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A Method of Measuring Temperature Changes Casued by Strong Shock Phenomena

Benjamin J. Goodier

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By

Benjamin G. Goodier

A Thesis

Submitted in Partial Fulfillment of

the Requirements for the Degree of

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This thesis, directed and approved by the candidate's committee, has been accepted by the Graduate Committee of the University of New Mexico in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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I. INTRODUCTION

Experimental studies of materials under extreme pressures can be done by producing strong shock waves in a material and observing the behavior of the material. Measurements of the motion of materials and of shock waves through materials and of density variations in materials under the influence of shock waves yield values for the pressure and specific volume at various states of the shock wave. Experimental data are needed which can yield another variable such as internal energy, entropy, or temperature changes of materials. The purpose of the work for this thesis is to develop a device that is capable of measuring the temperature of the free surface of a plate during a portion of the time after it is set in motion by a strong shock wave.

Any temperature measuring device attached directly to a surface would probably be affected by the shock wave and, therefore, its response characteristics would probably be affected. A radiation monitoring device could escape the mechanical effects of the shock during the time that it is needed for temperature measurements. For this thesis the detector is an infrared sensitive multiplier phototube. The fast response of this tube makes it valuable for measuring signals occurring in times in the order of microseconds.

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temperature of the free surface of the substance will change as the shock is reflected from it. The compressed material immediately behind the shock front reaches a state v, P, T, (Figure 1) which has an entropy increase over the initial state. This increase occurs because the compression was not performed under conditions of thermal equilibrium. The expansion behind the shock wave from this state does occur under thermal equilibrium conditions and is adiabatic, lying above the shock compression curve as is shown in Figure 1 (1).* A measurement of the temperature difference, $T_2 - T_0$, called the residual temperature, will yield the change in entropy. Calculations of this temperature by Group GMX-6 for a number of materials included the basic assumptions of thermal equilibrium and isotropy, and an estimation of the ratio of specific heats, γ, which is probably inaccurate at high pressures (2).

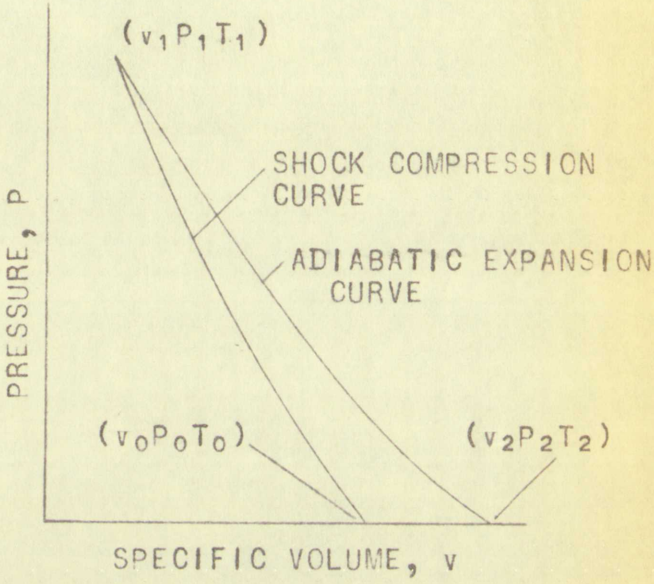

Figure 1

Because the free surface of a material cannot support the high pressure of a shock wave, the wave is reflected from it and the temperature change of this surface should be the residual temperature. Measurements of this temperature change would provide valuable experimental data which could be compared to the calculated values.

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* Number references are listed in Section X.

II. SCOPE OF THE INVESTIGATION

This thesis is concerned with the development of a method to measure the temperature of a metal surface during a time interval of a few microseconds while it is being subjected to a strong shock. The temperature of special interest is the temperature of the free surface which appears after a strong shock has been reflected from that surface. This temperature remains constant until another shock wave is reflected from the surface, except for the change caused by heat loss to the surroundings by radiation.

The work for this thesis consists of the following items:

(1) Investigating the various temperature detectors that are available, and evaluating their suitability for this application.

(2) Designing and building apparatus suitable for calibrating the detector and for using the detector in experiments employing high explosives to produce strong shock waves.

(3) Conducting experiments which will yield data from the shock wave phenomena, and establishing the validity of the results.

(4) Evaluating the experimental data and investigating the sources and magnitudes of the errors.

(5) Comparing the data obtained from the experiments with the theoretical results obtained by others.

III. LITERATURE REVIEW

In the thermocouple work done by Minshall (3) an attempt was made to measure the temperature of a metal under shock conditions. The temperatures reported are associated with the high pressure of the shock front rather than with the zero pressure of the free surface. Figure 2 is a diagram of his apparatus. Other experimental work was performed by William Otto of GMX-6 in an attempt to measure the temperature of a shock wave in water, using an infrared sensitive multiplier phototube. His estimated temperature of 1200°C for a 190 kilobar shock pressure is not a reliable figure because he had difficulty distinguishing between electronic noise and signal on his photographic records. Also his pressure figure was only a rough calculation. His work is described in an informal report in GMX-6 files. Recently GMX-6 has continued work in the field by building equipment to measure the temperature of a copper plate under shock conditions, but no results have been reported.

Gibson and others (4) reported high speed temperature measurements in detonation fronts of high explosives. They used a technique similar to Otto's; i. e., employing a plexiglass rod which transmitted the signal from inside the high explosive to a multiplier phototube detector.

