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Project 8.2

MEASUREMENT OF THERMAL RADIATION WITH A VACUUM MICROPHONE

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REGRADED UNCLASSIFIED
BY AUTHORITY OF AG 24/073
BY Burman Wode, Jr., JUL 14 1964

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OPERATION UPSHOT-KNOTHOLE

Project 8.2

MEASUREMENT OF THERMAL RADIATION WITH A VACUUM MICROPHONE

REPORT TO THE TEST DIRECTOR

REGRADED UNCLASSIFIED
BY AUTHORITY OF AG 24/073
BY Burman Woods Jr. JUL 14 1964

by

J. Lloyd Bohn
Ralph J. Cowie, Jr.
Marcus D. O'Day

March 1954

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Geophysics Research Directorate
Air Force Cambridge Research Center
Cambridge 39, Massachusetts

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ABSTRACT

The object of this project was to obtain a quantitative proof of the feasibility of the vacuum microphone for the measurement of the intensity of thermal radiation from nuclear detonations. Ten sets of measurements were made on the thermal radiation from as many shots. Data were recorded on magnetic tape and later filmed from an oscilloscope. Sensing elements were placed near ground zero at distances varying from 5309 ft to 10,568 ft. Additional units were located at the manned stations at distances varying from 6.49 to 13.0 miles. Time intensity curves for all shots have been integrated to obtain total thermal energy. Times to first minima and second maxima are given for all 10 detonations. Curves of Thermal Energy (KT) vs Total Weapon Yield (KT), Thermal Energy per KT vs Slant Range, and Times of First Minima and Second Maxima vs Total Weapon Yield, are plotted.

Sufficient engineering data have been obtained to demonstrate that the vacuum microphone is a suitable device for the measurement of intense thermal radiation with good time resolution. Microphones have been developed with high sensitivity and low noise factors.

The values for the thermal yields are in substantial agreement with those obtained by NRL and NRDL. The values obtained with this equipment for Shots 4 and 10 are closer to those reported by NRDL, and are slightly closer to the results of NRL for Shot 9. However, in this case there is only a maximum deviation of 5 per cent in the data submitted by all three agencies.

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FOREWORD

This report is one of the reports presenting the results of the 78 projects participating in the Military Effects Tests Program of Operation UPSHOT-KNOTHOLE, which included 11 test detonations. For readers interested in other pertinent test information, reference is made to WT-782, Summary Report of the Technical Director, Military Effects Program. This summary report includes the following information of possible general interest.

a. An over-all description of each detonation, including yield, height of burst, ground zero location, time of detonation, ambient atmospheric conditions at detonation, etc., for the 11 shots.

b. Compilation and correlation of all project results on the basic measurements of blast and shock, thermal radiation, and nuclear radiation.

c. Compilation and correlation of the various project results on weapons effects.

d. A summary of each project, including objectives and results.

e. A complete listing of all reports covering the Military Effects Tests Program.

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PREFACE

In May of 1950, it was proposed by one of the authors that a pressure type microphone could be used in a vacuum to measure the intensity of light by its pressure. Among the experts in the use of such devices whom he consulted was Professor J. Lloyd Bohn, Head of the Physics Department of Temple University, who agreed to test the hypothesis with one of the microphones which he and his colleagues were developing to measure the acoustical properties of the turbulence encountered on the skin of a V-2 rocket in flight. In these experiments a chopping rate of about 10,000 cycles per second was used to interrupt the light before it reached the microphone diaphragm. This rate was also the resonant frequency of the microphone diaphragm. A very good signal to noise ratio was obtained with an ordinary projection lamp as a source and when Air Research and Development Command called upon the Geophysics Research Directorate of the Air Force Cambridge Research Center to participate in thermal radiation measurements from nuclear detonations, a project was set up utilizing this type of sensing element. Preliminary checks were made in the TUMBLER-SNAPPER test of 1952, but time did not allow for the proper design of the microphone and container for field work. In the present series of tests, new types of microphones were used with silvered glass diaphragms; the microphone and the associated oscillator circuit components were housed in a Pyrex glass tube and highly evacuated. Arrangements were made to locate our sensing elements near those used by other agencies for the same purpose but based entirely upon calorimetric measurements. This report describes the experiments and the results of the tests.

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CHAPTER 1

INTRODUCTION

1.1 OBJECTIVE

The objective of these experiments was primarily of a scientific and engineering nature. It was based on the hypothesis that it is possible to measure the intensity of light from the ultraviolet to the infrared by the mechanical effect it has on a highly reflecting surface. In order to check this proposal, a particular device, namely a capacitor type microphone of a special design, is placed in a high vacuum together with a coil and electron tube to form a radio-frequency oscillator circuit. The mechanical effect of the light changes the frequency of the oscillator and this change is detected by means of an appropriate receiver. The specific purpose of Project 8.2 was to compare the results of these experiments with data obtained by purely thermal devices.

There were also several engineering objectives to the experiments. Even though satisfactory data may be obtained, it does not follow that a satisfactory instrument can be developed based on the above principle. From an engineering standpoint, it was desired to determine the feasibility of the utilization of such a device for the routine measurement of thermal radiation. For instance, even with a silver reflector, from 3 to 8 per cent of the light is absorbed, heating the diaphram and causing it to expand. It was desired that the deleterious effect of such heating be determined for the particular design of microphone being used. The behavior of the microphone to intense light transients such as result from nuclear detonations was to be studied. A third engineering objective was to study the methods of recording the data; for example, the use of magnetic tape.

CHAPTER 2

EXPERIMENT DESIGN

2.1 GENERAL

The fact that light exerts a pressure has been known for over 50 years. For a perfect reflector, the pressure in dynes per square centimeter is equal to two times the energy density measured in ergs per cubic centimeter of the radiation striking normal to the surface. The advantage claimed for the use of a reflector is that a sensitive detector with high time resolution can be used for measuring high intensity thermal radiation without being destroyed. In these experiments, the distance from ground zero was determined by the requirement that the data are to be compared with those obtained from other equipment placed at particular locations. Otherwise, the only consideration of importance is that the sensing unit be located at a distance from the burst so that the shock wave does not arrive before the light signal is over.

Whenever high intensity thermal radiation impinges upon a surface, some heat is absorbed since in practice, no perfect reflector is available. This statement applies to the diaphragm of the microphone being employed. Figure A.1 of the Appendix illustrates the design of the capacitor type microphone used. The capacitance is formed by a center pole piece and a thin diaphragm separated by a thin dielectric of air. The periphery of the diaphragm being clamped and held at a fixed distance from the pole piece, permits changes in electrical capacitance between these two elements to take place only by flexure of the diaphragm material.

Laboratory experiments at Temple University have shown that flexures caused by light pressure impinging upon the diaphragm increase the effective electrical capacitance of the microphone; while those due to the heating of the microphone diaphragm by thermal absorption cause the diaphragm to buckle, increasing the dielectric spacing. This produces a decrease in the electrical capacitance of the microphone. When the microphone is used as the capacitive component of an oscillator tank circuit, light pressure produces an effective decrease in the basic operating frequency of the oscillator, and thermal absorption by the diaphragm produces a slow but quite evident rise of the basic frequency appearing as oscillator drift. Although this heading of the diaphragn, referred to as "The Thermal Effect," does not materially affect the measurements of light intensity, it is a nuisance, adding complexity to both transmitting and receiving equipment. A great deal of work at Temple University has been done to reduce the thermal effect. It was found that glass diaphragms were much superior to metal diaphragms in this regard. Also, a method of clamping the diaphragm was introduced so as to let the glass move slightly, and this greatly reduced the possibility of it buckling. The use of quartz or pyrex glass will minimize the thermal effect, but time was not available to use either of these materials for UPSHOT-KNOTHOLE. It is interesting to note that, if high time resolution is not necessary, a very sensitive detector could be made utilizing the thermal effect in such a microphone. It is contemplated that laboratory tests of such a device will take place later in the year.

All of the early experiments at Temple University were made utilizing the standard circuits associated with this type of microphone. However, when it was contemplated that one of the units would be near ground zero, it was realized that the Christov effect 1/ would invalidate any measurements taken with an amplitude modulated system. Hence the microphone was made the capacitive element of the tank circuit of an oscillator and the frequency modulation of this oscillator by the light pulses would produce frequency deviations proportional to the change in capacitance of the microphone which are proportional to the pressure from the light pulses on the microphone diaphragm. From the equation for resonance in an oscillating tank circuit

$$4\pi^2 f^2 = 1/LC,$$ it is readily shown that

$$df = \frac{-dc}{C}\,\frac{f}{2}$$

where f = resonant frequency

L = inductance of tank circuit

C = capacity of tank circuit

which verifies the above statement. It is apparent that for maximum sensitivity the value of C must be low and f must be high. As a practical compromise, 68 megacycles per second was chosen for the oscillator frequency during the tests.

At various times the question has been asked, "How does the system respond to light transients such as arise from a nuclear detonation?" This question must be broken down into two parts: (1) the microphone itself, and (2) the receiving and recording equipment. As far as the microphone is concerned, it receives transient pulses of light 1430 times per sec., i.e., the chopping frequency. Chopping frequencies as

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1 The Christov effect refers to the large electromagnetic pulse associated with large explosions.

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high as 10,000 cycles per second have been used successfully with this type of microphone. As the resolution is dependent upon the period of the chopping frequency used, which at 1430 cps is 0.7 millisecond, this would indicate the transient response time of the microphone itself to be more than adequate to provide the resolution required during these tests. The 1430 cps chopping rate therefore enables us to measure times to the first minimum and second maximum of the total thermal radiation response measured with these microphones to within 0.7 msec. The transient response time of the complete system, including microphone, FM receivers, audio filters, and tape recorders was checked experimentally during calibration periods when the sky was unusually clear. An additional chopper of wood 5x12 inches was spun in front of the standard sensing element chopping disc at a rate of several times per second thus causing sharp transients of solar radiation to strike the microphone diaphragm. These high intensity pulses were transformed by the sensing unit microphone-oscillator into the corresponding electrical impulses which were recorded on magnetic tape and transcribed on film in the usual manner. A portion of the film records of these experiments is shown in Fig. 2.1. Analysis of these records fails to detect any time delays in the system which might cause difficulty. The rise time and decay time for each wave train of Fig. 2.1 is not due to poor transient response but to the manner in which the added wooden interrupter cut off the solar radiation reaching the sensing unit. The conclusion is that the over-all system has a transient response which is ample for the purpose for which it is used.

2.2 INSTRUMENTATION

Several pieces of apparatus are necessary to obtain thermal data with this system. This series of equipment is termed a "chain" and in order to make sure that data would not be lost, several chains were used in each test. A chain consists of the following elements:

The microphone sensing element.
FM receiver at the proper frequency.
An audio frequency filter with an 18 db per octave pass band characteristic centered at the chopping frequency.
A magnetic tape recorder.
An oscilloscope and camera.

Some of these pieces of equipment can be common to several chains; as, for instance, the FM receiver. Two microphone sensing elements were usually used, one near ground zero and the other located in the immediate vicinity of the manned stations. Figure 2.2 shows the sensing unit being installed in the Frenchman Flat area. Figure 2.3 shows the sensing unit in position, the antenna and the power supply—timing box; the latter of which is placed in the foxhole for the actual firing. The piece of equipment which was most essential to duplicate in each chain was the magnetic tape recorder. In all, five recorders were used, two of which had six channels and one with two channels. The object of this duplication was to record at different levels on each channel so

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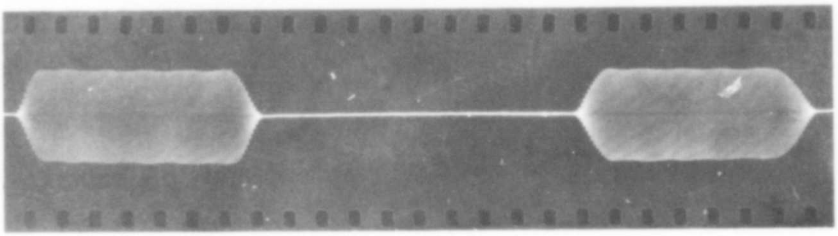

Fig. 2.1 Intermittent Calibration Showing Time Response of the System. Each cycle is 0.7 msec

that one channel would have saturated signals at the maximum light intensity, and at least one other would be of such a low level that no saturation would be possible. By this method, a wide dynamic range of recording levels could be achieved. The signal follows the sequence shown above. It is generated at the microphone by the light signal, transmitted to the manned receiving station where an FM receiver takes the signal, detects it, and passes it as an audio frequency to the electronic filter which eliminates a great deal of interference and thereby improves the signal to noise ratio. From the filter the signal is fed to the magnetic tape recorder. Later the record is retranscribed from the tape, displayed on an oscilloscope, and photographed. These receiving chains were located in mobile vans of the K-53 variety, (Fig. 2.4) which were located from 6.5 to 13 miles from ground zero depending upon the specific test. The interior of such a van is shown in Fig. 2.5. The original plans did not call for the tape recorders to be an essential part of the system, only a "back-up." In this case, the signal would be photographed from the oscilloscope at the time it occurred. However, the camera motors would sometimes cause interference without warning and spoil the record. Therefore, it was decided to record on tape and later transcribe on film so that no data would be lost. Figure 2.6 shows the microphone and all components associated with the sensing unit oscillator. Both the exploded view and the complete

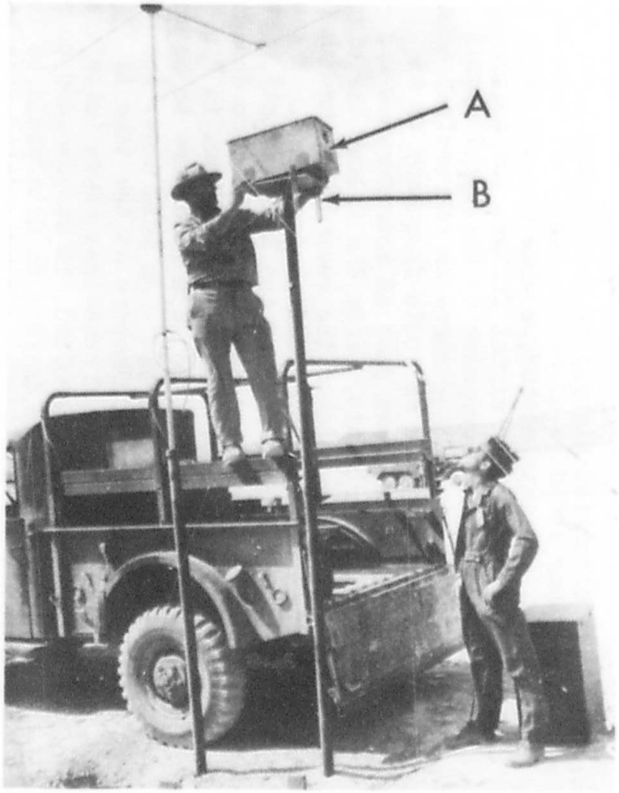

Fig. 2.2 Remote Unit Near Ground Zero. A - Sensing Unit. B - Planning Head, adjustable for obtaining correct azmuth and elevation.

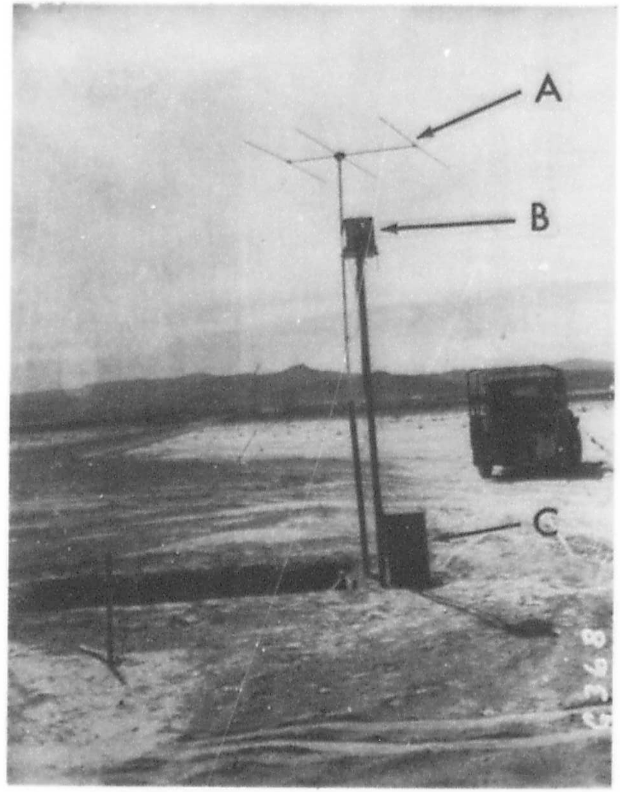

Fig. 2.3 Remote Station. A - Antenna. B - Sensing Unit. C - Battery Box with Timers; placed in protective trench the night before detonation

Fig. 2.4 Manned Stations. Note antennas for receiving signals from remote units.

