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Operation WIGWAM

May 1955

Scale 16

Project 1.2.1

FREE-FIELD PRESSURES, STATION ZERO

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Report to the Scientific Director

FREE-FIELD PRESSURES, STATION ZERO (U)

By

C. B. Cunningham

[redacted]

Approved by: A. B. FOCKE
Scientific Director

Approved by: J. P. WALSH
Project Officer
Project 1.2.1

Approved by: Lt Col G. F. WATKINS, USAF
Director, Program I

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U. S. Naval Research Laboratory
Washington 25, D. C.
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ABSTRACT

Free-field pressures as a function of time were measured at eight positions above the Wigwam weapon at distances from the charge varying from 800 to 1975 ft. Tourmaline PE gauges were used. Signals were either telemetered to a remote receiving location or were recorded in place on a magnetic-tape recorder that was recovered after the shot.

The variation of maximum observed pressure in pounds per square inch with distance in feet from the weapon in this range is given by the expression

$$P_{max} \quad \frac{2.03 \times 10^{7}}{R^{1.16}}$$

Impulse, at locations not affected by surface cutoff, is given by the expression

$$I \quad \frac{3.36 \times 10^{4}}{R^{0.77}}$$

where I is in pound seconds per square inch.

Energy flux density, at locations not affected by surface cutoff, is given by the expression

$$E \quad \frac{3.81 \times 10^{10}}{R^{1.87}}$$

where E is in inch pounds per square inch.

The fiducial pulse was recorded at 12.5 ± 1 msec before weapon detonation. The shock wave arrived at the water surface 385.5 msec after the fiducial pulse.

The equivalent weight of TNT required to produce the same peak pressures as the Wigwam weapon at 2000 ft was 4.05×10^{7} lb.

ACKNOWLEDGMENTS

The experiment described in this report was conducted by members of the Structures Branch of the Mechanics Division of the Naval Research Laboratory (NRL). J. P. Walsh, Branch Head, was the Project Officer for the experiment. C. B. Cunningham, Head of the Field Engineering Section of the Branch, was responsible for coordinating all electronic and electrical work on the project. E. E. Bissell was responsible for the telemetering systems. M. W. Oleson was responsible for the subcarrier generator and demodulator aspects of the telemetering system. A. L. Howard was responsible for the self-contained magnetic-tape recording system. R. W. Stroup was responsible for the recording trailer. J. L. Bachman and R. C. Cowan furnished excellent assistance on a large variety of jobs.

LCDR B. F. Seeger, USN, a member of the Director's Staff at NRL, kindly agreed to assist on this project. He was responsible for the design of the instrument can for the tape recording system and the gauge handling gear. His assistance in many other ways is gratefully acknowledged. E. L. Smith, experimental machinist, and J. C. Modlin, laboratory technician, of the Engineering Services Division of NRL, were of great assistance to the group.

The cooperation of the Naval Ordnance Laboratory group under C. J. Aronson was enjoyed, as it was on Operation Castle. It is a pleasure to work with them.

The assistance of Lt Col George Watkins, USAF, Director Program I, is gratefully acknowledged. He understood the problems of the experimenter.

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CHAPTER 1

INTRODUCTION

The first underwater nuclear explosion was fired in Bikini lagoon in 1946. The weapon, which was the second of a series, was at a comparatively shallow depth in water not more than 180 ft deep. A third explosion (Shot Charlie) was originally scheduled for deep water but was canceled. Operation Wigwam had as its purpose the determination of the effects of a nuclear explosion in deep water.

1.1 HISTORY

Program I of Operation Wigwam had the objective of measuring the free-field pressures resulting from the explosion. It was believed that the chances of survival of any pressure-time recording equipment near the weapon were extremely poor; thus the use of telemetering techniques to relay data from gauges near the weapon to a recorder a safe distance away was the logical solution. Since the Structures Branch of the Mechanics Division of the Naval Research Laboratory (NRL) had acquired experience in telemetering underwater pressure data during Operations Ivy and Castle, the group was requested[1] to telemeter the pressure-time data in Operation Wigwam as Project 1.2.1. The problem was accepted[2] and was assigned NRL Problem No. F03-89. The problem number was later changed to F02-07. Work commenced at NRL in June 1954. The NRL field group was transferred to San Diego in January 1955 and remained until June 1955. A maximum of 10 men was involved during the field phase of the operation. All experimental data are recorded in NRL Notebook 8348.

1.2 OBJECTIVE

The objective of Project 1.2.1 was to measure the characteristics of the shock wave in water from close-in to 2500 ft.[3] To accomplish this objective, it was planned to measure pressures along a vertical line directly over the weapon and along a vertical line 2500 ft away from the first line. This laboratory assumed primary responsibility for obtaining data from the station directly over the weapon. Measurements at the 2500-ft station were a cooperative effort of the Naval Ordnance Laboratory (NOL) as Project 1.2 and NRL. Project 1.2 had the primary responsibility at the 2500-ft station, with Project 1.2.1 providing telemetering as a "backup."

1.3 THEORETICAL PREDICTIONS

Figure 1.1 is a graph of predicted peak pressure vs distance which was used in predicting the signal levels from the various gauges for Project 1.2.1. Also included are two extrapolated

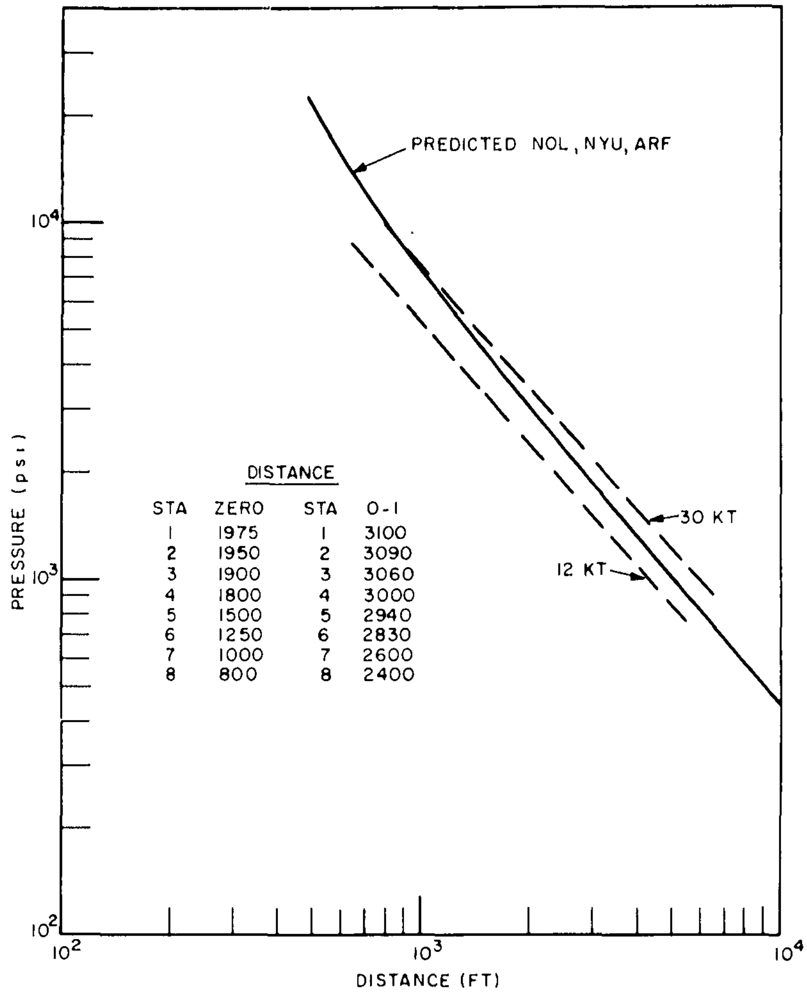

Fig. 1.1 – Predicted maximum pressures.

curves for equivalent weapon yields of 12 and 30 kt of TNT. The data for the graph were obtained from NOL and the Armour Research Foundation as Project 4.4. Since the peak pressure is approximately proportional to the cube root of the charge weight, variations in weapon yield produce much smaller variations in peak pressure.

REFERENCES

1. Confidential Letter from the Chief, AFSWP, SWPFP, Serial No. 0111, to the Director, NRL, 8 March 1954.
2. Confidential Letter from the Director, NRL, C4010-86/54 (03131), to the Chief, AFSWP, 6 May 1954.
3. J. M. Coogan, Experimental Plan for Operation Wigwam, May 1955.

CHAPTER 2

INSTRUMENTATION

The instrumentation used to measure pressures in Operation Wigwam was the culmination of at least four years of development and field testing pressure-time recording equipment. In both Operations Ivy and Castle, one of the objectives was to gain field experience with prototypes of equipment to be used in Wigwam. In retrospect, the firing delays and operational difficulties encountered in Castle greatly influenced the instrumentation philosophy for Wigwam, because in Castle it was learned just how difficult field operating conditions could get.

2.1 INSTRUMENTATION PHILOSOPHY

The two most important features of the experimental philosophy employed in Project 1.2.1 were, first, duplication of equipment and, second, rehearsal. It was decided early in the planning of the experiment to set up enough completely independent recording systems so that the probability of failure of all systems was very small. Thus, if any one system operated satisfactorily, the data would be obtained. If more than one system operated, the data could be checked.

A multichannel telemetering system is an extremely complex electronic device which is subject to many kinds of unpredictable failures, any one of which will render the system useless. Its reliability is inversely proportional to the number of components, such as tubes, resistors, relays, condensers, and soldered joints. For this reason it was decided to install two completely independent telemetering transmitter equipments at each station, each with its own power supplies, controls, and its own set of pressure pickups. On Station Zero the two systems were designated System A and System B. The only items to be common to both telemetering transmitters would be the primary power and transmitting antenna. Only one transmitting equipment was to be used at shot time, however.

In addition to the telemetering, a third recording system (System C) using a magnetic-tape recorder was to be employed at Station Zero. The recorder was to be housed in a rugged container designed to survive the forces present after the shock wave arrived at the surface. After recovery, it was planned to play back the magnetic tape to get the pressure-time records. The two prime considerations in selecting auxiliary equipment such as gauge handling gear and power supplies were reliability and the ability to operate during adverse conditions.

An important factor in successfully conducting an experiment is familiarity of the personnel with equipment. It is important to know the operating limitations and the probable sources of trouble from various units. The best way to acquire this information is through continued operation of the gear. For this reason an entire telemetering system was set up to operate across Chesapeake Bay nine months before the experiment. This system was operated, and improved, until December 1954, when the equipment was moved to San Diego. There again the systems were set up and were continually checked. The group participated in the January and April 1955 handling trials to acquire more experience in operating the equipment. There were many full-scale rehearsals of the experimental procedure in the final two weeks before the shot.

2.2 PHYSICAL LAYOUT

Figure 2.1 shows the physical arrangement of the part of the weapon array which concerned Project 1.2.1. Station Zero was located on a converted 500-ton steel barge (YC-473) which housed and later supported the weapon. The barge served as a working platform for Project 1.2.1 as well as for numerous other experiments. The power room contained the diesel engine generators which furnished the prime power for the weapon firing control circuits, power for the telemetering equipment, and power for ship lighting. Between the power room and the helicopter landing platform or "heliport" was the weapon lowering gear including a large "A" frame. The telemetering transmitting antenna was mounted on a mast atop this frame. Directly under the landing platform was a battery room which housed the storage batteries for the project. Aft of the heliport was an open deck area approximately 15 by 30 ft which was used for the Project 1.2.1 instrument house, pickup messenger cable winch, and the magnetic-tape recorder can. Directly under this open deck was a hold which was used for storing the gauge cable bundle before lowering.

The pressure pickup cable bundle was suspended from the after end of the barge and attached to the weighted steel messenger. The distance between the pickup cable bundle and the weapon support cable was approximately 70 ft.

Station 0-1 (also referred to as Site 1-B) was a converted LCM used as a floating platform. The engines, as well as the pilot house, were removed so that the deck was flush aft the cargo well. The Project 1.2.1 instrument house was secured at the forward end of the cargo well next to the landing ramp, which was welded shut. Aft of the instrument house was a gasoline-engine generator for equipment testing, and at the center line was a telescoping telemetering transmitter antenna mast which could be extended from 20 to 40 ft. The mast was hinged at the base so it could be lowered for storage. The after end of the LCM was used by NOL for Project 1.2. The storage batteries, which were the prime power on the LCM, were located in the engine room space next to the stern bulkhead.

Station 0-1 was secured to the main tow cable about 2500 ft forward of Station Zero. The pickup cable bundle was suspended from the after end of the LCM and secured to a weighted steel messenger similar to Station Zero. Project 1.2 was responsible for the gauge cable bundle, furnishing eight pickup leads to Project 1.2.1 for telemetering to the USS Curtiss.

The telemetering receiving station was located on the USS Curtiss (AV-4) which had a position during the shot as shown in Fig. 2.2. The receiving and recording equipment were housed in a 35-ft trailer which was secured on the starboard side of the boat deck. To make room for the trailer, two of the boats were off loaded from the ship at San Diego, which more than compensated for the trailer weight. The telemetering receiving antennas were mounted on a telescoping tower between the trailer and the starboard side of the vessel. Power for the trailer was obtained from one of the turbogenerators of the ship. A small instrument storage house was installed just aft the trailer for storage of spare parts, tools, and handling gear. All but one of the project personnel were quartered on the Curtiss. One man spent most of the time on the USS Comstock (LSD-19), where the LCM was kept prior to putting it in the tow.

2.3 GAUGES AND CALIBRATION

As a result of field experience in Operation Castle and upon the recommendation of NOL, it was decided to use tourmaline piezoelectric pressure pickups for Operation Wigwam. The predicted pressures were large enough to produce adequate signals, even with large cable lengths. The techniques for waterproofing the gauges were satisfactory, and the ease of calibrating the entire recording system was attractive.

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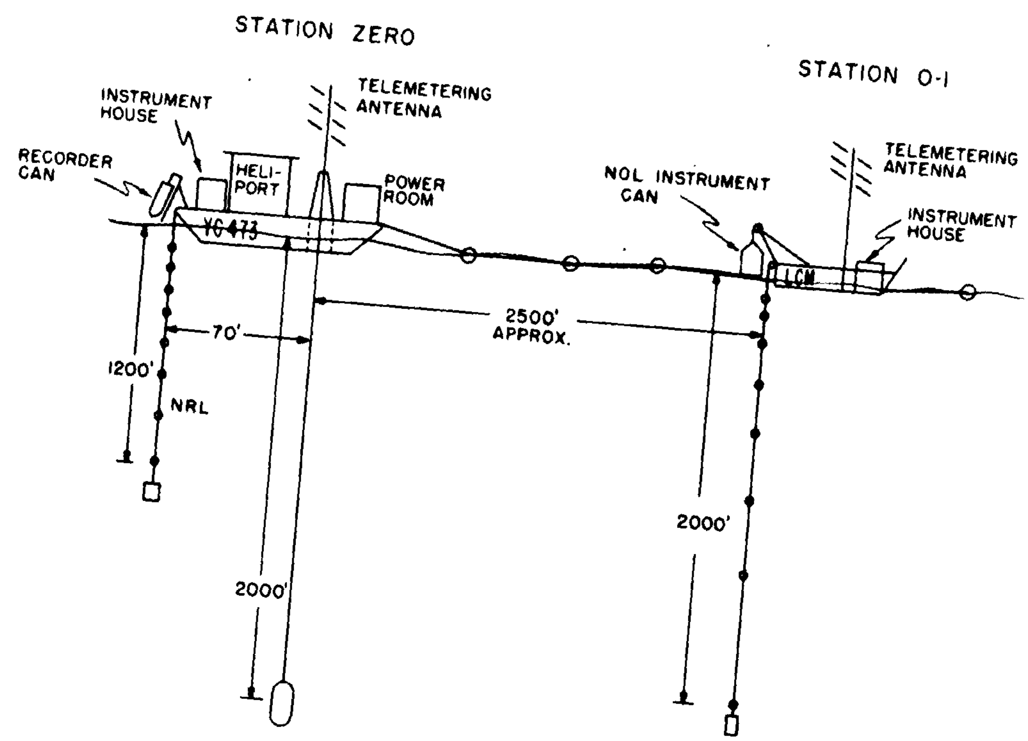

Fig. 2.1 — Arrangement of weapon array.

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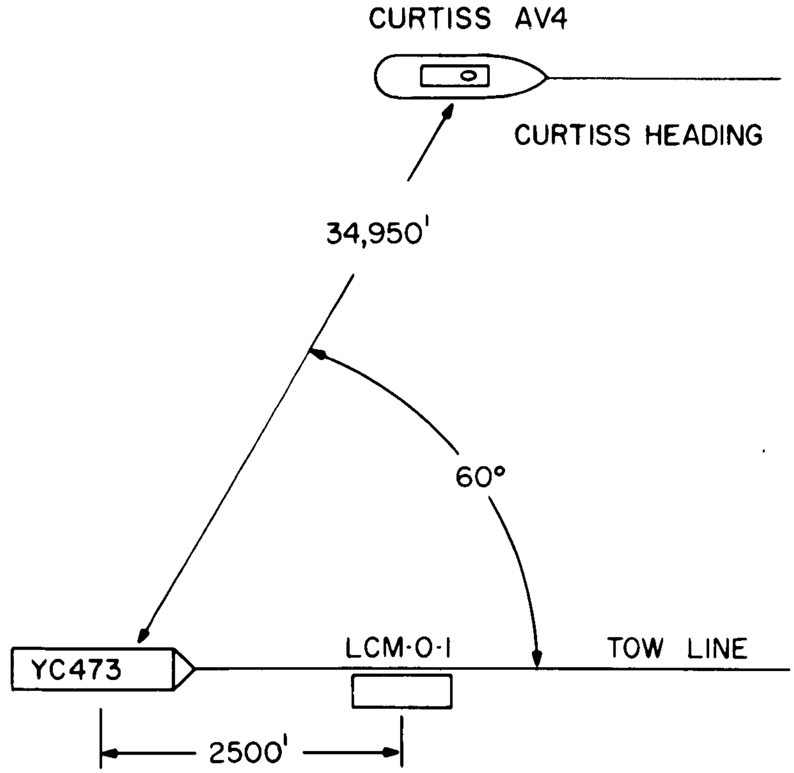

Fig. 2.2—Relative positions of telemetering transmitter and receiver stations, shot time.

The tourmaline gauges used in the Wigwam experiment were manufactured by Crystal Research, Inc., Cambridge, Mass. Each gauge cable was a single-conductor, shielded, low noise, neoprene-covered cable developed especially for PE gauges by Simplex Wire & Cable Co., Cambridge, Mass. The gauges were calibrated and assembled at the NOL Field Station, Naval Powder Factory, Indian Head, Md., under the supervision of John Slifko.

At Station Zero, 30 gauges were assembled in a bundle as shown in Fig. 2.3. Eight gauges were used for telemetering System A, eight for telemetering System B, eight for the magnetic-tape recording system, and the remaining six were kept as spares. At Station 0-1, eight gauges were incorporated in the Project 1.2 gauge string. The cable bundle was bound every 8 ft with a $^5/_8$-in. stainless-steel banding strip, under which a piece of old fire hose had been placed to prevent chafing. The banding process is shown in Fig. 2.4.

The cable bundle was clamped to a $^3/_8$-in. nontwisting steel messenger every 25 ft along the messenger. A 500-lb cylindrical steel weight on the bottom end of the messenger kept it taut. The messenger cable was lowered and raised with a gasoline-engine powered winch, shown in Fig. 2.5. A 7.5-hp gasoline engine operated a hydraulic pump which, in turn, operated a hydraulic motor. The motor was coupled to the winch spindle through suitable reduction gears. The mechanism was conceived by LCDR B. F. Seeger and was built from surplus winches and gun director parts. The unique feature of the winch was the extremely flexible control of cable speed and direction. As an emergency precaution, the winch spindle was designed to be operated by a hand crank in case of gasoline-engine failure.

