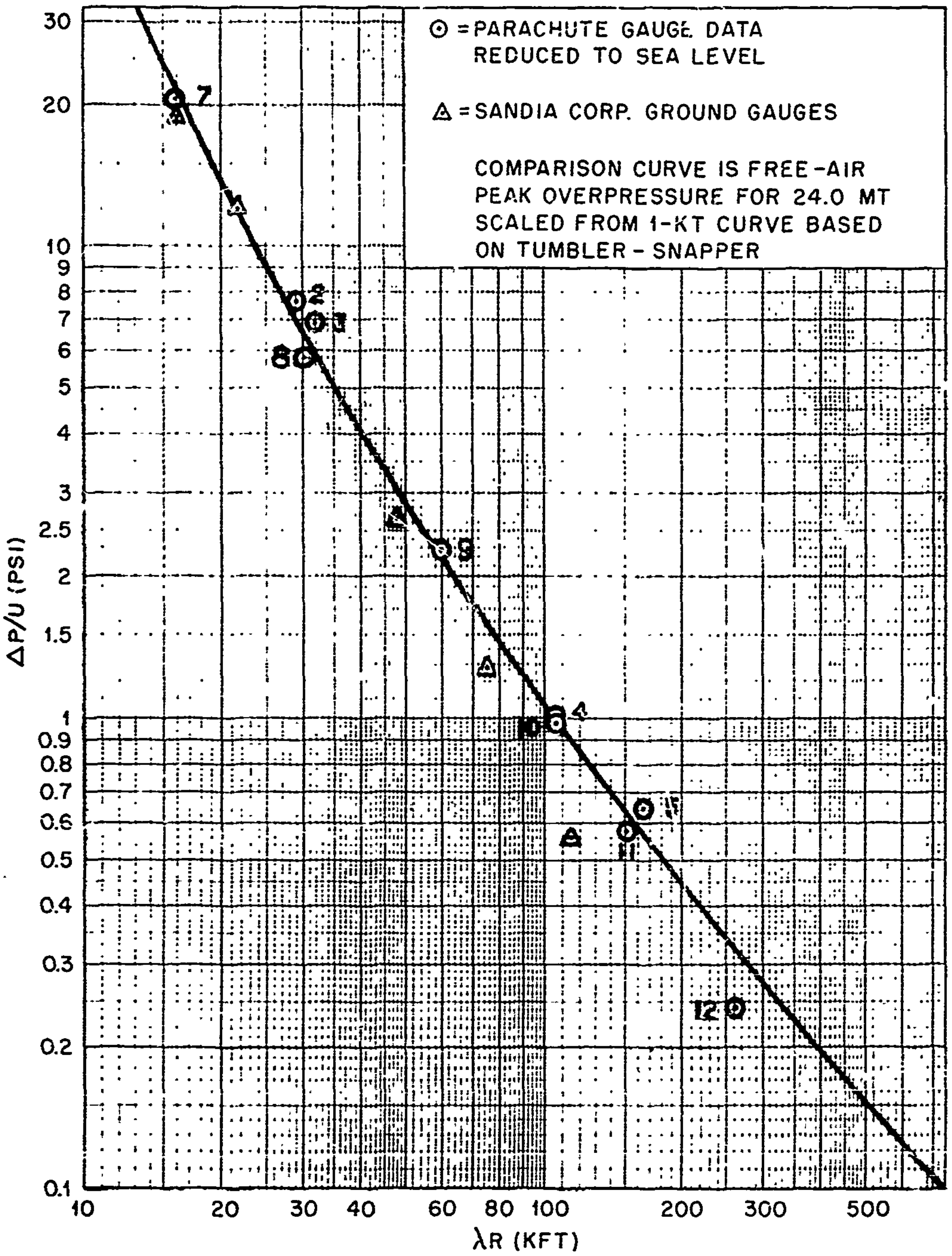


Fig. 3.7—Peak overpressure vs slant range reduced to homogeneous atmosphere at sea-level ambient pressure (Fuchs scaling), Mike shot.

the effective blast yield is the product of the actual yield and the ground reflection factor, the effective yield of 24 Mt corresponds to an actual yield of 12 Mt if the ideal ground-reflection factor of 2 is assumed. The best current estimate of the actual yield is 11.0 ± 0.2 Mt;* therefore it appears that Mike shot had a slightly greater blast efficiency than the Tumbler-Snapper average.