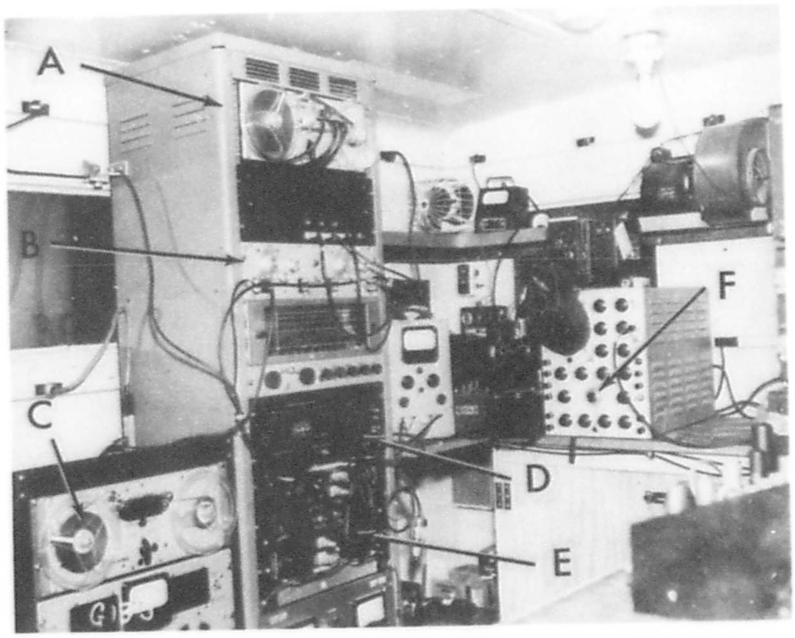

Fig. 2.5 Interior of Van A. A - Six Channel Recorder. B - Spencer-Kennedy Audio Filter. C - Single Channel Recorder. D - Test Oscillator. E - FM Receivers. F - Oscilloscope and Camera

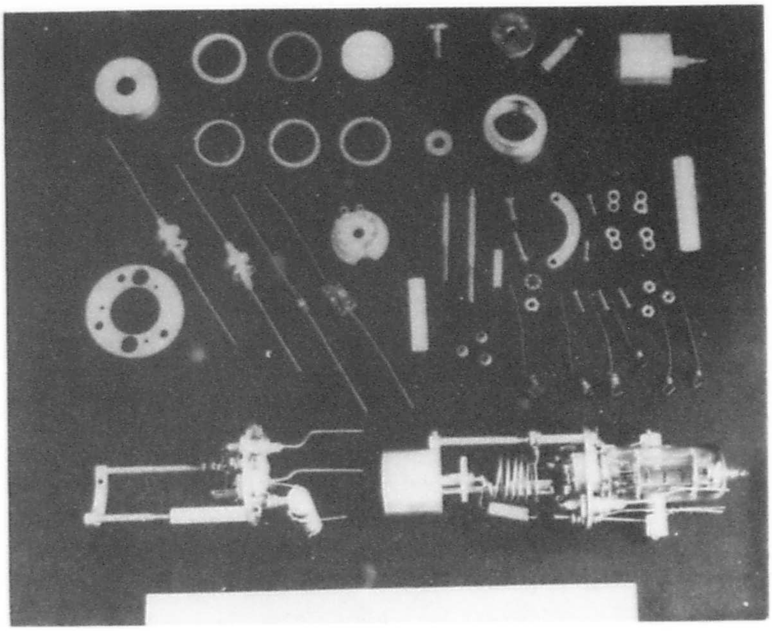

Fig. 2.6 Exploded View of Microphone and Associated Oscillator Components

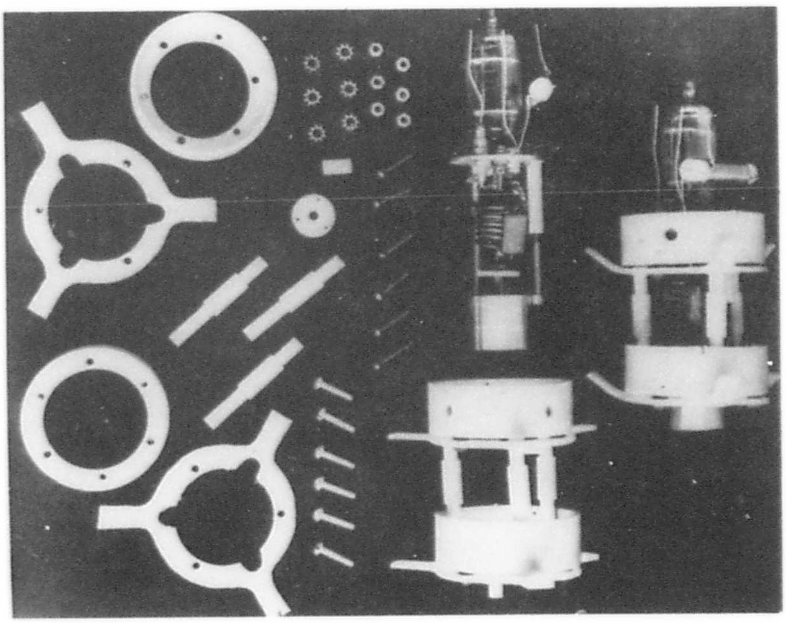

Fig. 2.7 Teflon Carriage for Supporting the Microphone and Oscillator Components Including the Oscillator Tube Type 6C4

assembly are shown. The teflon carriage for supporting the microphone is shown in Fig. 2.7. Teflon was used because of its sound absorbing properties and its inherent durability at temperatures such as prevail during the baking out process while evacuating. Figure 2.8 is a photograph of the completed microphone unit in its evacuated glass envelope. This photograph shows the entrance and exit seals where nitrogen gas was circulated through the envelope during the final sealing operation to prevent tarnishing of the highly polished silver surface of the microphone diaphragm.

2.3 CALIBRATION

The importance of the calibration procedure is second only to the acquisition of the primary data. In these tests the technique of calibration has steadily improved. In all cases the sun was the source of the radiation used for calibration. In the early experiments it was used without concentration. Later an 8 in. concave mirror designed for use with a telescope served to concentrate the solar radiation so as to produce a high intensity spot on the mirror surface of the microphone diaphragm. A calibrated Eppley thermopile served as a standard to measure the light intensity. Figure 2.9 illustrates the apparatus and the procedure. The brass box on the board contains the microphone and associated equipment shown in detail in Fig. 2.10. The Eppley thermopile protected by a 16 to 1 neutral density filter is held in a small vise to the left of the brass box at the same distance from the mirror as the microphone. The operation is as follows:

(1) The spot of light is first reflected upon the thermopile and a reading is taken of a millivoltmeter matched to it.

(2) The spot of light is switched to shine upon the microphone and the operator in the van notified to record the signal with the magnetic tape recorders associated with the particular chain which is being calibrated.

(3) After about 10 sec of recording, the spot of light is then switched back to the thermopile and another reading is taken of the millivoltmeter. These two readings are averaged to obtain the average light intensity focused on the microphone diaphragm during the recording period.

(4) This operation is repeated four or five times for each microphone unit depending upon the steadiness of the sunlight available.

For the last four shots, the calibrations were taken at from 10 to 50 times the normal intensity of sunlight. Figure 2.1 can be referred to as a sample of this type of calibration. A sample calibration data sheet is in Table 2.1.

2.4 OPERATIONS

The final operational procedure developed was as follows:

(1) On the third day preceding the shot the sensing elements were checked for electrical operation. If the sky was clear and the weather not too windy, a preliminary calibration run was made.

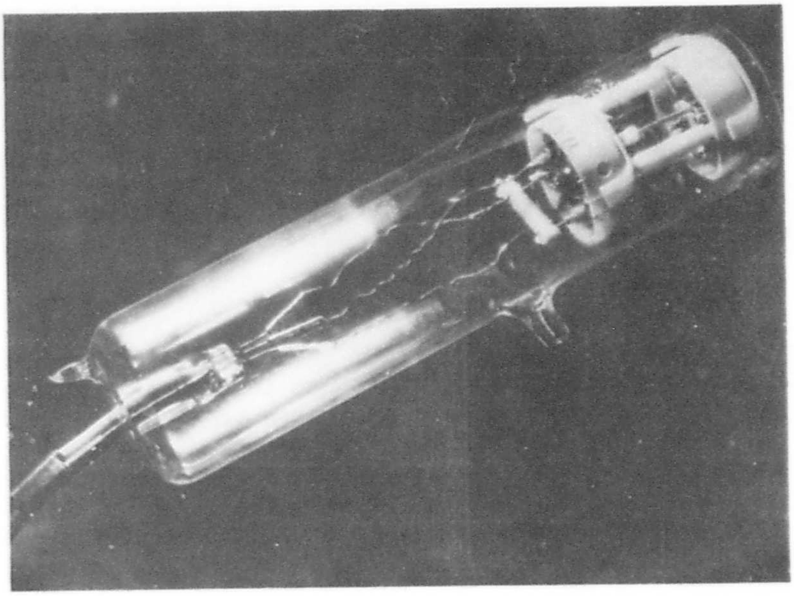

Fig. 2.8 Completed Microphone-Oscillator Unit
Sealed in Glass Envelope and Evacuated

(2) At this same time, the receivers and associated equipment were checked. The storage batteries for use during the shot were placed on charge.

(3) On the next day, the sensing elements were calibrated and a record made on the magnetic tape used at shot time. The receivers were checked with an FM signal generator so that for a 30 kilocycle deviation and a modulation frequency of 1000 cps, the audio output voltage was 700 millivolts. If there was to be a dry run the next day, the sensing element used near ground zero was installed, and the timers set to operate at H minus 30 min.

(4) This entire operation was repeated during the next day. At that time, the gain settings of the recorder amplifiers were set at the proper levels as determined from the predicted yield of the nuclear detonation and the results of the preceding calibration runs. A final check and measurement of the chopping frequency was made.

(5) At H minus 2 hr, the receivers were checked with the FM signal generator after warm up. This check was to make certain they produced the same results as during the calibration runs. They were checked again at H minus ½ hour.

(6) At H plus 15 min, the receivers were again checked and frequency measurement was made on the carrier of the sensing unit operating in the vicinity of ground zero. This frequency measurement indicated any damage to the microphone diaphragm that might have been caused by the detonation.

TABLE 2.1 Project 8.2 Data Sheet

SHOT CODE NAME: 10 DATE: May 26, 1953

CALIBRATION DATA

SENSING UNIT NO. 3 ______ MICROPHONE NO. 11

DATE OF CALIBRATION May 26, 1953 TIME 1530 PST

RECORDER TYPE Single SERIAL No. 865

RECORDER TYPE ______ SERIAL No. ___

SUN CONDITIONS Good but weather windy

METHOD - - DIRECT SUNLIGHT ____ CONCAVE MIRROR X

WITH ~~OR WITHOUT~~ FILTER 16-1

THERMOPILE C. C. METER RANGE ~~0.5 MILLIVOLTS OR~~

0.10 MILLIVOLTS

THERMOPILE READINGS:

MILLIVOLTS		GRAM CALORIES/cm^2/min
3.01	record 3.01	0.80 x 16
3.01	" 2.96	0.80 x 16
2.96	" 2.96	0.79 x 16
2.96	"	0.79 x 16

CHOPPER FREQUENCY DURING ABOVE READINGS 1430 CPS

REMARKS: This is a post firing calibration of the microphone used as a local station on Shot 10, Station 8.2C, Van # 60106364, chain #1.

DATE May 26, 1953

SIGNATURE Operator

[redacted]

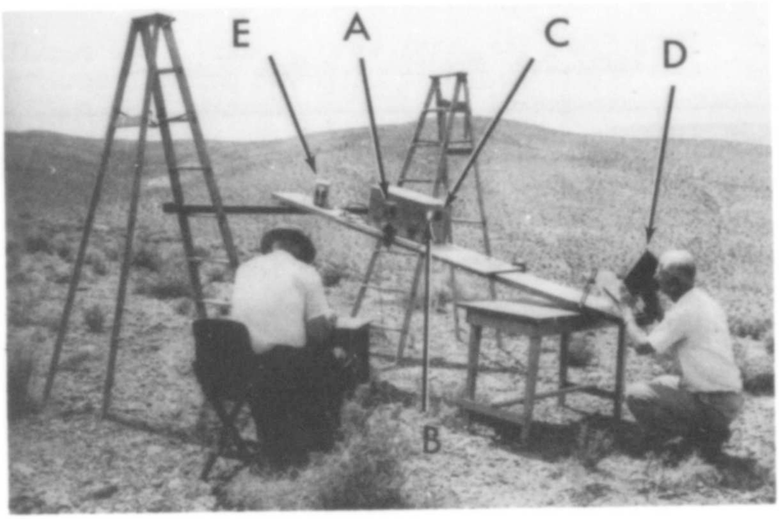

Fig. 2.9 Calibration Set-up. A – Thermopile Covered with Neutral Filter. B – Spot of Sunlight from Concave Mirror. C – Aperture to Microphone. D – Concave Mirror. E – R. F. Wattmeter and Calibration Antenna

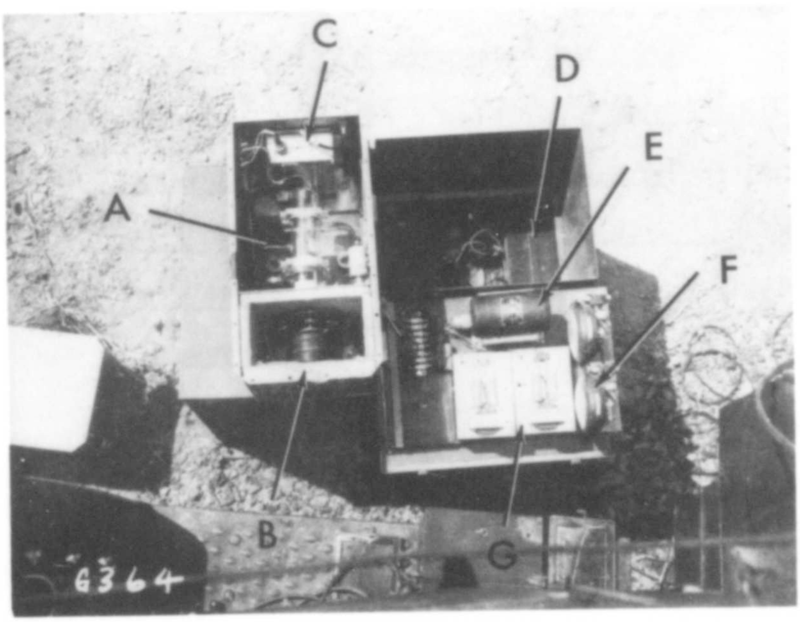

Fig. 2.10 Sensing Element and Battery Box. A – Sensing Microphone and Oscillator. B – Chopping Motor and Disc. C – Class "C" R. F. Amplifier. D – Storage Batteries. E – Dynamotor "B" Supply. F – Timers. G – "B" Supply Filters.

(7) At H plus 5 hr, the local sensing element was recalibrated if weather conditions permitted. Also if it was possible to retrieve the equipment located near ground zero, it was brought back for a calibration check.

(8) On H plus 1 day, the data on the magnetic tapes were transcribed on film.

2.5 METHODS FOR HANDLING DATA

The data on the magnetic tapes are in the form of amplitude modulated 1430 cycle waves. The first step in reduction was to transcribe from the tape to photographic film. This was accomplished by displaying the signal from the tape recorders on an oscilloscope. A Fairchild camera was used to photograph the trace of the oscilloscope. The signal from the tape recorder was fed into the horizontal sweep amplifier of the oscilloscope while the film passed across the screen of the cathode ray tube at a rate of 20 in/sec. This formed a time base. The record appears on 35 mm film as a time-intensity plot which is symmetrical about the horizontal axis. The appearance is similar to the diagram of an amplitude modulated radio-frequency carrier wave.