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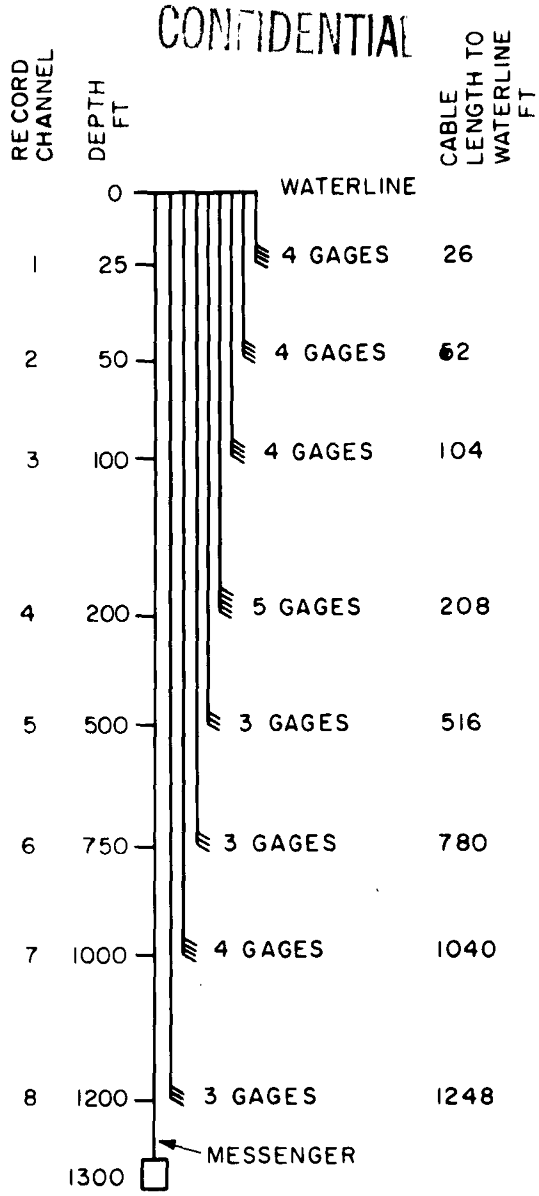

Fig. 2.3—Station Zero cable bundle.

The length of the instrument cable bundle between the 25-ft cable clamps was 26 ft so that the instrument cables were not required to support more than 26 ft of their own weight from any single support. At each of the eight gauge locations, a special pickup guard was installed. The guard served to support the gauges when the bundle was stored in the hold as well as to position the gauges when the bundle was lowered in the water.

The detailed characteristics of tourmaline PE gauges are adequately described in reference 1. Only the unique features of the gauges used and the methods of calibration will be described in the following paragraphs.

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Fig. 2.4—Banding cable bundle.

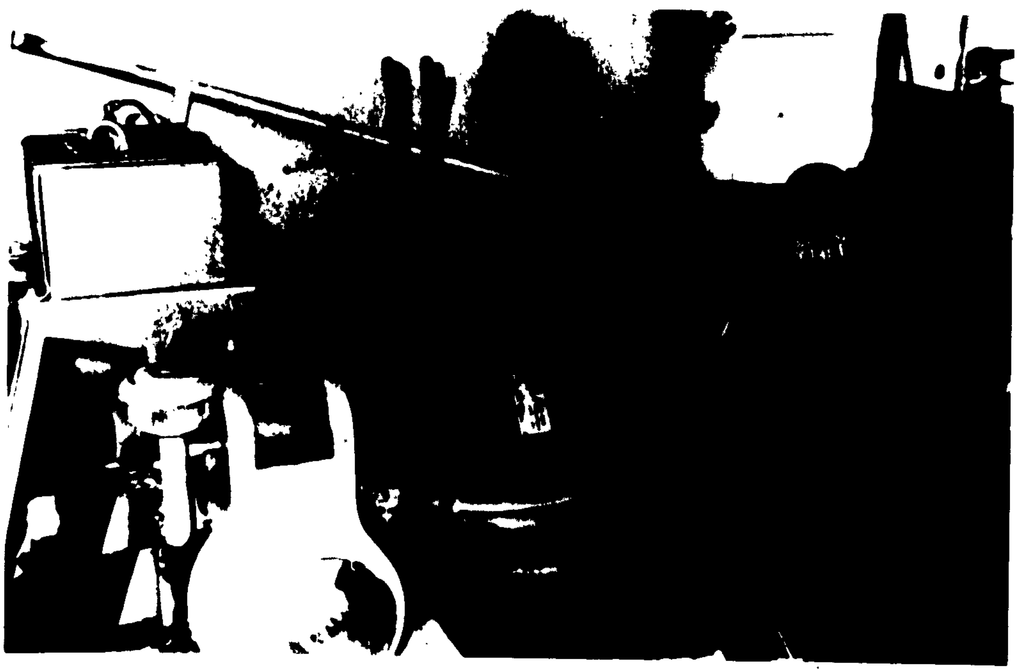

Fig. 2.5—Cable messenger winch.

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The tourmaline PE gauge has the fundamental characteristic of an ideal generator in series with a small capacitance (a few hundred micromicrofarads). Application of pressure will produce an electric charge across the capacitance.

$$Q = KAP$$

where Q is charge, KA is crystal constants, and P is pressure. Since this charge is across the capacitance of the gauge and its associated cable, there is a voltage produced at the pickup cable terminals.

$$V = \frac{Q}{C} = \frac{KAP}{C}$$

where V is voltage and C is total capacity across gauge.

If there were no leakage (infinite insulation resistance), the charge due to applied pressure would hold as long as the pressure was applied. There is leakage, however; thus the output voltage decays according to the law of capacity and resistance in parallel.

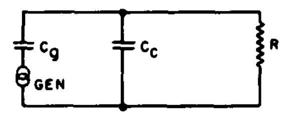

Fig. 2.6—Equivalent PE gauge circuit. C_g, capacity. C_c, cable capacity. R, total resistance across gauge.

The voltage across R at any time after a step voltage is generated is given by the expression

$$V = E_0 \, e^{-t/RC}$$

where t is time and E_0 is initial voltage.

$$\theta = \frac{t}{\log_e \frac{E_0}{V}} \tag{2.1}$$

θ is a measure of the time constant of the circuit, which is the time for a voltage step to decay to 1/e, or 0.37, of the initial value. For the Wigwam experiment, it was desired to have a θ of about 5 sec or more so that for the duration of the explosion pressure transient the system response would be constant. This was accomplished in all but the shallow gauges, which had circuit time constants of 2 sec, an acceptable value because of the short pressure durations resulting from the surface cutoff.

The system was calibrated by applying a known charge in parallel with the gauge. The voltage step produced can be directly related to pressure times a constant. This is known as the "Q"-step method of calibration.

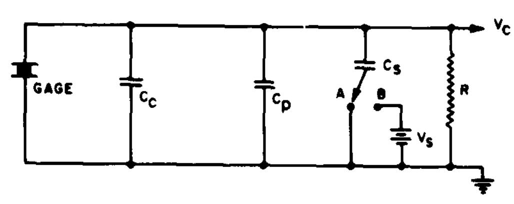

Fig. 2.7—System calibrating circuit. C_p, padding capacitor. V_c, calibrate output voltage. C_c, cable and gauge capacity. C_s, calibrating capacity. V_s, calibrating voltage.

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The calibrating capacity C_s is charged by throwing the switch from A to B. The charge Q on C_s is then

$$Q = C_s V_s$$

When the switch is thrown back to A, this charge is applied to the gauge circuit, producing a voltage step at the output which can be equated to a step in pressure.

$$Q = C_s V_s = V_c (C_c + C_p + C_s)$$

or

$$V_c = \frac{C_s V_s}{C_c + C_p + C_s} \tag{2.2}$$

C_p is a padding capacity which is selected so that, for a given pressure, the voltage output will be a quantity compatible with the recording system. The equation for pressure should then be written as

$$V_p = \frac{KAP}{C_c + C_p + C_s} \tag{2.3}$$

where V_p is pressure signal output voltage. The equivalent pressure due to the calibration step P_{cal} is found by equating V_p to V_c so that

$$C_s V_s = KAP_{cal}$$

or

$$P_{cal} = \frac{C_s V_s}{KA} \tag{2.4}$$

From Eqs. 2.2 and 2.3 the calibrating capacity C_s is

$$C_s = \frac{KAP_{max}}{V_p} \frac{V_c}{V_s} \tag{2.5}$$

where P_{max} is maximum or peak signal pressure, and the padder capacity is

$$C_p = \frac{KAP_{max}}{V_p} \left(1 - \frac{V_c}{V_s}\right) - C_c \tag{2.6}$$

Since the tourmaline gauge is a high-impedance device, the load resistance must be high to maintain a long time constant. For this reason the gauge output was fed to a high-impedance-input cathode follower with a voltage gain of 0.7 whose output was compatible with either the telemetering or magnetic-tape recording systems. Figure 2.8 shows the complete basic schematic circuit for the calibrating and cathode-follower circuits. The calibrating voltage V_s was a series of six uniform steps. The calibration sequence also included a long step at the maximum calibrate voltage to permit a measurement of the low frequency response of the entire recording system.

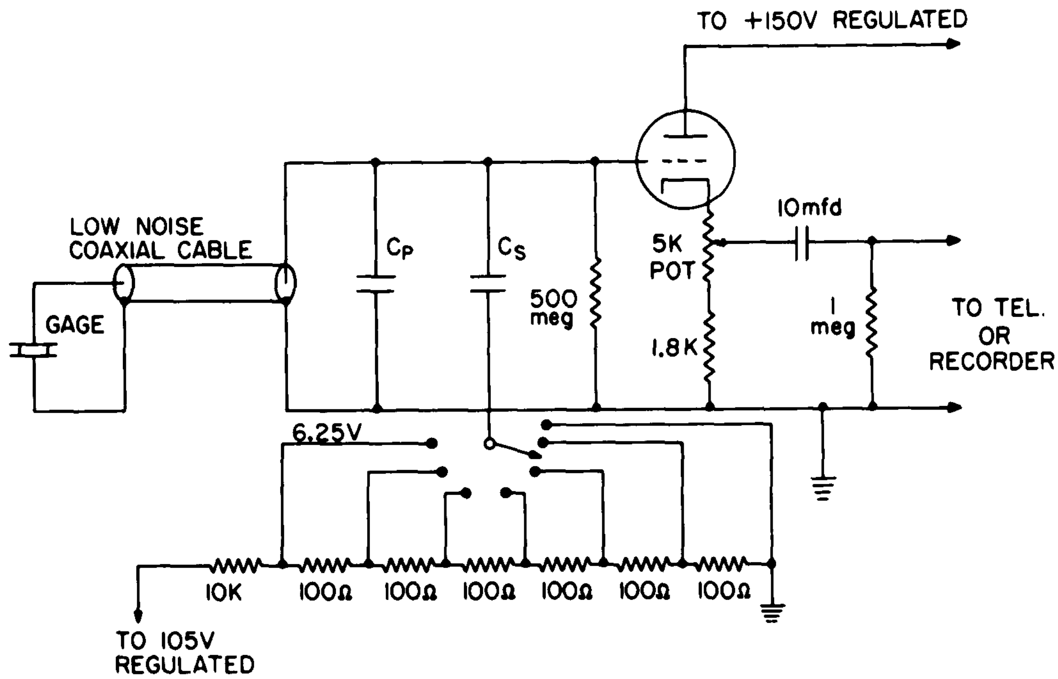

Fig. 2.8 — Gauge and system calibration circuit.

Based on the input requirements of both systems, the following gauge circuit constants were established:

V_s = maximum 6.25 volts
V_c = 2.37 volts (the cathode-follower gain of 0.7 reduces the V_c applied to the recording systems to 1.66 volts)
V_p = 1.90 volts (to allow for variations in the predicted pressure, this value was set at 0.8 of the maximum calibrate step)

At a given pressure gauge location, the predicted maximum pressure P, the KA of the gauge at that location, and the cable capacity C_c were fixed. When the KA of a gauge is expressed in micromicrocoulombs per pound per square inch, then all capacities may be expressed in micromicrofarads, and all potentials in volts. From the above data the values of C_s and C_p were computed. The actual values used in the equipment were selected to be within ±4 per cent of these computed values and were measured on a General Radio type 650-A impedance bridge with an accuracy of 1 per cent.

Table 2.1 lists the data on the gauges available at Station Zero. From these data, and knowing the values of all calibrating parameters, tables were made up of equivalent pressure steps for all recording systems, using Eq. 2.4. These tables were then used in computing the peak pressures from the film records of the shot. Only the tables for the systems which operated during the shot are presented in this report and appear as Tables 2.2 and 2.3.

The signals from the six calibration steps appear as trace displacements on the record film. Knowing the displacements of the traces and the corresponding equivalent pressure steps from Tables 2.2 or 2.3, a pressure-displacement calibration curve may be constructed by connecting the points with straight lines. The equations of the lines take the form

$$P = bd + a \tag{2.7}$$

where b = slope
d = spot deflection
p = pressure
a = constant

The constant a is zero except for nonlinear calibration curves. After determining the slope b and the constant a from the calibration curves, the pressures may be computed directly from the shot record. This method assumes a linear pressure-displacement relation between calibration points which is entirely satisfactory for small values of nonlinearity such as were encountered in the two pressure-time recording systems.

2.4 TELEMETERING

The telemetering equipment employed was an eight-channel FM-AM system originally developed under ONR contract by the General Electronics Laboratories, Boston, Mass., for use by NRL in telemetering pressure-time data during Operation Ivy. The equipment was modified and improved for Operation Castle and again modified and improved for Operation Wigwam so that about all that was used of the original equipment was the basic circuitry. Practically all the units used during Wigwam were constructed by the Engineering Services Division of NRL.

An incoming electrical signal (Fig. 2.9) frequency modulates an oscillator operating at a center frequency between 1.975 and 3.664 Mc. There are eight of these individual oscillators; each frequency deviation is ±50 kc. The outputs of these eight oscillators are combined to produce a complex video signal with frequency components between about 1.9 and 3.75 Mc. This complex signal is then used to amplitude modulate a crystal-controlled transmitter op-

Table 2.1—STATION ZERO GAUGES

Gauge No.	Depth, ft	KA*	Cable Capacity C_c†
1007	25	8.44	2660
1008	25	8.48	2680
1006	25	8.44	2670
899	25	8.30	2730
910	50	8.20	3290
1011	50	8.35	3300
1010	50	8.62	3300
1009	50	8.42	3360
1013	100	8.50	4680
1016	100	8.36	4650
1012	100	8.53	4630
911	100	8.02	4610
913	200	8.12	7200
1018	200	8.00	7230
914	200	7.91	7170
1019	200	8.24	7200
1017	200	8.78	7300
1045	500	25.6	15000
1039	500	23.8	15100
1023	500	22.4	15000
1050	750	17.8	21300
1053	750	18.8	21400
1044	750	25.4	21500
1056	1000	19.6	28900
1057	1000	18.8	28800
1055	1000	19.25	29200
1060	1000	18.8	28800
1061	1200	19.5	33700
1058	1200	17.2	32800
1059	1200	19.1	32700

* KA is given in micromicrocoulombs per pound per square inch.
† Cable capacity is given in micromicrofarads.

erating on either 255 or 265 Mc. The transmitted signal is received by a standard superheterodyne broadband receiver (Fig. 2.10) with a crystal-controlled local oscillator. The intermediate frequency is 60 Mc with a nominal bandwidth of 8 Mc. The rectified intermediate frequency output from the second detector is a reproduction of the complex video signal originally fed to the transmitter, containing the eight subcarrier frequencies. The complex signal is then fed to the subcarrier demodulator unit which is a bank of eight band-pass filter units, each filter passing a separate subcarrier frequency band. The output from each filter is fed to its frequency discriminator whose output in turn is a reproduction of the original incoming signal fed to the subcarrier generator.

The reproduced signal was fed to cathode-ray or magnetic-tape recording equipment. Figure 2.11 shows the over-all frequency response of each channel in the system. System noise was a function of signal strength at the receiver; therefore for a good signal-to-noise ratio (40 db or better, peak-to-peak) a radio-frequency signal of 100 μv or better was required at the receiver input. For this reason, the transmitter radio-frequency power output was established at 40 watts.

For additional receiver input radio-frequency voltage, high-gain antennas at both transmitter and receiver were employed. Each antenna consisted of eight driven half-wave elements in phase backed up by eight half-wave parasitic reflectors. The basic antenna is described in reference 2. Dimensions for the telemetering antennas were scaled from 144 to 260 Mc and were as follows: radiator length (half wave), 21$^3/_8$ in.; reflector length (half wave), 22$^3/_8$ in.; and phasing spacing (half wave), 22$^1/_8$ in. Antenna voltage gain measured between 11 and 13 db

Table 2.2—CALIBRATION STEP PRESSURES, STATION ZERO, SYSTEM A (TELEMETERING)

	Calibrate equivalent pressure step, psi					
Channel	Step 1 1.05 volts	Step 2 2.10 volts	Step 3 3.15 volts	Step 4 4.21 volts	Step 5 5.26 volts	Step 6 6.31 volts
1	634	1270	1905	2542	3180	3810
2	635	1271	1910	2545	3185	3820
3	675	1352	2030	2710	3385	4060
4	755	1513	2270	3035	3790	4540
5	920	1836	2750	3675	4600	5560
6	1124	2245	3370	4500	5620	6740
7	1570	3140	4710	6280	7850	9420
8	2200	4400	6600	8810	11050	13250

Table 2.3—CALIBRATION STEP PRESSURES, STATION ZERO, SYSTEM C (MAGNETIC TAPE)

	Calibrate equivalent pressure step, psi					
Channel	Step 1 1.05 volts	Step 2 2.10 volts	Step 3 3.16 volts	Step 4 4.21 volts	Step 5 5.26 volts	Step 6 6.32 volts
1	645	1290	1940	2580	3230	3870
2	680	1355	2040	2715	3400	4080
3	710	1422	2140	2845	3560	4270
4	760	1520	2290	3045	3810	4570
5	920	1836	2750	3675	4600	5560
6	1150	2300	3460	4600	5750	6900
7	1600	3200	4820	6420	8030	9650
8	2055	4110	6180	8240	10300	12350

over a dipole with horizontal polarization. At the transmitting stations the antennas shown in Fig. 2.12 were fixed in azimuth; at the receiving location on the Curtiss, the two antennas (one for Station Zero and one for Station 0-1) shown in Fig. 2.13 were rotatable on a common mast. Horizontal polarization was employed because the antenna beam width in azimuth was greater than for vertical polarization for the particular antenna configuration. At Station Zero the coaxial feed line from the transmitter to the antenna was approximately 115 ft. long. To reduce line losses, gas-filled coaxial line, manufactured by the Andrew Corp., Chicago, Ill., under the trade name Heliax type HX-O, was used. At Station 0-1 RG/8U coaxial feed line was used because of the shorter run.

The telemetering transmitting equipments, along with the pickup and control units, were housed in a steel instrument house or "transportainer" approximately 7 by 7 by 8 ft. This shipping container had full opening front doors and was lined and waterproofed so that it made an ideal instrument house. The transportainers were fitted out at NRL, shipped by truck to San Diego, and then transferred to Stations Zero or 0-1.

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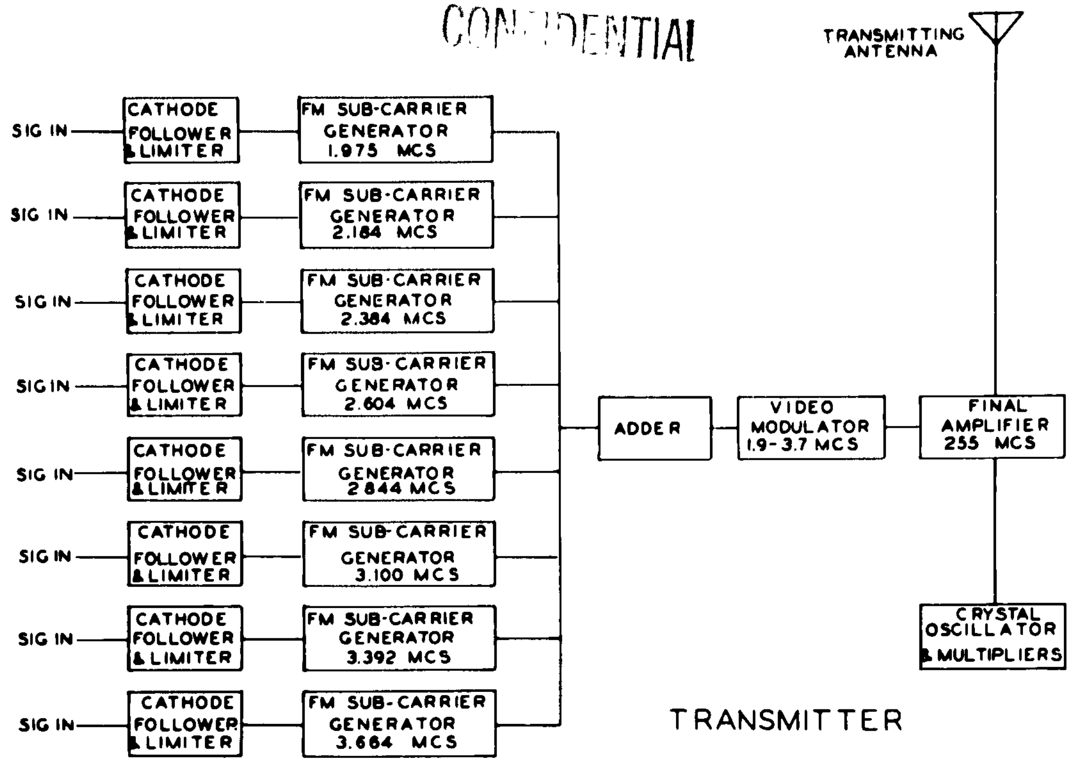

Fig. 2.9—Block diagram of telemetering subcarrier generator and transmitter.