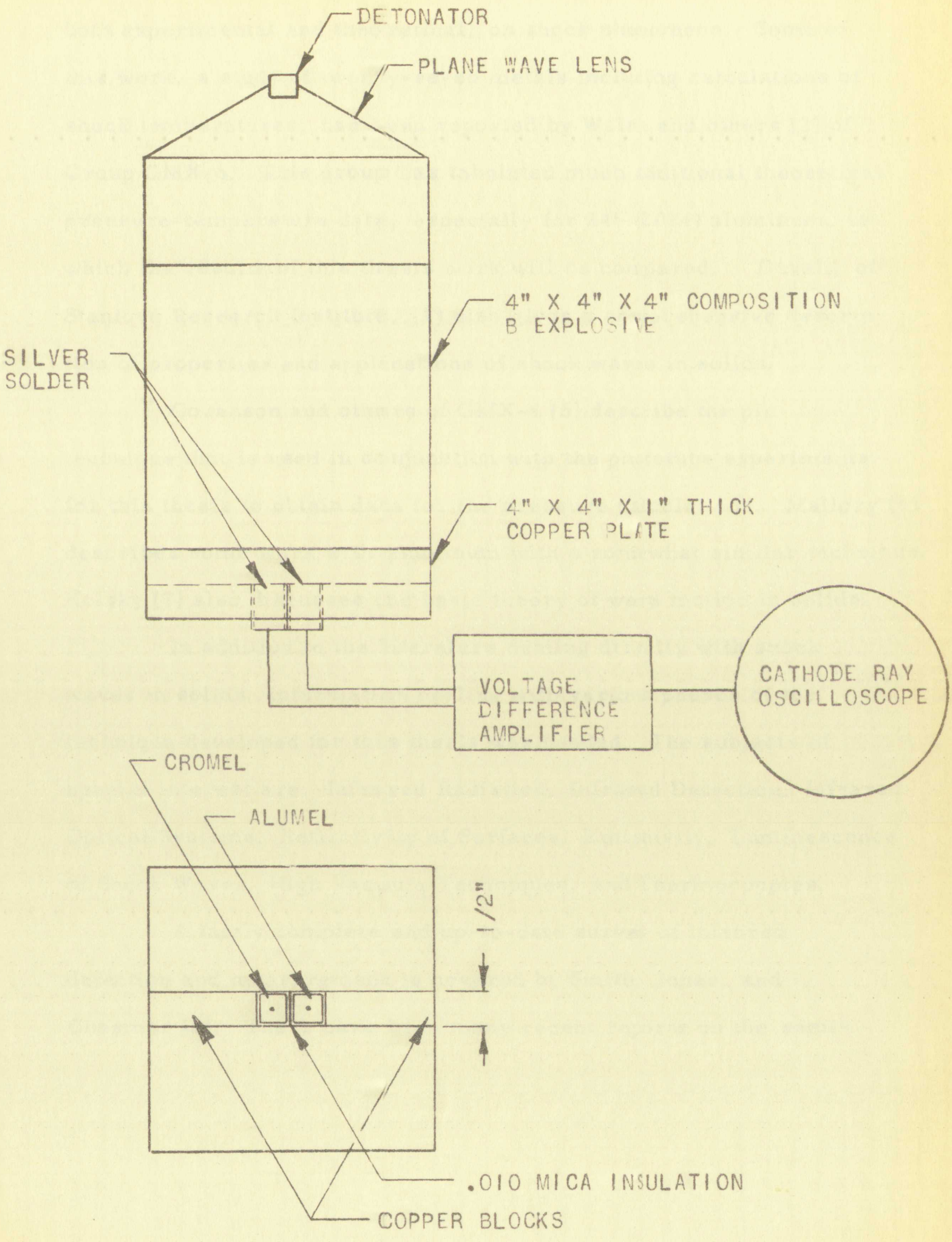

FIG. 2. MINSHALL THERMOCOUPLE EXPERIMENT

The Los Alamos Scientific Laboratory has done much work, both experimental and theoretical, on shock phenomena. Some of this work, a study of twenty-seven metals including calculations of shock temperatures, has been reported by Walsh and others (2) of Group GMX-6. This group has tabulated much additional theoretical pressure-temperature data, especially for 24S (2024) aluminum, to which the results of this thesis work will be compared. Duvall, of Stanford Research Institute, (1) also gives a comprehensive description of properties and applications of shock waves in solids.

Goranson and others of GMX-4 (5) describe the pin technique that is used in conjunction with the phototube experiments for this thesis to obtain data for the pressure calculations. Mallory (6) describes some work with aluminum with a somewhat similar technique. Kolsky (7) also discusses the basic theory of wave motion in solids.

In addition to the literature dealing directly with shock waves in solids, information dealing with various phases of the technique developed for this thesis was needed. The subjects of special interest are: Infrared Radiation, Infrared Detection, Infrared Optical Systems, Reflectivity of Surfaces, Emissivity, Luminescence of Shock Waves, High Vacuum Techniques, and Thermocouples.

A fairly complete and up-to-date survey of infrared detection and measurement is covered by Smith, Jones, and Chasmar (8). There have been many recent reports on the semi-

conductor type infrared detectors having wide spectral and fast time responses as described by Lasser, Cholet, and Wurst (9), but because of the availability and even better time response of the infrared sensitive multiplier phototube, RCA type 7102, the primary effort of this thesis was directed away from the crystal detectors. The development and design considerations of a tube similar to the 7102 are described by Weaver (10).

Gill (11) discusses some problems in low temperature pyrometry such as the effect of a change in the emissivity of a body on its temperature, and the effect of temperature gradients in a body upon its surface temperature.

Rutgers (12) includes the design considerations of a black-body source in his paper together with much other information on the temperature radiation of solids.

Both Gier and others (13) and Gates and others (14) give values for the reflectance of aluminum, and this is compared to the reflectance of copper and silver. Aluminum reflectance drops off considerably below about 1.5 microns wavelength and is lower than that of silver for all wavelengths. Ballard and others (15) list the optical, elastic, and other properties of infrared materials and show that fused and crystalline quartz transmit energy to about 3.5 microns wavelength compared to the limit of about 2.5 microns for ordinary glass. Glaze and others (16) describe a variety of glasses some of which transmit energy to about 5.2 microns.

Drude (17) provides basic theory in the field of optics. Harrison (18) and Conn and Avery (19) provide additional information about the application of infrared methods to radiation pyrometry.

Information on the dissociation and luminescence of air under shock conditions has considerable bearing on this work. Petschek and others (20) describe some shock tube experiments. In one experiment, air at a pressure of 5 cm Hg had about 30 per cent dissociation with a shock wave traveling at Mach 9.55. Wood (21) shows that shock waves up to Mach 14 in air dissociates the oxygen more quickly than the nitrogen. Lin (22) gives the rate of ionization of air at 20 microns pressure and at various shock velocities up to Mach 20.

Much valuable information on experimental techniques, especially in relation to building a vacuum system is given by Strong and others (23). Jepson and others (24) describe more fully the technique of cryopumping; i.e., using a getter such as cooled charcoal in a vacuum system to absorb gas from the rest of the system. Van Atta (25), Gutherie and Wakerling (26), and Yarwood (27) also discuss characteristics of high vacuum systems. Hees and others (28) describe a knife edge seal which can be used for systems that are heated to high temperatures, and Lange and Riemersma (29) report that Teflon can be outgassed effectively by baking for ten hours at temperatures between 290°C and 430°C.

The Instrument Society of America (30) gives much data on thermocouple techniques as does the American Institue of Physics (31). The latter also presents much detailed information on all phases of temperature measurement and control.

IV. EXPERIMENTAL INVESTIGATION

The purpose of the experimental investigation was to find if the apparatus could measure the temperature changes on the surface of the aluminum plate when these changes were produced by a strong shock wave traveling in the plate.

The experiments of the investigation may be divided into three groups. The largest group of experiments consists of calibrating the output of the phototube before each shot and firing these shots. For this, a plate was heated either electrically or with a torch to about 750°C and then allowed to cool. The phototube monitoring the surface of the plate was pulsed to a conducting state at about 10° temperature intervals as indicated by a galvanometer connected to a thermocouple. The thermocouple was imbedded in the plate near the surface being monitored by the multiplier phototube. The output of the phototube was displayed on cathode ray oscilloscopes and the traces photographed. Comparing the signal from the phototube when the high explosive was detonated to these calibration traces would give the apparent temperature of the plate under shock conditions.

The second group of experiments were performed to check the validity of certain assumptions made in designing the apparatus and in establishing the procedure for calibrating and firing a shot. An experiment was conducted to check the effect on the output of the phototubes of heated plates with various surface finishes. A blackbody cavity was

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The experiments of the investigation may be divided into three groups. The largest group of experiments consists of calibrating the output of the phototube before each shot and firing these shots. For this, a plate was heated either electrically or with a torch to about 300°C and then allowed to cool. The phototube monitoring the surface of the plate was pulsed to a conducting state at about 10° temperature intervals as indicated by a galvanometer connected to a thermocouple. The thermocouple was imbedded in the plate near the surface being monitored by the multiplier phototube. The output of the phototube was displayed on Tektronix 545 oscilloscopes and the traces photographed. Comparing the signal from the phototube when the high explosive was detonated to the calibration traces would give the apparent temperature of the plate under shock condition.

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constructed and its radiation was compared to that of the machined metal surfaces. This experiment also indicated the maximum error that could be expected if the surface of the aluminum should change its emissivity under shock conditions.

Another experiment conducted in a light-tight box with a fast pulsed light source revealed the time response characteristics of the multiplier phototube and its related circuitry. Other experiments were performed to compare the responses of thermocouples in various geometries, to find under what conditions serious temperature gradients might exist in the calibration plate. The response of one thermocouple was compared to that of another and the temperature indicated by a number of thermocouples for the melting point of lead was noted at various times during the course of the investigation.

A shot was fired at GMX-6 to find how closing off the light pipe by wrapping primacord around it could be accomplished. A few recovery type shots were fired at GMX-6 and at GMX-4 to attempt to find evidence of melting of aluminum after the samples had been subjected to shocks similar to those produced in the phototube experiments.

The third group of experiments consisted of firing pin shots to measure the motion of an aluminum plate driven by a high explosive assembly like that used for the phototube experiments. The velocities

calculated from the data of these experiments indicated the maximum pressure of the shock wave in the aluminum. Thus, the residual temperatures of aluminum, as calculated for a range of pressures by GMX-6, can be compared to temperatures obtained from the phototube experiments.

V. APPARATUS

Much apparatus was used in conducting the experimental work for this thesis. The major portion of the electronic apparatus and the techniques associated with its use are a part of Group GMX-4's specialty; i. e., measuring the motion of shock waves in solids and the motion of materials affected by these shock waves with an electrical contactor technique described later. Multiplier phototube experiments are also part of the work of GMX-4, so that the electronics and the handling and firing of the high explosives for these experiments departed very little from the everyday work of the group. The high explosive charges were standard parts designed and supplied by Group GMX-3, and only the hardware directly associated with the phototube experiments and the nonexplosive parts for the other experiments were of special design. Therefore, this description of the apparatus will not cover the control room equipment or the explosive system in much detail.