In order to obtain the total thermal yield, it was necessary to integrate this time-intensity plot. A typical time-intensity plot is shown in Fig. 2.11. This is an actual record from Shot 9. Figure 2.12 is a time-intensity plot from Shot 10. These photographs illustrate the contrast between the times of minima and maxima, rise and decay, of thermal intensity for different yields. Figure 2.13 illustrates the type of time-intensity plot received from the low yield of Shot 6. This plot is included because the time-energy distribution appears so different from that obtained for higher yield detonations. Figure 2.14 shows an enlarged portion of the time-intensity plot from Shot 4. This is to illustrate the facility with which time to minima can be obtained merely by counting cycles. Normalized time-intensity curves for each shot appear in Fig. 3.5 through Fig. 3.14. The integration of a time-intensity plot is accomplished graphically by placing the film record over an illuminated ground glass screen sectioned in square centimeters and with the aid of a calibrated magnifying eye piece the amplitude of the signal response is measured in millimeters and the number of cycles per centimeter are determined. From this, the number of millimeter cycles are calculated. The amplitude of the calibration signal is then measured in millimeters and the ratio between the thermopile reading in calories per centimeter squared minute to millimeters is established as the calibration constant for the film in calories per millimeter cm^{2}min. The film calibration constant and the area of the signal response are combined to calculate the total amount of heat received at the microphone. The thermal yield in KT can then be calculated by the following formula:

$$Y = \frac{Q 4 \pi d^2}{T^D 10^{12}} = \text{Thermal yield in KT (uncorrected)}$$

Q = Calories received at the microphone per square centimeter

D = Distance in statute miles from burst

[redacted]

d = Distance in centimeters from burst
T = Transmissivity per statute mile

A sample integration data sheet with calculations included is illustrated in Tables 2.2 and 2.3.

TABLE 2.2 Sample Integration Data Sheet

Film Record No. 5	Shot Number 1
Transmissivity	94%
Transmission Factor T_β	0.699
Distance from point of burst	37,303 feet = 7.065 miles
Chopping frequency	1430 cycles/second
Cycle period	0.70 milliseconds
Cycles per unit length	27 cycles/cm (for integration)
Time per unit length	0.189 seconds/cm (for integration)
Length per unit time	53 cm/second (for integration)
Time to second peak	122 milliseconds
Time to first minimum	14.3 milliseconds
Calibration signal from concentrated light	2.6 calories/cm^2 minute
Maximum rate of irradiation	0.944 calories/cm^2 second
Calibration constant for film record	5.2 calories/mm cm^2 minute
Integration of time-intensity curve	4780 millimeter cycles
Total heat received at microphone	0.290 calories/cm^2
Calculated thermal yield	6.8 kilotons

TABLE 2.3 Sample Calculation Shot 1

Total radiation received at the microphone = 4780 mm cycles x 1.166 min/cycle x 5.2 cal/mm cm^2min = 0.290 cal/cm^2

Total thermal yield = Y

$$Y = \frac{Q\, 4\pi d^2 \times 10^{-12}}{T^D} = KT$$

$$\text{Total thermal yield} = \frac{0.290\ \text{cal/cm}^2 \times 4\pi\,(37303 \times 30.48)^2\ \text{cm}^2}{(0.94)^{7.065} \times 10^{12}} = 7.3\ \text{KT}$$

A correction for scattering and field of view must now be made. From NRL Report 4031, Diffuse Atmospheric Transmittance depends upon the field of view, the reflectance of the surface, and upon the specular transmittance. A simplified equation reads as follows:

$$T_\beta = T' \quad 0.75\ (1-T')\ (1-e^{-\beta})*$$

T = Diffuse Atmospheric Transmission

T' = Specular transmission = T^D

β = Field of view in radians.

For a field of view of 0.25 radian which is the case for the microphone sensing element,

$$T_\beta = T' + 0.75\ (1-T')\ (1-e^{-.25})$$

$$= T' + 0.75\ (1-T').2$$

$$= T' + (1-T').15$$

$$T_\beta = 0.646 + (1-0.646)(.15) = 0.699$$

$$\text{The total thermal yield (corrected)} = \frac{0.646}{0.699} \times 7.3 = 6.8\ \text{KT}$$

* Value of 0.75 in this equation was supplied by director of Program 8 as being most suitable for the Nevada desert.

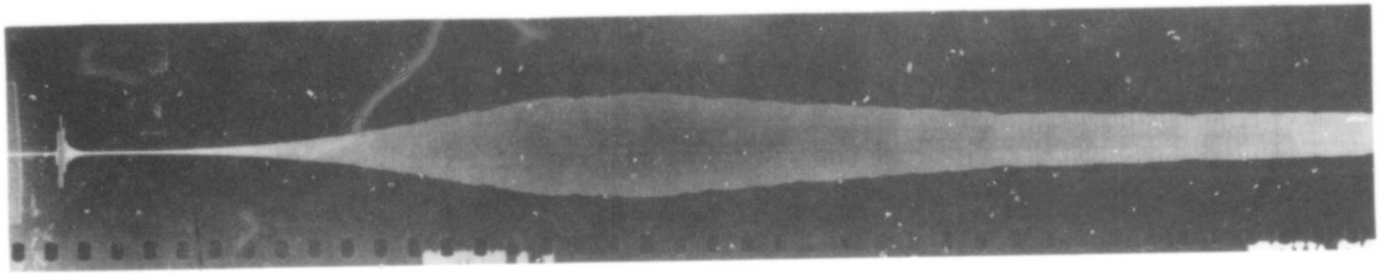

Fig. 2.11 Time Intensity Plot for Shot 9

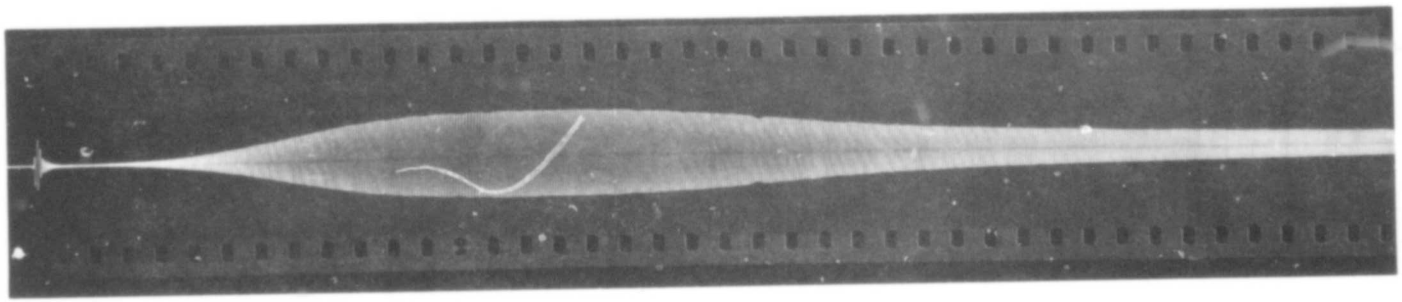

Fig. 2.12 Time Intensity Plot for Shot 10

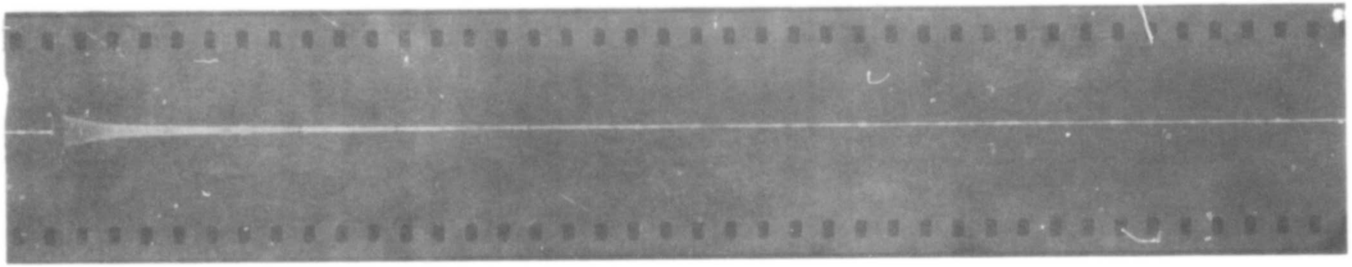

Fig. 2.13 Time Intensity Plot for Shot 6

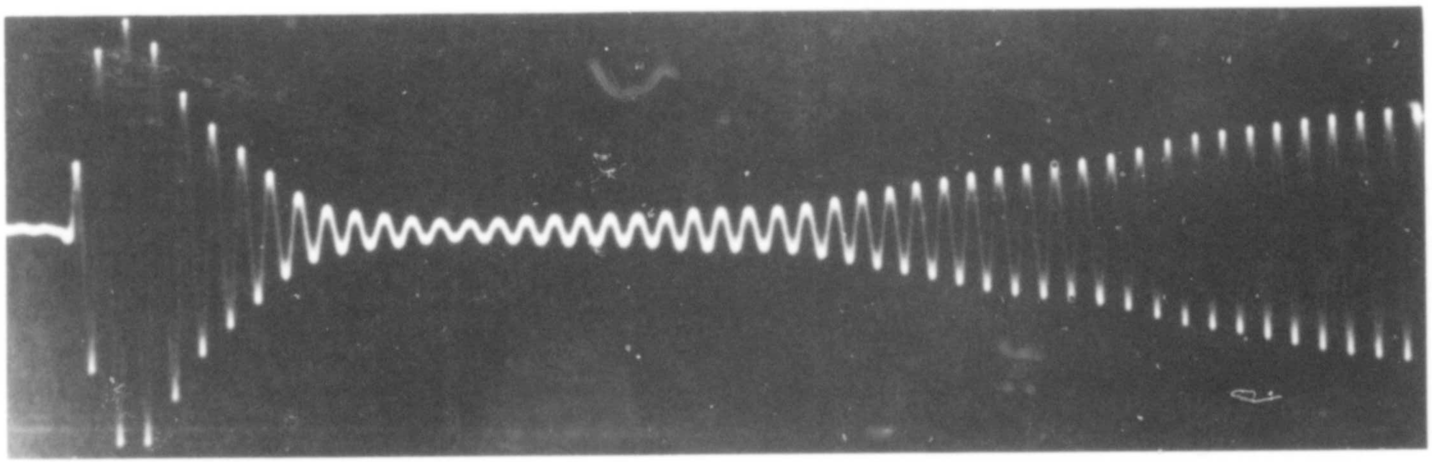

Fig. 2.14 Enlargement of Section of Time Intensity Plot of Shot 4 Showing First Minimum

CHAPTER 3

RESULTS

3.1 GENERAL

The results obtained are summarized in Table 3.4 under the heading Project 8.2. Dashed lines indicate that no useful data were obtained. In the case of Shot 1 time did not permit the installation of a remote station. Shot 2, the gain controls on the receiver for remote station were set too high so that the magnetic tape saturated on all channels. Shot 3, the gain controls were set too low on the receiver at the manned station. The small yield of this shot did not give a useful signal at this station. The same statement applies to Shot 6. For Shot 5, an attempt was made to use a neutral density filter at the remote station. However this filter was so badly injured by the heat as to render the data incapable of analysis. In the case of Shot 8, no remote station was possible because there did not exist a radio line of sight between the target area and the receiving point. In this case the microphone was located on Bldg. 400 which had line of sight both to the shot and the receiving station. Just before Shot 9 the operator inadvertently disconnected the power line to the receiving equipment at the manned station.

An examination of Table 3.4 will disclose that the results obtained by Project 8.2 are in substantial agreement with those obtained by other agencies and also compare reasonably well with the calculated thermal yield as shown in column 7. In two cases the results are somewhat inconsistent within themselves as can be seen by an examination of Fig. 3.2 where the corrected thermal energy received at the microphone is divided by the calculated thermal yield of the explosion and plotted against the slant range. It is seen that in the case of the manned station for Shot 4 the value obtained was too low and for Shot 10 it was too high. If these points were to fall on the straight line in this figure the value of 3.3 as given in Table 3.4 would need to be raised to make it more than 5 and the value of 6.5 obtained for Shot 10 would have to be reduced to agree more closely with the value obtained at the remote station. If this were done the values obtained with the vacuum microphone equipment would be in substantial agreement with the preliminary data submitted by U. S. Naval Radiological Defense Laboratory.

With the high time resolution obtained with equipment used in Project 3.2 it has been possible to obtain the times to the first minimum and to compare these times with those measured by the Bhangmeter. It is seen by comparing columns 9 and 10 of Fig. 3.7 that these times are in substantial agreement. However it is sometimes very difficult to obtain this time to minimum intensity accurately as can be seen from Fig. 2.14, since the minimum is not a sharply defined quantity.

The time resolution of this equipment is not sufficient to show the first maximum. This quantity is therefore integrated by the equipment and appears to have a smaller value than the second maximum which lasts for a considerable length of time. In this report the term "maximum rate of irradiation" refers to the maximum as shown by the oscillographic records. In reality it is the amplitude of the second maximum of light intensity.

In the early shots a large amount of trouble was experienced by the signal overloading the magnetic tape recorder and were it not for the fact that good backup equipment was used no data would be available for the first five shots. This difficulty was inadvertently attributed to a non-linear response of the microphone itself in the early stages of the analysis because it had been assumed that a saturation would appear as a signal of constant amplitude. However, this is not the manner in which a magnetic tape saturates. The response merely becomes non-linear and until a number of photographic records were obtained on other channels it was not realized by the operator that the fault was entirely in the recording equipment. For the last three shots a technique was developed for calibrating the microphone with concentrated light from a telescope reflector so that the thermal energy striking it was comparable to that received from the explosion. When this was done it became apparent that the response to the microphone itself was linear. Additional data are shown in the time intensity curves, Figs. 3.5 - 3.14.

Key to Graphs

Data for the various curves can be found as follows:

Data for Fig. 3.1 are in Table 3.3, columns 12 and 14.
Data for Fig. 3.2 are in Table 3.3, columns 2, 11 and 13.
Data for Fig. 3.3 are in Table 3.2, column 8
Data for Fig. 3.4 are in Table 3.2, column 9 and Table 3.3, column 14.
Data for Figs. 3.5 through 3.14 are in Table 3.3, columns 11 and 13, plus detailed data not tabulated but taken directly from oscillograms.