Table 3.6—REDUCED OVERPRESSURES AND SLANT RANGES, MIKE SHOT

Canister No.	$\Delta P/\mu$, psi	λR, ft
2	7.65	29,240
3	6.92	31,970
4	1.00	107,010
5	0.65	162,510
7	20.63	15,670
8	5.74	30,080
9	2.25	58,870
10	0.96	108,730
11	0.57	151,250
12	0.24	262,040

The root-mean-square percentage deviation of the observed peak overpressures from the computed curves is 20 per cent if the large deviation at canister No. 12 is included and 12.2 per cent if this point is omitted.

It will be observed in Fig. 3.7 that there is quite satisfactory consistency between the reduced data obtained from the parachute-gauge measurements and the overpressures measured on the ground for overpressures greater than about 1 psi. However, at the most distant ground point (114,240 ft), the ground-gauge value is decidedly low as compared to the airborne-gauge value at an equivalent reduced range. It is very probable that this discrepancy at long ranges and low overpressures is due to upward refraction of the blast wave by the decrease of sound velocity with altitude.

The reduced peak overpressures and slant ranges for King shot are given in Table 3.7 and are plotted (circled points) in Fig. 3.8. Since the peak overpressures obtained at canisters Nos. 2, 3, and 5 are considered to represent the free-air peak overpressure in the direct wave

Table 3.7—REDUCED OVERPRESSURES AND SLANT RANGES, KING SHOT

Canister No.	$\Delta P/\mu$, psi	λR, ft
2	2.24	17,680
3	1.19	29,790
5	1.10	32,050
6	0.224	119,020
7	0.822	48,010
9	0.738	52,640
10	0.740	51,970
11	0.651	55,460

*Information from E. F. Cox as of 26 May 1953.