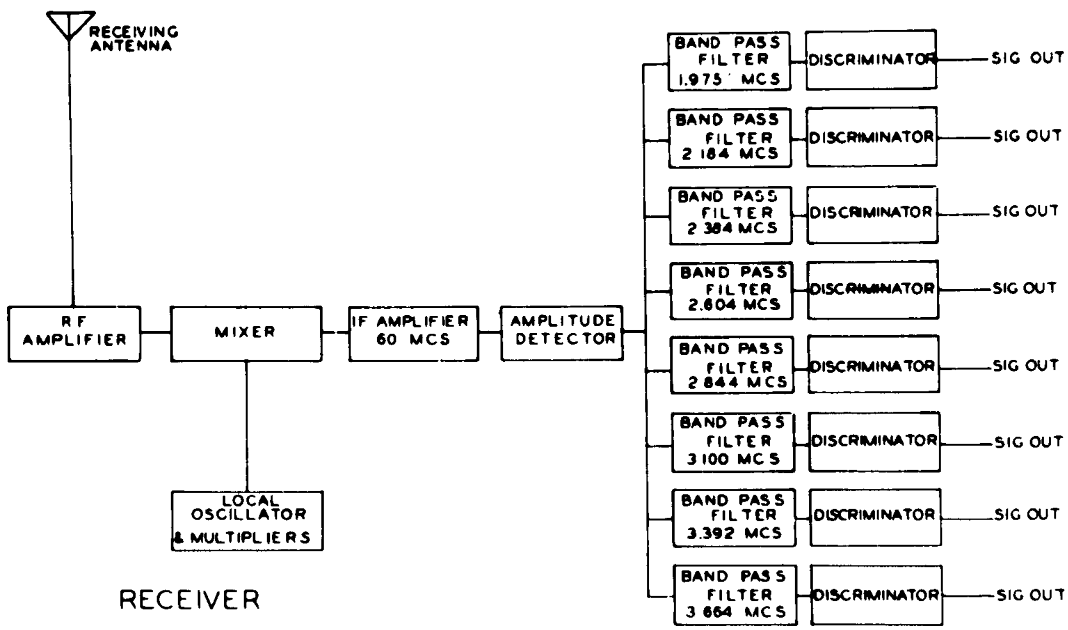

Fig. 2.10—Block diagram of telemetering receiver and subcarrier demodulator.

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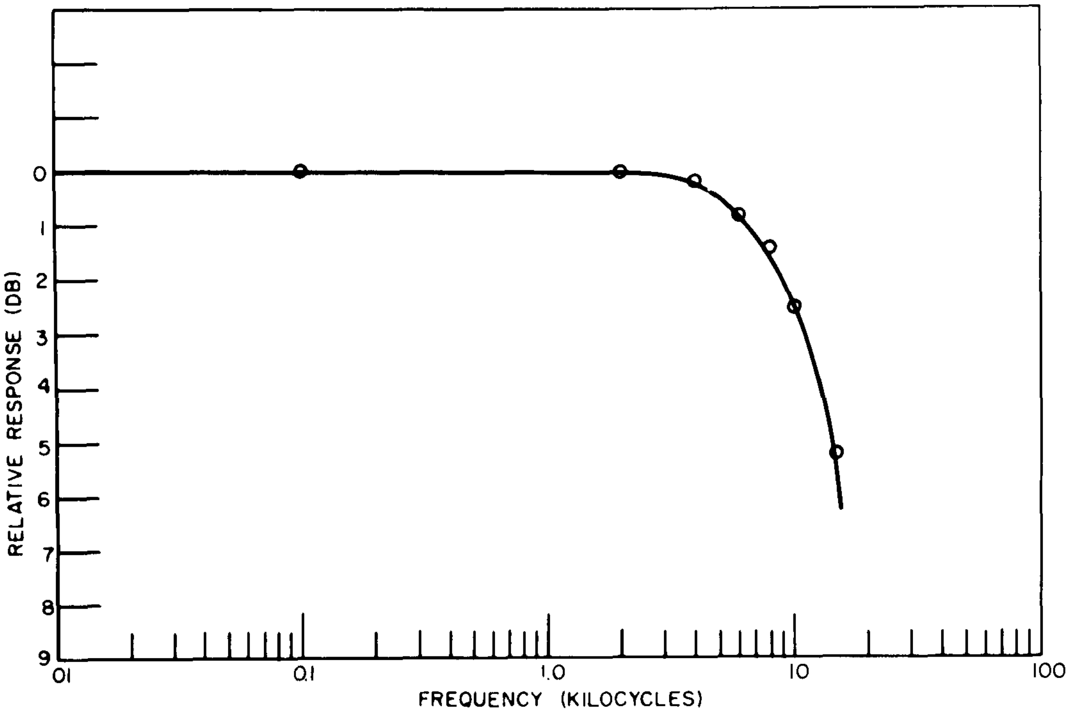

Fig. 2.11—Frequency response, NRL FM-AM telemetering system.

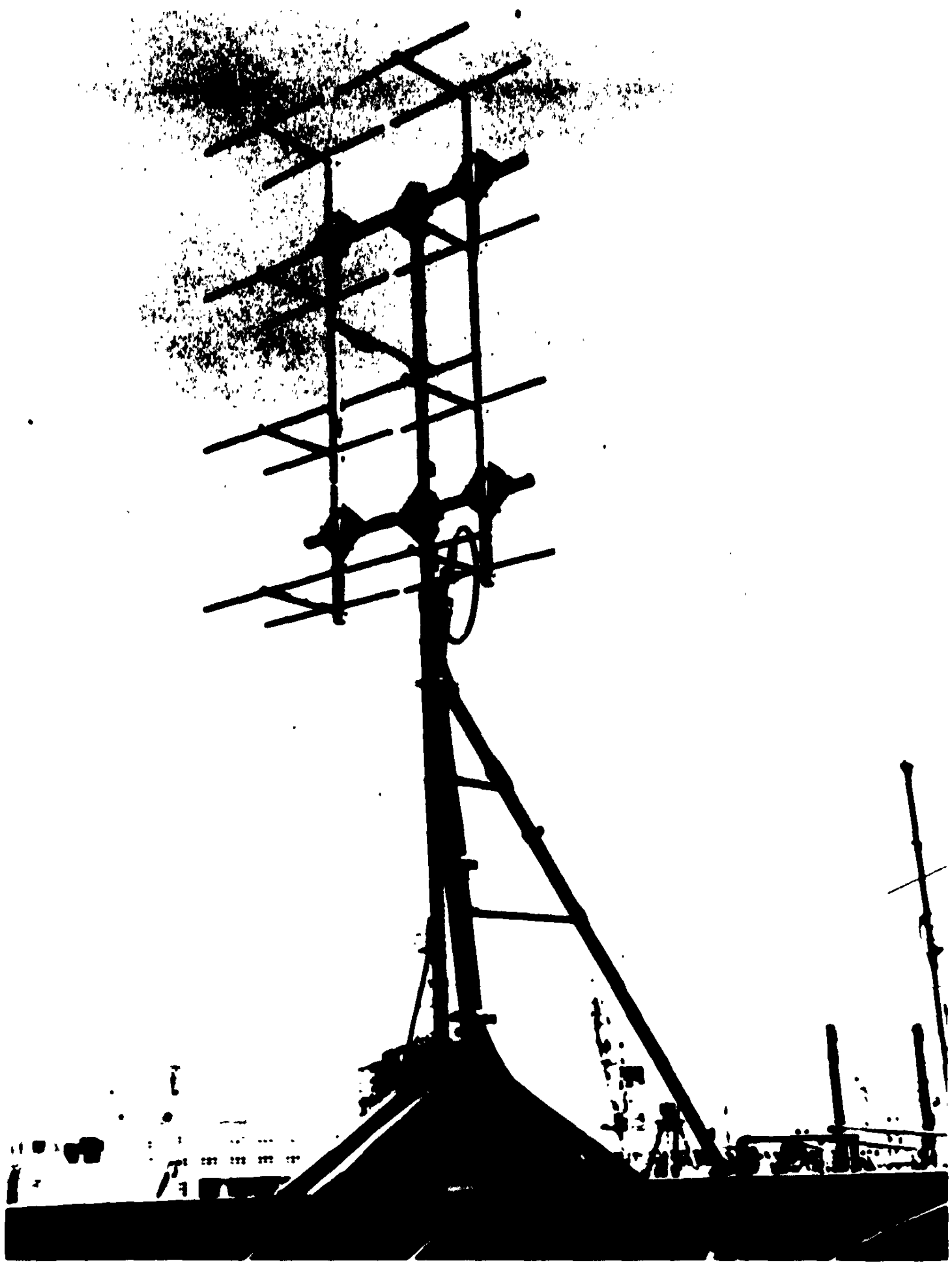

Fig. 2.12—Telemeter transmitting antennas.

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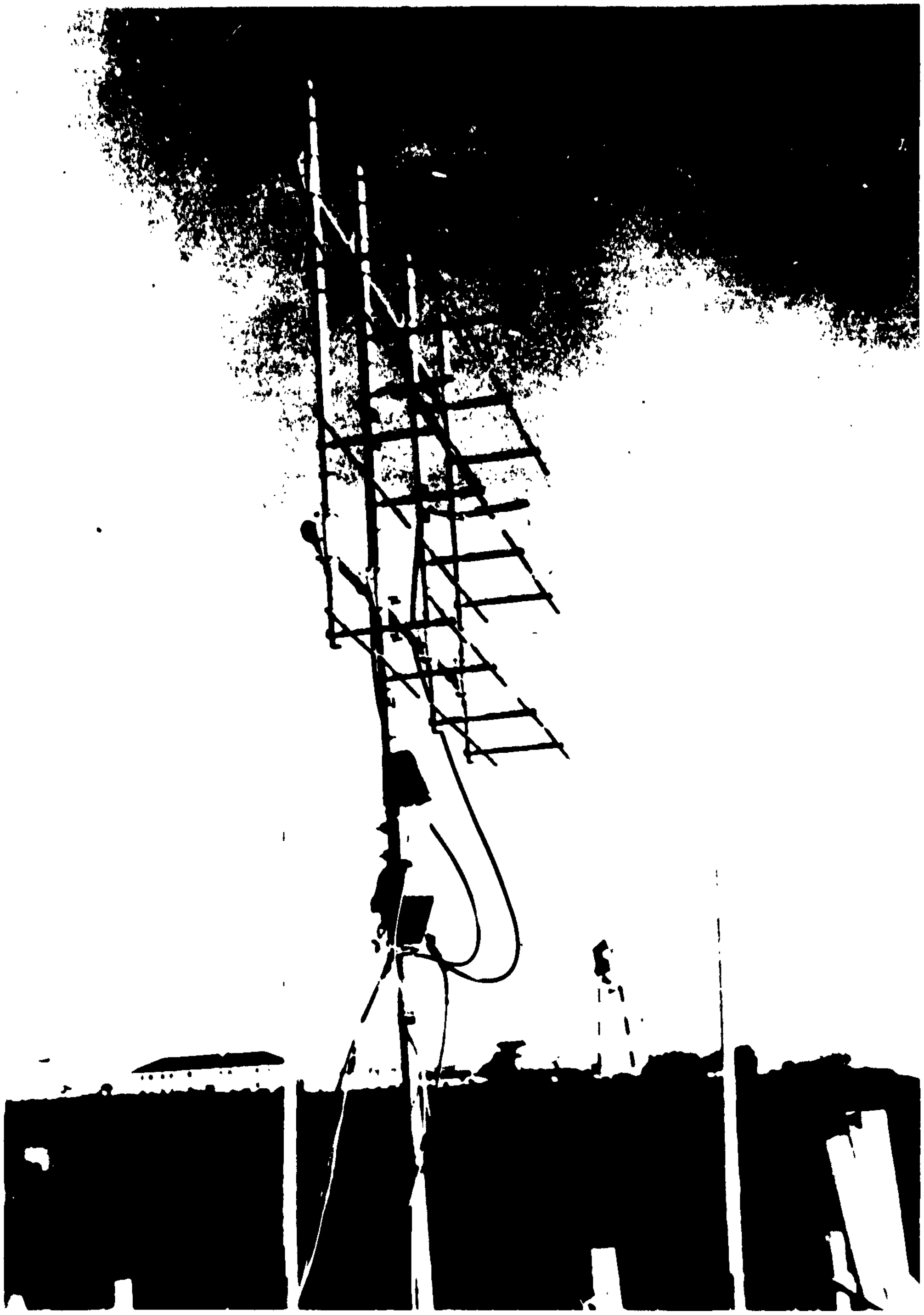

Fig. 2.13—Telemeter receiving antennas.

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The telemetering receiving and recording equipment was housed in a 35-ft stainless-steel trailer mounted on the boat deck of the USS Curtiss. The telemetering receiving antennas were mounted on a 40-ft mast erected alongside the trailer.

All equipment was designed for panel mounting in standard 19 in. racks with all controls and connections on the front panel. This arrangement was not particularly neat, but it did permit rapid replacement of units for servicing. Spare units were carried on board the Curtiss so that only minor repairs were attempted at the transmitting stations. The telemetering transmitting equipment was designed to operate on 115-volt 60- or 400-cycle a-c power. When 60-cycle power from a diesel-generator was not available, high-capacity 30-volt storage batteries were used to drive a 115-volt 400-cycle alternator which supplied power to the transmitting equipment. This arrangement eliminated carrying a special 400-cycle test power supply aboard the Curtiss.

2.5 MAGNETIC-TAPE RECORDING SYSTEM

The magnetic-tape recording system had five major units: gauge electronics, control panel, recorder, playback, and photographic recorder. The gauge electronics, control panel, and recorder were located at Station Zero; the playback and the photographic recorder were located at the laboratory. The unique feature of the system was the packaging of the recorder for recovery after the Wigwam explosion. It was realized that the support barge probably would be destroyed; thus the major problem was to protect and eventually recover the magnetic tape.

It was decided from the first to attempt recovery of only the magnetic-tape recorder unit; therefore a protective container was designed to house only this unit. Figure 2.14 is a photograph of the container and its launching rack. The container was a domed-head steel cylinder constructed of $\frac{1}{4}$-in. high-tensile steel plate with ring stiffeners. The cylinder had a calculated collapse pressure of 1000 psi. The steel container was enclosed in a 6-in. wood jacket for splinter protection and for additional buoyancy. The lower end of the wooden jacket was tapered to reduce water entry shock during launching. The recorder was mounted on rails within the container for easy insertion and removal. Power and signal leads were fed through special Teflon and plastic insulated pressure-tight connectors on the container.

The container was hung from the top of the launching rack (Fig. 2.15) which was inclined 6 deg from the vertical to prevent swinging. A shear pin was installed in the can hanger assembly. It was designed to fail and thus release the container at barge accelerations greater than 3 g. The design also included a provision for the can to float free if the barge acceleration was less than 3 g but enough to cause the barge to sink. The power and signal cables external to the container were equipped with disconnect plugs which parted during launching.

The magnetic-tape recorder and playback units were manufactured by Davies Laboratories, Inc., Riverdale, Md. The recorder accepts eight data signals and one timing signal. A tenth internal channel is used to compensate for recorder wow and flutter in conjunction with the playback equipment. In the recorder each input signal is used to frequency modulate an oscillator with a zero signal frequency of about 30 kc and deviation sensitivity of 6.0 kc/volt. For a maximum voltage change from the gauge of 0 to 1.66 volts, the frequency shift is from 30 to 20 kc. The frequency modulated carrier is then recorded on one channel of the 10-channel recorder. The playback, located at the laboratory, demodulates the carrier by squaring up, differentiating, and counting the reproduced signal. Figure 2.16 shows the over-all frequency response of a single channel which extends to direct current as the lower limit. Measured root mean square signal-to-noise ratios for the system were about 42 db.

The signal input requirements for the magnetic-tape recorder were the same as for the telemetering system so that the PE gauge amplifier and calibration circuits were identical. The gauge electronics and the control panel were located in the instrument house alongside the telemetering equipment. This arrangement permitted a quick interchange of gauges between the telemetering and magnetic-tape recording systems and also permitted common feed of both systems from a single gauge. An independent timing signal for the magnetic-tape recorder was generated in the gauge electronics panel from a General Radio tuning fork whose frequency was

Fig. 2.14—Magnetic-tape recorder can in launching rack-stowed position.

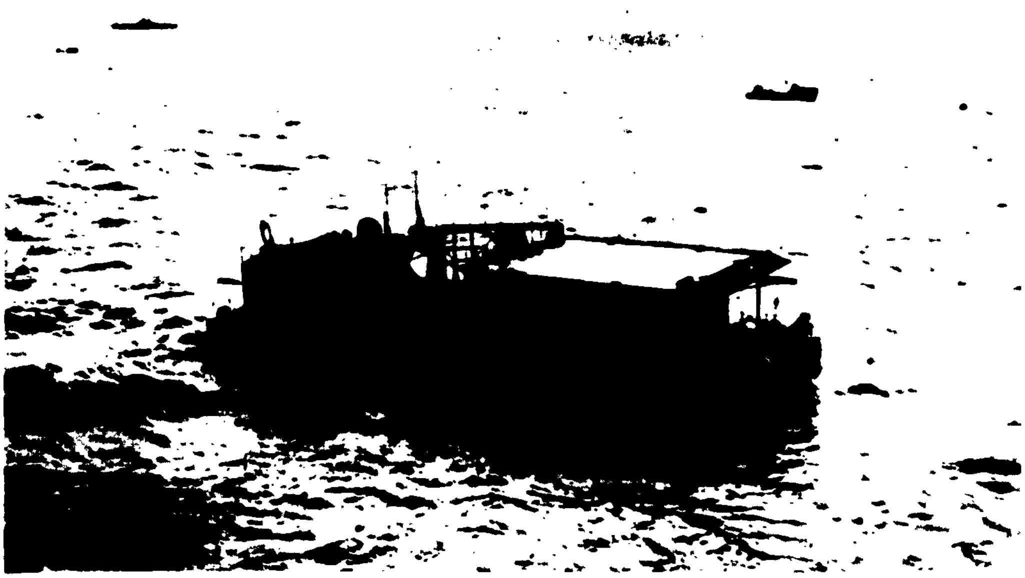

Fig. 2.15—Station Zero showing magnetic-tape recorder can in launching position.