Because the apparatus used for the experiments amounted to a large number of different types of assemblies, they shall be grouped according to function in the following order:

I. Apparatus for various phototube experiments

   A. Preliminary testing

   B. Calibrating

   C. Shot firing

   D. Other testing

V. APPARATUS

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I. Apparatus for various [illegible] operations

A. Preliminary testing

B. Calibrating

C. Shot firing

D. Other testing

II. Other apparatus for high explosive experiments

A. Electrical contactor (pin) experiments

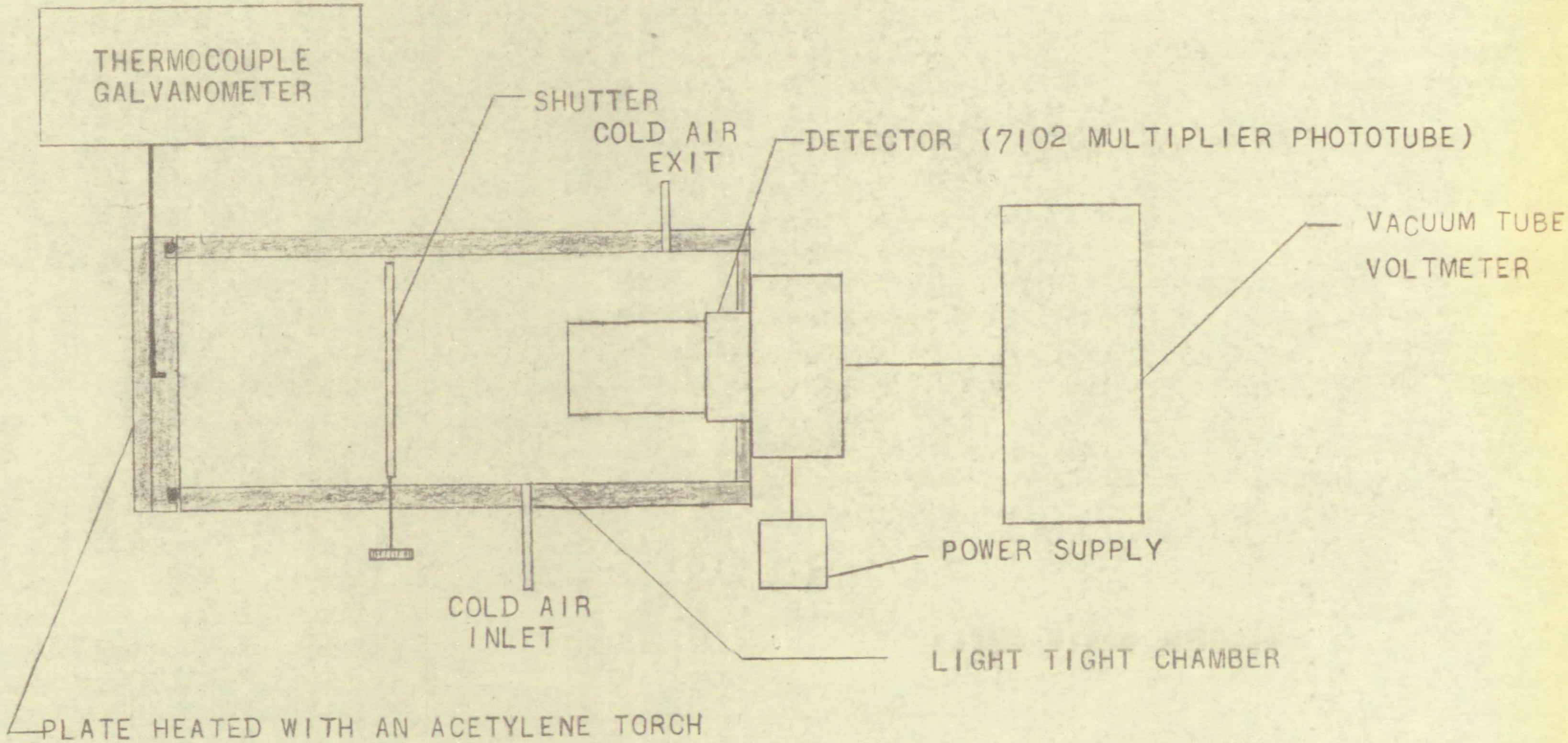
B. Recovery experiments

I. Apparatus for various phototube experiments

A. Preliminary testing

The first apparatus constructed for the experimental work consisted of a brass tube with a plate at one end that could be heated with a torch or electrical heater, and with provisions for mounting the RCA type 7102 multiplier phototube as shown in Figure 3. A hand operated shutter near the center of the tube kept radiation from heating the phototube, except when it was to detect the radiation from the surface of the plate. The temperature of the plate was indicated by a Chromel-Alumel thermocouple attached near the center of the plate on its inside surface. A Brown millivoltmeter pyrometer measured the current in the thermocouple circuit and indicated the temperature directly after its zero point was set. A vacuum tube voltmeter indicated the output of the phototube when the shutter was opened.

Because the dark current of the phototube output can be reduced by about 50% for each 6° reduction in the temperature of the photocathode starting at 25°C, cold air was circulated around the phototube. In the geometry of this apparatus with no restriction of



INFRARED SENSITIVE MULTIPLIER PHOTOTUBE TEST

FIG. 3

the area of the plate exposed to the phototube and with the photocathode about 6 inches away from the plate the phototube was capable of detecting a minimum plate temperature of about 180°C. Other observations on its output at higher temperatures provided information which aided in the design of the electronic circuitry for the apparatus built after this test.

B. Calibrating

Apparatus like that shown in Figures 4, 5, and 6 was used for calibrating shots and modifications were used for other experiments. Figure 4 shows the calibrating apparatus at the firing pit including the cables used to connect the apparatus with the control room. Figure 5 shows the hardware around the phototube in more detail. A considerable amount of care was taken to shield the multiplier phototube from stray magnetic and electrical fields that could be produced during the time the high explosive was detonating. A tubular mu-metal shield around the phototube and a sheer stainless steel screen in front of the photocathode were both connected electrically to the photocathode voltage supply. (Tests showed a high resistance connection here adversely affected the response of the tube when used with the gated circuit.) The rest of the metal around the phototube was kept at ground potential by the shielding on the cables and a special cable that connected the barricade to the firing unit ground connection. (This arrangement does provide ground loops, but no difficulty from this was noticeable in any of the records.)

BILL OF MATERIAL			
PART NUMBER	NUMBER REQD.	PER	DESCRIPTION
33	1	ASSY	DETONATOR
34	1		SIGNAL, GATE, FIDUCIAL & HIGH VOLTAGE CABLES
35	1		REGULATOR VALVE FOR CO_2 SUPPLY
36	1		.020 THK. BRASS SLEEVE
37	1		PRIMACORD WITH TWO DETONATORS
38	2		HOSE CLAMP - LASL STK. CAT # HF-6040
39	1		O-RING - 2 3/4 O.D. × 2 9/16 I.D. × .103 WALL