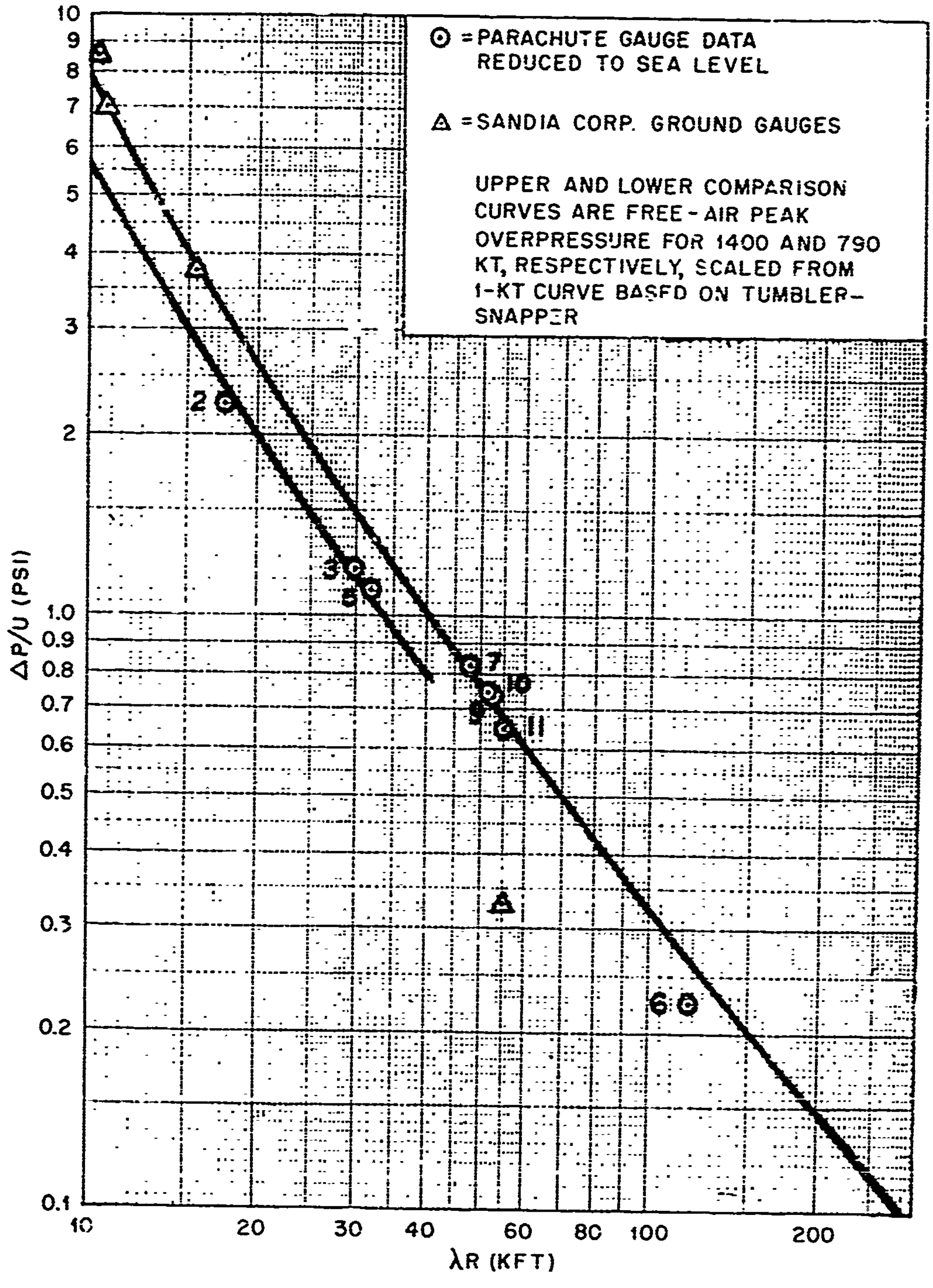


Fig. 3.8—Peak overpressure vs slant range reduced to homogeneous atmosphere at sea-level ambient pressure (Fuchs scaling), King shot.

before the arrival of the reflected wave and those measured at the other canisters represent the superposition of direct and reflected waves in the Mach stem, the two groups are considered separately. For canisters Nos. 2, 3, and 5, the mean effective yield, determined by using Eqs. 3.4 and 3.5 for 1 Kt as described previously, is found to be 790 Kt. This is considerably greater than the currently reported radiochemical yield of 550 ± 15 Kt. For the canisters in the Mach region, the mean effective yield is found to be 1400 Kt, and it will be noted that the overpressure vs distance curve computed on this basis gives very satisfactory agreement with the Sandia ground-pressure measurements plotted in Fig. 3.8, except that, as in the case of Mike shot and presumably for the same reason, the overpressure measured on the ground at very long range is quite low compared to the equivalent reduced values from the high-altitude gauges.

The data from the canisters in the Mach region are consistent with the free-air values measured at canisters Nos. 2, 3, and 5 if it is assumed that the overpressure in the Mach stem at points far below the triple point is equal to that which would result from a surface burst with a reflection factor of 1400/790 = 1.77. Whether this value of the energy-reflection factor is consistent with the observed reflected-shock-pressure increments at canisters Nos. 2, 3, and 5 cannot be determined since there is not available a theoretical treatment of the pressure distribution in the neighborhood of the triple point that would permit a comparison between the two.

The root-mean-square percentage deviation of the observed values from the computed curves is 6.8 per cent including the data from canister No. 6 and 3.1 per cent omitting this point.

3.3.2 Thermal Radiation

The information on thermal radiation may be most conveniently examined by comparing it with the best data now available from Tumbler shots Nos. 1 to 4 and the preliminary information from Mike shot as given in the report from the University of California.[5] Thermal-radiation Measurements at Operation Ivy. The points and referenced data are given in Fig. 3.9. For the UCLA data the mean of the two values from the B-36 was used. From this single point an "attenuated" curve and a "vacuum" plot of intensity vs distance are estimated. Since only preliminary data are involved, crude assumptions were used for the effective attenuation without attempts at refinement.

Both these comparisons and the bomb-radiation yields would lead to estimates of higher thermal-radiation intensities than recorded by the canister thermocouple. It is therefore necessary to review possible sources of error. Among these possibilities are the following:

It was known that a bare thermocouple, i.e., unenclosed by a translucent envelope, is subjected to wind effects. Wind blowing across a hot junction causes it to give low readings because the junction is cooled. (A possible type, as yet not thoroughly tested and which could not be procured in time to use on this operation, is described in Sec. 4.2.) As controlled by the parachutes, the descent rate is approximately 30 ft/sec. Horizontal wind and blast winds add to the uncertainties of the data.