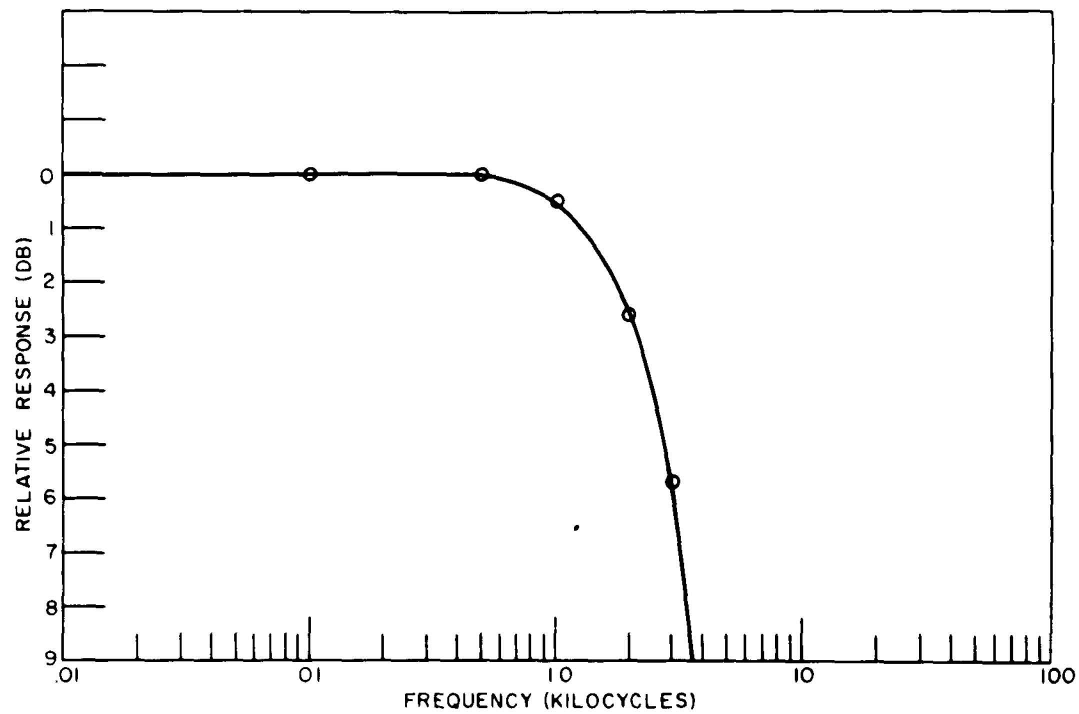

Fig. 2.16—Frequency response, magnetic-tape recording system.

subsequently determined to be 993.7 cycles/sec. The Wigwam fiducial pulse supplied by Edgerton, Germeshausen & Grier, Inc. (EG&G) was superimposed on the timing channel. Primary power for the system was supplied by a 30-volt 300 amp-hr storage battery.

The reproduced signal from the playback unit was presented on a cathode-ray oscillograph which was photographed by a 35-mm continuous motion camera. A second cathode-ray oscillograph alongside the signal cathode-ray oscillograph presented simultaneously the timing and fiducial pulse traces. Since the the playback equipment could reproduce only one signal channel at a time, the magnetic-tape record was played back eight times to recover all the recorded information.

2.6 RADIO CONTROL

Control of all operating functions of the telemetering system was maintained by a radio command system, using a command transmitter at the telemetering receiving station, and two command receivers at each telemetering transmitter location. Tone coded pulses from the command transmitter actuated stepping relays in the receivers to provide the following control functions at each telemetering transmitter location:

Filaments ON
Plate Power ON
Transmitter Changeover (System A to B and back to A)
Single Sequence System Calibration
Continuous Step Calibration
Single Channel Sine Wave Calibration (8 functions)
All Channel Sine Wave Calibration
Plate Power OFF
All OFF

The command transmitter was crystal controlled with a radio-frequency output of about 100 watts on 140.22 Mc. Two spare command transmitters were installed for system reliability, one of which had an output of only about 5 watts. This low power was sufficient for complete system control, however. The two command receivers, located in the telemetering instrument house, were completely independent of each other, even to separate receiving antennas. The outputs from the control relays from each receiver were paralleled so that if either receiver operated the telemetering transmitter could be controlled. The superheterodyne command receivers employed crystal-controlled local oscillators for stability.

In addition to the NRL radio control of the telemetering equipment, provision was made for the EG&G (Program V) equipment to control the minimum essential functions, which were "Filament and Plate ON" at H – 45 min and "Single Sequence System Calibrate" at H – 1 min. Each of these functions were duplicated by separate EG&G circuits. The telemetering transmitter control system was so connected that any function actuated by EG&G control was irreversible; thus once the equipment was turned on at H – 45 min, it could not be turned off by NRL command. In addition, the EG&G H-15 min control circuit was paralleled with the H – 45 min circuit so that, if the EG&G H – 45 min control failed and the NRL command system failed, a final possibility of turning on the equipment at H – 15 min existed.

Only the EG&G command circuits were used for the magnetic-tape recording system. These EG&G circuits were independent of the telemetering control circuits, however.

At the telemetering receiver location, EG&G command circuits were used to automatically actuate the camera control sequence timer so that the recording camera drive motors were energized at the proper moment.

The EG&G fiducial pulse sent at approximately zero time was received at Station Zero and at the telemetering receiving station. At Station Zero, the pulse was recorded by the magnetic-tape recording system. At the telemetering receiving station, the pulse was recorded on all cathode-ray oscillograph records by interruption of a line when the fiducial pulse was received.

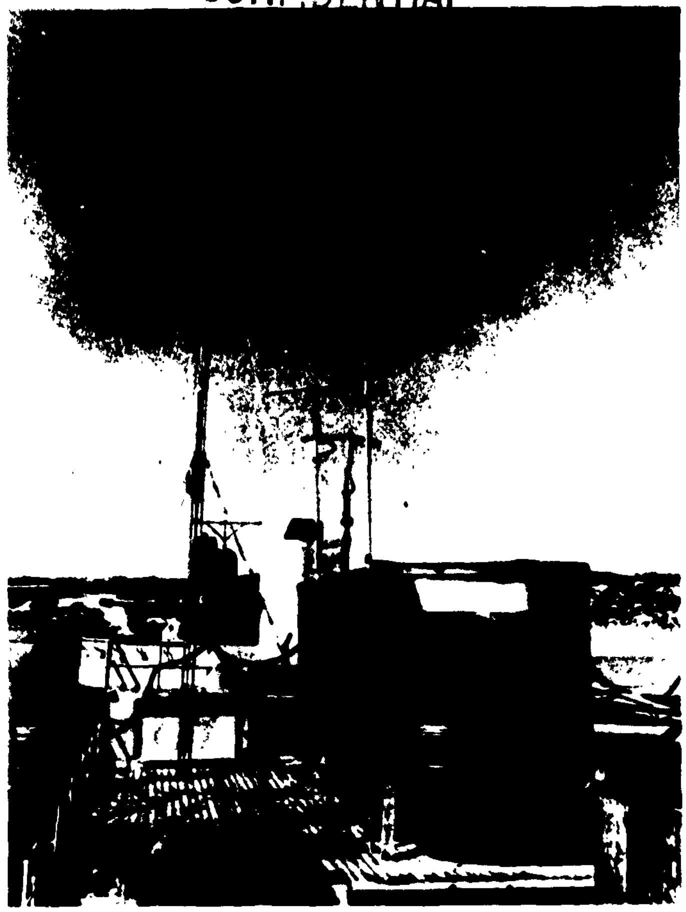

Fig. 2.17—Telemetering recording trailer on board USS Curtiss.

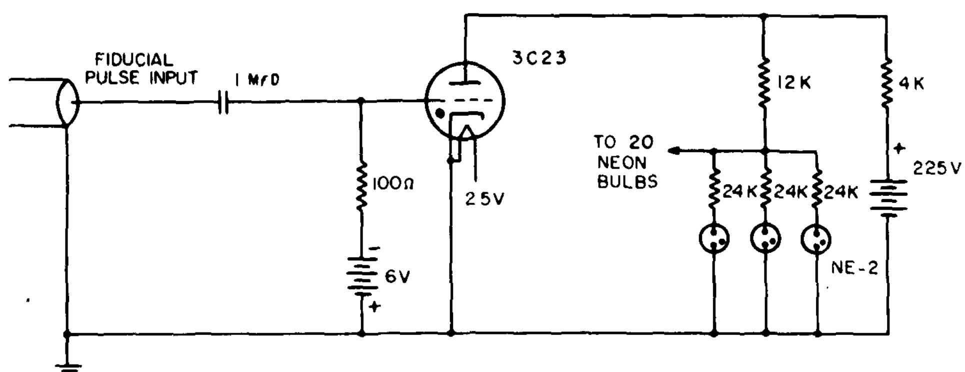

Fig. 2.18—Schematic of fiducial pulse recording circuit.

The fiducial pulse was also recorded on a magnetic-tape recorder installed in the telemetering receiver trailer which recorded the telemetered signals as a "backup" to the film recording.

2.7 TELEMETERING RECORDING

The telemetered signals were received and recorded in a trailer located on the Curtiss (Fig. 2.17). The trailer also housed the NRL radio command system transmitter and the project communication units.

Each of the 16 telemetered signals (8 from Station Zero and 8 from Station 0-1) was recorded by 6 cathode-ray oscillographs. In addition, the 8 telemetered signals from Station Zero were recorded on on 8-channel magnetic-tape recorder acting as a backup to the cathode-ray oscillograph recording. The cathode-ray oscillograph recording channels were arranged in trapezoidal groups of 5. Each group, along with the timing lights, was photographed by a 35-mm continuous motion camera running at a film speed of either 2 or 7.5 ft/sec. At 2 ft/sec the camera lens opening was f/2.3. At 7.5 ft/sec the lens opening was f/4. Tri-X panchromatic film was used. Cathode-ray oscillograph spot intensities were adjusted by means of a Weston photocell to produce maximum definition with adequate brightness at each of the two camera speeds and lens openings. The camera motors were controlled by an automatic sequence timer which, in turn, was activated by EG&G command or by manually throwing a switch.

In addition to the five signal traces on each film, timing marks generated by a crystal-controlled secondary frequency standard were recorded. The timing marks, which appeared as 3 rows of dots on the edge of the film, were spaced at 1, 10, and 100 msec intervals. The fiducial pulse generated by EG&G was also recorded as an interrupted line on each film. To eliminate the variable error of a mechanical relay, an electronic interrupter which quenched a neon tube was used as shown in Fig. 2.18. A positive fiducial pulse from EG&G fired the type 3C23 thyratron, reducing the voltage across the neon tube below the minimum operating voltage. The moving film record shows a continuous line interrupted when the fiducial pulse is received. The firing delay time of the equipment is only a few microseconds.

The multiple recording of each channel permitted three different voltage gain settings for each channel; therefore a deviation from the predicted pressure of ±25 per cent would produce at least one good full-scale record.

The magnetic-tape recorder used as a backup for the film recording of Station Zero telemetered signals was identical to the recorder described in Sec. 2.5; in fact, it was the spare recorder for the magnetic-tape recording system. The timing frequency was obtained from a tuning fork whose frequency was 1001.75 cycles/sec. The fiducial pulse was also recorded independently on this recorder. The output of the telemetering receiver was not high enough to fully modulate the tape recorder channels; thus the signal-to-noise ratio on the played-back record was not as high as on the telemetered film recording.

To summarize, each telemetered channel was displayed on six different cathode-ray tubes, each photographed by a different camera. Two camera speeds and three gain settings were employed for each telemetered channel.

REFERENCES

1. R. H. Cole, "Underwater Explosions," pp. 159-198, Princeton University, Press, 1948.
2. The Radio Amateur's Handbook, 27th ed., p. 445, American Radio Relay League, Inc., Hartford, Conn.

CHAPTER 3

OPERATIONS

Two opportunities arose to conduct operation rehearsals before the actual experiment took place—the so-called "January trials" and the "April trials." Project 1.2.1 participated in both.

3.1 JANUARY TRIALS

During January 1955 (about 4 months before the Wigwam experiment), Project 1.2.1 participated in sea trials to obtain information on instrument-cable-bundle handling problems and to determine radio propagation characteristics for the telemetering equipment. The results of the trials may be summarized as follows:

1. Lowering of the cable bundle required approximately 2 hr and went about according to plan.
2. There apparently was no interference between the instrument cable bundle and the weapon supporting cable. The two cables were separated 70 ft at the surface, but there was some concern over possible interference when the instrument cable bundle was fully lowered.
3. No unusual effects were observed in the radio propagation paths from Stations Zero and 0-1 to the Curtiss. However, the yaw of the barge was much greater than anticipated, whereas the pitch and roll were much less. Because of this, it was concluded that the beam antenna configurations should be rotated 90 deg to give maximum beam width in azimuth rather than elevation. For the final installation, half-power beam widths were 75 deg in azimuth and 44 deg in elevation.
4. Numerous small mechanical difficulties were uncovered which required changes in equipment or procedure to ensure reliable equipment operation. Nut sizes had to be standardized, the winch gasoline engine needed a better method of starting, and the messenger cable needed to be wound on the reel under tension.

3.2 APRIL TRIALS

During April additional tests were conducted at sea to determine the performance of the complete telemetering system and to uncover any interference with other equipment or systems. Rough seas limited the scope and duration of the tests. However, interference between the voice communication circuits and the EG&G timing circuits was experienced. The NRL radio command circuit caused some interference to the Sandia telemetering system. A schedule was subsequently worked out whereby the NRL radio command system was not operated during critical periods for Sandia. The telemetering system worked quite well during the trials.

In general, the most useful result of the April trials was the opportunity for recording-procedure rehearsal. The defects discovered during the trials were worked out before the final experiment.

3.3 TEST PROCEDURE

The procedure followed during the final days of the Wigwam operation deviated from the original plan in several important respects. The rough seas affected the entire operation so that, beginning about D−1, the test procedure plan became a sequence of events rather than a time schedule.

Prior to D−1 all equipment had been checked out and placed in tip-top condition. By the afternoon of D−1 the gauges at Station 0-1 had been lowered, and the magnetic-tape recording system had been checked out and calibrated. The launching rack for the magnetic-tape recorder was raised into launching position with the safety bolt in place. Early in the afternoon the wind increased, causing the large balloon supporting the Sandia telemetering equipment at Station Zero to wallow violently. The cable securing the balloon caught the NRL telemetering antenna, bending the supporting mast almost to a right angle. Shortly after this the balloon cable was cut to prevent additional damage to other experiments. With the help of the barge operating crew from Naval Ordnance Test Station (NOTS), the antenna mast was cut down, repaired, and reinstalled in about 2 hr at about 1800. At this time Station 0-1 was checked out, and both telemetering systems were calibrated. These calibrations were run so that if the −1-min calibrations were missed the earlier calibration records would be available. The calibration procedure was completed about 1900, and the station was secured until morning.

The operation plan called for the early calibration run at Station Zero to be accomplished after the gauges were in the water. However, the high seas had slowed down the entire operation so that the decision was made to calibrate the telemetering systems with the gauges still in the hold of the barge and to wait until the last possible moment to lower the gauge string. The early calibration of the telemetering systems at Station Zero was finished by about 2100.

At 0515 on D-day, gauge lowering began. By this time the requirement for streaming the drogue behind the weapon barge had been abandoned by the task force because the whole array was moving backward through the water. At 0600 a trip was made to Station 0-1 to run a final check-out and to energize the command system. At that time everything was in good operating condition. Gauge lowering on Station Zero was completed about 0715. A final gauge check showed that gauge No. 1023 at 500 ft for telemetering System A was shorted. There was no spare at this level; thus, according to a prearranged plan, the 500-ft gauge from the magnetic-tape recording system was substituted. The output from the gauge cathode follower was connected to the Channel 5 input of both systems. At about H−4 hr the telemetering systems at Station Zero were given a final check-out. Telemetering System A was left in an operating condition, whereas telemetering System B was left in stand-by, with the NRL command system energized. The telemetering transmitting antenna was oriented to give a maximum signal to the Curtiss at her zero time position, and the safety bolt on the magnetic-tape recorder can was removed. The project personnel left the station at about H−$3^1{}_2$ hr for the Curtiss.

At the Curtiss the signal from the telemetering System A at Station Zero was continuously monitored. One man was detailed to keep the receiving antenna aimed at Station Zero up to shot time.

At H−50 min both systems at Station 0-1 and the stand-by system at Station Zero were turned on by NRL command. At H−30 min the better of the two systems at Station 0-1 was chosen for recording, and at H−15 min the better system at Station Zero was chosen. This was the system which had been energized 4 hr earlier. At about H−15 min it was reported that Channel 4 on Station Zero was out. However, the Project Officer had previously decided that a loss of at least two gauges would be necessary before calling for a change-over to the alternate telemetering system so this was the condition going into zero time.

CHAPTER 4

RESULTS

4.1 INSTRUMENT PERFORMANCE

At about H – 4 hr the NOL instrument can at Station 0-1 carried away. Attached to the can were the gauge cables for pressure signals to be transmitted by Project 1.2.1; thus while the telemetering equipment operated satisfactorily no pressure data were obtained. The shock wave arrival time at the telemetering equipment was observed, however.

The telemetering system at Station Zero operated beautifully. Signals were recorded from all channels except Channel 4 which was doubtful at H – 15 min. However, even on Channel 4 the shock wave arrival time was observed. At the receiving station on the Curtiss, all cameras operated, and data were recorded on at least five oscillographs for each channel.

As far as could be determined, all EG&G radio commands operated as scheduled. The fiducial pulse was received at all stations.

On D + 3, when hope had about faded, the magnetic-tape recorder container was located and recovered 53 miles from Ground Zero. The wooden jacket around the container was dented in one place, but the recovery party said this might have occurred during the recovery operation. The container was radioactive (verbal reports of 50 mr/hr); therefore after the recorder was removed the container was jettisoned. The recorder was damaged when the vibration isolators failed. The rubber wafers sheared so that the recorder was free to tumble about in the container.

When the magnetic tape was played back, pressure-time curves were obtained from all channels except Channel 7. The Channel 7 failure was apparently in the recorder rather than in the gauge electronics. The 1000 cycles/sec timing wave and the fiducial pulse were also recorded.

All – 1-min calibrating sequences operated; therefore the early calibrations were not needed.

4.2 RECORD REDUCTION

All signals from both systems (telemetering and magnetic tape) were recorded on 35-mm film. Each film had from 1 to 5 pressure-time signatures, the fiducial pulse, and either a 1000 cycles/sec sine wave or millisecond and 10-msec dots. The pressure-time signature was a calibration sequence followed by the explosion pressure signal. Enlargements of representative telemetered film records from Station Zero are shown in Figs. 4.1 to 4.3. An enlargement of a representative magnetic-tape playback record is shown in Fig. 4.4. The dots at the bottom of each figure are millisecond timing marks.

For preliminary evaluation the records were photographically enlarged about eight times. From these enlargements the peak pressures were obtained by extrapolating the smooth portion of the pressure-time curve back to the start of the rise and by scaling this value from the calibration step equivalent pressures. The shock wave arrival times were also determined in terms of the fiducial pulse mark.

For final analysis the records were read by means of a "Telereader" manufactured by Telecomputing Corp., Los Angeles, Calif. An enlarged image of the film record is projected on a ground-glass screen. The operator then adjusts horizontal and vertical fine line cursors on the screen to coincide with points on the pressure-time record. The cursor positions are coupled into digital converters so that the trace positions are converted into numbers. The pressure-time signal displacement was read every $\frac{1}{2}$ msec from arrival time to the end of the record. This digital information was put on IBM punch cards, along with the calibration step displacements. From the calibration step IBM cards, calibration curves of trace displacement vs pressure were constructed. The slopes of the calibration curves were then used in the IBM calculator to compute the pressure in pounds per square inch for each point. This value was punched in the card for tabulation or later integration. The computed pressure-time data from the IBM cards were replotted to give pressure-time curves in which nonlinearity of the recording systems was eliminated. A representative curve for each of the 14 recorded channels at Station Zero is shown in Figs. 4.5 to 4.18 inclusive. The logs of each of these pressure points were then plotted against time. The plot was a straight line which was extrapolated back $\frac{1}{2}$ msec to zero time to obtain the log of the maximum pressure. From the slopes of these log plots, the pressure-time decay constants were computed.

The values of impulse and energy flux density at each gauge location were readily obtained by integration, at $\frac{1}{2}$ msec increments, of the pressure values on the IBM cards and multiplying by the appropriate constants.

4.3 PRESSURE VS DISTANCE

Table 4.1 tabulates the extrapolated maximum pressures from all analyzed records. The "series" column designates the particular cathode-ray oscillographic film record from which the data were obtained. At the top of each column is listed the vertical distance of the gauge from the weapon. The average maximum for each gauge location is plotted in Fig. 4.19. From the 14 data points, the equation for the pressure-distance relation was computed by the method of least squares and is shown as the line in the same figure.

The maximum pressure at a distance R from the Wigwam weapon is given by the expression

$$P = \frac{2.03 \times 10^7}{R^{1.16}} \tag{4.1}$$

where P is the maximum pressure in pounds per square inch and R is the distance from the weapon in feet.

4.4 PRESSURE-TIME DECAY CONSTANTS

The slope of the log pressure vs time curve is a measure of the rate of pressure decay. From the straight line segment of the log plots used to obtain maximum pressures, the time decay constant was computed using the equation

$$\theta = \frac{t_1 - t_2}{\log_e \left(\frac{P_1}{P_2}\right)} \tag{4.2}$$

where P_1 is pressure at time t_1, P_2 is pressure at time t_2, and θ is time constant or time required for pressure to decay to $1/e$ of maximum. Decay time constants of all pressure-time curves were obtained and are tabulated in Table 4.2. The average values for each of the

(Text continues on page 55.)