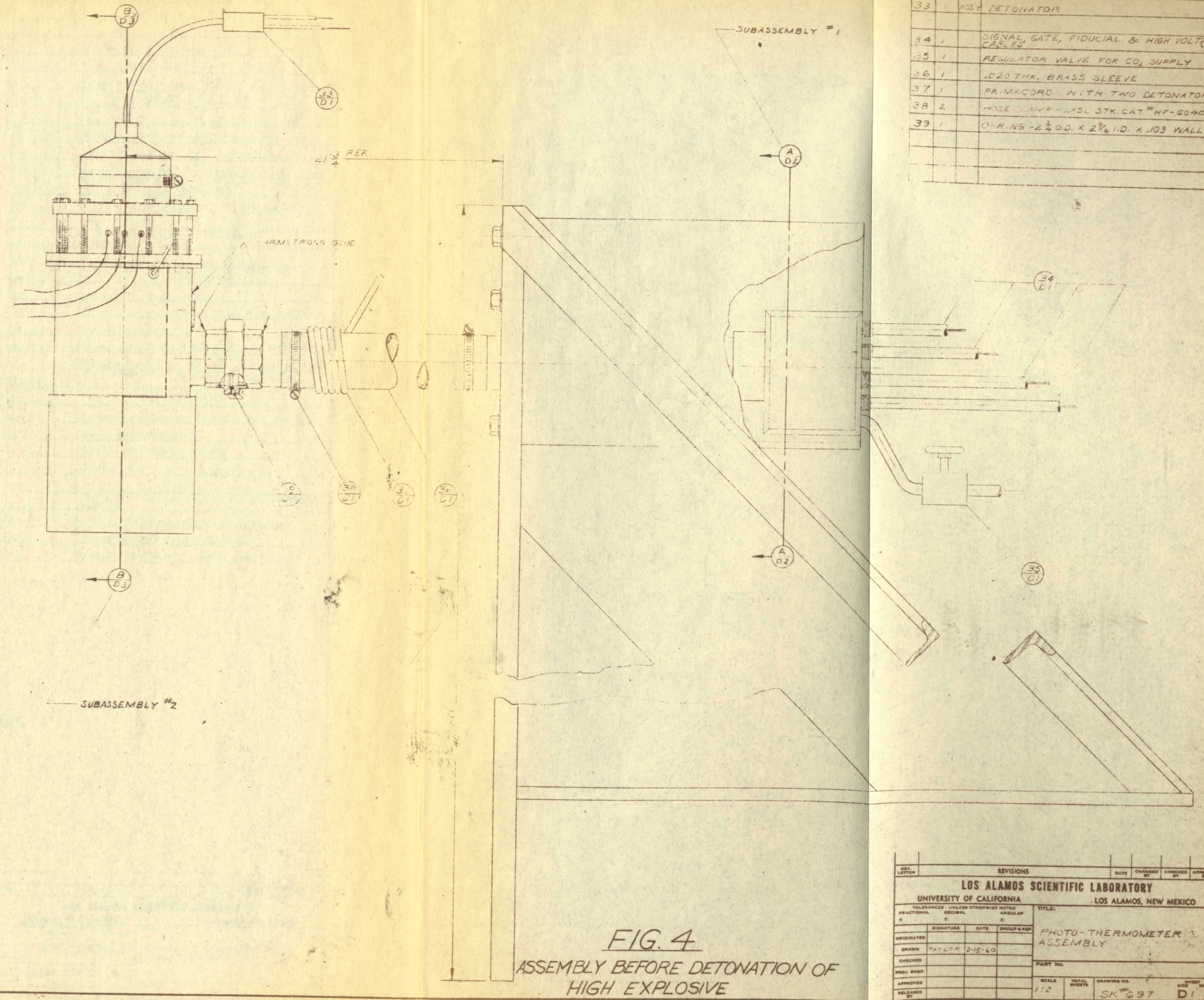


FIG. 4
ASSEMBLY BEFORE DETONATION OF HIGH EXPLOSIVE

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	SIGNATURE	DATE	GROUP & REF.
ORIGINATED			
DRAWN	TAYLOR	2-15-60	
CHECKED			
PROJ. ENGR.			
APPROVED			
RELEASED BY			

TITLE: PHOTO-THERMOMETER ASSEMBLY

PART No.

SCALE	TOTAL SHEETS	DRAWING NO.	SIZE	SHEET NO.
1:2		SK # 697	D	1

BILL OF MATERIAL

PART NUMBER	NUMBER REQD.	PER	DESCRIPTION
1	1	ASSY	SARAN TUBE - SK #698D9
2	3		1/4-20NC-2 X 2 1/4 LG. HEX HD. BOLT- HEX NUT & WASHERS
3	7		3/8-16NC-2 X 1 3/4 LG. HEX. HD. M.S.
4	1		STL. BARRICADE - SK #698C11
5	1		PHOTOTUBE FLANGE - BRASS (SK #698D3)
6	1		COPPER TUBE - 3/8 O.D. X .065 WALL X 1/2 LG. (1/8-27 NPT ON ONE END)
7	2		2 1/4 O.D. X 2 I.D. X .139 WALL O-RING
8	6		RUBBER GROMMET- 7/8 O.D. X 1/4 I.D. X 5/16 THK.
9	1		BLAST SHIELD - STL. (SK #698D3)
10	1		PHOTOTUBE SHIELD - BRASS (SK #698D3)
11	6		#12-24NC-2 FIL. HD. BOLT WITH HEX. NUT & PLAIN WASHERS
12	1		LOCK RING - DURAL (SK #698A6)
13	1		3/16 X 1/8 WALL RUBBER TUBING
14	1		3/16 I.D. X 1/8 WALL RUBBER TUBING 11 IN. LG.
15	1		RCA 7102 ELECTRON TUBE
16	1		LEAF SPRING CONTACT - COPPER (FABRICATED BY USER)
17	1		TEFLON INSULATOR
18	1		#0-80 FIL. HD. BOLT WITH NUT & WASHER
19	1		TUBE SOCKET
20	1		CHASSIS - 9 1/2 X 5 1/2 X 4 3/8 - 1/16 THK AL
21	1		#5-40NC-2 X 3/8 LG. FIL. HD. BOLT-NUT & WASHER
22	4		#5-40NC-2 X 1/4 LG. FIL. HD. SCR.
23	1		TEXTOLITE SPACER RING
24			O-RING 2 3/4 O.D. X 2 9/16 I.D. X .103 WALL
25	1		MU-METAL SHIELD
26	2		TEXTOLITE GUIDE RING
27	1		EXTRA FINE S. STL. WIRE MESH
28	1		TEXTOLITE SPACER RING
29	1		3/16 I.D. X 1/16 WALL X 3 FT. LG. RUBBER TUBING
30	1		O-RING 3 3/8 O.D. X 3 I.D. X .210 WALL
31	1		CLEAR QUARTZ DISC - 1/4 THK.
32	1		O-RING 2 3/8 O.D. X 2 1/8 I.D. X .139 WALL