The hot, radiation-sensing junction is a minute bead. The directional sensitivity of a spherical receiver differs from that of a plane receiver. The radiometers nearest the burst cannot be assumed to be "looking" at the point source; hence the dependence on the inverse square of the distance may deviate somewhat.

Changes in the spectral character of the burst resulting from absorption by the products of photochemical reactions and by radiation degeneration to the infrared would tend to result in lower thermal yields.

Reflection of radiation from ground (earth and water) and from clouds would increase the intensities; a cloud between the burst and a radiometer would decrease the intensity.

In comparison with an air burst, for a surface burst the effects of reflection from the ground are even more difficult to assess.

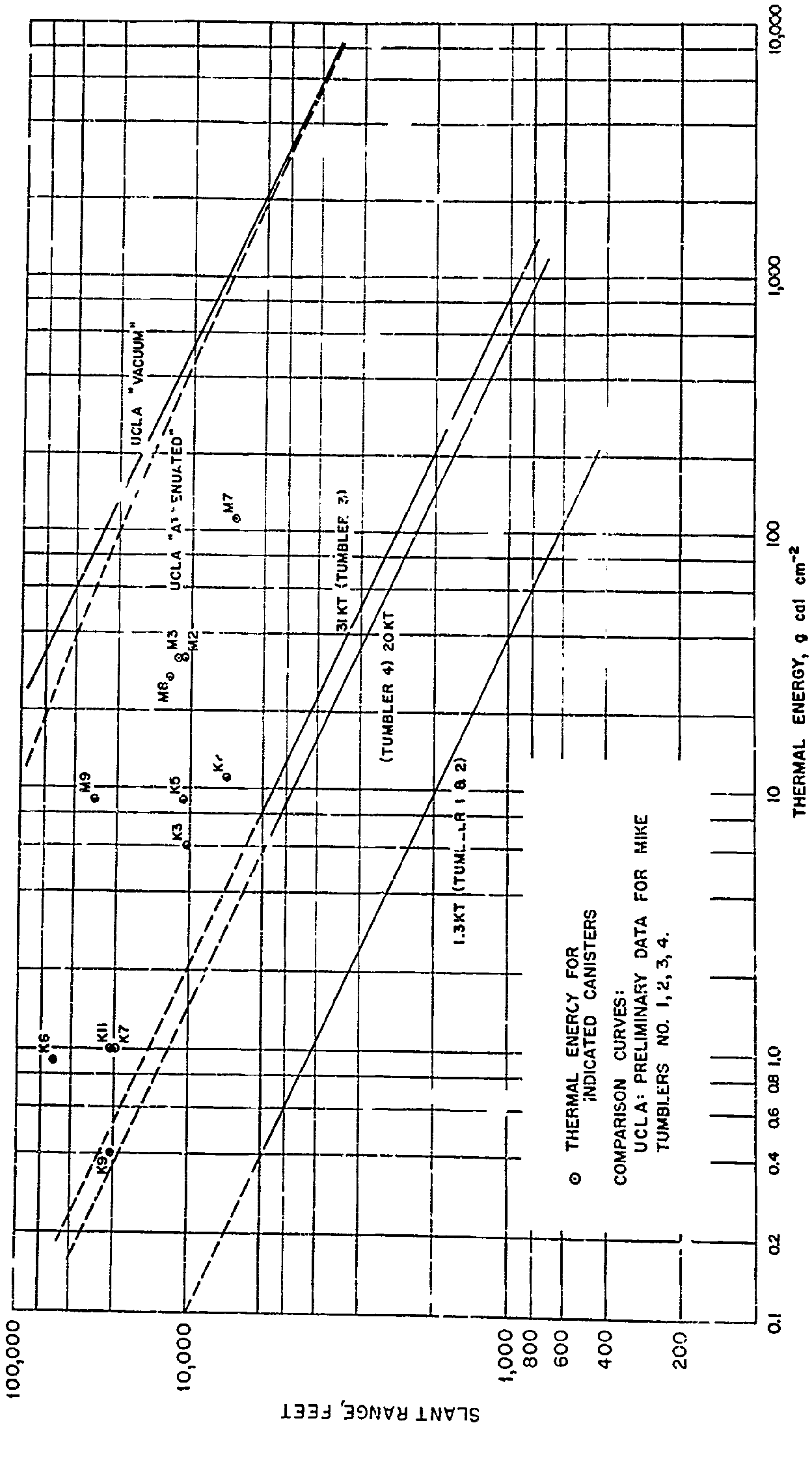


Fig. 3.9—Thermal-radiation energy vs slant range for Mike and King shots.