[redacted]

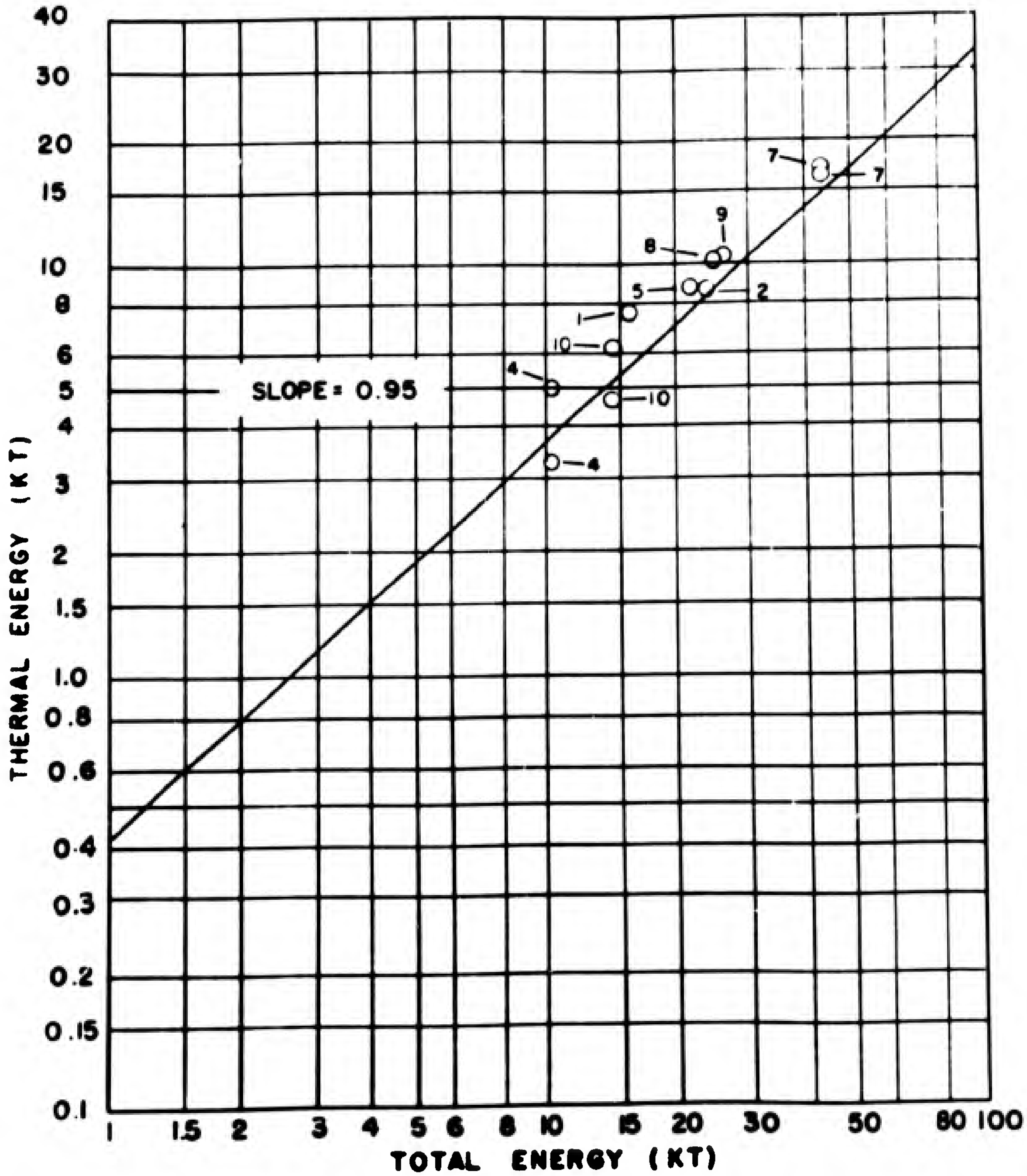

Fig. 3.1 Thermal Energy (KT) vs Total Weapon Yield

[redacted]

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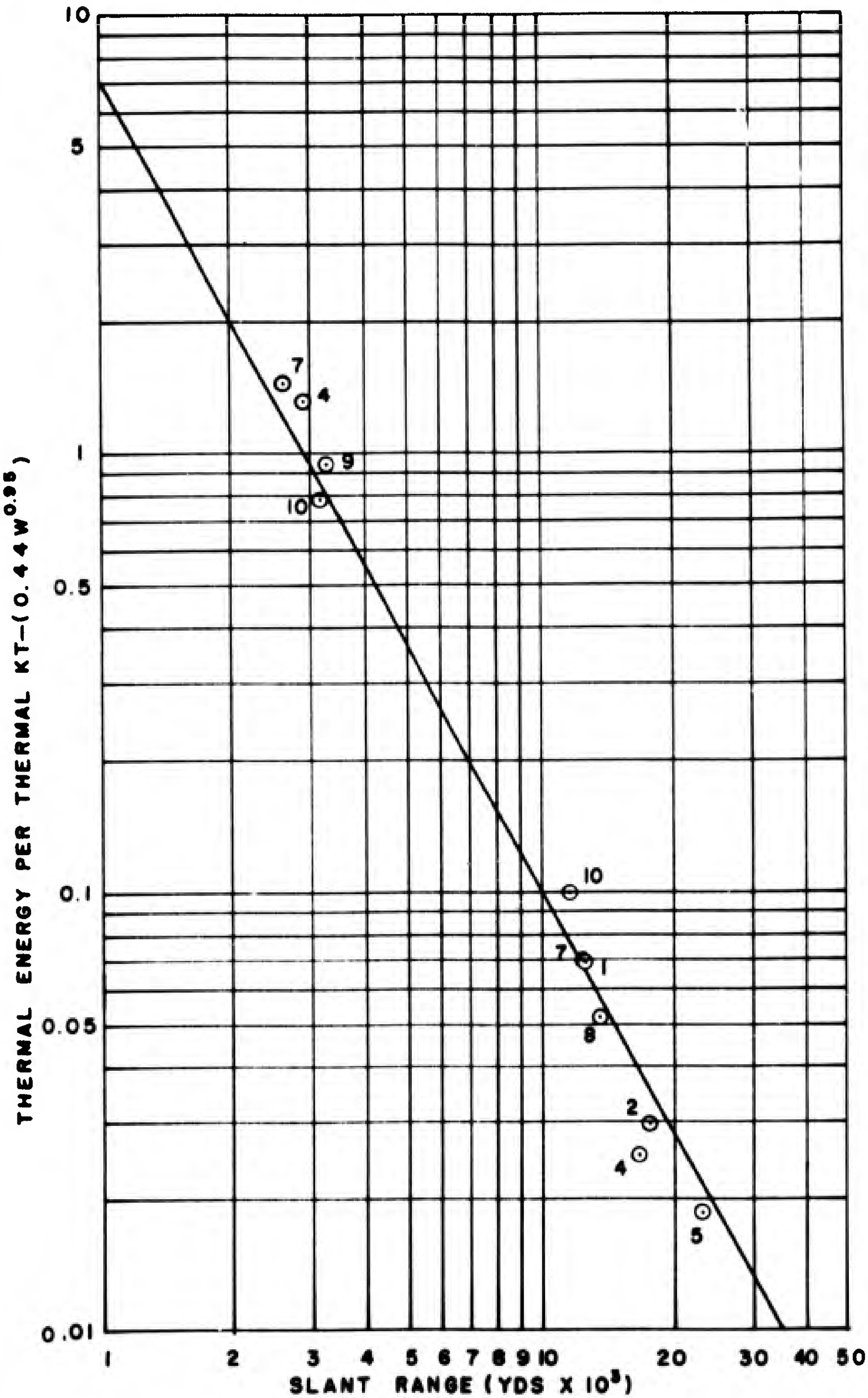


Fig. 3.2 Energy per KT vs Slant Range

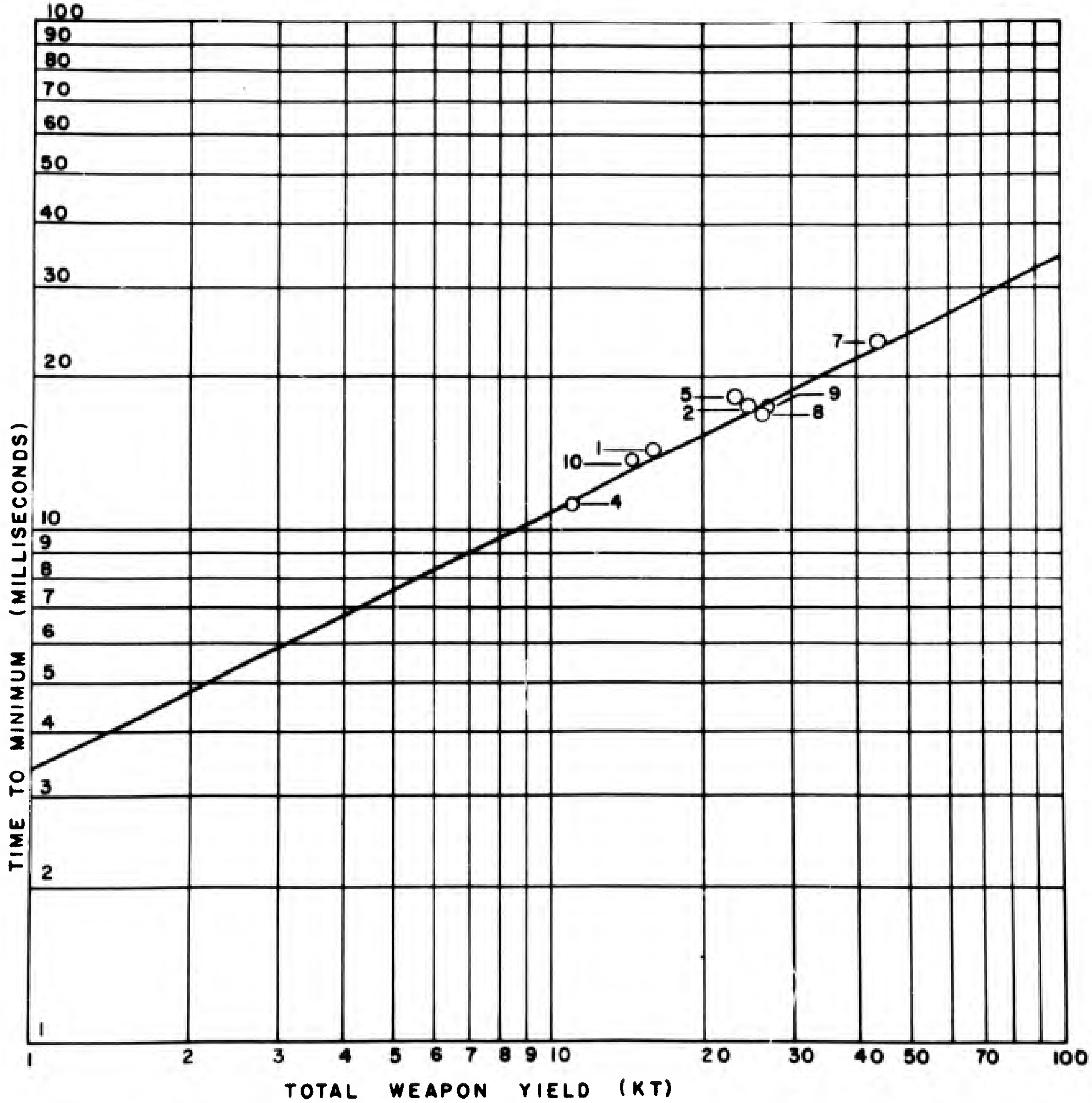


Fig. 3.3 Time to Minimum vs Total Weapon Yield

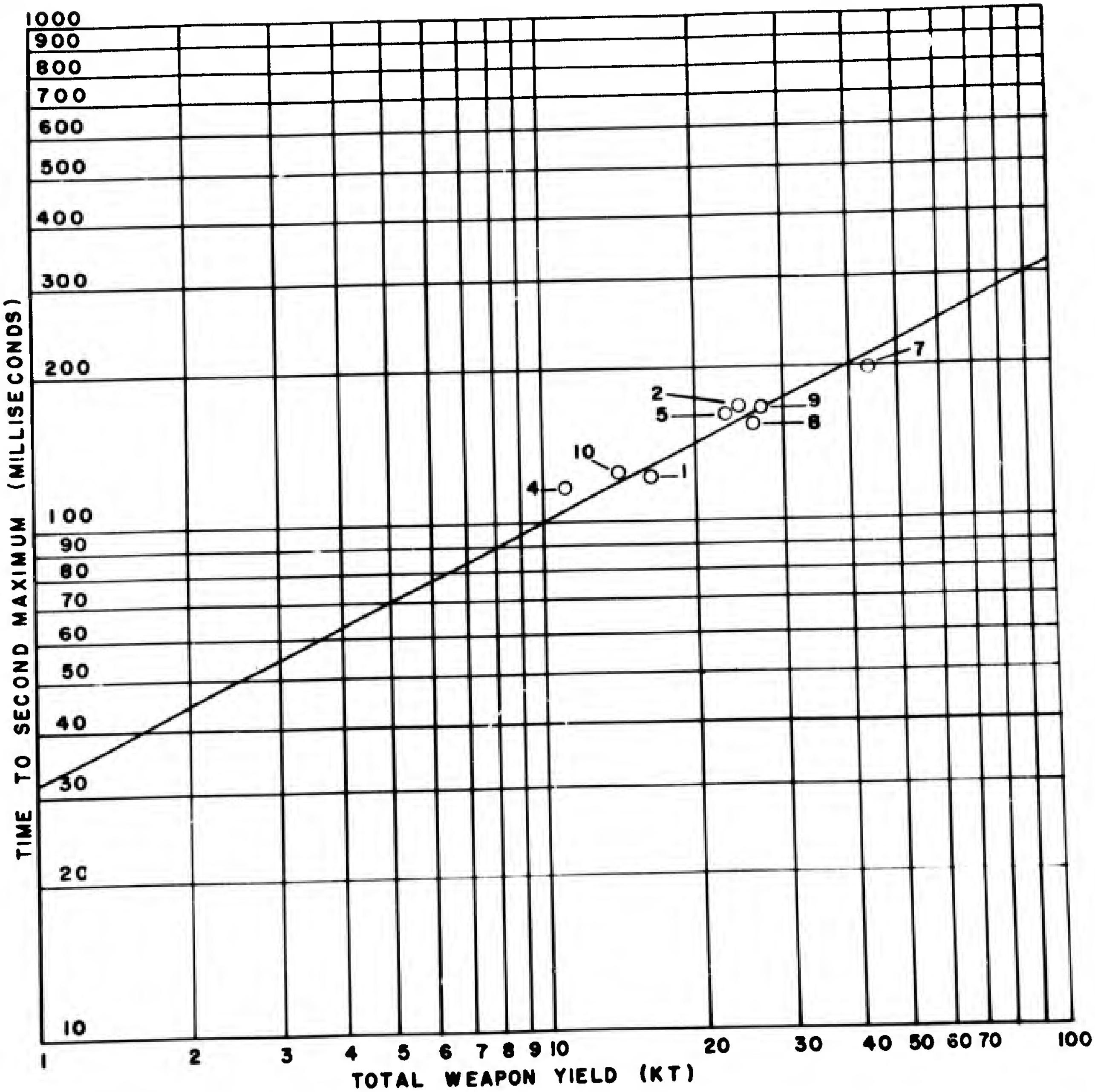


Fig. 3.4 Time to Second Maximum vs Total Weapon Yield

[redacted]

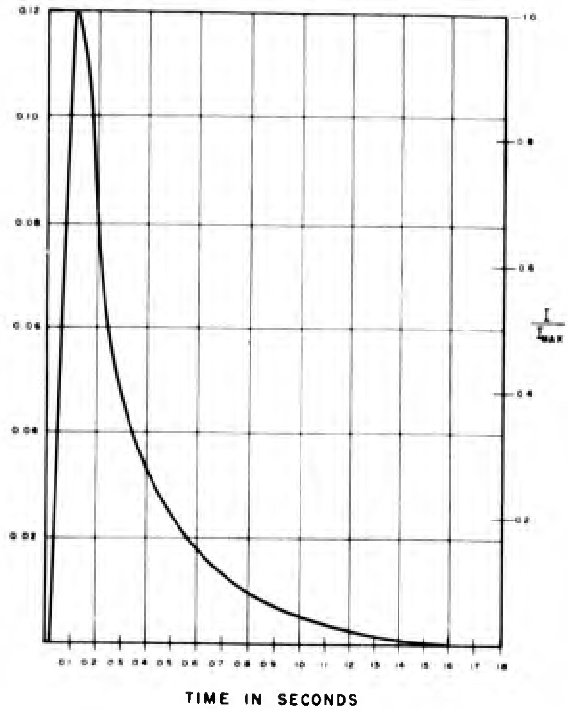


Fig. 3.5 Time-Intensity Curve for Shot 1

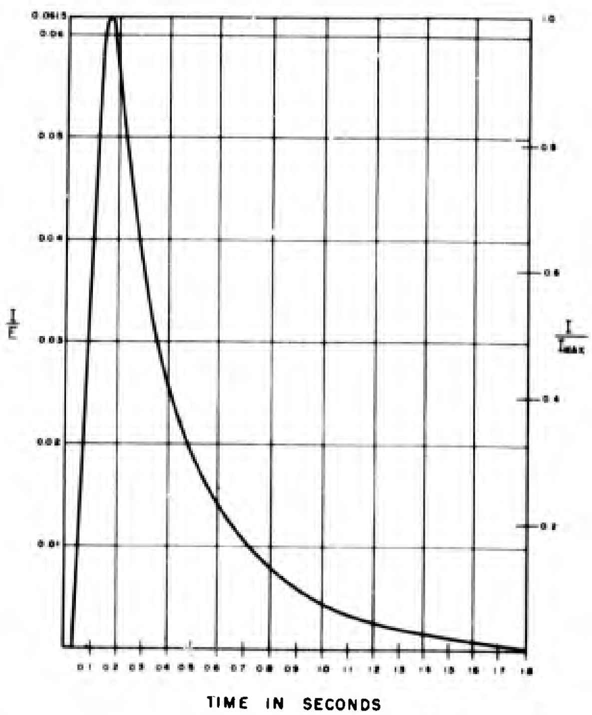


Fig. 3.6 Time-Intensity Curve for Shot 2

[redacted]