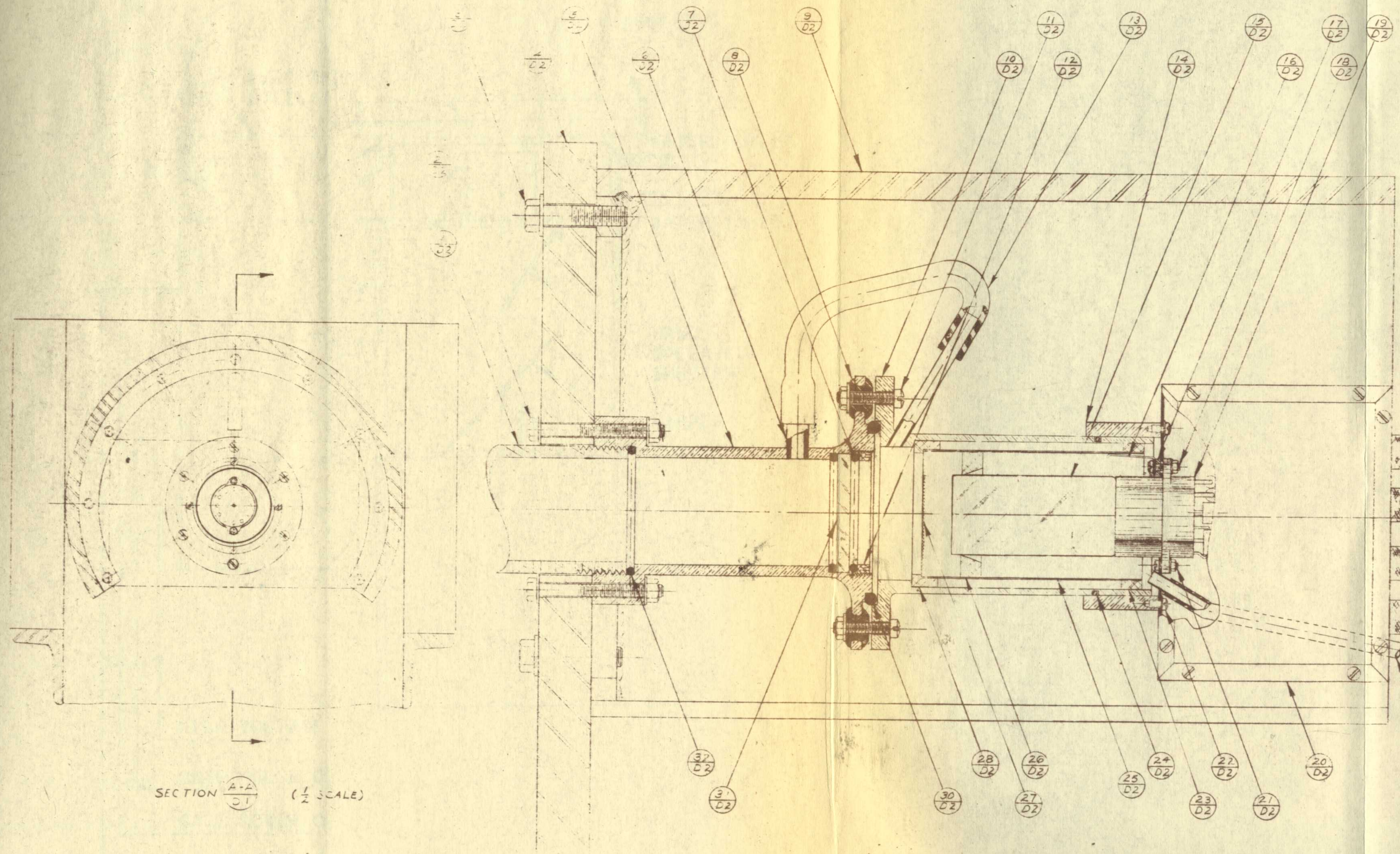

FIG. 5 MULTIPLIER PHOTOTUBE ASSEMBLY BEHIND BARRICADE

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APPROVED			
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TITLE: PHOTO-THERMOMETER SUBASSEMBLY #1

PART No.

SCALE: FULL & NOTED — TOTAL SHEETS: — DRAWING NO.: SK #637 — SIZE: D — SHEET NO.: 2

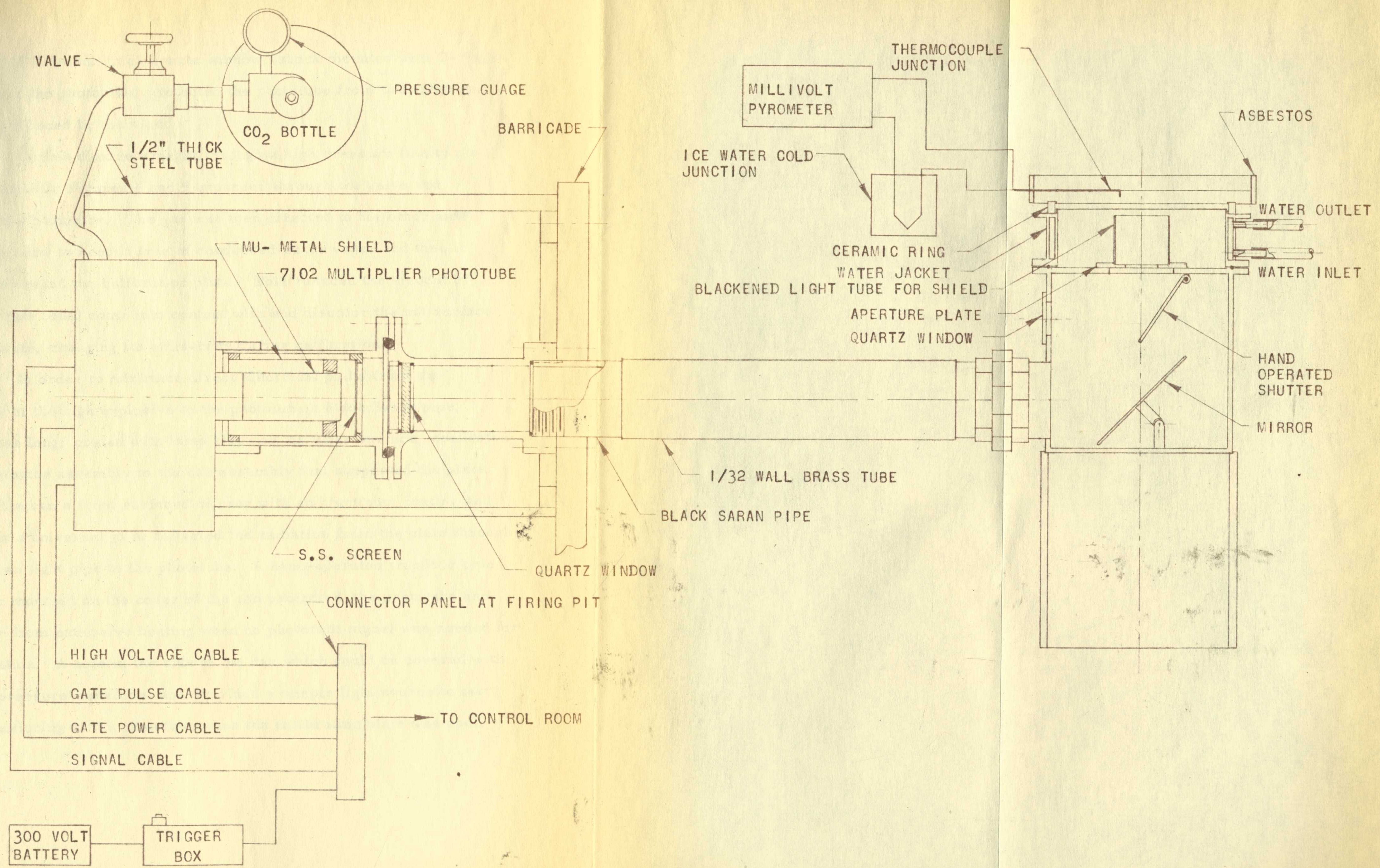

FIG. 6 APPARATUS FOR CALIBRATION

A 1/4-inch thick quartz window, shock mounted with O-rings in front of the phototube, protected the phototube from the shock and debris produced by the blast.

Carbon dioxide brought through a high pressure line to the valve shown in Figures 4 and 5 expanded through the valve and cooled the phototube. The gas was then directed to the other side of the window to keep it free of condensed water vapor and then it escaped around the calibration plate. This reduced the amount of oxygen that could come into contact with and discolor the hot surface of the plate, changing its emissivity during calibration.

In order to minimize direct electrical paths from the vicinity of the high explosive to the phototube a black Saran pipe, 15 inches long, coated with lamp black on its inner surface, connected the phototube assembly to the can assembly that supported the plate. Inside the can a front surfaced mirror with an aluminum coating and glued to a universal joint reflected the radiation from the plate through the Saran light pipe to the phototube. A hand-operated trapdoor type shutter mounted on the cover of the can protected the phototube and mirror from excessive heating when no phototube signal was needed for calibration. A hole in the side of the can which could be covered with black pressure-sensitive tape provided a simple light source to test the functioning of the phototube when the calibrating plate was cool.

An aperture plate and a brass tube light shield were mounted above the trapdoor opening to limit the area of the plate that could radiate to the phototube. The brass tube was glued to a 1/16-inch quartz disc. A water jacket and a ceramic ring supported a calibration plate above the aperture and brass light shield. Except for the plate all the surfaces in this cavity were coated with lamp black by playing an oxygen-starved acetylene flame over them.

Several different calibration plates were used in the experiments. The first plates were 3/8-inch thick 1100 aluminum which were actually fired after the calibration runs were completed. Later a brass plate was substituted for the aluminum so that a higher calibrating temperature could be attained, and so that the plate used with the high explosive would not be warped. Near the center of these plates a 1/32-inch diameter hole was drilled to within 1/16-inch of the surface facing the aperture and a thermocouple junction made of No. 28 gage Chromel-Alumel wire was staked in place. A 3/4-inch thick brass plate with a groove to accomodate the thermocouple lead was screwed above the calibrating plate. The outside diameter of the two plates was wrapped with several layers of 1/16-inch thick asbestos which was held in place with a large hose clamp. This brass plate protected the calibration plate and the thermocouple from the flame of the oxygen-acetylene torch used to heat them and, together with the asbestos, also prevented the calibration plate from cooling too rapidly during calibration.