Temperature of Blast. During the passage of the blast a rise in temperature was shown by the thermocouples in two of the Mike canisters (Fig. 3.3). The values are as follows:

Array position	Slant distance, ft	Blast overpressure, psi	Blast temperature	
			mv	°C
2	21,130	8.6	6	180
8	24,740	6.2	12	360

REFERENCES

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2. K. Fuchs, "The Effect of Altitude," Los Alamos Technical Series, Report LA-1021, Vol. VII, Blast Wave, Part II, Chap. 9, August 1947.
3. G. W. Rollosson, Air Shock Pressure-Time vs Distance, Ivy Project 6.1 Report, WT-602, November 1952.
4. N. A. Haskell and J. O. Vann, The Measurement of Free-air Atomic Blast Pressures, Operation Jangle, Project 1.3c, Air Force Cambridge Research Center, April 1952 (reprinted in Blast and Shock Measurements II, Operation Jangle Report, WT-367).
5. N. A. Haskell and J. O. Vann, The Measurement of Free-air Atomic Blast Pressures, Operation Snapper, Project 1.1, Air Force Cambridge Research Center, February 1953 (reprinted as Operation Snapper Report, WT-511).
6. University of California at Los Angeles, Thermal Radiation Measurements at Operation Ivy, Report 53-P3, February 1953.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

For peak overpressures greater than about 1 psi, there is a highly satisfactory degree of consistency between the overpressures measured at sea level and the parachute-gauge measurements when the latter are corrected for varying ambient atmospheric conditions according to the Fuchs scaling law. Peak overpressures of less than 1 psi were reached at such great distances (>40,000 ft for King and >100,000 ft for Mike) that it was to be expected that refraction effects would reduce the overpressures at sea level relative to those at high altitudes, and this is in accordance with the observations.

If it is assumed that the ground-reflection factor of 1.77 found by comparing the Mach and free-air peak overpressures in King shot is also applicable to Mike shot, the peak overpressures of Mike shot should be equal to those of a bomb of yield 11 × 1.77 = 19.5 Mt in free air. Actually, as noted in Fig. 3.7, the Tumbler-Snapper free-air curve scaled up to an effective yield of 24 Mt more nearly represents the observed data. On this basis Mike shot appears to have had a blast efficiency of 24/19.5 = 1.23 relative to the average of the Tumbler-Snapper shots. Similarly, the present data indicate for King shot a blast efficiency relative to Tumbler-Snapper of 790/550 = 1.44. These figures are regarded as tentative and should not be accepted as indicative of a systematic departure from $W^{1/3}$ scaling in the direction of increased effective blast yield at very large energies until further comparison with data from other nuclear explosions has been made.

4.2 RECOMMENDATIONS

Thermal Detectors. Should attempts again be made to measure the thermal energy by devices on parachuted canisters, consideration should be given to a modification which would provide a transparent envelope for the hot junction. Such a device, which could not be obtained in time for Ivy, is shown in Fig. 4.1 in both assembled and exploded views. Thermocouples of this type are under construction and will be tested for response under both quiet and windy conditions, for optical efficiency as omnidirectional detectors, for freedom from susceptibility to shock, etc.; that is, for all such requirements as may suggest themselves.