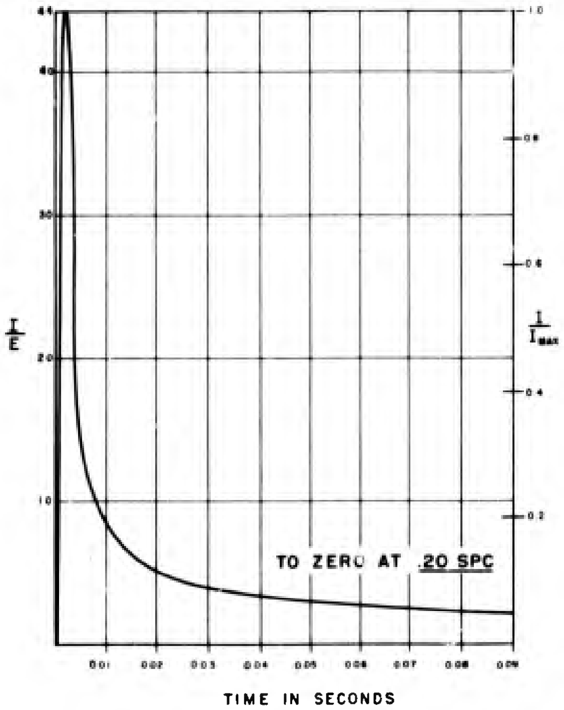


Fig. 3.7 Time-Intensity Curve for Shot 3

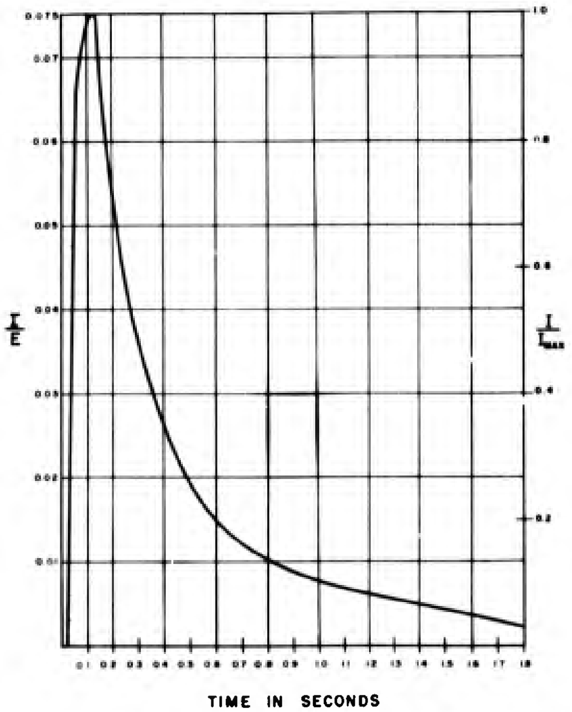


Fig. 3.8 Time-Intensity Curve for Shot 4

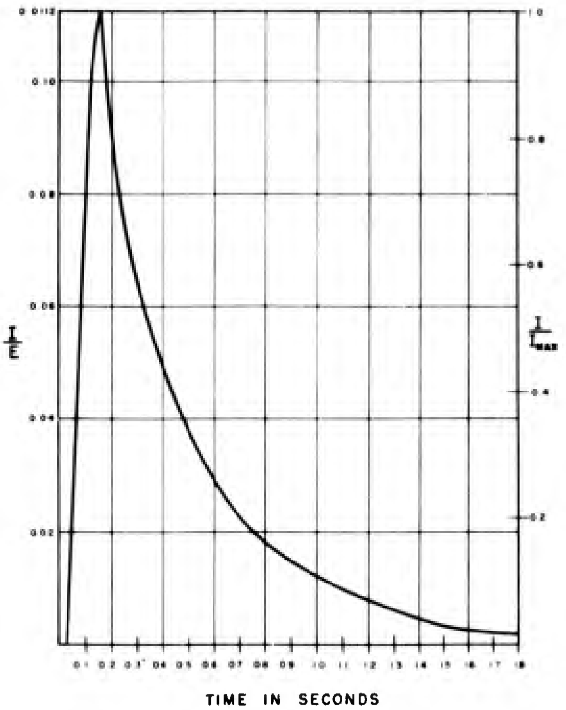


Fig. 3.9 Time-Intensity Curve for Shot 5

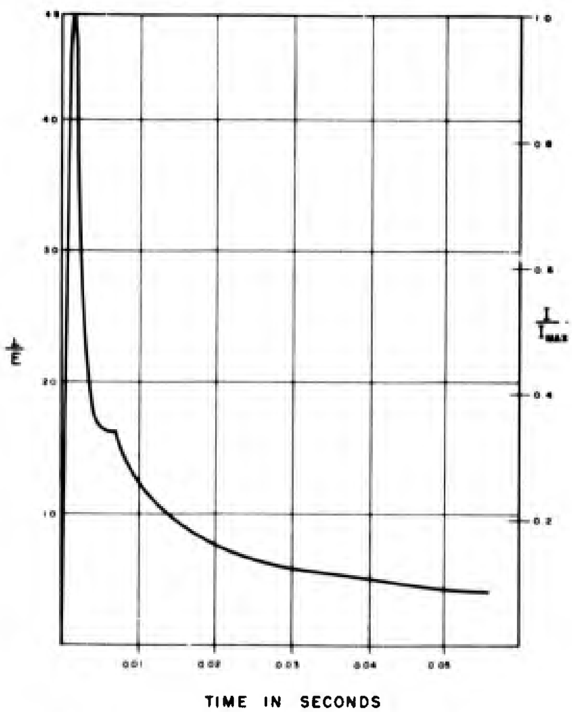
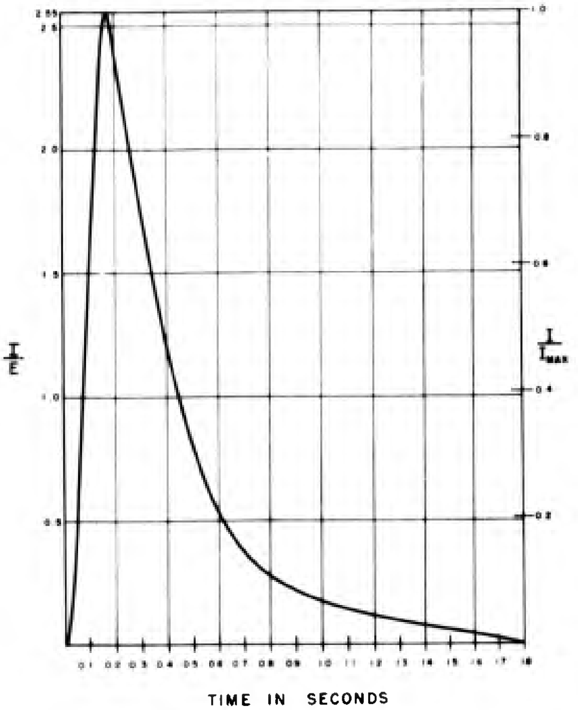
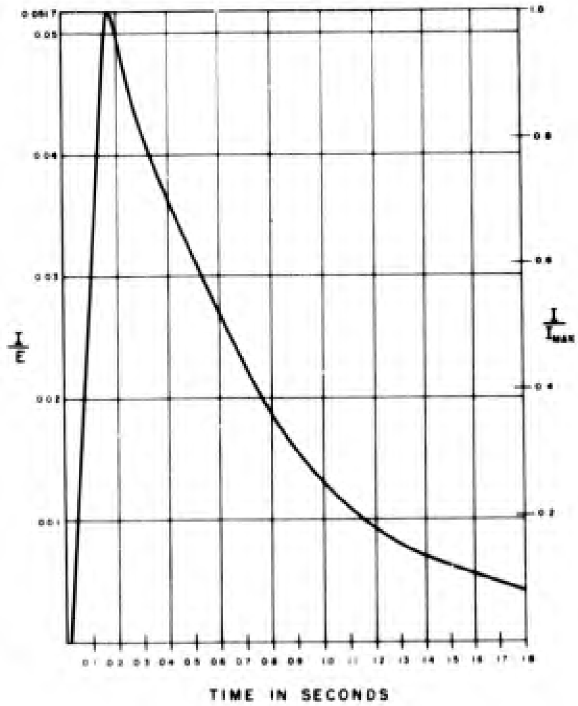


Fig. 3.10 Time-Intensity Curve for Shot 6



Remote Station



Local Station

Fig. 3.11 Time-Intensity Curves for Shot 7

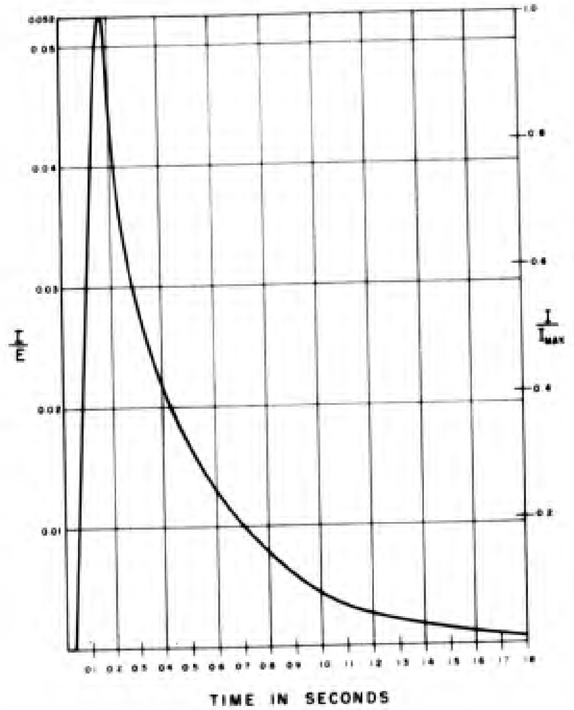


Fig. 3.12 Time-Intensity Curve for Shot 8

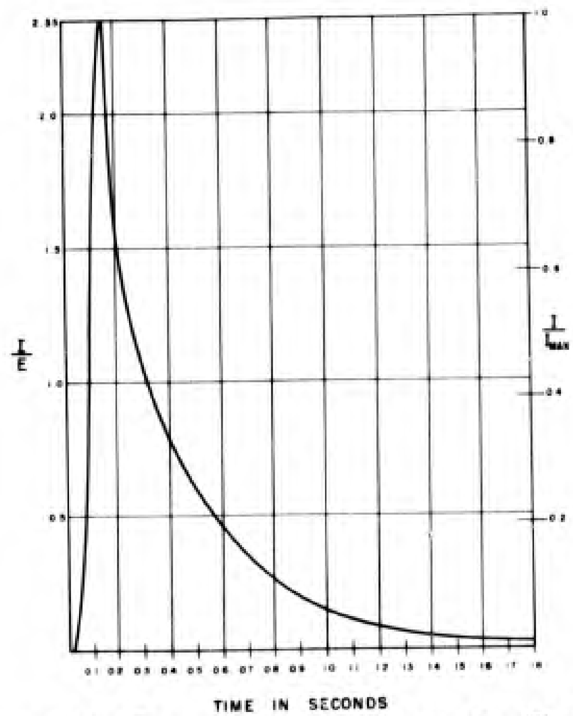
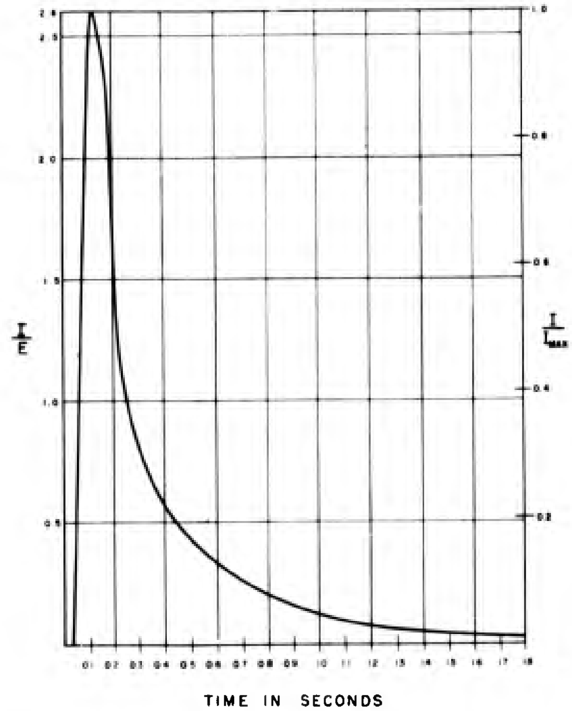
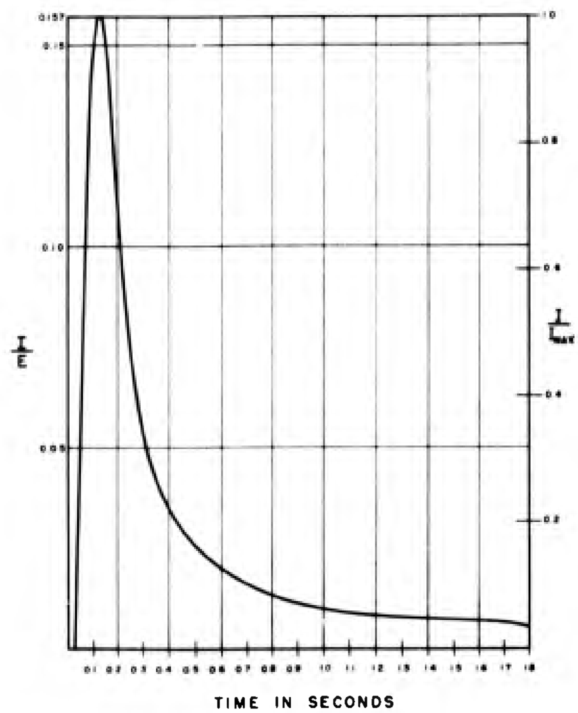


Fig. 3.13 Time-Intensity Curve for Shot 9



Remote Station



Local Station

Fig. 3.14 Time-Intensity Curves for Shot 10

[redacted]

TABLE 3.1 - Shot Numbering System and Locations of Microphone Stations

Shot	Code Name	Actual Firing Date	Tower Station	Target Area	Distance From Burst (Yards)	Station	Slant Range (Yards)
1	Annie	17 March	None	3	Not Applicable	8.2a	12,434
2	Nancy	24 March	4-413	4	3,536	8.2a	17,492
3	Ruth	31 March	7-234	7-5a	1,769	8.2a	16,332
4	Dixie	6 April	7-234	7-3	2,902	8.2a	16,366
5	Badger	18 April	2-413	2	3,522	8.2a	22,883
6	Ray	11 April	4-413	4-a	3,308	8.2a	17,752
7	Simon	25 April	1-413	1	2,643	8.2a	12,451
8	Harry	19 May	None	3-a	Not Applicable	Bldg. 400	13,626
9	Encore	8 May	F-295	FF	3,275	8.2c	11,423
10	Grable	25 May	F-295	FF	3,143	8.2c	11,565

Shot results are numbered in this report as they were originally scheduled, NOT as fired. Project 8.2 results are tabulated according to the above sequence.

This listing is as originally submitted to AFCRC by letter dated 25 Sep 53 from LCDR R.G. Preston, Director of Program 8; Field Command Control No. FC-53-6212.

Due to the close proximity of stations 8.2a and 8 2b, and the long ranges involved, all calculations were based on the Nevada State Grid Coordinates for Station 8.2a. Station 8 2b was located 5.5 ft North and 153 ft West of Station 8.2a. The difference in elevation between the two stations was 20.8 ft.