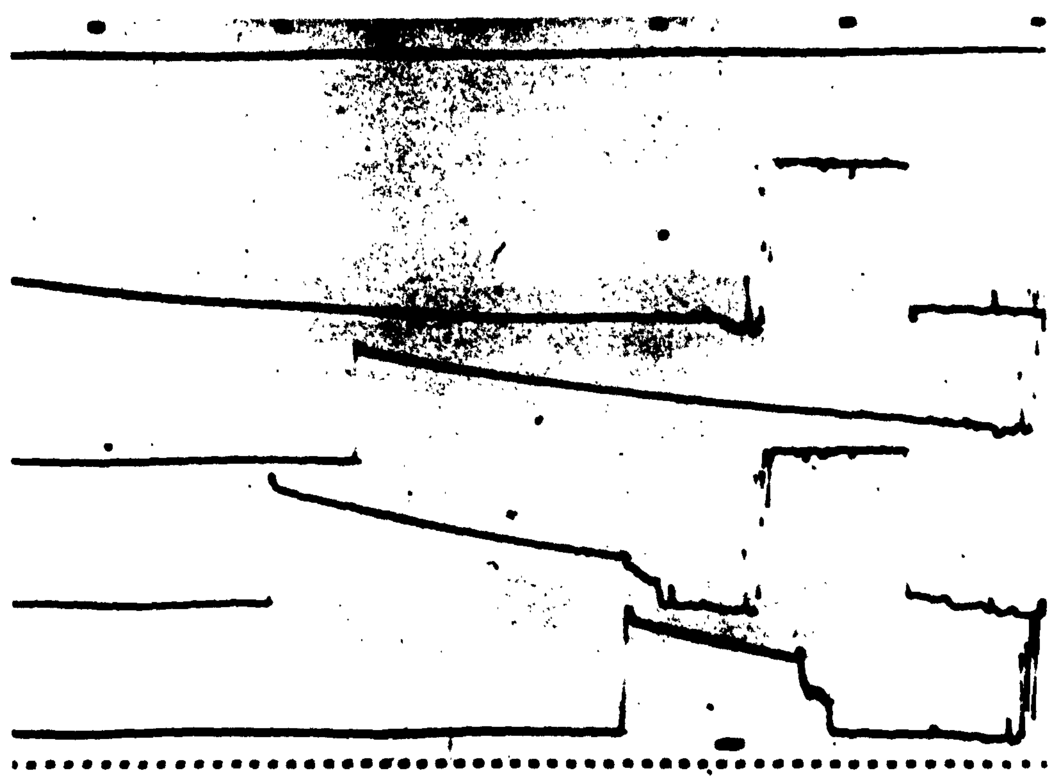

Fig. 4.1—Enlargement of telemetered record, Channels 1, 2, and 3.

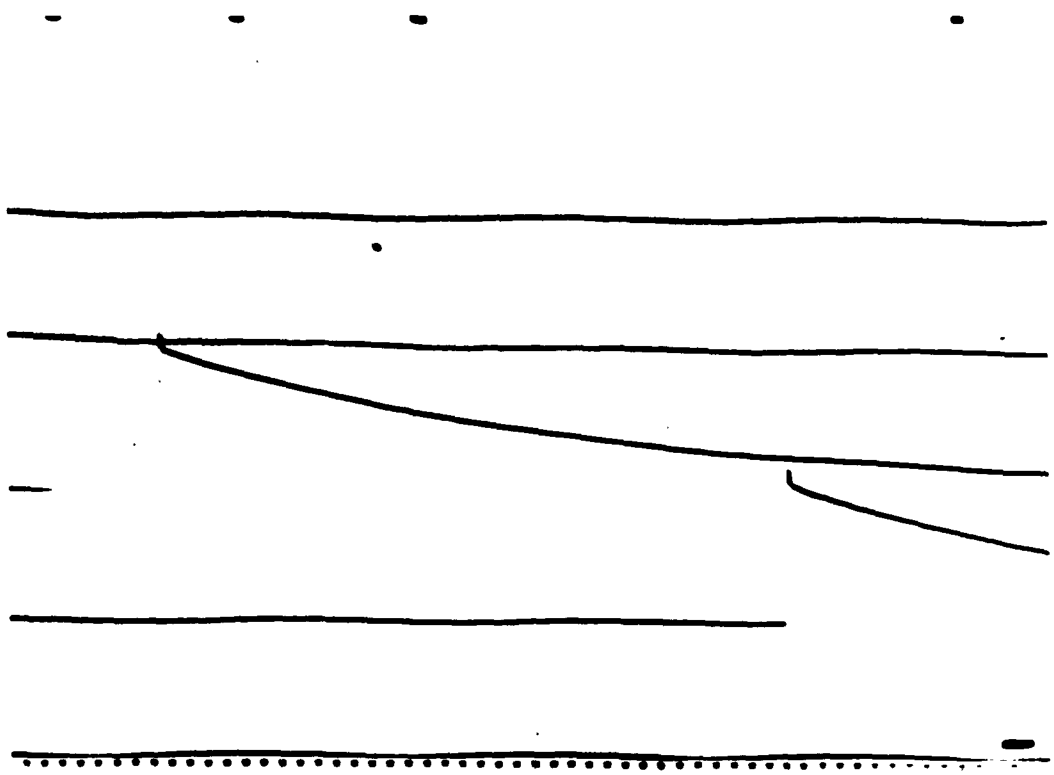

Fig. 4.2—Enlargement of telemetered record, Channels 5 and 6.

Fig. 4.3—Enlargement of telemetered record, Channels 7 and 8.

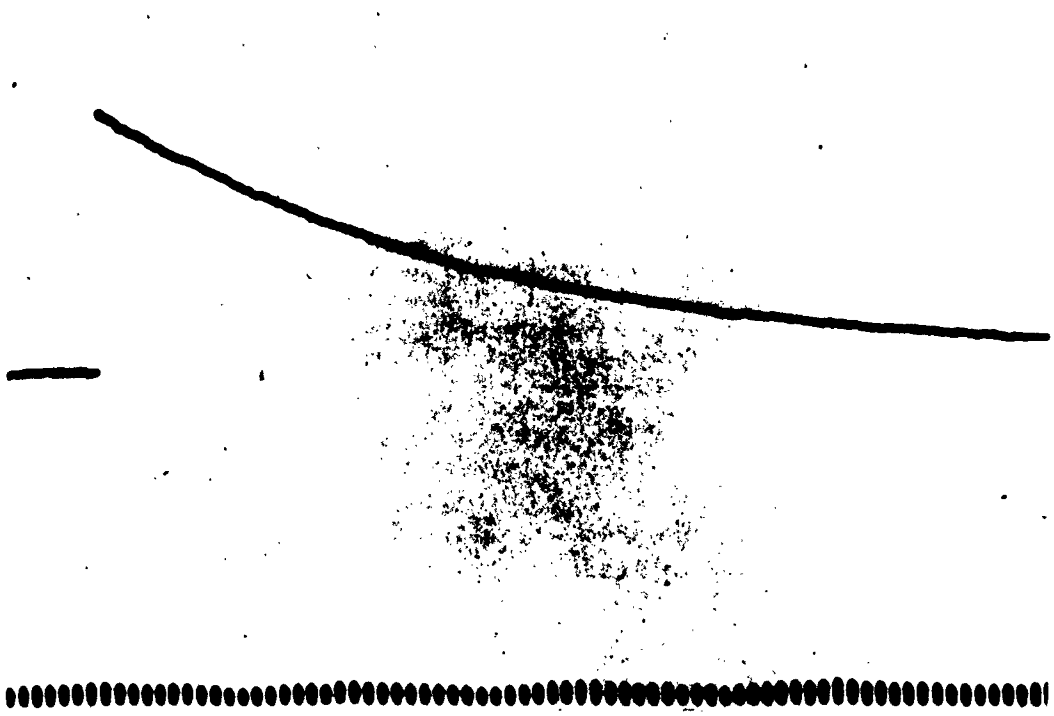

Fig. 4.4 — Enlargement of magnetic-tape playback record, Channel 6.

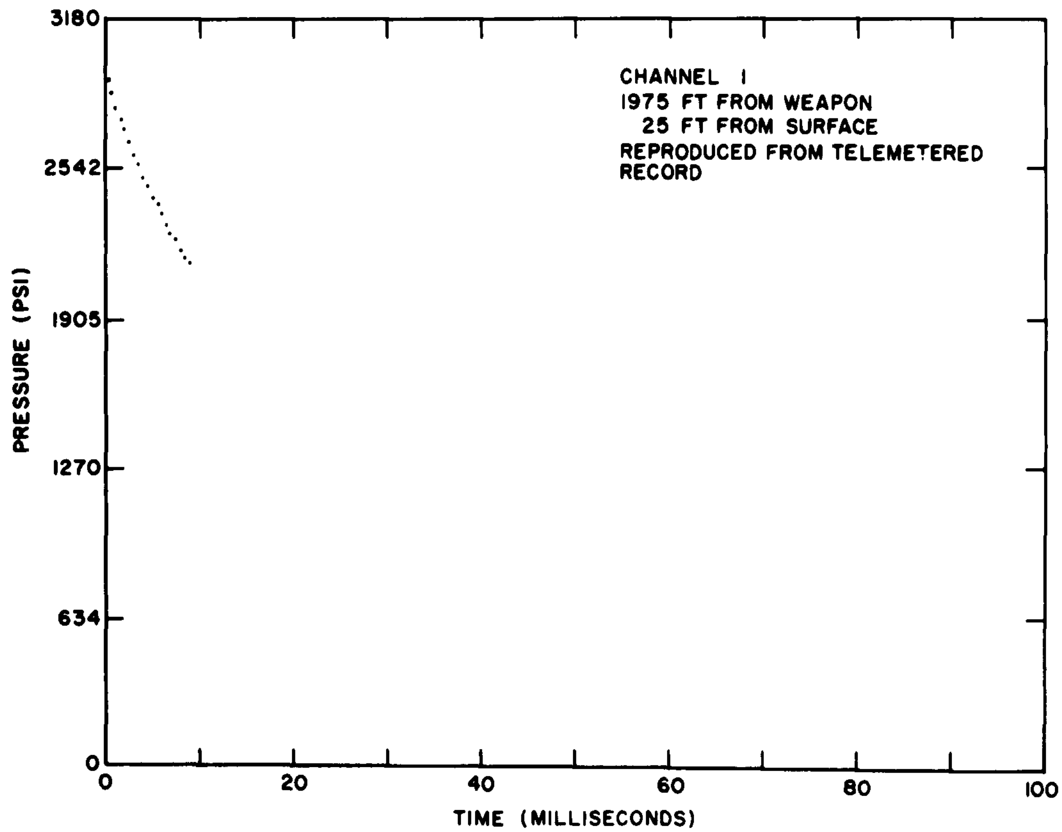

Fig. 4.5—Pressure vs time, Channel 1, System A.

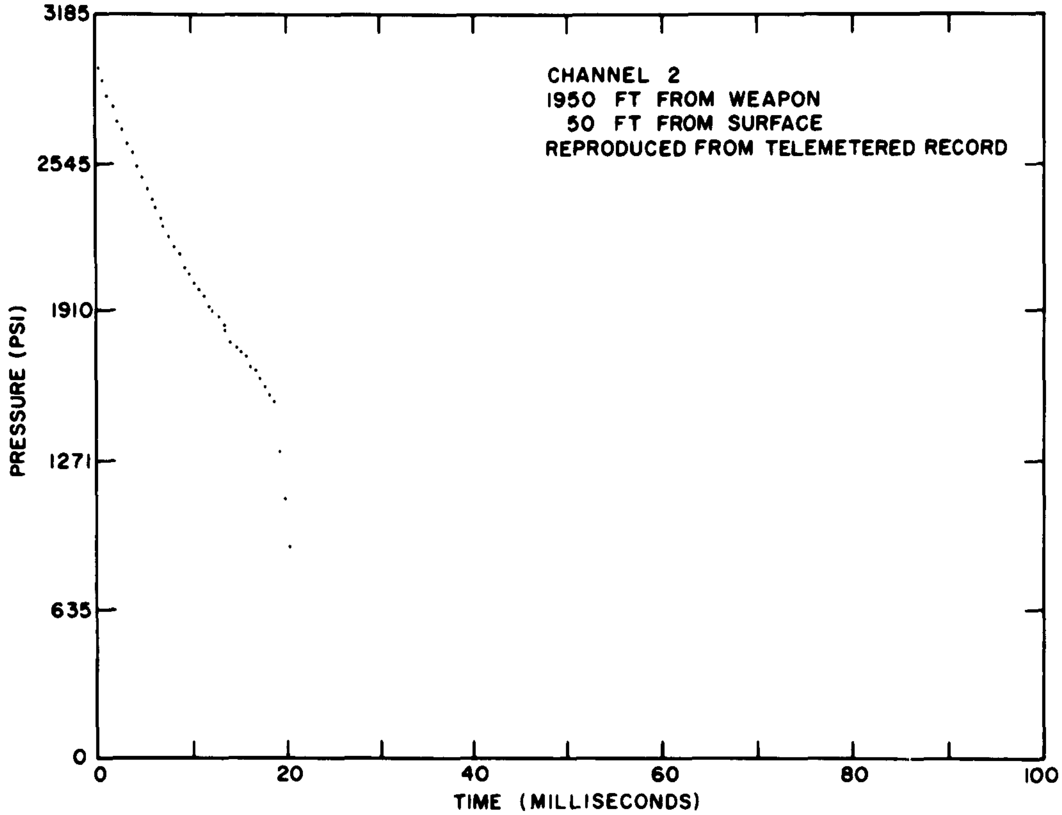

Fig. 4.6—Pressure vs time, Channel 2, System A.

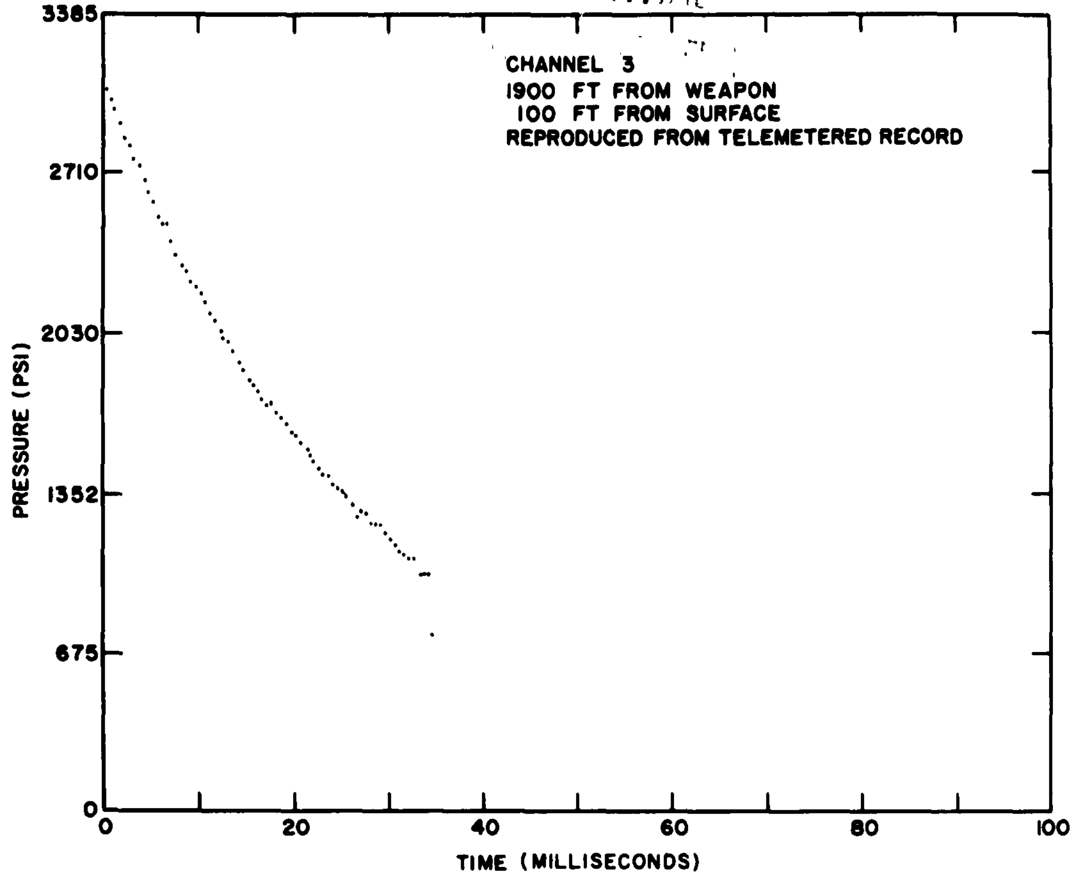

Fig. 4.7—Pressure vs time, Channel 3, System A.

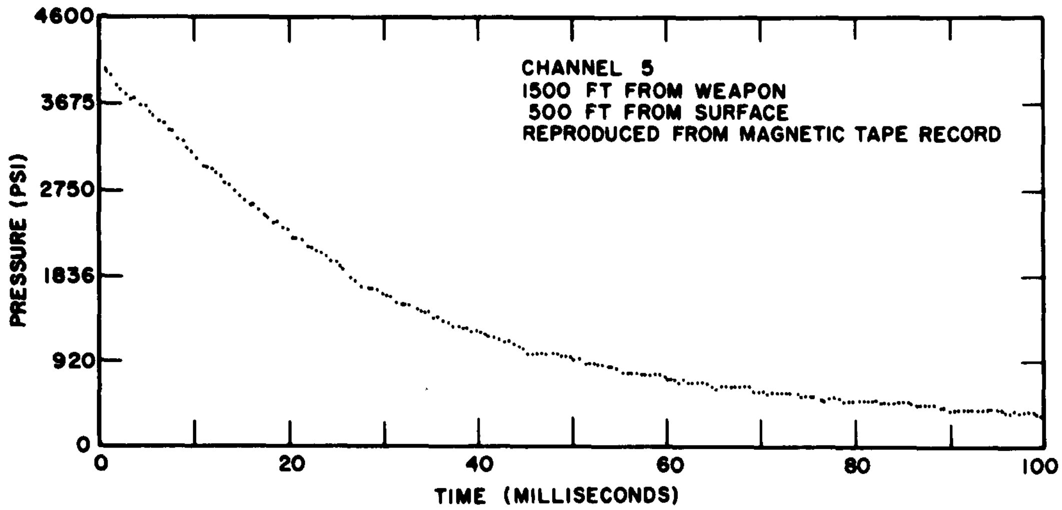

Fig. 4.8—Pressure vs time, Channel 5, System A.

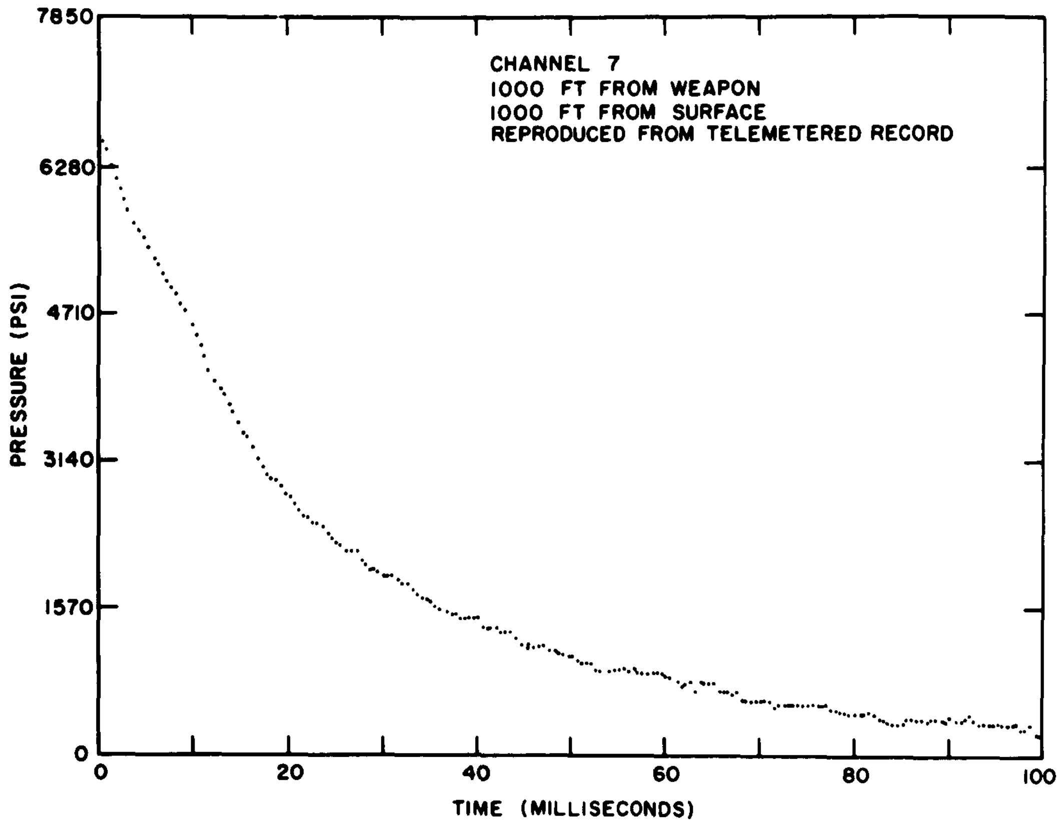

Fig. 4.10—Pressure vs time, Channel 7, System A.