An aperture plate and a brass tube light shield were mounted above the graphite opening so that only the area of the plate that would radiate to the phototube. The brass tube was glued to a 1/4-inch quartz disc. A water jacket and a ceramic ring supported a calibration plate above the aperture and brass light shield. Except for the plate all the surfaces in this cavity were coated with lamp black by playing an oxygen-starved acetylene flame over them.

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A stainless steel calibrating plate as shown in Figure 7 was constructed so that an electrical heat source could be used in place of the torch. This allowed more control over the cooling rate and reduced the amount of equipment needed for an experiment. The plate had a thermocouple junction in a hole through its center and pressed flush against the radiating surface. The thermocouple leads were brought out through a lateral groove in the top of a brass plate above it and held in the groove by a ceramic cover plate. The heating element was Nichrome V wire inside of 1/16-inch diameter alumina tubes, placed in grooves on the top surface of the stainless steel plate. A Powerstat variable transformer and a 230-115 volt transformer reduced the 115 volt line voltage to that required to operate the heating element at the desired power level. Alumina cement filled the spaces around the alumina tubes and helped to hold the brass plate uniformly against the heating element and to the stainless steel plate. These plates were supported by a ceramic ring with the same outside diameter as the aluminum and brass calibrating plates already described.

The thermocouple leads from these plates were connected in series to a junction kept in ice water and to a Brown millivoltmeter pyrometer calibrated in degrees Centigrade. Periodic checks on the hot junctions were made by observing their indicated temperature when they were immersed in a bath of freezing lead.

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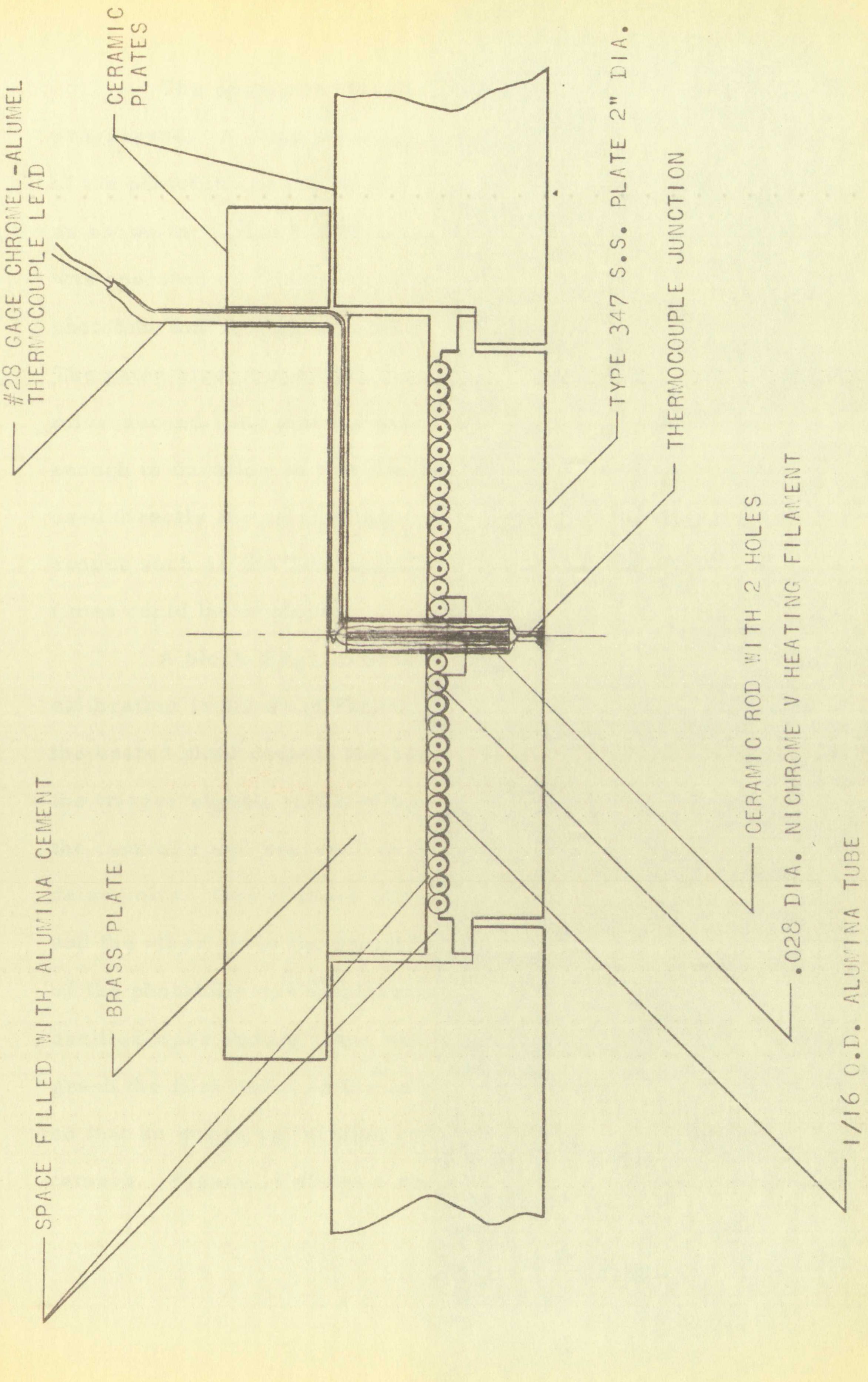


FIG. 7. ELECTRICALLY HEATED CALIBRATING PLATE

The phototube circuitry also changed as the experiments progressed. A simple voltage dividing network between the dynodes of the phototube as shown in Figure 8 was changed to a gated circuit as shown in Figure 9. This change eliminated a camera shutter which was operated at 1/200 second to provide a short light pulse to the phototube and a trigger pulse to the control room for the oscilloscopes. The gated circuit operated much more reliably, and the 10 to 40 microsecond time that the gate allowed the tube to conduct was short enough in duration so that the Tektronix 517 oscilloscopes could be used directly for calibration. With the camera shutter, only oscilloscopes such as the Tektronix 545 with provisions for long sweep times could be employed.

A block diagram of the control room equipment during calibration is shown in Figure 10. At about $10^{o}C$ intervals, as the heated plate cooled, the hand-operated shutter was opened and the trigger signal, initiated by a switch on the trigger box, started the control room sequence of operations. This signal triggered the delay units. One of these units started the sweep on the oscilloscopes and the other gated the phototube to a conducting state. The output of the phototube was displayed on the cathode ray tube of the oscilloscopes and its trace was photographed. After each photograph the film racks on the cameras were moved up about 1/8 inch so that an entire calibration run could be recorded on one plate per camera. Figure 11 shows a representative calibration film.