TABLE 3.2 - Results of Shots 1 Through 10

Shot	Range to Burst (in yards)	Precipitable** Millimeters of Water in Path	Trans-missivity (%/mile)	Trans-mission Factor T_β	I.R.* Correction	Corrected T_β	Time to Minimum (msec)	Time to Second Peak (msec)	Total Heat at Microphone (cal/cm^2)
1	12,400	35.0	0.94	0.70	0.85	0.60	14.3	122	0.290
2	17,490	57.0	0.94	0.61	0.82	0.50	17.5	166	0.135
3	1,770	4.3	0.95	0.96	0.93	0.89	7.0	—	0.0042
4	16,866	26.0	0.95	0.67	0.86	0.58	11.2	117	0.0627
4	2,902	4.4	0.95	0.93	0.93	0.86	11.2	117	4.87
5	22,883	64.0	0.96	0.65	0.81	0.53	18.2	162	0.085
6	3,176	5.2	0.95	0.93	0.93	0.86	5.6	—	0.010
7	12,451	39.0	0.95	0.75	0.84	0.63	19.6	179	0.706
7	2,643	8.2	0.95	0.94	0.91	0.86	18.0	173	19.7
8	13,626	68.0	0.92	0.60	0.81	0.49	16.8	155	0.257
9	3,275	5.7	0.93	0.89	0 93	0.83	16.8	151	7.7
10	11,565	28.0	0.91	0.61	0.86	0.52	14.0	122	0.31
10	3,143	7.5	0.91	0.87	0.92	0.80	13.3	127	3.57

* Corrections for Infrared Absorption are Based on Preliminary Report on the Attenuation of Thermal Radiation from an Atomic Bomb (Secret), 1 Jun 54, R. M. Chapman and M. H. Seavey. Data were obtained from Fig. 4.

** Two significant figures. Transmissivity values used were obtained from a letter dated 6 Nov 53 from LCDR R. G. Preston, Director of Program 8.

TABLE 3.3 - Additional Results of Shots 1 through 10

Shot	Range to Burst (in Yards)	Film Record	Cycles per Unit Length on Film (cycles/cm)	Time per Unit Length on Film (sec/cm)	Length per Unit Time (cm/sec)	Calibration Signal from Concentrated Light (cal/cm²sec)	Maximum Rate** of Irradiation (cal/cm²sec)	Calibration Constant for Film Record (cal/mmcm²min)	Integration of Time Intensity Curve (mm cycles)	Corrected Thermal Energy at Microphone per KT (cal/cm²/KT)	Heat at Microphone Corrected for Transmission Losses Including Infrared	$E = 0.44W^{0.95}$	Total Weapon* Yield (KT)
1	12,400	5	27.0	0.0189	53.0	2.60	0.944	5.20	4780	0.0299	0.0687	7.04	16.2
2	17,490	25Z	25.1	0.0175	57.0	5.22	0.535	4.02	2890	0.0110	0.0293	9.20	24.5
3	1,770	8	20.5	0.0143	70.0	5.32	0.070	1.33	197	0.0235	0.049	0.0955	0.20
4	16,866	19	28.0	0.0196	51.0	1.40	0.247	1.55	3080	0.00982	0.0251	4.29	11.0
4	2,902	10	24.3	0.0170	58.8	1.32	21.6	120.0	3480	0.515	1.32	4.29	11.0
5	22,883	28	29.0	0.0203	49.2	16.8	0.100	2.00	3665	0.00696	0.0185	8.67	23.0
6	3,176	15	24.7	0.0173	57.8	4.54	0.72	3.8	230	0.0528	1.154	0.104	0.22
7	12,451	27	28.5	0.0199	50.2	17.5	0.91	10.9	5190	0.0260	0.0704	15.9	43.4
7	2,643	25	27.6	0.0193	51.8	119.2	42.6	852.0	1990	0.528	1.44	15.9	43.4
8	13,626	29	24.5	0.0171	58.5	32.3	0.538	6.52	3380	0.0194	0.052	10.1	27.0
9	3,275	22	26.0	0.0182	55.0	21.2	24.5	10.3	6400	0.357	0.954	9.72	26.0
10	11,565	35	26.0	0.0182	55.0	12.5	1.02	4.91	5360	0.040	1.04	5.72	14.9
10	3.143	32	26.8	0.0187	52.[illegible]	72.0	12.2	45.0	5800	0.299	0.78	5.72	14.9

* Radiochemical results.
** Maximum rate of irradiation = amplitude of second maximum.

TABLE 3.4 - Comparison of Data

Shot	Naval Research Lab. Calculated Yields*		NRDL Prelim. Data	Project 8.2 Station		$0.44W^{0.95}$	Radiochemical Yield = W	Time to First Minimum		Time to Second Maximum
	Station 413	Station 400		Local	Remote			Proj. 8.2	Bhangmeter	Proj. 8.2
1	5.8	7.6		7.9	——	7.04	16.2	14.3	14.5	122
2	10.0	14.0		8.7	——	9.20	24.5	17.5	13.0	166
3	0.026		0.03	——	0.0016	0.0955	0.20			
4	3.8	3.6	4.0	3.3	5.0	4.29	11.0	11.2	10.5	117
5	10.2	9.9		8.9	——	8.67	23.0	18.2	17.7	162
6				——	0.015	0.104	0.22	5.6		
7	5.8	16.0		17.6	16.7	15.9	43.4	19.6	23.5	176
8	7.1	10.4		10.3	——	10.1	27.0	16.8	17.8	155
9		10.6	10.9	——	10.4	9.72	26.0	16.8	19.25	151
10		7.5	5.3	6.5	4.7	5.72	14.9	14.0	14.9	124

* Communication from LCDR R. G. Preston, December 1953. All yields in kilotons.

Bhangmeter times to minimum were obtained from a letter dated 4 Dec 53 from Col. P. T. Preuss, Director of Weapons Effects Tests (FCWET 53-959-0). All times in milliseconds.

Radiochemical yields were obtained from a letter dated 25 Sep 53 from LCDR R. G. Preston, Director of Program 8 (FC-53-6212 inclosed).

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CHAPTER 4

DISCUSSION

The studies undertaken during these tests have been primarily of research nature; the equipment is far too complicated in its present state for practical measurements. Every effort was made not to lose data which might be significant in the understanding of the physics of the sensing element. For this reason, duplicate and complex receiving equipment was used. During the early stages of the operation surges of unsteady and high voltage on the primary power supply (a gasoline driven generator was used) caused failures of some of the electronic equipment resulting in disruption of carefully laid plans for the utilization of the project personnel. In contrast, the behavior of the sensing units themselves was surprisingly good compared to TUMBLER-SNAPPER. All of the difficulties experienced during those tests have been eliminated to the extent that the microphones were exceedingly sensitive with a very good signal-to-noise ratio. To make the sensing element and associated equipment simple, the chopper must be eliminated. This cannot be done without the elimination of the thermal effect on the diaphragms. If this were done, the microphone could be calibrated when constructed and would not require recalibration in the field. The use of magnetic tape recorders of the six channel variety on this project was unfortunate because of the inherent poor magnetic shielding and isolation between each section of the commercially constructed recording head. Considerable effort was expended in the field to re-fabricate these heads in an endeavor to shield each channel to prevent 120 cycle pickup from associated apparatus and severe inter-channel cross-talk between head segments. This intermodulation was experienced when large signal levels were applied to adjacent channels. The six channel magnetic heads caused almost all of the recorder difficulties encountered.

The time resolution in these experiments was excellent. If necessary, it could easily be increased by a factor of 5. The sensitivity, considering that it is a total radiation intensity device (not spectroscopically selective) is such that it could be used in an aircraft for thermal radiation measurements such as those at large distances 40 to 50 miles away for medium yield detonations.

The possible sources of error in the experimental procedure and apparatus used during the UPSHOT-KNOTHOLE operation were:

1. Voltage variations in gasoline driven generators.
2. Frequency variations in gasoline driven generators.
3. Variations in chopper motor speed.
4. Calibration of microphones.
5. Dust penetration of equipment particularly the sensing unit placed near ground zero.
6. FM receiver nonlinearity.
7. Recorder amplifier nonlinearity.
8. Dynamic characteristics of tape.
9. Nonlinearity of oscilloscope sweep amplifiers.
10. Transmissivity values.
11. Field of view of microphone assembly.

Items 1 and 2 of this list are very important to reliable over-all manned station performance and to ensure valid calibration of the microphone units we must rely upon maintaining constant amplifier gains throughout our recording chains and constant motor speeds for the recorder synchronous motors during the period between the times of final calibration and actual detonation. The primary A.C. supply voltage and frequency should be well regulated with respect to load and motor-generator speed variations. Also when using gasoline driven generators, they must be equipped with well-shielded ignition systems to prevent radiation of spark plug and breaker point transient noise pulses.

Item 3 is an important subject because variations in the chopping motor speed cause variations in the actual light chopping frequency. It is important to know this chopping frequency accurately to establish the correct time base and cycle period of the time-intensity response received by the microphone. The accuracy with which the chopping frequency is known determines the accuracy with which the times to first minima and second maxima can be measured. For most cases, the chopper motor is of the D.C. type, operated from storage batteries. A serious difficulty is overcoming the effects of wide variations in temperature on motor speed. The ideal motor for this purpose has been found to be one having a continuous duty rating of the constant speed D.C. series wound variety with a Lee centrifugal governor. Motors so equipped will hold their speed regulation within $\frac{1}{2}$ per cent for all loads from zero to full load and for supply voltage variations of $\pm$ 10 to 15 per cent. When a contact making governor of this type is used, precautions must be taken to use a spark suppressing network, usually of the R-C type, shunted across the governor contacts to minimize the possibility of sharp transient noise radiation.

Item 4, microphone calibration, is of utmost import and the techniques used were satisfactory. However, by using a larger mirror to obtain more intense calibration signals from the sun, the accuracy with which the amplitudes of the calibration signal can be compared with the actual detonation signal response would be greatly increased.

Item 5, dust, is a natural constituent of the Nevada desert. Precautions were taken to protect the surface of the sensing element envelope by shielding it with a solenoid controlled shutter mechanism. This shutter was controlled by a timer set to operate just before H time. However, the scattering and diffusion of the light by dust and sand

[redacted]

particles accumulated in a few minutes of exposure is unpredictable. In very short time, if the wind were right, a thin film of dust could cover the surface of the microphone envelope and reduce the effective radiation pressure by some unknown factor.

Item 6, F.M. receiver non-linearity, is not a possible source for large error when discussing the receivers used during the tests. These receivers were surplus Navy units of the R-156/ARR16B variety and they had been slightly modified to provide additional monitor metering facilities. Four such receivers were in constant use at the manned stations. The sensitivity, I.F. response, and discriminator linearity were checked periodically during the tests. While it was not possible to obtain perfectly linear discriminator response curves, the slight non-linearity occurring in the region of very small frequency deviations was insignificant. The automatic frequency control characteristic of these receivers was excellent, and could be adjusted to hold within limits of ± 1.75 mc. The average sensitivity of these receivers was approximately 1 microvolt for a 6 db signal-to-noise ratio. For perfect quieting and limiting, a 10 microvolt signal was required. As these receivers had only one stage of audio amplification following the discriminator and the gain of this stage was variable, precautions had to be taken in adjusting this gain control so that signals producing large frequency deviations, such as those received from high intensity solar radiation pulses used for calibration and those from the actual detonations, would not be distorted or clipped. The correct setting for this gain control was easily established with the aid of an FM signal generator. Further assurance of receiver reliability in performance was attained by the use of a separate high quality regulated power supply to provide the "B" voltage for each unit. One difficulty encountered with the receiver units was their great tendency to become microphonic when tuned to a strong carrier signal. This tendency was greatly minimized by selecting low noise type 6AK5-W tubes for use in the high gain R.F. amplifier stages. It can therefore be surmised that the only major source for error with these receivers, assuming the filament supply storage batteries are maintained fully charged, would be variations in the "B" supply voltage causing gain changes to take place between the time of calibration and the actual time of detonation or for an operator to make a gross error in the adjustment of the audio gain control, either of which could invalidate data received. An easy check for non-linearity of the discriminator circuitry is to examine the time-intensity plots. If severe non-linearity exists, these response curves will appear non-symmetrical about the horizontal axis. If optimum results are desired, that is distortion-free FM transmission, the receiver design problem is much more critical. One of the requirements for distortion-free transmission is that all side bands maintain their original amplitudes and their original relative phases. Since the FM signals originate with constant amplitude, a good limiter will completely compensate for non-linear phase characteristics, and as a consequence, most FM receivers cause considerable third harmonic distortion except at small deviations.[1/] A further distortion component

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1 S. Goldman, Frequency Analysis, Modulation and Noise, N.Y., McGraw-Hill, 1948

is added by the discriminator - especially if this unit is used at the same time as a source of AFC signals. In the latter case discriminator distortion is often increased because the optimum peak separation[1] may be greatly exceeded in order to obtain wide pull-in range. In order to eliminate discriminator distortion, the conventional discriminator can be replaced by a counter type FM detector after first transforming the amplitude limited FM signal into the corresponding pulse repetition rate modulation signal. To accomplish this it will first be necessary to convert the FM signal to a lower center frequency, possibly using a crystal controlled second local oscillator. The converter will be followed by an amplifier, a pulse forming stage and then the counter detector. The counting detector circuit is identical to the circuit commonly used in counting rate meters. It has been used in FM reception by a number of workers,[2,3,4] and has three very decided advantages: high stability, since only resistors, capacitors, and rectifiers are used in this circuit, exceedingly good linearity even over extreme ranges of frequency deviation, and no tuning adjustments. The disadvantages of this circuit - additional tubes required, low output voltage in comparison with the discriminator, and the difficulty of obtaining an AFC voltage, have prevented its more general use.

Items 7 and 8 - Recorder amplifier non-linearity and dynamic characteristics of the magnetic tape, can be discussed together. Amplifier linearity over the range of signals expected is the main requirement. In this case, amplitude limiting and phase distortion are both important factors. The commerically built amplifiers used during the tests did not function as well as would be expected. For one thing, they did not have the wide signal acceptance range preferred. They could be adjusted to accept practically any signal level by increasing or decreasing the input attenuation but the actual dynamic range of the amplifier units was not sufficient to cope with the nature of the signals received from nuclear detonations and still provide output amplitudes desirable for rapid data reduction techniques. This was the reason for using several recorders in cascade. For most detonations, several amplifier channels would be overloaded and usually at least one channel would yield valid data. A wide frequency response characteristic is not essential as the amplifier is required to pass only one frequency, i.e., the chopping frequency. The signal, being nearly a pure sinusoid of varying amplitudes, presents few amplifier design problems. However, an effort must be made to minimize the phase shift characteristic of the amplifiers because an accurate cycle-to-cycle time relationship must be maintained. In high level pulse recording, the dynamic characteristic of the magnetic tape, and the

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1 L. Arguimbau, Vacuum-Tube Circuits, N.Y., John Wiley, 1948

2 Proceedings of the National Electronics Conference, Vol. 3, P.634

3 D.G.C. Luck, Frequency Modulated Radar, N.Y., McGraw-Hill, 1949

4 A. Vallarino et al, Counter Circuit Multiplex Receiver, Electronics, July 1953, P.178

saturation point of the recording heads must be considered. Laboratory studies of the recording heads and tape used for the UPSHOT-KNOTHOLE series of tests have shown that neither the tape nor the heads were ever driven to saturation. It was impossible for the amplifiers to produce output levels high enough to do so. In most cases, the pre-amplifier stages produced grid clipping and harmonic distortion, resulting in a severely overloaded record of moderate level. Therefore, the only possible error that could be introduced by items 7 and 8 would be of the most serious nature, i.e., complete loss of data, because experience has shown that valid thermal yield data cannot readily be resolved from severely overloaded signals.

Item 9, the non-linearity of oscilloscope sweep circuitry, enters into the possible error category during the re-transcription of the data from magnetic tape to photographic film. The technique used is to feed the desired signal into the horizontal sweep binding posts of a tektronix model 511-A oscilloscope, and adjust the sweep to trigger coincident with the signal applied. The actual record traces a horizontal line of varying length on the face of the cathode ray tube. This variable length trace is then converted to a display of the type shown in Fig. 2.12. The time base is represented by the speed at which the photographic film is passed over the face of the cathode ray tube. The film moves perpendicular to the direction of movement of the actual signal trace, spreading out the response on the film. The film speed is held constant so that each record has the same time base relationship. The time base is actually formed by the period of the chopping frequency which in turn is represented as time per unit length of the film. Actual time is measured by counting cycles, the main object of the moving film photography is to spread these cycles out over a sufficient length of film to facilitate the counting. A serious error can be introduced into the record by not having a linear relationship between the CRO spot deflection and applied signal voltage. This is especially true when recording the calibration signals and the shot record on the same film for amplitude comparison measurements. The accuracy with which the value of the thermal energy received at the microphone can be measured is dependent upon the accuracy with which the amplitude of the calibration signal can be compared with the amplitude of the signal received from the nuclear detonation. A true linear relationship must exist between all amplitudes presented by the deflection of the oscilloscope trace.