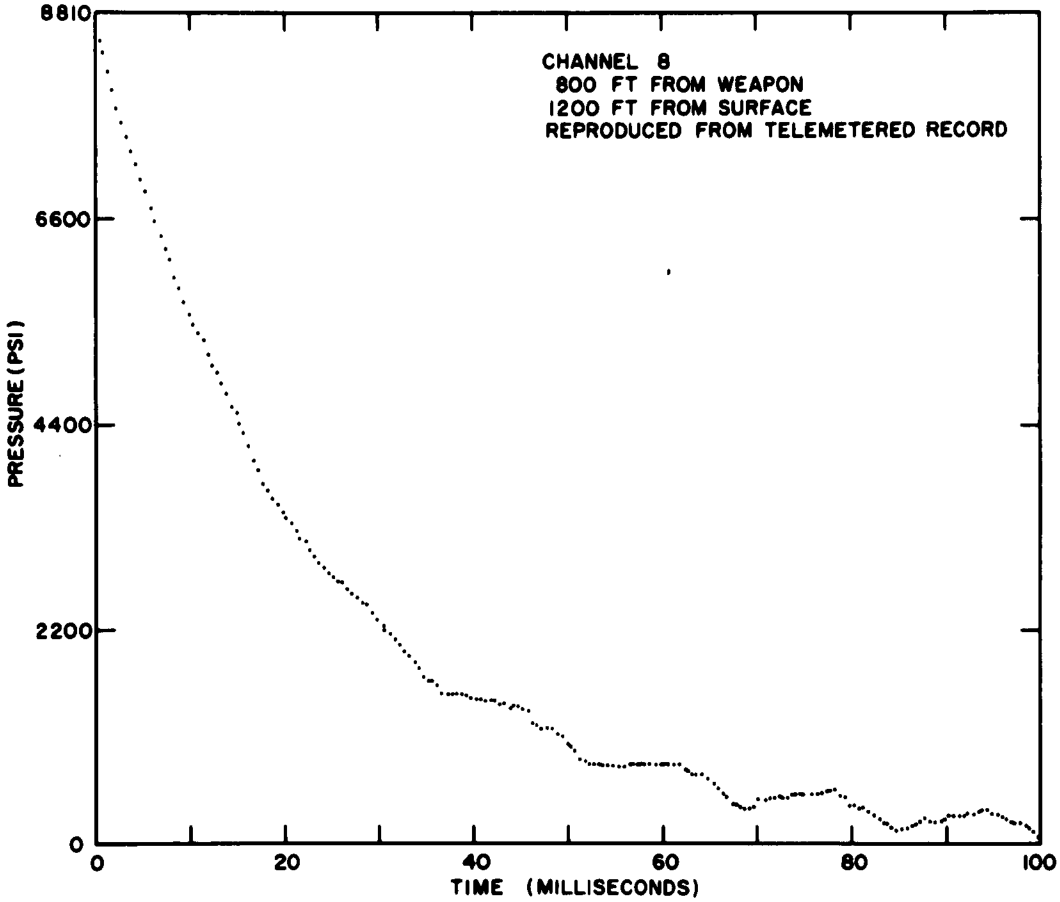

Fig. 4.11—Pressure vs time, Channel 8, System A.

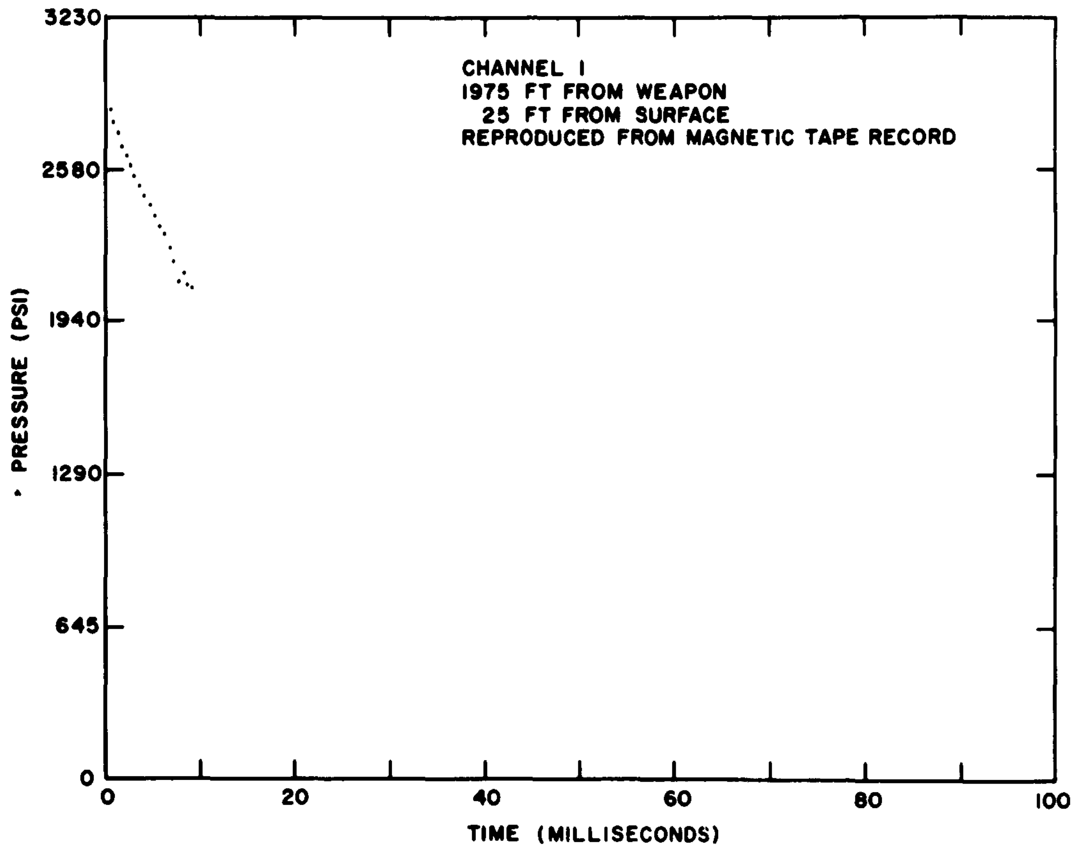

Fig. 4.12—Pressure vs time, Channel 1, System C.

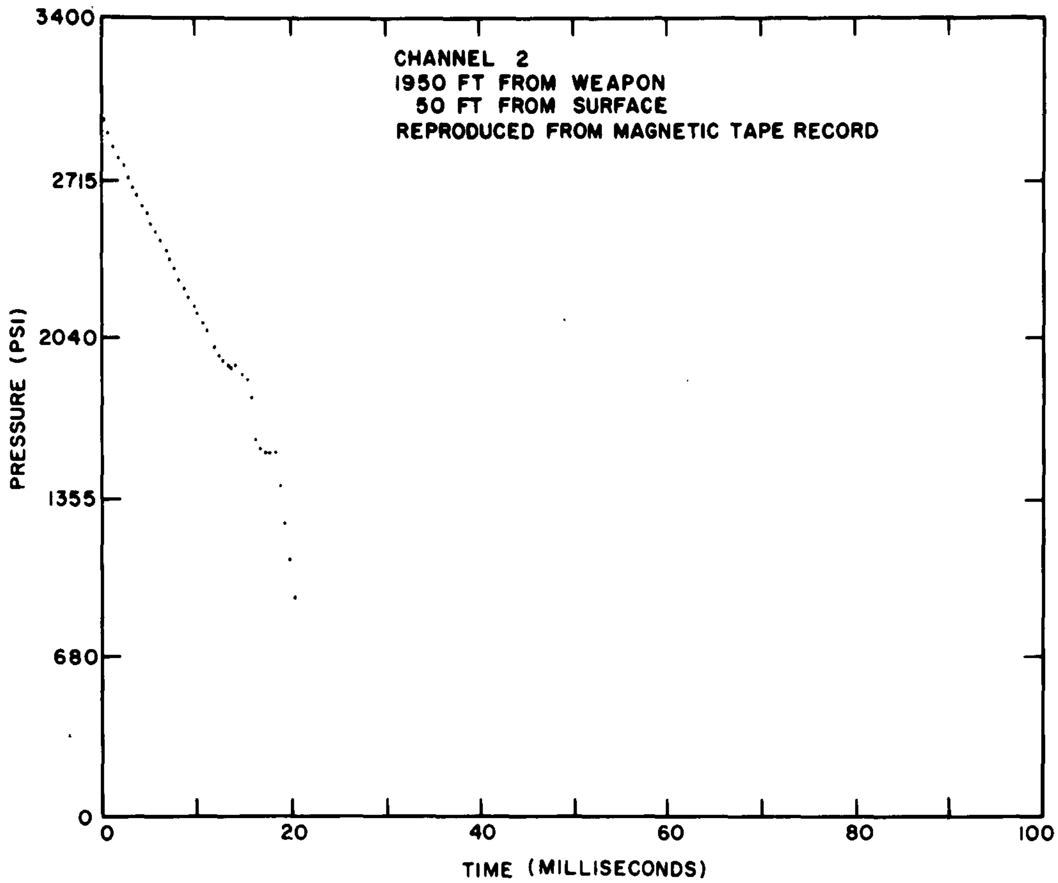

Fig. 4.13—Pressure vs time, Channel 2, System C.

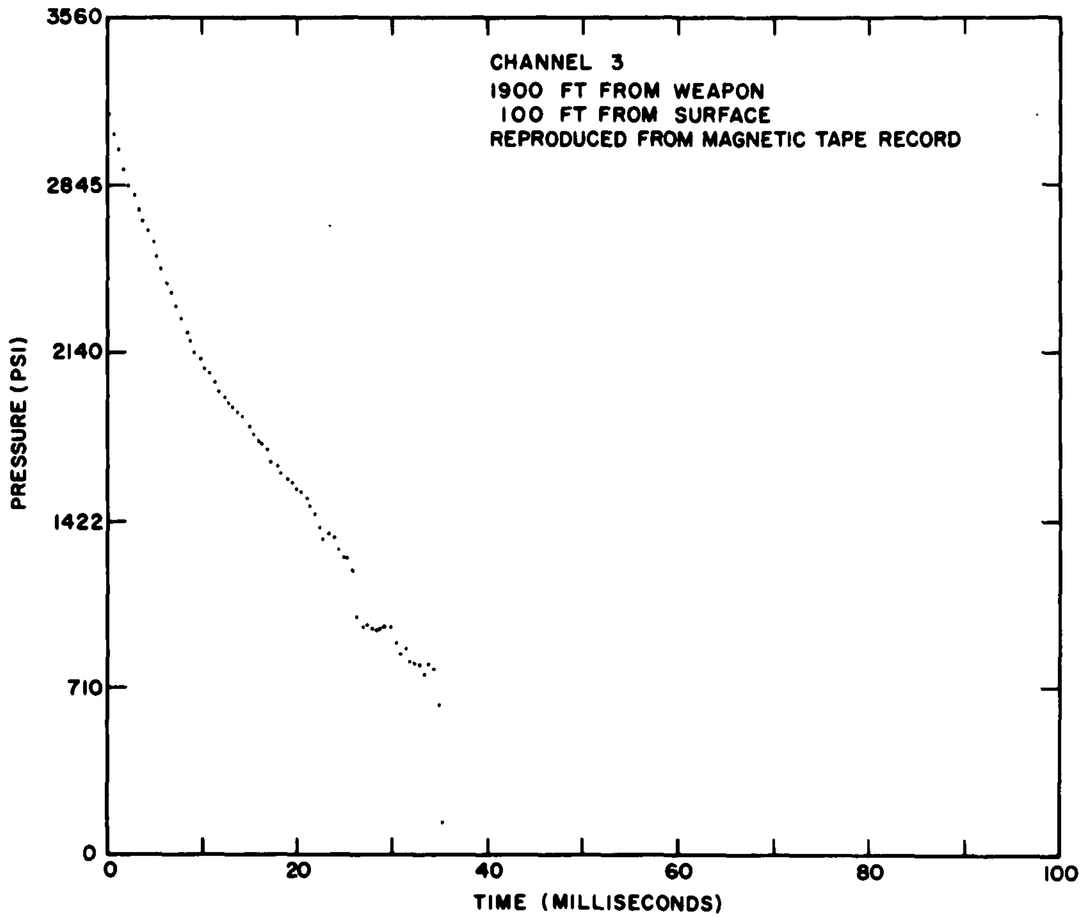

Fig. 4.14—Pressure vs time, Channel 3, System C.

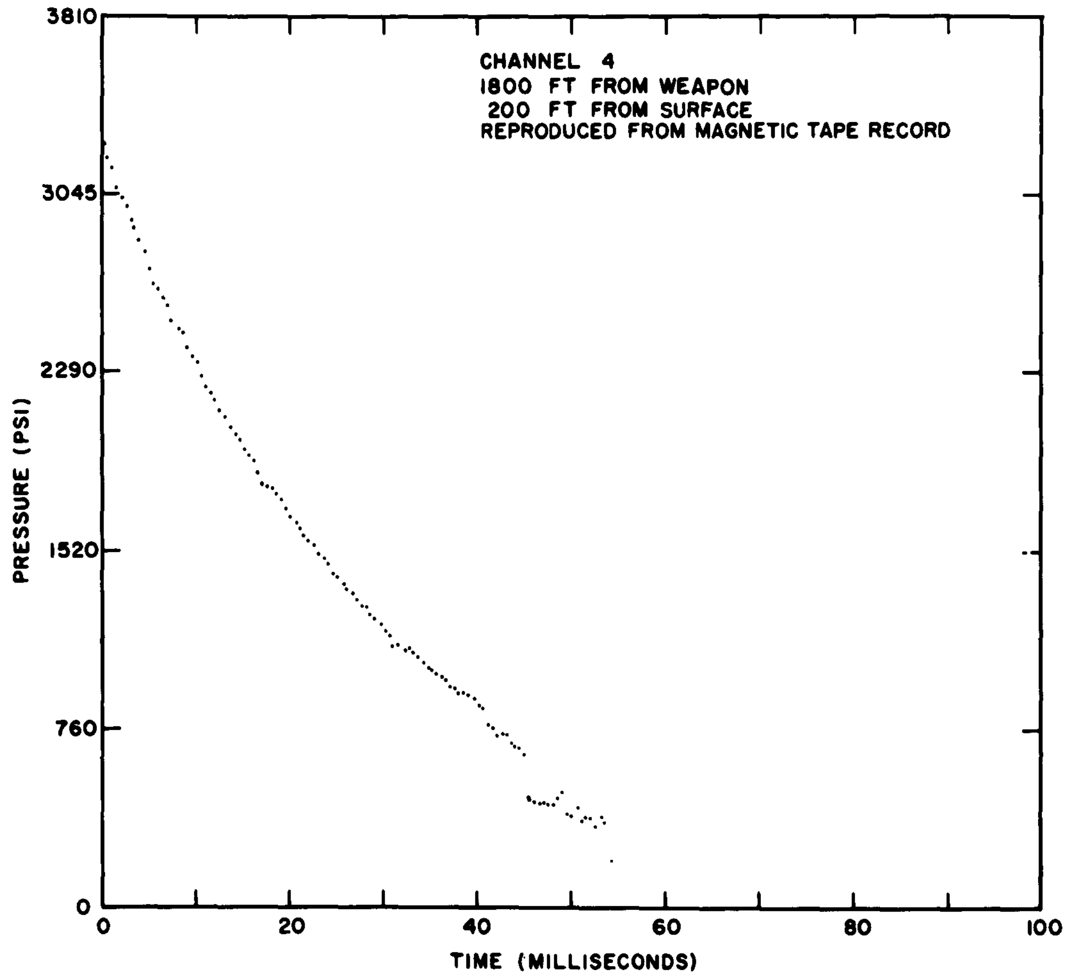

Fig. 4.15—Pressure vs time, Channel 4, System C.

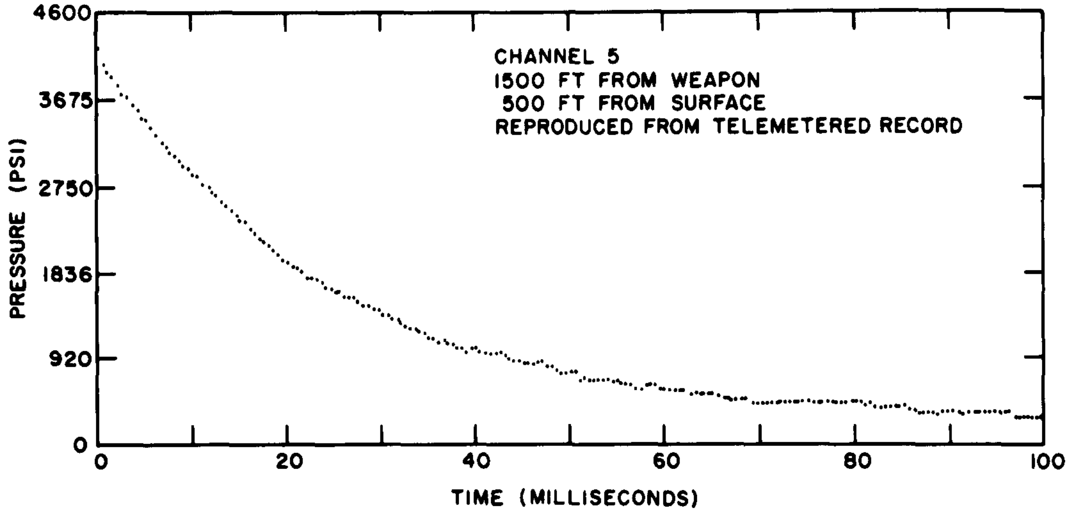

Fig. 4.16—Pressure vs time, Channel 5, System C.

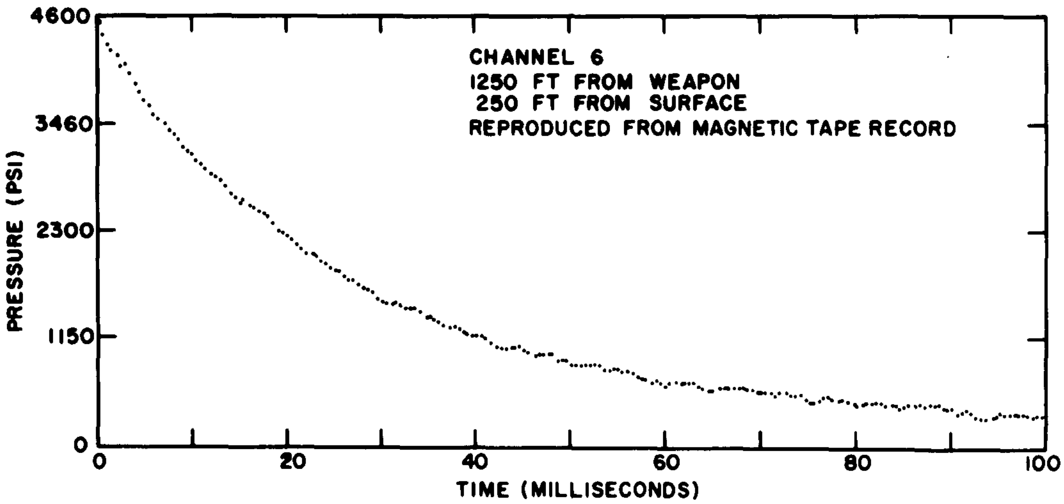

Fig. 4.17—Pressure vs time, Channel 6, System C.