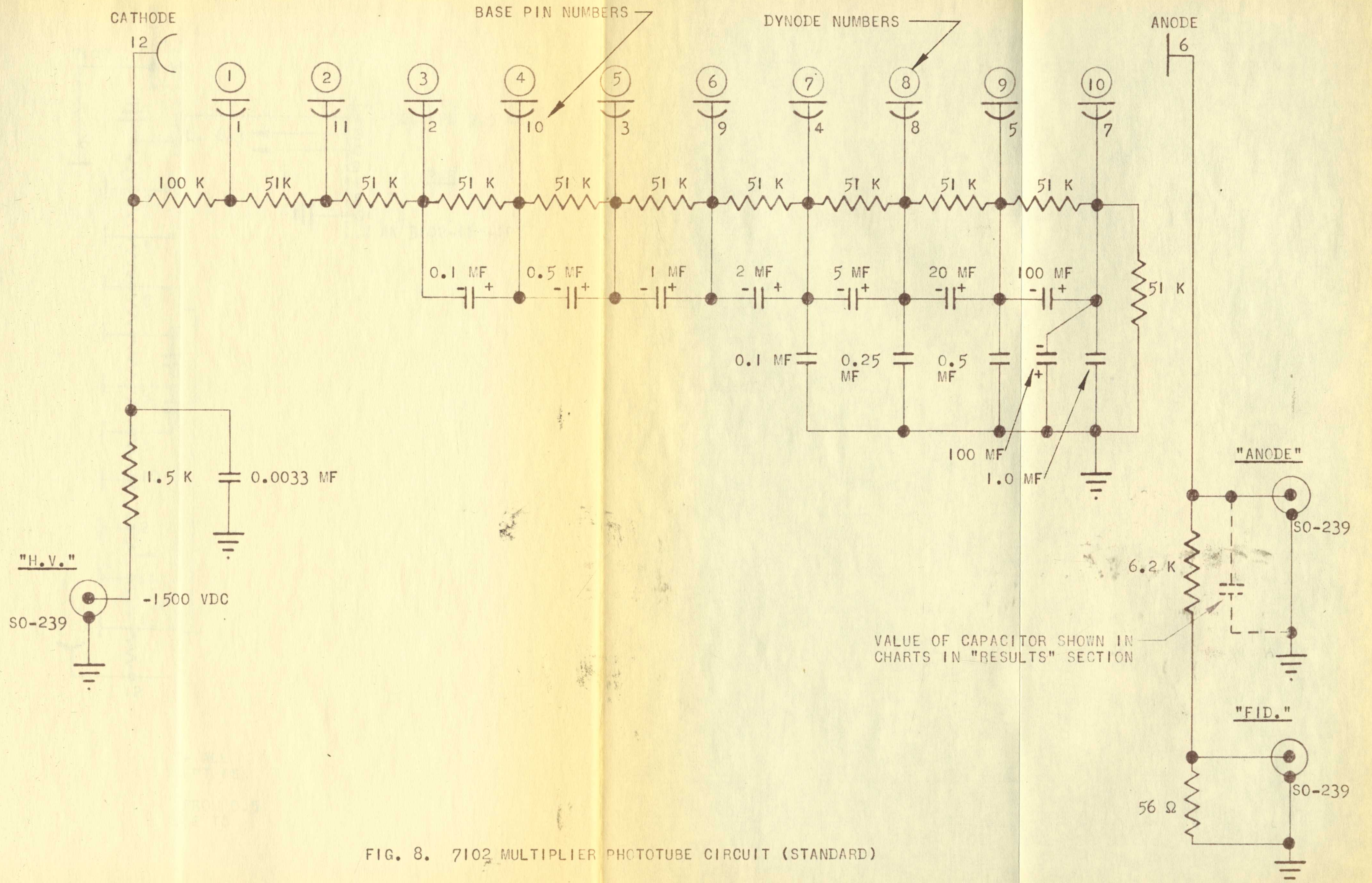
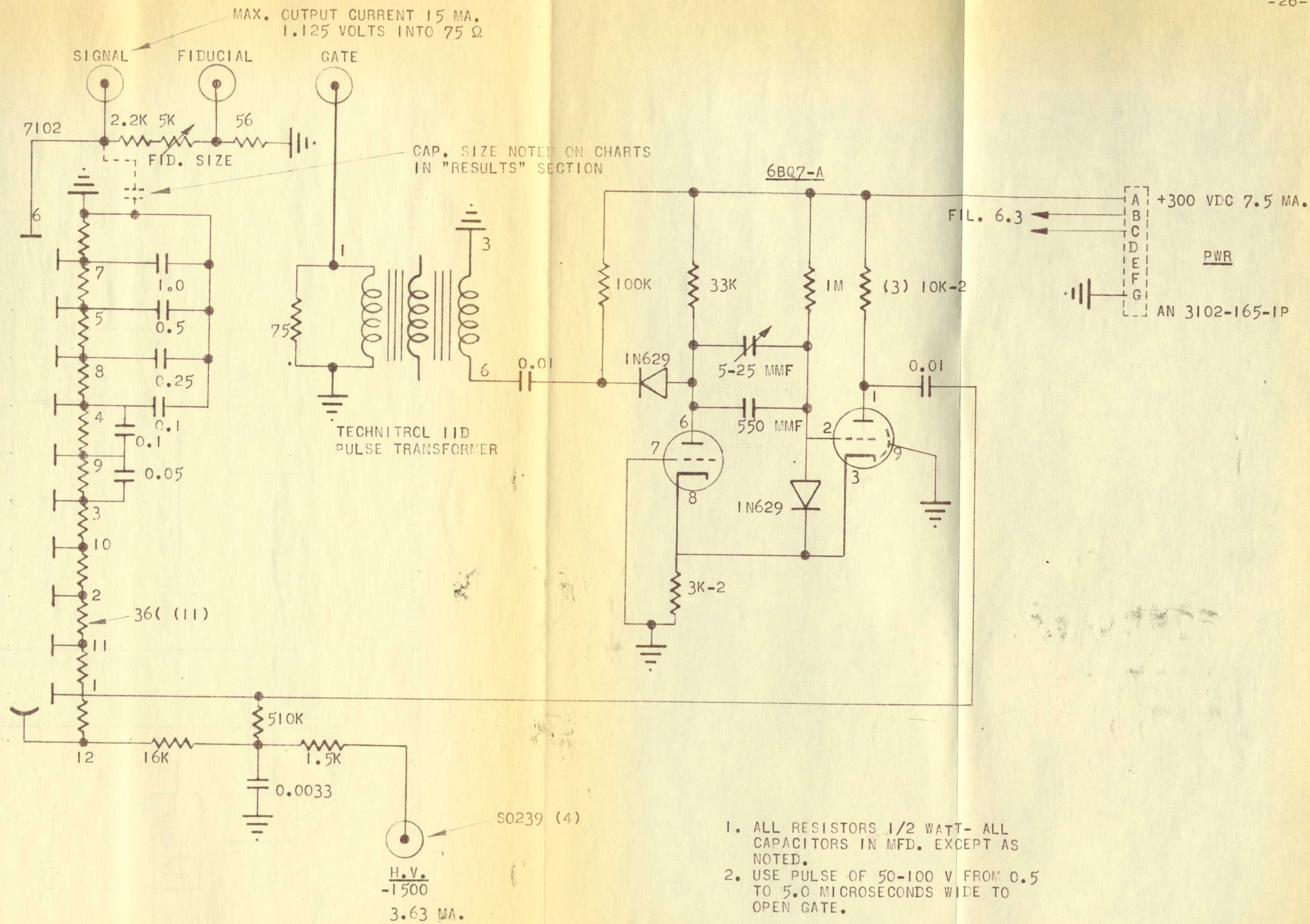


FIG. 8. 7102 MULTIPLIER PHOTOTUBE CIRCUIT (STANDARD)



1. ALL RESISTORS 1/2 WATT- ALL CAPACITORS IN MFD. EXCEPT AS NOTED.
2. USE PULSE OF 50-100 V FROM 0.5 TO 5.0 MICROSECONDS WIDE TO OPEN GATE.