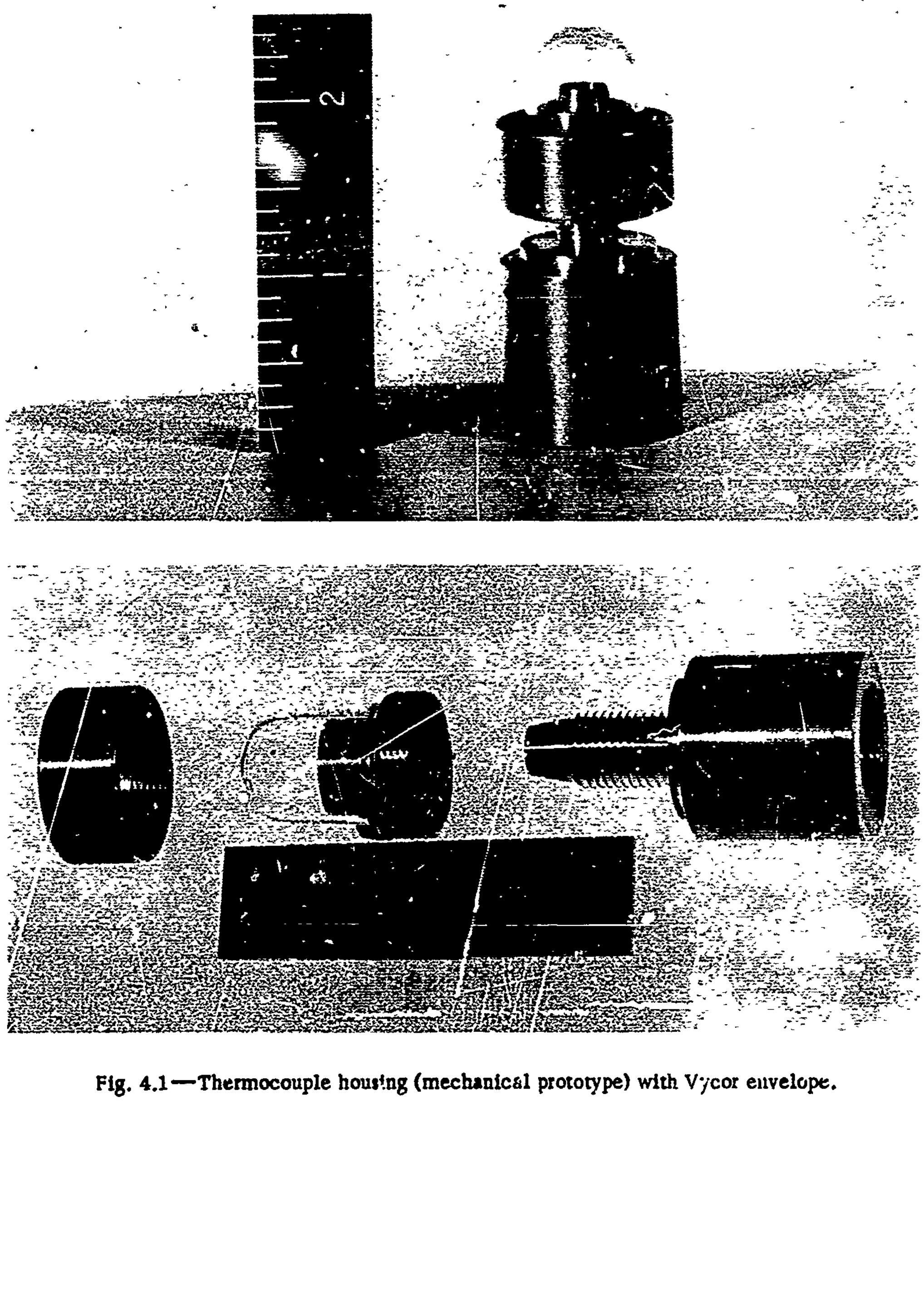

Fig. 4.1—Thermocouple housing (mechanical prototype) with Vycor envelope.

APPENDIX A

COMPUTATION OF RANGE FROM SHOCK TRAVEL TIME

For the purpose of computing slant ranges from the observed travel times, the following procedure has been adopted. First consider an isothermal atmosphere at constant pressure P_0 and sound velocity c_0 with no wind. The travel time of a spherical shock wave to a radial distance R from the source is then

$$t = \int_{3}^{R} U^{-1}\, dR \tag{A.1}$$

where U is the shock-wave velocity given by the Rankine-Hugoniot equation

$$U = c_0\left(1 + \frac{\gamma + 1}{2\gamma}\,\frac{\Delta P}{P_0}\right)^{1/2} \tag{A.2}$$

where γ is 1.4 for air and ΔP is the peak overpressure.

The integral A.1 has been evaluated numerically using the dependence of peak overpressure on distance given by Eqs. 3.4 and 3.5. This integration gives travel time as a function of range for a 1-Kt source in a hypothetical constant-pressure isothermal atmosphere. From this time vs distance function the average velocity, $V = R/t$, to a given distance may be computed. Then, using the assumed overpressure vs distance function, V may be tabulated and plotted as a function of peak overpressure. Since the yield scaling law transforms distances and times in the same ratio and leaves velocities and pressures unchanged, the relation between V and ΔP is independent of the yield of the source. It is, moreover, rather insensitive to the precise form of the assumed peak overpressure vs distance function. Values of V for a given ΔP computed from Eqs. 3.4 and 3.5 in the present report differ by a few tenths of 1 per cent at most from the values computed from the slightly different overpressure function used in the report on Operation Snapper, Project 1.1, over the range of overpressures covered by the present measurements.