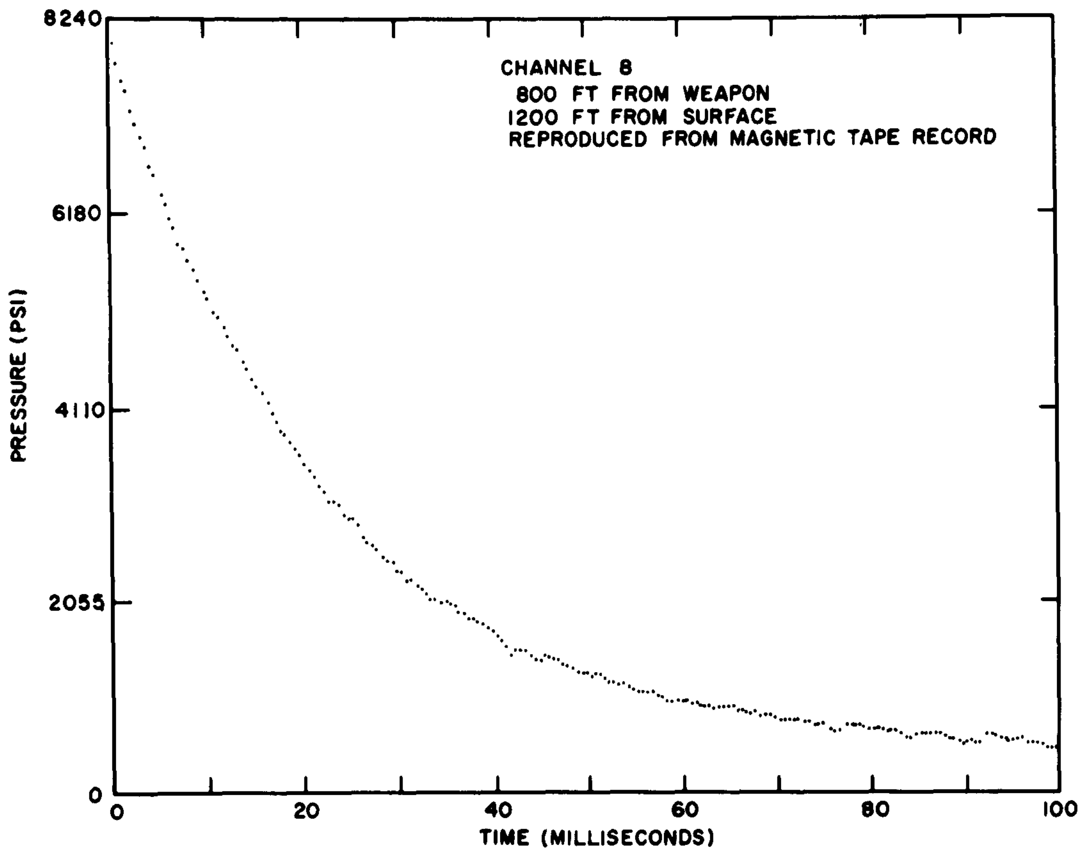

Fig. 4.18 — Pressure vs time, Channel 8, System C.

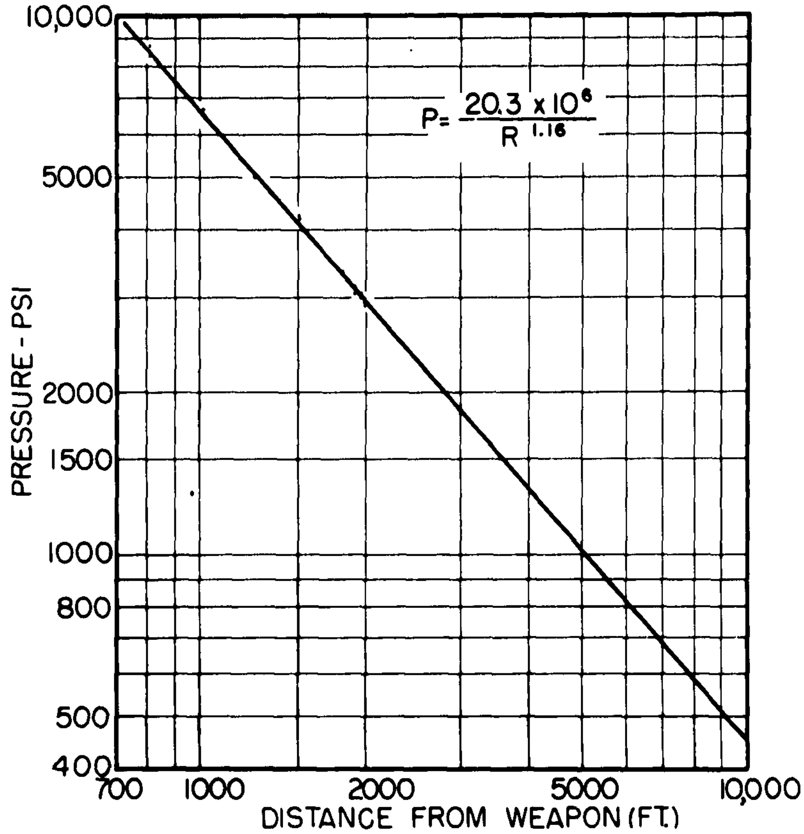

Fig. 4.19—Pressure vs distance from weapon.

14 gauge stations (Fig. 4.20) show considerable scatter near the surface. It is probable, however, that the time constant slowly increases with distance from the weapon. The preliminary report[1] of Project 1.3 lists average time constants of 38 msec at 5575 ft and 39 msec at 11,000 ft which is consistent with the sketched-in curve in Fig. 4.20.

4.5 IMPULSE AND ENERGY FLUX DENSITY

The impulse of a shock wave is the time integral of pressure.

$$I = \int_0^t P\, dt \tag{4.3}$$

Using the IBM punch cards of pressure-time data, the impulse was obtained by numerical integration of each pressure-time record to the time when the curve intersected the base line (Table 4.3). The log of the average values for each gauge is plotted against the log of 1/R, where R is the distance from the weapon, in Fig. 4.21. From the plot it is seen that as a result of surface cutoff the impulse values from the four channels nearest the surface fall below the projected straight line segment from the four deeper gauge locations. The relation between impulse and distance from the Wigwam weapon for points not affected by surface cutoff was determined by the method of least squares to be

Table 4.1 — MAXIMUM PRESSURES

Series	Channel 1 1975 ft	Channel 2 1950 ft	Channel 3 1900 ft	Channel 4 1800 ft	Channel 5 1500 ft	Channel 6 1250 ft	Channel 7 1000 ft	Channel 8 800 ft	Source of records*
	Pressure, psi								
	System A, Telemetering								
0	3110	3000	3160		4270	5100	6800	8700	A
0	2997	3125	3129		4287	5001	6494	8652	C
0	2978	3025	3062		4187	4968	6620	8710	B
1	2975	3050	3150		4400	5190	6780	9040	A
1	2958	3113	3039		4388	5248	6904	8808	C
1	2907	3000	3087		4266	5006	6737	8746	B
4	2960	2958	3017		4271	4972	6567	8778	C
4	3009	2965	3076		4315	4909	6676	8730	B
4	2980	3080	3100		4250	5100	6725	8850	A
6	2856	3125	3129		4148	4967	6757		C
6	2848	2955	3111		4145	5076			B
7	2958	3039	3063			5032	6846	8787	C
7	3003	3058	3034			5114	6494	8882	B
Average	2964	3030	3089		4266	5053	6700	8789	
	System C, Magnetic-tape Recording								
2	2950	3100	3190	3360	4400	4780		8420	A
2	2835	3006	3144	3334	4107	4461		8251	B
5	2936	3193	3273	3531	4315	4760		8623	C
5	2883	2993	3069	3311	4140	4808		8243	B
Average	2901	3073	3169	3384	4241	4702		8384	

*A, record read at NEL on Telereader; B, paper enlargements read at NRL; C, records read by Telecomputing Corp. at Washington, D. C.

Table 4.2 — PRESSURE DECAY TIMES*

Series†	Channel 1 1975 ft	Channel 2 1950 ft	Channel 3 1900 ft	Channel 4 1800 ft	Channel 5 1500 ft	Channel 6 1250 ft	Channel 7 1000 ft	Channel 8 800 ft
0	26.4	24.0	28.2		28.5	25.5	20.9	21.1
1	27.9	25.9	26.8		25.1	24.3	23.0	20.6
4	27.3	28.5	26.8		26.3	24.2	22.2	21.2
6	26.7	25.9	29.1		32.2	25.8	24.7	
7	28.3	27.3	30.6			27.1	23.0	32.0
Average	27.3	26.3	28.3		28.0	25.4	22.8	21.2
2	32.8	35.1	26.7	30.5	30.5	26.7		23.6
5	29.6	35.5	28.1	30.7	31.6	26.2		24.4
Average	31.2	35.3	27.4	30.6	31.0	26.4		24.0

*All times in milliseconds.
†Series 0, 1, 4, 6, 7, telemetered data System A; series 2, 5, magnetic-tape recorded data System C.

Table 4.3 — IMPULSE

Series*	Channel 1 1975 ft	Channel 2 1950 ft	Channel 3 1900 ft	Channel 4 1800 ft	Channel 5 1500 ft	Channel 6 1250 ft	Channel 7 1000 ft	Channel 8 800 ft
	Pound Seconds per Square Inch							
0	22.6	37.0	51.3		128.5	133.7	161.2	188.1
1	22.3	36.9	50.6		125.8	130.7	168.3	200.8
4	22.8	36.6	51.7		120.1	125.6	173.1	207.0
6	22.0	36.6	53.8		122.4	134.1	177.9	
7	22.7	36.4	53.1			132.0	153.8	212.7
Average	22.5	36.7	52.1		124.2	131.2	166.9	202.1
2	22.0	38.1	52.3	76.2	134.4	141.3		207.2
5	22.1	37.6	51.1	78.1	135.6	141.9		211.6
Average	22.1	37.8	51.7	77.1	135.0	141.6		209.4
	Time of Integration, Milliseconds							
	9	16.5	26	45	104	114	109.5	98

*Series 0, 1, 4, 6, 7, telemetered data System A; Series 2, 5, magnetic-tape recorded data System C.

$$I = \frac{3.36 \times 10^4}{R^{0.77}} \qquad (4.4)$$

where I is in pound seconds per square inch and R is distance from the weapon in feet.

Another significant measure of the effectiveness of a shock wave is energy flux density which is the energy flux across a unit area of a fixed surface normal to the direction of propagation. The complete equation is given by the expression

$$E = (1 - 1.67 \times 10^{-4}\, P_{max} - 4.9 \times 10^{-12}\, P^2_{max})\, \frac{1}{\rho_0 C_0} \int_0^t P^2\, dt \qquad (4.5)$$

where ρ_0 is the fluid density, C_0 is the velocity of sound, and P_{max} is the maximum pressure. The terms involving P_{max} are due to the "after-flow" and are insignificant at pressures less than 10,000 psi and therefore were dropped in the computation of energy flux density from the IBM pressure-time cards. For sea water

Table 4.4 — ENERGY FLUX DENSITY

	Inch Pounds per Square Inch							
Series	Channel 1 1975 ft	Channel 2 1950 ft	Channel 3 1900 ft	Channel 4 1800 ft	Channel 5 1500 ft	Channel 6 1250 ft	Channel 7 1000 ft	Channel 8 800 ft
0	10100	15030	18890		46770	57410	90300	144630
1	9780	14920	18930		45800	54600	93860	152460
4	10280	14710	19450		43040	54200	97080	155940
6	9580	14700	20790		43620	59320	100970	
7	10150	14550	20240			55800	86980	155690
Average	9980	14780	19660		44810	56270	93660	152182
2	9550	15880	19800	26850	50740	53570		141550
5	9635	15470	18870	27690	50530	55240		143480
Average	9590	15680	19340	27270	50640	54400		142510

$$\rho_0 C_0 = 5.58 + 0.0065T$$

where T is temperature in degrees centigrade. The equation used to compute energy flux density with the IBM cards was

$$E = 0.1763 \int_0^t P^2 \, dt \tag{4.6}$$

The computation was accomplished by squaring and numerically integrating values from each data point. Table 4.4 presents the results of the integrations. The time of integration was the same as for the impulse calculations.

From the log-log plot (Fig. 4.21) of the energy vs distance from the weapon, it is evident that the four channels nearest the surface are affected by surface cutoff. For the four stations not affected by cutoff, the relation between energy flux density and distance from the weapon was determined by the method of least squares to be

$$E = \frac{3.81 \times 10^{10}}{R^{1.87}} \tag{4.7}$$

where E is in inch pounds per square inch and R is distance from the weapon in feet.

4.6 ARRIVAL TIMES

The arrival time of the shock wave at each of the gauge locations at Station Zero was obtained with three independent methods. All arrival time measurements used the fiducial pulse as zero time; thus a necessary assumption is that the arrival of the fiducial pulse was the same at all stations.

The fiducial pulse and shock wave arrival times were recorded on the magnetic-tape recorder at Station Zero. This recording system had a tuning fork as a timing source, whose measured frequency was 993.7 cycles/sec. The telemetered records utilized at 100 kc crystal-controlled secondary frequency standard as the timing source whose accuracy was better than 1 ppm. In addition to being recorded on film, the telemetered signals from Station Zero were also recorded in the trailer on a magnetic-tape recorder used as a recording backup. This recorder had a separate tuning fork as a timing source, whose measured frequency was 1001.7 cycles/sec. Shock wave arrival times from all three recording sources are tabulated in Table 4.5.

The telemetered film record from Station 0-1 was examined to determine shock wave arrival time. A tracing (Fig. 4.22) shows the first indication of a signal occurring 602 msec after the fiducial pulse. The transmitted signal disappeared 9 msec later.

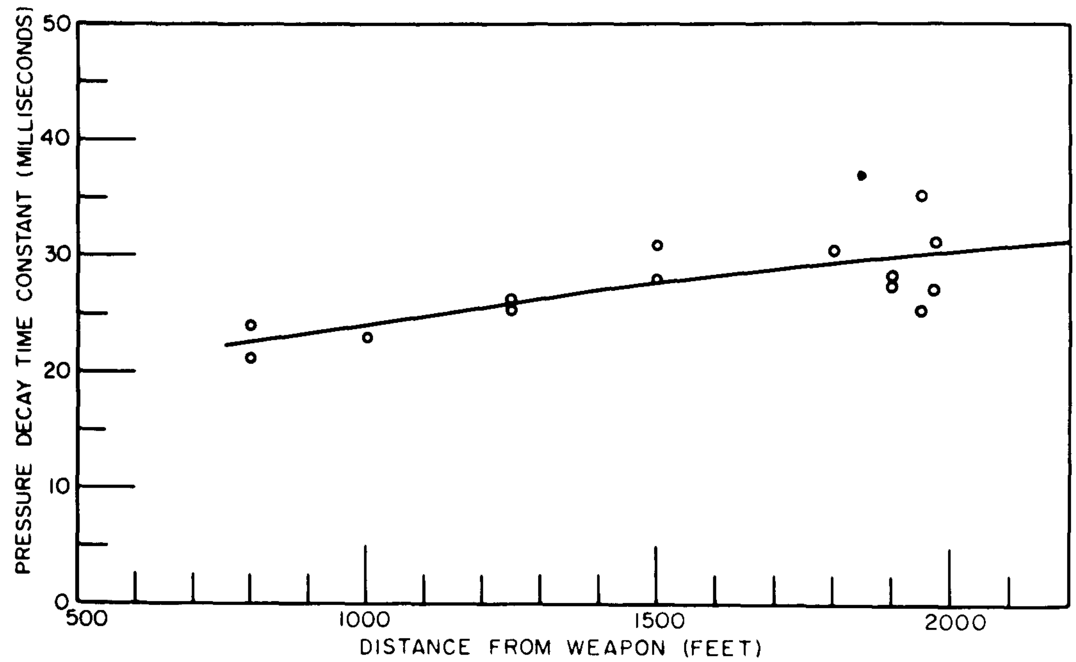

Fig. 4.20—Decay constant vs distance from weapon.

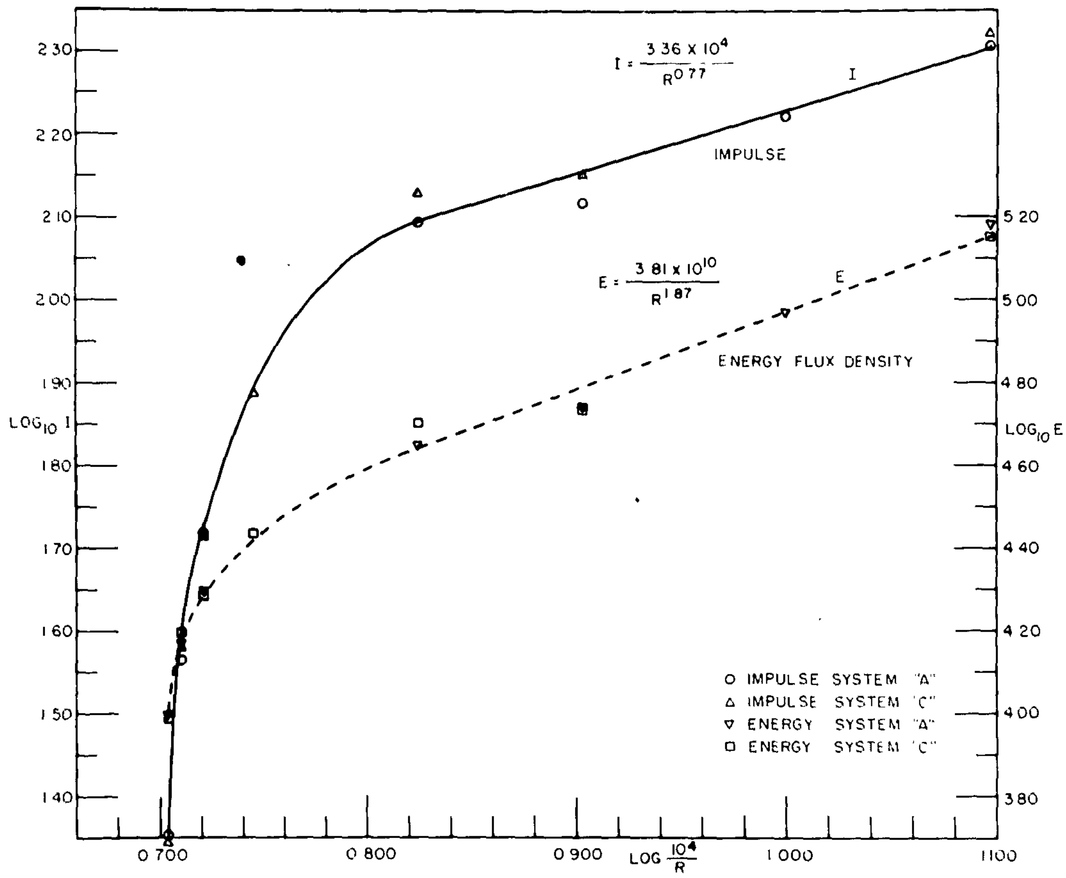

Fig. 4.21—Impulse and energy flux density vs distance from weapon.

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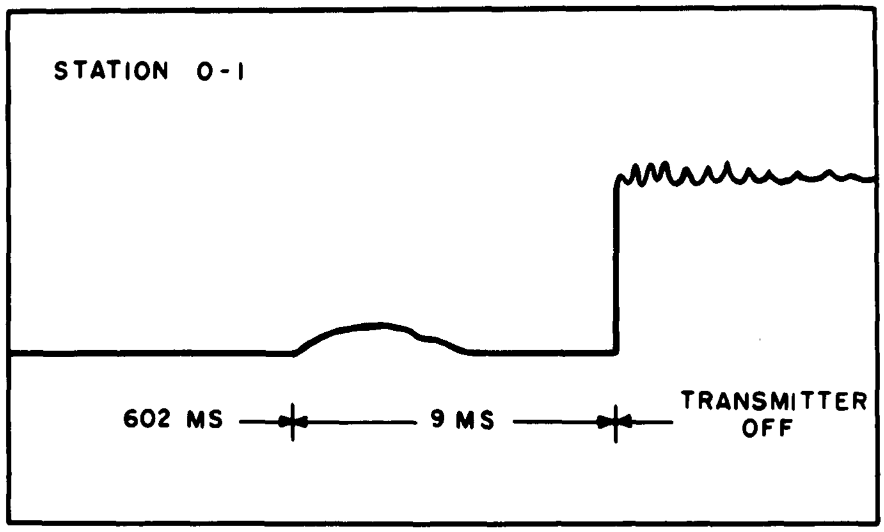

Fig. 4.22—Film record from Station 0-1 showing shock wave arrival.