Item 10, the transmissivity value used for calculating total thermal yield is supplied by another agency. However, the values supplied are not often of sufficient accuracy for use with measurements made at distances of 8 to 10 miles from the point of burst. The value for the transmissivity per statute mile enters the equation for the calculation of uncorrected thermal yield in KT as a value raised to a power. The power is the distance from the point of burst in miles. As this quantity appears in the denominator of the equation, and is multiplied by 10^{12} it has a significant effect upon the results of the equation, therefore very small errors in the values for transmissivity when raised to powers of large distances (8 to 10 miles) result in substantial errors in the value of the calculated thermal yield. Since the value for transmissivity is measured over a different path than that used for our radiation pressure measurements, there is good chance for an additional error in this value.

Item 11, the field of view of the microphone, can easily be increased. At present, it is approximately $\frac{1}{4}$ radian. It was originally contemplated that this device would be used to measure thermal radiation received at points several miles from the point of detonation. For this purpose, the field of view was sufficient for accurate alignment to the point of burst. However, when the sensing units are moved to within a mile of the detonation point, accurate alignment becomes more critical. This is especially true for air bursts where the predetermined detonation point is not always accurately forecasted. It is needless to discuss the possible error that could be incurred by slight misalignment with a narrow field of view.

Most of the foregoing items can be easily improved to obtain more accurate results. Of these experimental errors, the most serious is obtaining accurate transmissivity information over the transmission path between the microphone and the point of detonation.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The engineering data described by the project leaders during these tests have been obtained. The vacuum microphone appears to have adequate sensitivity and a sufficiently low noise factor to measure thermal radiation over large distances. The time resolution seems to be much greater than required at this time in weapons effects studies.

5.2 RECOMMENDATIONS

The field investigation covered by this report has been complicated because of "back-up" procedures to make certain that no data were lost. Had the objective of Project 8.2 been a measurement of the total caloric content of radiation, many of the data reduction difficulties encountered would have been eliminated by the addition of an appropriate integrator involving a tuned circuit with a very high Q (ratio of reactance to resistance) and suitable band pass filters to the detection system. This would have provided a very high rejection of interferring signals and produced a record of operational results that would have been almost immediately available for distribution. The problems connected with the vacuum microphone as a radiation detector are now thoroughly understood and it has been demonstrated that this instrument has a very large dynamic range. The time resolution can be made better than one-tenth of a millisecond, which is adequate for any measurements of this type. It is not effected by the Christov phenomenon, at least up to within one mile of ground zero. It is the opinion of the writers of this report that the vacuum microphone has been developed to the point where it is a suitable instrument for the measurement of thermal radiation for an atomic burst. The package is small and compact and the minimum amount of associated equipment is not bulky.

APPENDIX A

DISCUSSION OF CAPACITOR MICROPHONES

In discussing capacitor microphones, two separate cases must be considered and appropriate approximations made in each case. The two cases are (1) a stretched membrane as a diaphragm, (2) a plate clamped along the edge as a diaphragm. The first type was used in the TUMBLER-SNAPPER tests, and the second during UPSHOT-KNOTHOLE.

Case (1) For forced vibration of a stretched diaphragm, the equation of motion is

$$\sigma \frac{\partial^2 u}{\partial t^2} = T\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + i\omega Z u_{av} + A e^{-i\omega t} \qquad (A.1)$$

σ = Surface density of the membrane
T = Tension
ω = Angular velocity of driving force = $2\pi f$
A = Amplitude of driving force
u = Displacement
Z = Specific acoustic impedance = R−iX

In polar coordinates, equation (A.1) becomes

$$\sigma \frac{\partial^2 u}{\partial t^2} = T\left[\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\left(\frac{\partial u}{\partial r}\right) + \frac{1}{r^2}\left(\frac{\partial^2 u}{\partial \theta^2}\right)\right] + i\omega Z u_{av} + A e^{-i\omega t} \qquad (A.2)$$

$$u_{av} = \frac{1}{\pi a^2}\int_0^{2\pi} d\theta \int_0^a ur\, dr = \frac{1}{\pi a^2}\iint u\, ds \qquad (A.3)$$

For the steady state it is obvious that the vibrating membrane must have the same period as the driving force. Furthermore, if restrictions are made to the simplest mode, then the vibration is independent of θ and the solution must then be made up of Bessel functions of zero order. The motion must vanish along the periphery were r=a. The solution is then seen to be

$$u = K\left[J_0\left(\frac{\omega r}{v}\right) - J_0\left(\frac{\omega a}{v}\right)\right] e^{-i\omega t} \qquad (A.4)$$

where

$$v = \sqrt{\frac{T}{\sigma}}$$

$$u_{av} = \frac{2\pi}{\pi a^2}\int_0^a K\left[J_0\left(\frac{\omega r}{v}\right) - J_0\left(\frac{\omega a}{v}\right)\right] e^{-i\omega t}\, r\,dr$$

$$= \frac{2K}{a^2}\left[\int_0^a J_0\left(\frac{\omega r}{v}\right) r\,dr - \int_0^a J_0\left(\frac{\omega a}{v}\right) r\,dr\right] e^{-i\omega t}$$

$$= \frac{2K}{a^2}\left[\int_0^a \frac{v^2}{\omega^2} J_0\left(\frac{\omega r}{v}\right)\left(\frac{\omega r}{v}\right) d\left(\frac{\omega r}{v}\right) - \int_0^a J_0\left(\frac{\omega a}{v}\right) r\,dr\right] e^{-i\omega t}$$

since

$$\int J_0(x)\,dx = x J_1(x)$$

$$u_{av} = \frac{2K}{a^2}\left[\frac{v^2}{\omega^2}\left(\frac{\omega r}{v}\right) J_1\left(\frac{\omega r}{v}\right) - J_0\left(\frac{\omega a}{v}\right)\frac{r^2}{2}\right]_0^a e^{-i\omega t}$$

$$= \frac{2K}{a^2}\left[\frac{va}{\omega} J_1\left(\frac{\omega a}{v}\right) - J_0\left(\frac{\omega a}{v}\right)\frac{a^2}{2}\right] e^{-i\omega t}$$

however

$$\frac{2n}{x} J_n(x) - J_{n-1}(x) = J_{n+1}(x)$$

and $$u_{av} = K\left[\frac{2v}{\omega a} J_1\left(\frac{\omega a}{v}\right) - J_0\left(\frac{\omega a}{v}\right)\right] e^{-i\omega t} = K J_2\left(\frac{\omega a}{v}\right) e^{-i\omega t} \qquad (A.5)$$

By putting equations (A.4) and (A.5) into equation (A.2) and solving for K,

$$K = \frac{\frac{A v^2}{T \omega^2}}{J_0\left(\frac{\omega a}{v}\right) - \frac{iZ}{\sigma\omega} J_2\left(\frac{\omega a}{v}\right)} \qquad (A.6)$$

Substituting this value for K in equation (A.5) yields equation (A.7).

$$u_{av} = K J_2\left(\frac{\omega a}{v}\right) e^{-i\omega t} \qquad (A.5)$$

$$u_{av} = \frac{A J_2\left(\frac{\omega a}{v}\right) e^{-i\omega t}}{\omega\sigma\left[J_0\left(\frac{\omega a}{v}\right) - \frac{iZ}{\sigma\omega} J_2\left(\frac{\omega a}{v}\right)\right]} \qquad (A.7)$$

For a given microphone and a given frequency, all parameters are constant except the amplitude A so that

$$u_{av} = A K' e^{-i\omega t} \qquad (A.8)$$

and the change in frequency in the frequency modulated system will then vary directly with the intensity of the light pressure on the diaphragm.

Case II A condenser microphone with a plate clamped at the edges for a diaphragm has its forced vibration described by the following equation

$$\frac{\partial^2 u}{\partial t^2} + \frac{\omega^2}{k^4}\nabla^4 u + \frac{R}{\pi a^2 h\rho}\iint \frac{\partial u}{\partial t}\, r\, dr\, d\theta - \frac{A}{h\rho}\, e^{-i\omega t} = 0 \qquad (A.9)$$

where $$k = \frac{3\omega^2\rho(1-\mu^2)}{q h^2}$$

ω = angular velocity of applied form
$2h$ = thickness of the diaphragm
ρ = density of the diaphragm
μ = Poisson's ratio
q = Modulus of elasticity.

The solution for the above equation is a combination of Bessel's functions and the hyperbolic Bessel's function to satisfy the boundary conditions (a) $u=0$ when $r=a$, (b) $\frac{\partial u}{\partial t} = 0$ when $r=a$. It must also have the period of the applied force for the steady state.

Starting with the simpler equation

$$(\nabla^4 - k^4)\,\omega = 0$$

where $$\omega = F(r, \theta)\, e^{-i\omega t}$$

it can easily be shown that

$$J_n(kr) \text{ and } J_n(ikr) \qquad (A.10)$$

are solutions. For the simplest mode,

$$u = e^{-i\omega t}\left[\beta J_0(kr) + C I_0(kr) - \beta J_0(ka) - C I_0(ka)\right] \qquad (A.11)$$

This would satisfy condition (a) but not condition (b). However it is easy to see that since the derivatives enter into the second boundary condition B and C must be replaced by I (Ka) and J (Ka) respectively so that

$$u = k\, e^{-i\omega t}\left[I_1(ka) J_0(kr) + J_1(ka) I_0(kr) - I_1(ka) J_0(ka) - J_1(ka) I_0(ka)\right] \qquad (A.12)$$

meets all the boundary conditions and if K can be determined it is a solution of the differential equation of motion.

K can be shown to be a constant for a particular frequency.

$$u_{av} = \frac{1}{\pi a^2}\iint u\,ds = \frac{2\pi}{\pi a^2}\int_0^a ur\,dr \qquad (A.13)$$

$$= \frac{2Ke^{-i\omega t}}{a^2}\int_0^a \left[I_1(ka)J_0(kr)+J_1(ka)I_0(kr)-I_1(ka)J_0(ka)-J_1(ka)I_0(ka)\right]r\,dr$$

$$= \frac{2Ke^{-i\omega t}}{a}\left[I_1(ka)J_1(ka)\frac{a}{k}+J_1(ka)I_1(ka)\frac{a}{k}-I_1(ka)J_0(ka)\frac{a^2}{2}-J_1(ka)I_0(ka)\frac{a^2}{2}\right]$$

$$= \frac{2Ke^{-i\omega t}}{a^2}\left[I_1(ka)\left\{J_1(ka)\frac{2}{ka}-J_0(ka)\right\}\frac{a^2}{2}-J_1(ka)\left\{I_1(ka)\frac{2}{ka}+I_0(ka)\right\}\frac{a^2}{2}\right]$$

$$= k\,e^{-i\omega t}\left[I_1(ka)J_2(ka)-J_1(ka)I_2(ka)\right]$$

$u_{av} = De^{-i\omega t}$ where $D = k\left[I_1(ka)J_2(ka)-J_1(ka)I_2(ka)\right]$ (A.14)

and is a constant for a given frequency.

It can also be shown that D is inversely proportional to the thickness and to the density of the diaphragm.

In a system using the microphone capacitance as a tuning capacitance, consider the U_{av} as dx where X is the distance between the diaphragm and pole piece, Fig. A.1.

$$dx = u_{av} = De^{-i\omega t} \qquad (A.15)$$

Differentiate the equation $f = \frac{1}{2\pi\sqrt{LC}}$ with respect to C

$$\frac{df}{dc} = \frac{-1}{4\pi\sqrt{LC}\,C} = \frac{-f}{2C}$$

$$\frac{df}{f} = \frac{-dc}{2c} \qquad (A.16)$$

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but

$$C = \frac{A k}{4 \pi x}$$

$$\frac{dc}{dx} = \frac{-A k}{4 \pi x^2} = \frac{-C}{x}$$

$$\frac{dc}{c} = \frac{-dx}{x} \qquad \text{(A.17)}$$

therefore

$$\frac{df}{f} = \frac{-dc}{2c} = \frac{dx}{2x} = \frac{D}{2x} e^{-i\omega t} \qquad \text{(A.18)}$$

and the frequency deviation is directly proportional to the radiation pressure.

For a considerable time doubt existed as to whether or not the sole actuating force on the diaphragm of the microphones actually was radiation pressure. This problem has been at least partially solved. The diaphragms used in the field operations were made out of glass, and it was known that a shift in frequency took place when radiation was absorbed by the diaphragms. Even though this effect was very slow compared to the chopping rate, it was not definitely ascertained that some thermal effect was not taking place at the chopping frequency. Quartz diaphragms 0.003 inches thick have since been tried in an effort to reduce all thermal effects. However, so near as can be determined, no change in sensitivity of the microphone has taken place. This would indicate that radiation pressure actuates the diaphragm but does not preclude the possibility that some radiometer effect might also be present.

As a further check, the response of the microphone was measured at various angles. Any thermal effect should vary with the cosine of the angle of incidence while the radiation pressure effect should vary with the square of the cosine. Actually the measured results indicate a power slightly in excess of the second. This can be explained as follows: As the angle is changed, less reflected light strikes the diaphragm. This reflected light is from the inside of the pyrex envelope back on the diaphragm and amounts to about 4 per cent for normal incidence. A similar reflection takes place at the front glass air interface and accounts for another 4 per cent. Results are given in Fig.A.2.

The quartz diaphragms have been operated over a frequency range of from 46 cps. to over 4000 cps. with a good response. This combined with the experiment on response vs. angle of incidence gives assurance that the force actuating the diaphragms is due to radiation pressure.

Figure A.3 illustrates the effective increase in the output signal from a capacitor microphone unit as the ambient air pressure is decreased. This curve definitely illustrates the advantage of evacuating the microphone sensing unit oscillators to obtain an increase in the effective microphone response.

Improvements in Microphones

1. Quartz diaphragms are now used. This greatly reduces center frequency shift due to absorbed radiation.

2. Smaller apertures allowing a greater chopping frequency and larger angle of view are also used. The central portion of the microphone is most sensitive and therefore a smaller aperture can be used without decreasing the sensitivity too much. This also means less absorption and the elimination of some of the slow shift of center frequency from radiation absorption.

3. The design of the chopping disc has been changed from round holes to radial slots. This allows a greater angle of view and makes the problem of alignment much simpler.

4. Changes have also been made in the glass envelope. The front face is now being made optically flat to reduce the possibility of diffraction or beam focusing occurring because of imperfections in the glass blowing.