To go from the hypothetical homogeneous isothermal atmosphere to the conditions of the actual atmosphere, use is made of a simplified scaling law for the effect on peak overpressure of variations in ambient atmospheric pressure and temperature, which Bond[1] has shown to be approximately equivalent to the more complex Fuchs scaling law. In this approximation overpressure is changed everywhere in the same ratio as ambient pressure; so $\Delta P/P_0$ is unchanged, and the shock velocity is changed in the same ratio as the velocity of sound. Thus, if $\bar{c}$ is an average value of the sound velocity over the path from source to gauge, the ratio $V/\bar{c}$, when expressed as a function of $\Delta P/P_0$, is approximately independent of the ambient pressure and temperature at either source or gauge as well as of the yield of the source. This function, when computed for 1 Kt in a homogeneous atmosphere, is then directly applicable to any yield in any atmosphere. With the use of this relation in determining the average shock velocity for a given measured value of $\Delta P/P_0$, the way in which the average sound velocity is defined is not particularly critical when only moderate accuracy is required since c varies by only 14 to 15 per cent between sea level and the tropopause. For the present purpose $\bar{c}$ is taken to be

$$\bar{c}(z) = \frac{z - h}{\int_h^z c^{-1}(z)\, dz} \qquad (A.3)$$

where z is the altitude of the gauge and h is that of the bomb. This function has been computed from the meteorological data for each shot by numerical integration.

The effect of wind has been taken into consideration by adding to the average shock velocity the average component of wind velocity, W_R, projected onto the line from shot to gauge (assumed to be along the flight path of the dropping aircraft). Since the wind component represents only a relatively small correction to the average shock velocity, the way in which the average is defined is not critical. In the present case the average has been computed by weighting the wind velocity in each small increment in altitude in proportion to the time that would be taken by a sound wave in passing through the given increment of altitude.

The numerical values used in the computation of slant ranges are tabulated in Tables A.1 and A.2.

Since this procedure for computing the slant range assumes rectilinear propagation from source to gauge, with the normal free-air decay of peak overpressure with distance, it is strictly applicable only to the direct shock in the region of regular reflection or to the case of a surface burst, where the direct and reflected shocks coincide from the start. However, at points that are not too close to the triple point and at distances large compared to the height of burst, the peak overpressure in the Mach stem does not appear to differ greatly from that which would result from a surface burst; therefore the present method should give a reasonably good approximation for the slant range in such cases also. Since the canisters that fell in the Mach region on King shot were all far from the path of the triple point, the slant ranges computed

Table A.1—AVERAGE SHOCK VELOCITY, MIKE SHOT

Canister No.	$\Delta P/P_0$	$V/\bar{c}$	$\bar{c}$, ft/sec	V, ft/sec	W_R, ft/sec	$V + W_R$
2	0.929	2.398	1118	2681	−17	2664
3	0.861	2.324	1117	2596	−18	2578
4	0.138	1.356	1114	1511	−22	1489
5	0.098	1.273	1110	1413	−22	1391
7	1.919	3.235	1128	3649	−17	3632
8	0.515	1.988	1126	2238	−19	2219
9	0.212	1.492	1127	1681	−20	1661
10	0.111	1.300	1120	1456	−21	1435
11	0.0656	1.199	1120	1343	−21	1322
12	0.0341	1.119	1113	1245	−22	1223

from the travel times to these canisters are considered to be sufficiently accurate for the purpose of this report.

In Project 1.1 of Operation Snapper, Shot No. 8, the slant ranges were determined both from travel times and by an electronic multiple-object tracking system (MOTS). The percentage difference between the MOTS and travel-time ranges had a root-mean-square value of 3.6 per cent and an algebraic mean difference of 2.2 per cent, the travel-time ranges being the larger on the average.