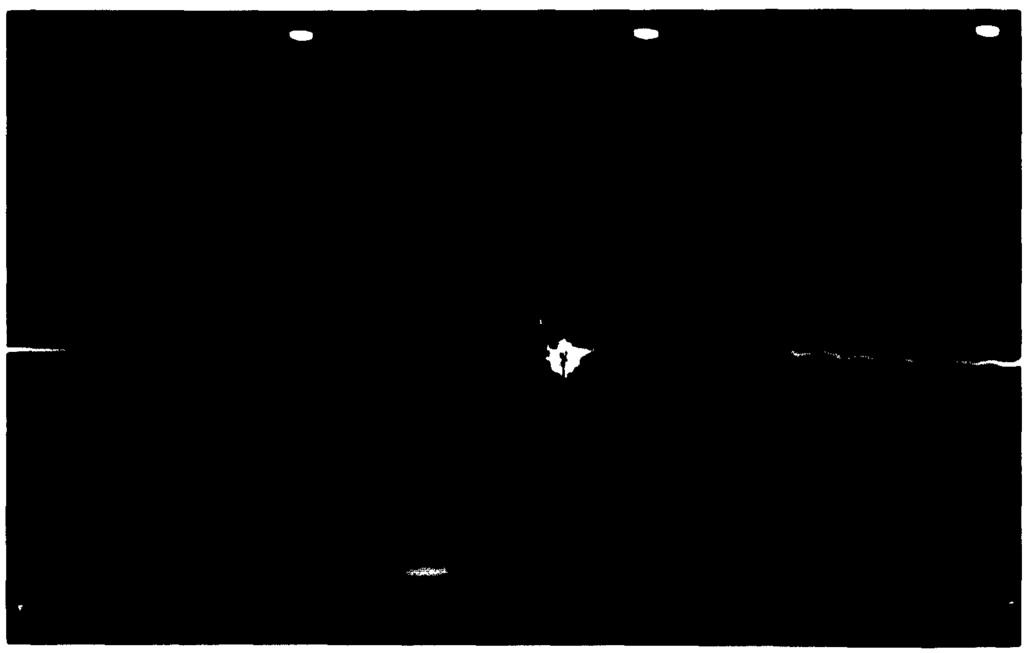

Fig. 4.23—Pressure vs time, USS Curtiss.

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Table 4.5—SHOCK WAVE ARRIVAL TIMES*

Channel	Distance from weapon	Station Zero magnetic-tape records	Telemetered record on film	Telemetered record on magnetic tape	Average
1	1975	379.9	379.8	380.3	380.0
2	1950	375.3	375.1	374.8	375.1
3	1900	364.8	365.0	365.2	365.0
4	1800	345.2	345.4		345.3
5	1500	286.3	286.3	286.0	286.2
6	1250	236.5	236.8	237.1	236.8
7	1000		187.5	187.7	187.6
8	800	147.9	148.1	148.2	148.1

*All times in milliseconds measured from fiducial pulse.

4.7 MEASUREMENTS ON THE USS CURTISS

A measurement of pressure and shock wave arrival time was made on the Curtiss as an incidental piece of information. A diaphragm pressure gauge with a strain gauge as the sensitive element was lowered 50 ft in the water over the side of the Curtiss about 1 hr before zero time. The output of the strain gauge was connected through a suitable amplifier to a spare cathode-ray oscillograph channel. Provision was made to electrically calibrate the system at −1 min.

Only the first shock wave was recorded because the camera ran out of film at about +8 sec. As can be seen from the record (Fig. 4.23), the pressure pulse was about 1 msec long. The high frequency modulation of the pulse is due to the vibration of the diaphragm at its natural frequency which was not filtered out. Timing marks at the bottom of the record are 1 msec apart.

The maximum pressure obtained from the record was 70 psi and occurred 7.106 sec after the fiducial pulse. After allowing for the time difference between the fiducial pulse and detonation (see Chap. 5, Sec. 5.1) and calculating the slant range from the reported position of the Curtiss at 34,950 ft, the average velocity of the shock wave was calculated to be 4935 ft/sec.

REFERENCE

1. Preliminary Report — Operation Wigwam Project 1.3, Free-field Pressure Measurements, WT-1007.

CHAPTER 5

DISCUSSION OF RESULTS

5.1 FIDUCIAL PULSE TIME DIFFERENCE

After the Wigwam experiment, the Preliminary Data Memorandum[1] stated that the EG&G fiducial pulse occurred at -30 ± 1 msec or 30 msec before detonation. A preliminary analysis of the Project 1.2.1 data from gauges directly over the weapon cast some doubt on the accuracy of the published time.

The Armour Research Foundation, as part of Project 4.4, measured the shock arrival times at distances from a few feet from the weapon to 1226 ft away along the weapon support cable.[2] Unfortunately, however, they did not include the EG&G fiducial pulse on their records; therefore an independent check of the fiducial pulse time difference is not available.

Project 4.4 gauges were hung on the weapon support cable. Project 1.2.1 gauges were hung on a cable 70 ft aft the weapon cable; thus in computing distances from the weapon, a slant range had to be used instead of a vertical distance. The computation of slant ranges is good only if it is known that the gauges and weapon cables were vertical and parallel. Undoubtedly this was not the case. However, it is possible to estimate the magnitude of this error.

The shock front arrival times along the weapon support string as determined by Project 4.4 were:

Nominal distance from weapon, ft	Time of arrival, msec
671	106
771	126
1226	217

These arrival times were measured from detonation as determined by the burst of electromagnetic radiation.

Figure 5.1 shows the above data plotted, along with the NRL arrival time data shown in Table 4.5. From 671 to 1226 ft the shock front velocity was 5.00 ft/sec along the weapon string. By extrapolation, the surface arrival time was 372 msec after detonation. A different method of arriving at the surface arrival time was accomplished by integrating the acoustic velocity (published in the Preliminary Data Memorandum)[1] in 100-ft steps from the 1226-ft location to the surface. This gave a surface arrival time of 374 msec. These two extrapolated points are also plotted on Fig. 5.1. It should be noticed that the NRL data and the Project 4.4 data lie on two essentially parallel lines with a time difference at the surface of 12.5 msec. This time represents the difference between the recorded fiducial pulse and weapon detonation.

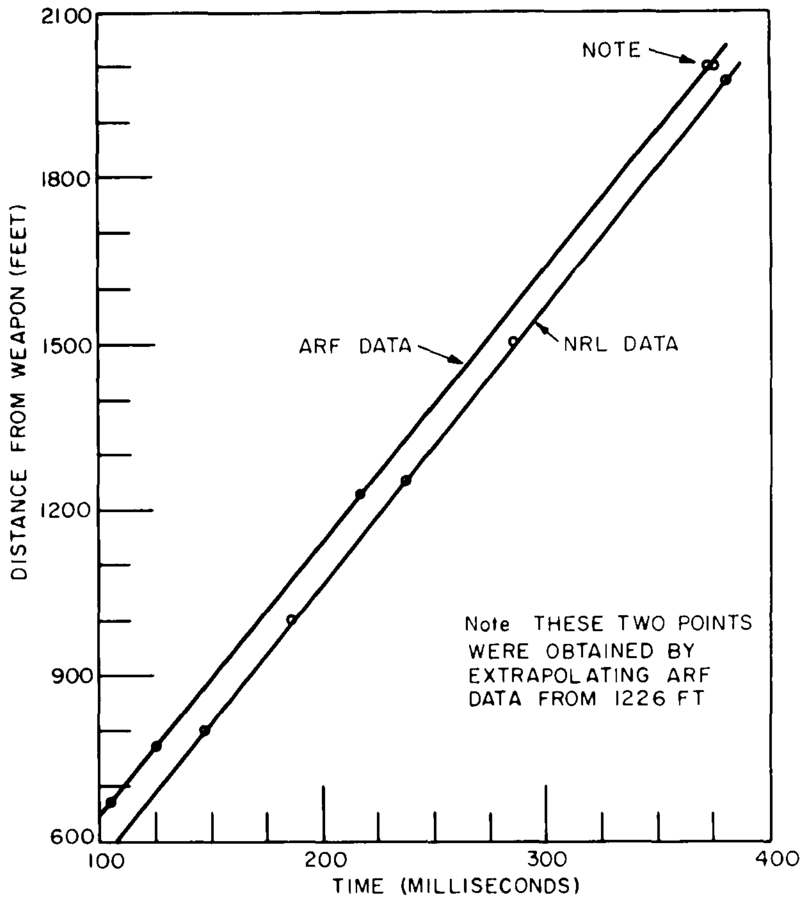

Fig. 5.1—Shock wave arrival times.

A second method of arriving at the difference between detonation and the recorded fiducial pulse requires a preliminary assumption that both the weapon string and the NRL gauge string were vertical and parallel which would establish a slant distance from the weapon to the NRL Channel 6 gauges of 1252 ft. According to the Project 4.4 data, the shock wave travel time would be 222.2 msec. The time from the recorded fiducial pulse to the shock wave arrival at Channel 6 gauges was 237 msec, a difference of −14.8 msec. Several cases of weapon and gauge string drift were considered, and the effect of drift is tabulated in Table 5.1.

The data in Table 5.1 show that the difference in time between detonation and the recorded fiducial pulse was no greater than −15.2 msec, and probably no less than −11.4 msec. Scripps has reported[3] that the weapon drift was not more than 50 ft. The large drifts shown in Table 5.1 illustrate the relative unimportance of weapon and gauge string drifts in affecting determination of the fiducial pulse difference. To summarize, the present determination of the EG&G fiducial pulse occurrence is −15.2 + 3.8 − 0 msec. The best estimate based on available data is −12.5 ± 1 msec, or 12.5 msec before weapon detonation.

From a tracing of the signal from Channel 1, 25 ft below the water surface (Fig. 5.2), the arrival time of the shock wave at the water surface has been computed. Since the pressure on the gauge is cut off 11 msec after arrival, the arrival of the shock wave at the surface should be one-half this interval, or 5.5 msec after arrival at the gauge. This means that the arrival time of the shock wave at the surface occurred 385.5 msec after the recorded fiducial mark, or about 373 msec after weapon detonation.

Table 5.1—EFFECT OF WEAPON AND GAUGE STRING DRIFT

Case	Slant distance, ft	Arrival time Channel 6 gauge, msec	Fiducial difference, msec
Both strings vertical and parallel	1252	222.2	−14.8
Gauge string vertical and weapon aft 200 ft	1250	221.8	−15.2
Gauge string vertical and weapon forward 200 ft	1269	225.6	−11.4
Gauge string 100 ft forward and weapon 200 ft forward	1258	223.4	−13.6

Table 5.2—OBSERVED OVERSHOOT

Telemetering channel	Signal overshoot	Calibration overshoot
1	Yes	No
2	Yes	No
3	Yes	No
5	Yes	Yes
6	Yes	Yes
7	No	No
8	Yes	Yes
Magnetic-tape channel		
1	Yes	No
2	Yes	No
3	Yes	No
4	Yes	No
5	No	No
6	No	No
8	No	No

5.2 OVERSHOOT

Some of the shot records (Fig. 4.2) show "overshoot" at the leading edge of the pressure signal. This overshoot is of the order of 200 μsec in length and is 10 to 15 per cent above the exponential decay curve. This overshoot was investigated, first, to determine if it was real and, if not, to determine the cause. The overshoot appears on some, but not all, of the telemetered and magnetic-tape records. A tabulation of the observed overshoot is shown in Table 5.2.

It should be noted that where overshoot occurs on calibration there is always overshoot on the signal. Since overshoot in calibration only occurs on the telemetered records, the telemetering system was investigated for possible causes, with the following deduction. The output from the subcarrier demodulators was fed through two-section low-pass pi network filters, which were sensitive to changes in terminating impedance. The filters were adjusted before the shot for no overshoot without the cathode-ray oscilloscopes being connected. Apparently the change in terminating capacity when the cathode-ray oscillographs were connected changed the filter characteristics sufficiently to distort the response to a step function. Where the overshoot occurs on calibration, the overshoot on the record may be ignored.

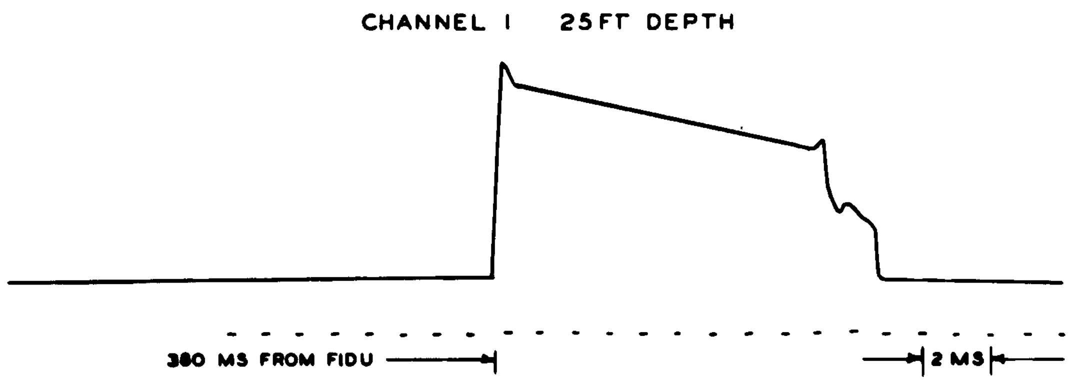

Fig. 5.2—Channel 1 signal 25 ft below surface.

However, there are several cases (confined to Channels 1 to 4 of both systems) where overshoot occurred on the signal but not on the calibration record. Channels 1 to 4 used $\frac{1}{2}$-in.-diameter tourmaline disks in the pressure pickup. Channels 5 to 8 used $\frac{3}{4}$- or $\frac{7}{8}$-in. disks. On the possibility that overshoot might be a characteristic of the $\frac{1}{2}$-in. gauges, the original calibration records of all gauges were reviewed at NOL. Gauge calibration was accomplished by comparing the gauge signal produced by a shaped charge to the signal from standardized $\frac{3}{8}$-in. gauges on the same charge rig. The pressure-time record from $\frac{3}{4}$- and $\frac{7}{8}$-in. gauges were very similar in appearance to the standardized gauges. However, the $\frac{1}{2}$-in. gauge records show a much higher leading edge "spike," about 100 msec long and about 20 per cent higher, than the standardized gauges for the same calibration height. This spike was ignored in establishing the gauge factors. The increased gauge sensitivity for an extremely short time would cause an apparent overshoot on the leading edge of the record from a spherical charge with exponential decay.

For the above reasons, it was concluded that the overshoot on the records is not real and should be ignored.

The irregularity in the cutoff on Channels 1 and 2 (Figs. 4.1 and 5.2) is apparently due to a reflection from the bottom of the weapon support barge. The characteristic reflection of a step pressure wave from an air-backed plate (in this case the bottom of the barge) is a brief upward spike of pressure followed by a quick drop to a negative pressure. This negative pressure just cancels the positive pressure wave to make the resultant pressure on the bottom of the barge zero. The reflected wave from the bottom of the barge spreads out laterally as it propagates downward; thus the magnitude of the positive and negative parts of the wave is reduced as the distance is increased.

When the reflected wave reached the gauges at 25 and 50 ft, it added a positive spike of pressure, followed by a drop in pressure which was not sufficient to wholly cancel the direct pressure from the bomb. 1.6 msec after the spike of pressure from the barge reflection, the reflection from the sea surface arrived to reduce the pressure at the gauges to zero in the characteristic fashion of "surface cutoff." The time of reflection arrivals is compatible with the approximate 4-ft draft of the barge.

5.3 YIELD

The maximum pressure from an underwater explosion in terms of charge weight and standoff is given by the expression[4]

$$P_{max} = K\left(\frac{W^{1/3}}{R}\right)^{\alpha} \tag{5.1}$$

where P_{max} is maximum pressure pounds per square inch, W is weight in pounds, and R is charge standoff in feet. For TNT, $K = 2.16 \times 10^4$; $\alpha = 1.13$. The equivalent charge weight in pounds of TNT for the Wigwam weapon was computed for a distance of 2000 ft from the weapon. Pressure was determined from the Wigwam pressure-distance equation (Eq. 4.1). For 2000 ft, $W = 4.05 \times 10^7$ lb. The above equivalent weight assumes the same shock conversion efficiency for TNT and the Wigwam weapon.

5.4 PRECISION OF MEASUREMENTS

The pressure-time measuring systems described in this report have two principal components: a pressure pickup with its calibration electronics and a "recording voltmeter," which is either telemetering or magnetic-tape recording, which includes cathode-ray oscillograph recording and film reading. The precision of the recording voltmeter is determined by the linearity of the recorder and the precision of reading the film record. The variation in measured peak pressure of any one channel in the various series of recordings is a measure of this precision. The probable error of the mean peak pressure for any one channel was computed from the data in Table 4.1 and was always less than 1.5 per cent for the telemetering records and less than 2 per cent for the magnetic-tape recorded records.

Channel 5 employed the same gauge and gauge calibration electronics for both the telemetering and magnetic-tape recording systems; therefore the measured peak pressure should have been identical for both systems. The fact that the mean values for the two systems differed by less than 1 per cent enhances confidence in the precision of the recording systems.

The accuracy of conversion of an observed deflection (or voltage) into pressure depends upon knowing the KA or piezoelectric constant of the gauge as well as upon the deflections, the calibrating voltage V_s, and the value of the calibrating capacity C_s. The gauge factors of the pressure pickups were determined by NOL by comparison with standardized gauges under explosive loads. The pressure pickup tourmaline gauge elements were also hydrostatically calibrated before the final protective coatings were applied. Differences between the dynamic and static calibrations varied by as much as 5 per cent. It is not possible to state the accuracy of the gauge factors clearly, but the error may be as much as ± 5 per cent. Calibrating voltages and capacities (Fig. 2.8) were determined with instruments whose rated accuracy was better than 1 per cent. The greatest difference between mean peak pressures from two different gauges at the same gauge location for the two recording systems was 7 per cent.

The probable error in determining the constant in the pressure-distance equation (Eq. 4.1) is a function of R and therefore is variable. However, the standard deviation for the exponent of R was calculated to be 0.026, corresponding to a probable error of 1.5 per cent.

REFERENCES

1. Preliminary Data for Project Use, 973.5, Serial No. 00608, by Deputy Technical Director, Operation Wigwam, May 25, 1955.
2. F. B. Porzel, Close-in Time of Arrival of Underwater Shock Wave, Project 4.4, Operation Wigwam, ITR-1082, May 1955.
3. Verbal Report by Dr. Horrey of Scripps Institute at Wigwam Conference, Oct. 18, 1955.
4. R. H. Cole, "Underwater Explosions," p. 242, Princeton University Press, 1948.

CHAPTER 6

CONCLUSIONS

The underwater pressures produced by detonation of the Wigwam weapon may be scaled to those produced by a spherical charge of a more conventional explosive. For the Wigwam weapon the pressure-time curve decays exponentially with a time constant varying from about 22 msec at 800 ft from the weapon to 30 msec at 2000 ft.

The maximum pressure is given by the expression

$$P_{max} = \frac{2.03 \times 10^{7}}{R^{1.16}} \qquad (6.1)$$

Impulse at locations not affected by surface cutoff is given by the expression

$$I = \frac{3.36 \times 10^{4}}{R^{0.77}} \qquad (6.2)$$

Energy flux density at locations not affected by surface cutoff is given by the expression

$$E = \frac{3.81 \times 10^{10}}{R^{1.87}} \qquad (6.3)$$

For the above equations, P is pressure in pounds per square inch, R is distance from weapon in feet, I is impulse in pound seconds per square inch, and E is energy flux density in inch pounds per square inch.

The fiducial pulse occurred at −12.5 msec ± 1 msec. The shock wave arrived at the surface of the water 385.5 msec after the fiducial pulse, or 373 msec after weapon detonation.

The equivalent weight of TNT required to produce the same pressure at 2000 ft as the Wigwam weapon was 4.05×10^{7} lb.

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