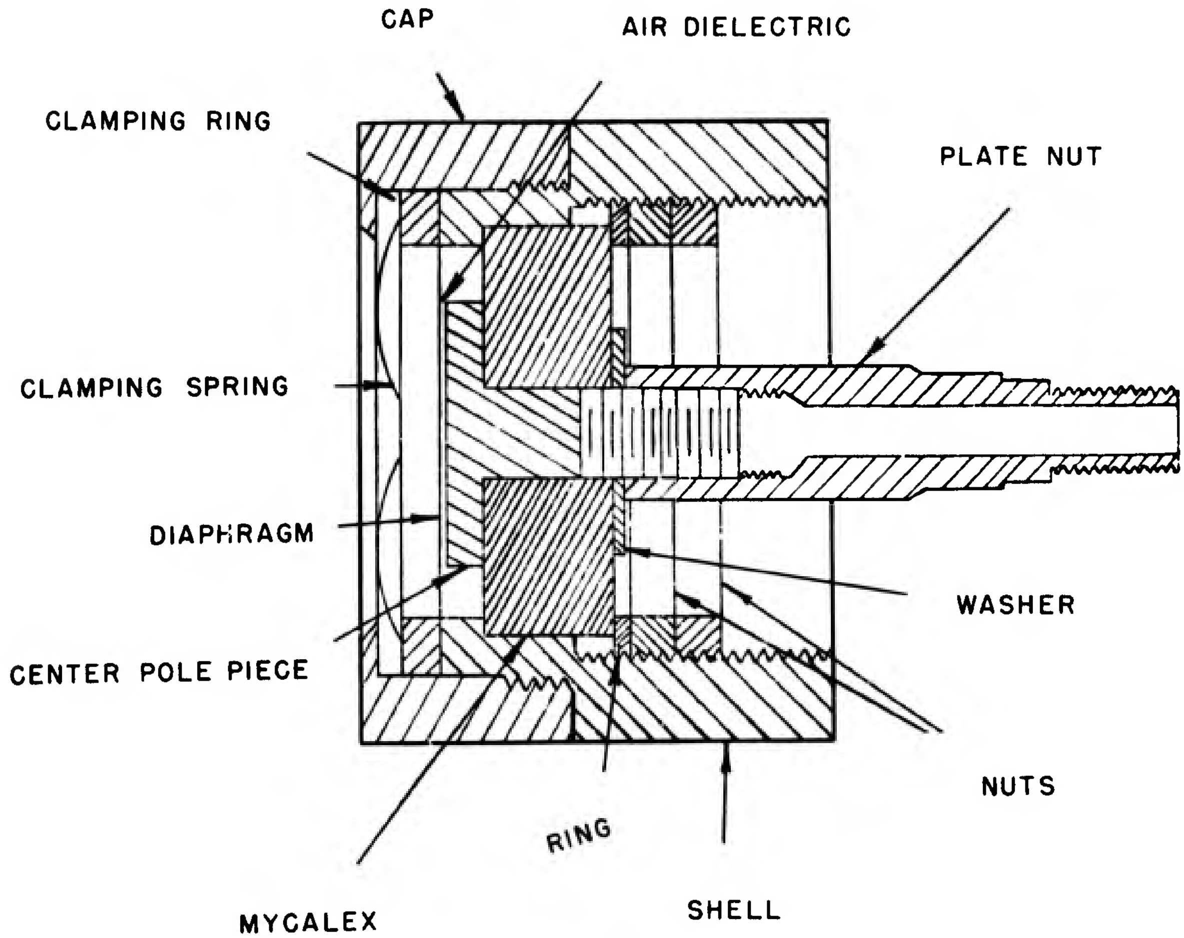

Fig. A.1 Capacitor Microphone

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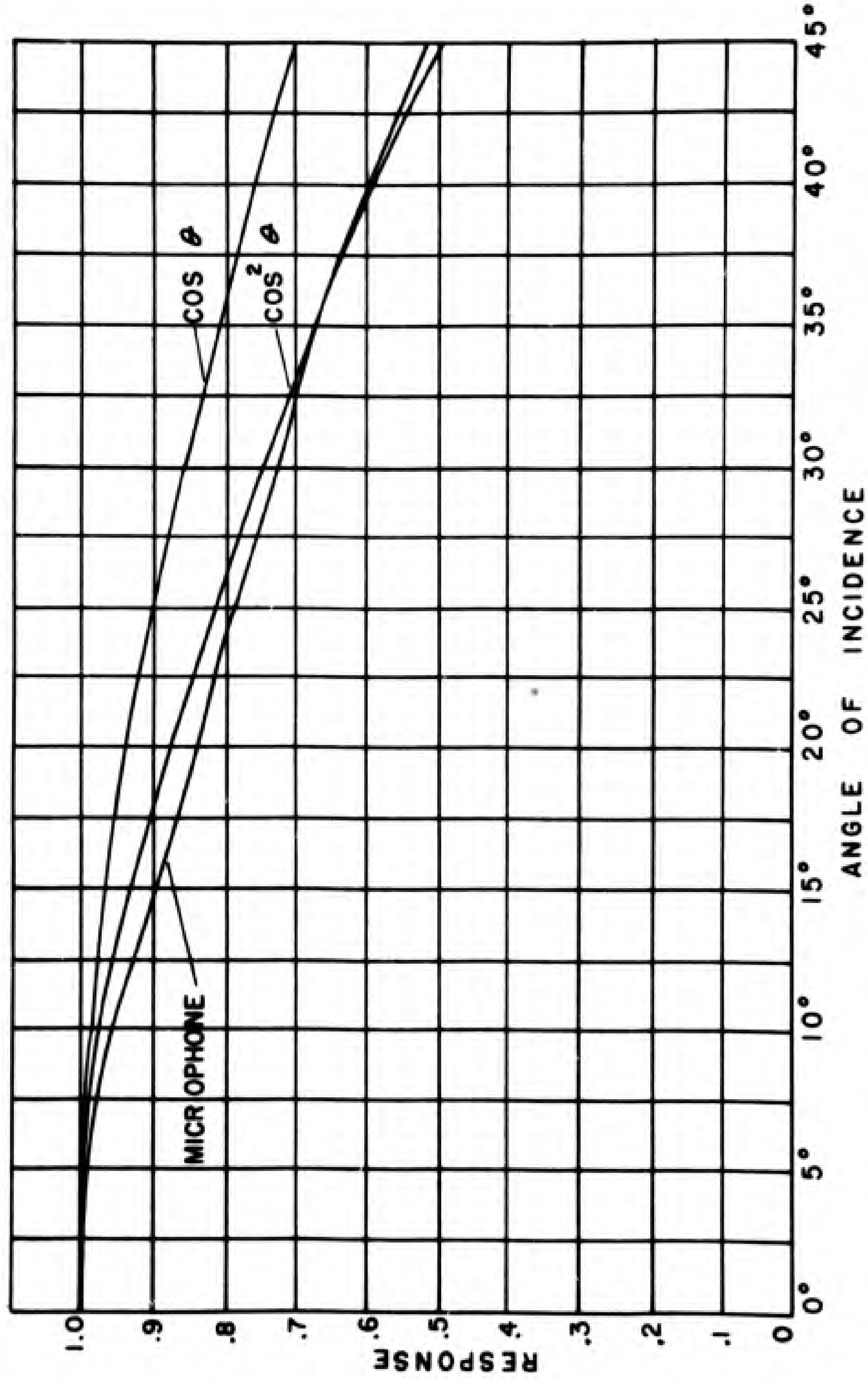

Fig. A.2 Microphone Response vs Angle of Incidence

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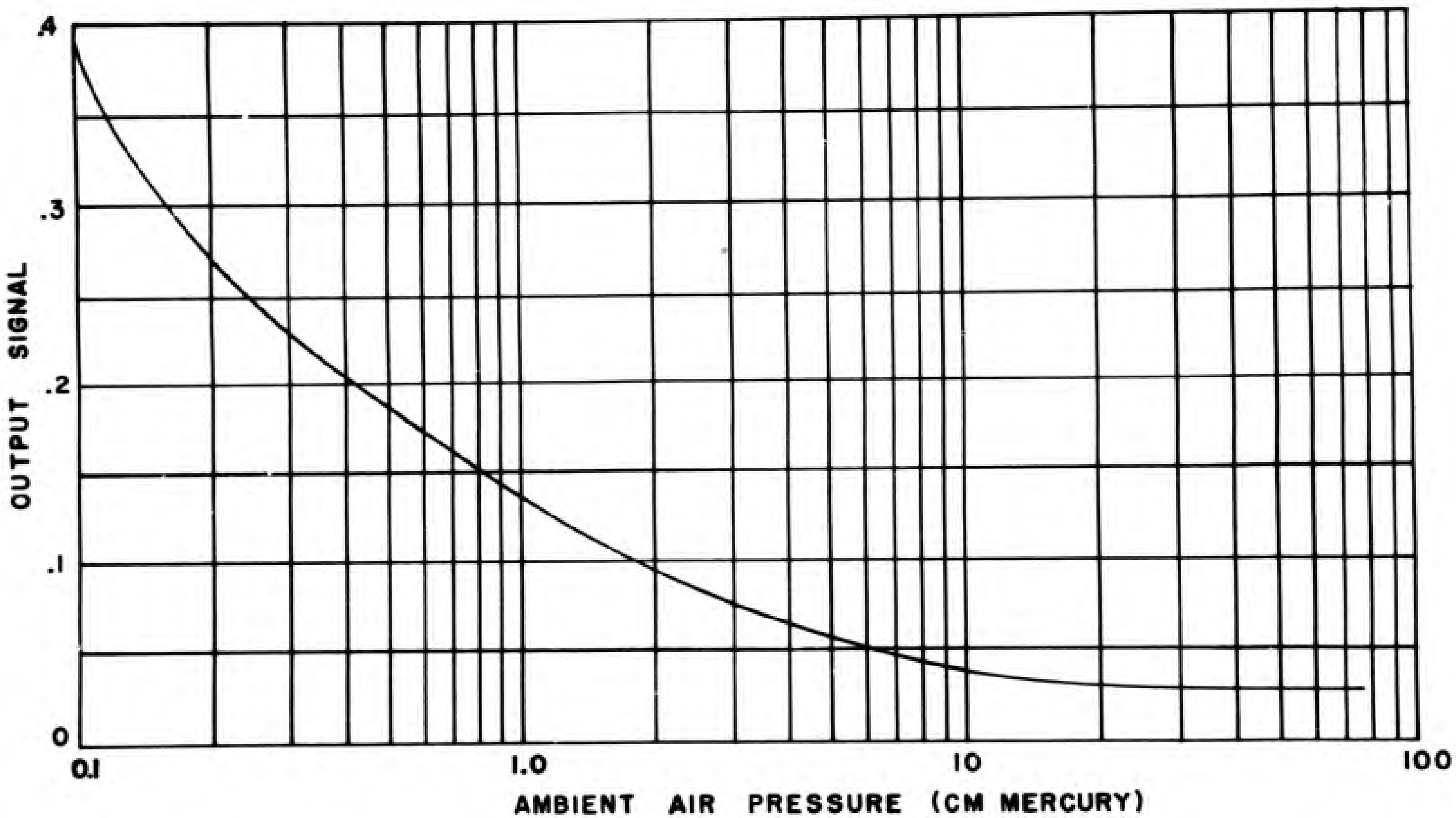

Fig. A.3 Microphone Response vs Ambient Air Pressure

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98 Commander, U.S. Naval Ordnance Laboratory, Silver Spring 19, Md. ATTN: R
99 Commander, U.S. Naval Ordnance Test Station, Inyokern, China Lake, Calif.
100 Commanding Officer, U.S. Naval Medical Research Inst., National Naval Medical Center, Bethesda 14, Md.
101 Director, U.S. Naval Research Laboratory, Washington 25, D.C. ATTN: Code 2029

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102 Director, The Material Laboratory, New York Naval Shipyard, Brooklyn, N.Y.

103 Commanding Officer and Director, U.S. Navy Electronics Laboratory, San Diego 52, Calif. ATTN: Code 4223

104-107 Commanding Officer, U.S. Naval Radiological Defense Laboratory, San Francisco 24, Calif. ATTN: Technical Information Division

108 Commander, U.S. Naval Air Development Center, Johnsville, Pa.

109 Director, Office of Naval Research Branch Office, 1000 Geary St., San Francisco, Calif.

110 Officer-in-Charge, U.S. Naval Clothing Factory, U.S. Naval Supply Activities, New York, 3rd Avenue and 29th Street, Brooklyn, N.Y. ATTN: R&D Division

111-117 Technical Information Service, Oak Ridge, Tenn. (Surplus)

AIR FORCE ACTIVITIES

118 Asst. for Atomic Energy, Headquarters, USAF, Washington 25, D.C. ATTN: DCS/O

119 Director of Operations, Headquarters, USAF, Washington 25, D.C. ATTN: Operations Analysis

120 Director of Plans, Headquarters, USAF, Washington 25, D.C. ATTN: War Plans Div.

121 Director of Research and Development, Headquarters, USAF, Washington 25, D.C. ATTN: Combat Components Div.

122-123 Director of Intelligence, Headquarters, USAF, Washington 25, D.C. ATTN: AFOIN-1B2

124 The Surgeon General, Headquarters, USAF, Washington 25, D.C. ATTN: Bio. Def. Br., Pre. Med. Div.

125 Deputy Chief of Staff, Intelligence, Headquarters, U.S. Air Forces Europe, APO 633, c/o PM, New York, N.Y. ATTN: Directorate of Air Targets

126 Commander, 497th Reconnaissance Technical Squadron (Augmented), APO 633, c/o PM, New York, N.Y.

127 Commander, Far East Air Forces, APO 925, c/o PM, San Francisco, Calif.

128 Commander, Strategic Air Command, Offutt Air Force Base, Omaha, Nebraska. ATTN: Special Weapons Branch, Inspection Div., Inspector General

129 Commander, Tactical Air Command, Langley AFB, Va. ATTN: Documents Security Branch

130 Commander, Air Defense Command, Ent AFB, Colo.

131-132 Commander, Air Materiel Command, Wright-Patterson AFB, Dayton, O. ATTN: MCAIDS

133 Commander, Air Training Command, Scott AFB, Belleville, Ill. ATTN: DCS/O GTP

134 Commander, Air Research and Development Command, PO Box 1395, Baltimore, Md. ATTN: RDDN

135 Commander, Air Proving Ground Command, Eglin AFB, Fla. ATTN: AG/TRB

136-137 Commander, Air University, Maxwell AFB, Ala.

138-145 Commander, Flying Training Air Force, Waco, Tex. ATTN: Director of Observer Training

146 Commander, Crew Training Air Force, Randolph Field, Tex. ATTN: 2GTS, DCS/O

147 Commander, Headquarters, Technical Training Air Force, Gulfport, Miss. ATTN: TA&D

148-149 Commandant, Air Force School of Aviation Medicine, Randolph AFB, Tex.

150-155 Commander, Wright Air Development Center, Wright-Patterson AFB, Dayton, O. ATTN: WCOESP

156-157 Commander, Air Force Cambridge Research Center, 230 Albany Street, Cambridge 39, Mass. ATTN: CRQST-2

158-160 Commander, Air Force Special Weapons Center, Kirtland AFB, N. Mex. ATTN: Library

161 Commandant, USAF Institute of Technology, Wright-Patterson AFB, Dayton, O. ATTN: Resident College

162 Commander, Lowry AFB, Denver, Colo. ATTN: Department of Armament Training

163 Commander, 1009th Special Weapons Squadron, Headquarters, USAF, Washington 25, D.C.

164-165 The RAND Corporation, 1700 Main Street, Santa Monica, Calif. ATTN: Nuclear Energy Division

166-172 Technical Information Service, Oak Ridge, Tenn. (Surplus)

OTHER DEPARTMENT OF DEFENSE ACTIVITIES

173 Asst. Secretary of Defense, Research and Development, D/D, Washington 25, D.C.

174 U.S. National Military Representative, Headquarters, SHAPE, APO 55, c/o PM, New York, N.Y. ATTN: Col. J. P. Healy

175 Director, Weapons Systems Evaluation Group, OSD, Rm 2E1006, Pentagon, Washington 25, D.C.

176 Armed Services Explosives Safety Board, D/D, Building T-7, Gravelly Point, Washington 25, D.C.

177 Commandant, Armed Forces Staff College, Norfolk 11, Va. ATTN: Secretary

178-183 Commanding General, Field Command, Armed Forces Special Weapons Project, PO Box 5100, Albuquerque, N. Mex.

184-185 Commanding General, Field Command, Armed Forces, Special Weapons Project, PO Box 5100, Albuquerque, N. Mex. ATTN: Technical Training Group

186-194 Chief, Armed Forces Special Weapons Project, Washington 25, D.C.

195-202 Technical Information Service, Oak Ridge, Tenn. (Surplus)

ATOMIC ENERGY COMMISSION ACTIVITIES

203-205 U.S. Atomic Energy Commission, Classified Technical Library, 1901 Constitution Ave., Washington 25, D.C. ATTN: Mrs. J. M. O'Leary (For DMA)

206-208 Los Alamos Scientific Laboratory, Report Library, PO Box 1663, Los Alamos, N. Mex. ATTN: Helen Redman

209-210 Sandia Corporation, Classified Document Division, Sandia Base, Albuquerque, N. Mex. ATTN: Martin Lucero

211-213 University of California Radiation Laboratory, PO Box 808, Livermore, Calif. ATTN: Margaret Edlund

214 Weapon Data Section, Technical Information Service, Oak Ridge, Tenn.

215-275 Technical Information Service, Oak Ridge, Tenn. (Surplus)

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