No convincing explanation has yet been found for either the systematic or the random component of this deviation since both appear too large to be accounted for by expectable error in either the meteorological data or the overpressure vs distance function used. It is perhaps as reasonable to attribute the differences as much to error in the MOTS range as to error in the travel-time ranges, but, since this cannot be proved, the given root-mean-square difference of 3.6 per cent is taken as the best empirical estimate of the standard deviation of the

Table A.2—AVERAGE SHOCK VELOCITY, KING SHOT

Canister No.	$\Delta P/P_0$	$V/\bar{c}$	$\bar{c}$, ft/sec	V, ft/sec	W_R, ft/sec	$V + W_R$
2	0.230	1.524	1126	1716	−28	1688
3	0.152	1.383	1119	1548	−29	1519
5	0.157	1.395	1115	1555	−26	1529
6	0.0374	1.128	1110	1252	−34	1218
7	0.0764	1.224	1130	1383	−34	1349
9	0.0781	1.228	1125	1382	−34	1348
10	0.0773	1.226	1126	1380	−34	1346
11	0.0735	1.217	1123	1367	−34	1333

travel-time ranges. In any case the percentage error in range is probably smaller than the percentage error in the measurement of peak overpressure.

REFERENCE

1. J. V Bond, Jr., Scaling of Peak Overpressure in a Nonuniform Atmosphere, Sandia Corporation, Report SC-1939(Tr), July 1951.

APPENDIX B

METEOROLOGICAL DATA

Table B.1 — MIKE SHOT, RADIOSONDE DATA FOR BIKINI, 1 NOVEMBER 1952, 0900 M*

True altitude above MSL kft	Pressure, psi	Temperature, °C	Sound velocity, ft/sec	Wind velocity, ft/sec	Wind direction, deg
0	14.66	29.4	1144	7	090
1	14.16	26.8	1139	24	090
2	13.70	24.5	1135	29	100
3	13.22	21.9	1130	29	110
4	12.75	19.4	1125	27	120
5	12.32	17.2	1121	27	120
6	11.90	15.9	1118	27	120
7	11.48	14.4	1115	29	110
8	11.06	13.0	1113	25	110
9	10.66	11.2	1109	42	110
10	10.27	9.4	1106	25	120
11	9.91	8.0	1103		
12	9.55	6.1	1099	30	110
13	9.20	4.4	1096		
14	8.85	2.5	1092	32	120
15	8.53	0.6	1089		
16	8.21	−1.1	1085	27	120
17	7.91	−3.2	1081		
18	7.62	−5.5	1076	20	130

*M, Marshall Islands Time.

Table B.2 —KING SHOT, RADIOSONDE DATA FOR ENIWETOK, 16 NOVEMBER 1952, 1200 M*

True altitude above MSL, kft	Pressure, psi	Temperature, °C	Sound velocity, ft/sec	Wind velocity, ft/sec	Wind direction, deg
0	14.66	28.0	1142	30	070
1	14.19	26.4	1138	39	080
2	13.71	24.3	1135	39	090
3	13.22	22.1	1130	41	090
4	12.75	20.5	1127	41	090
5	12.30	19.3	1125	39	090
6	11.88	17.8	1122	41	090
7	11.48	16.2	1119	42	100
8	11.07	14.7	1116	44	100
9	10.69	13.1	1113	46	090
10	10.30	11.8	1111	44	100
11	9.94	9.2	1106		
12	9.58	8.3	1104	41	080
13	9.23	7.5	1102		
14	8.89	4.5	1096	37	080
15	8.58	2.1	1092		
16	8.26	1.0	1090	34	060
17	7.95	−1.0	1086		
18	7.65	−2.7	1082	32	050
19	7.36	−3.8	1080		
20	7.08	−5.8	1076	30	050

*M, Marshall Islands Time.

APPENDIX C

ALTITUDE SCALE FACTORS FOR BOTH SHOTS

Altitude above MSL, kft	λ	μ	Altitude above MSL, kft	λ	μ
0	1.000	1.0000	11	1.315	1.101
1	1.025	1.010	12	1.350	1.111
2	1.050	1.019	13	1.386	1.122
3	1.076	1.028	14	1.424	1.132
4	1.103	1.037	15	1.463	1.144
5	1.130	1.047	16	1.504	1.156
6	1.159	1.056	17	1.547	1.169
7	1.188	1.065	18	1.592	1.184
8	1.218	1.073	19	1.640	1.195
9	1.249	1.082	20	1.639	1.208
10	1.281	1.091			

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