FIG. 9. GATE CIRCUIT FOR RCA 7102 MULTIPLIER PHOTOTUBE

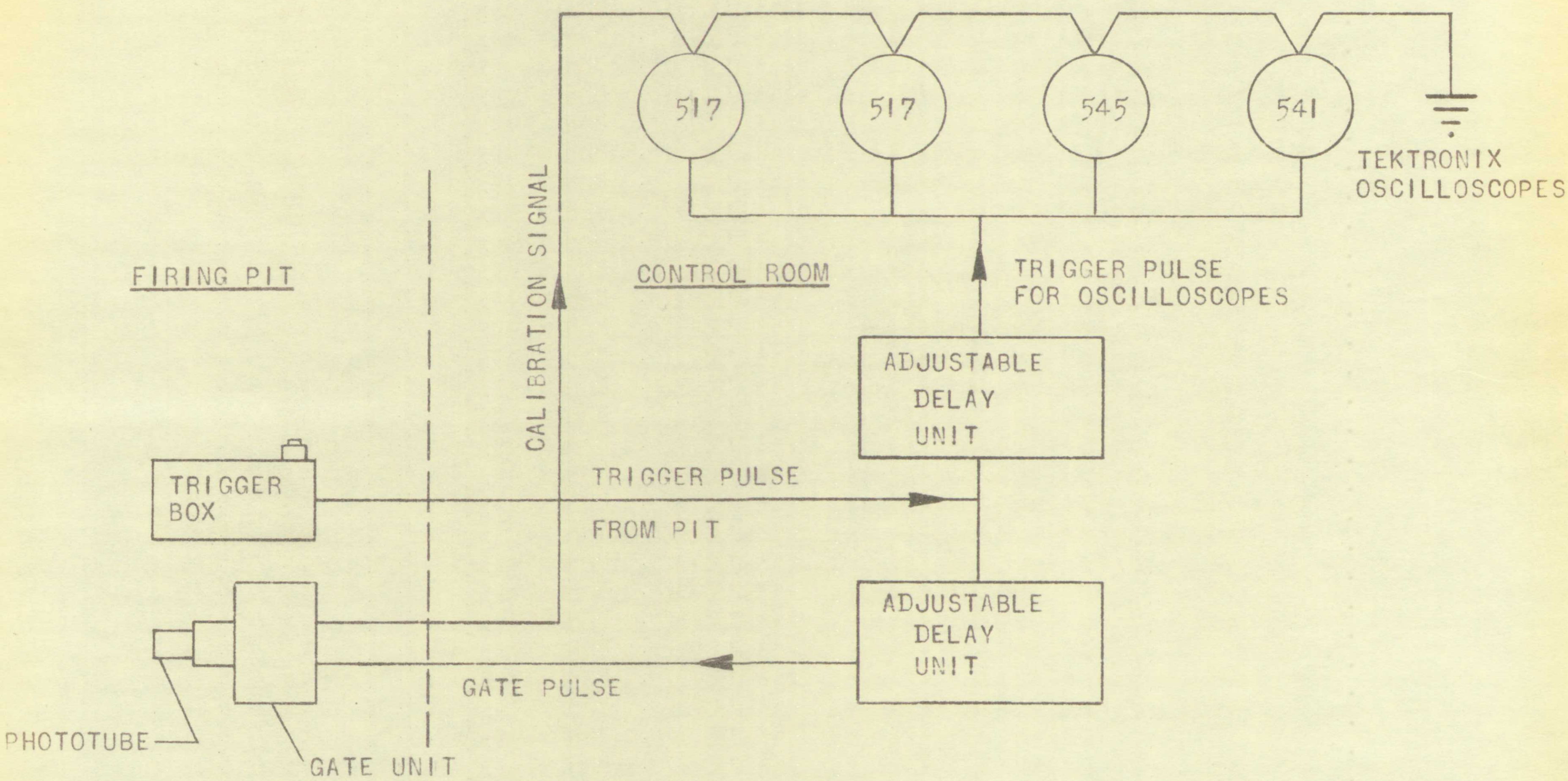


FIG.10. DIAGRAM FOR CALIBRATION OF PHOTOTUBE OUTPUT

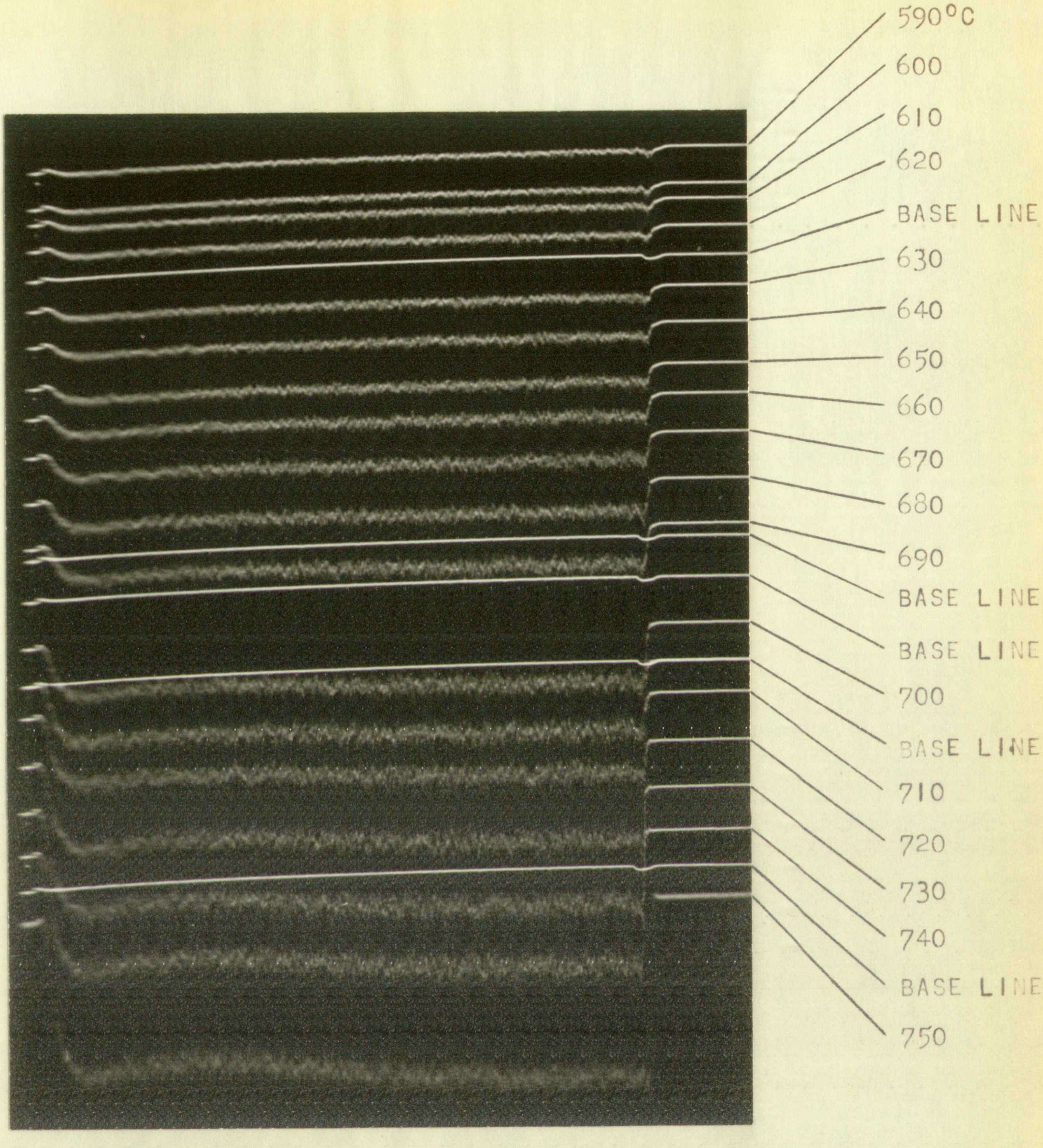


FIG. 11. PHOTOGRAPH OF TRACES RECORDED BY A CATHODE RAY OSCILLOSCOPE DURING THE CALIBRATION OF THE APPARATUS USED FOR FIRING A SHOT

C. Shot Firing

The validity of the temperatures reported for this work depends upon how closely the calibrating geometries and conditions are duplicated when the shots are fired. For this reason the calibration was always performed with the same cables, electronic system, and apparatus setup as that used for the firing of the shots. As the experiments progressed there were some differences between the calibrating conditions and the firing conditions, but it was felt that these did not introduce excessive errors. The charts in the "Results" section indicate the differences between the experiments and between calibrating and firing conditions. Except as is mentioned, the following apparatus description applies to Shot 24.

After calibration the blackened tube and quartz window assembly, the water jacket, the calibration plate, and the ceramic ring (Figure 6) were replaced by an evacuated cavity (Figure 12). The aluminum plate that was to be fired was the cover plate for the cavity and it was sealed against a 5-3/8 inch diameter knife edge (28) on the lip of the cylindrical section by a steel ring bolted to the bottom flange. The bottom plate of the cavity had an opening covered with a quartz disc the same thickness as that used in the calibration apparatus. The seal was a small amount of Apiezon Q sealing compound. An aluminum tube the same diameter and height as the brass tube that was removed but with a 0.005-inch wall thickness, was glued to the quartz with a few spots of Armstrong

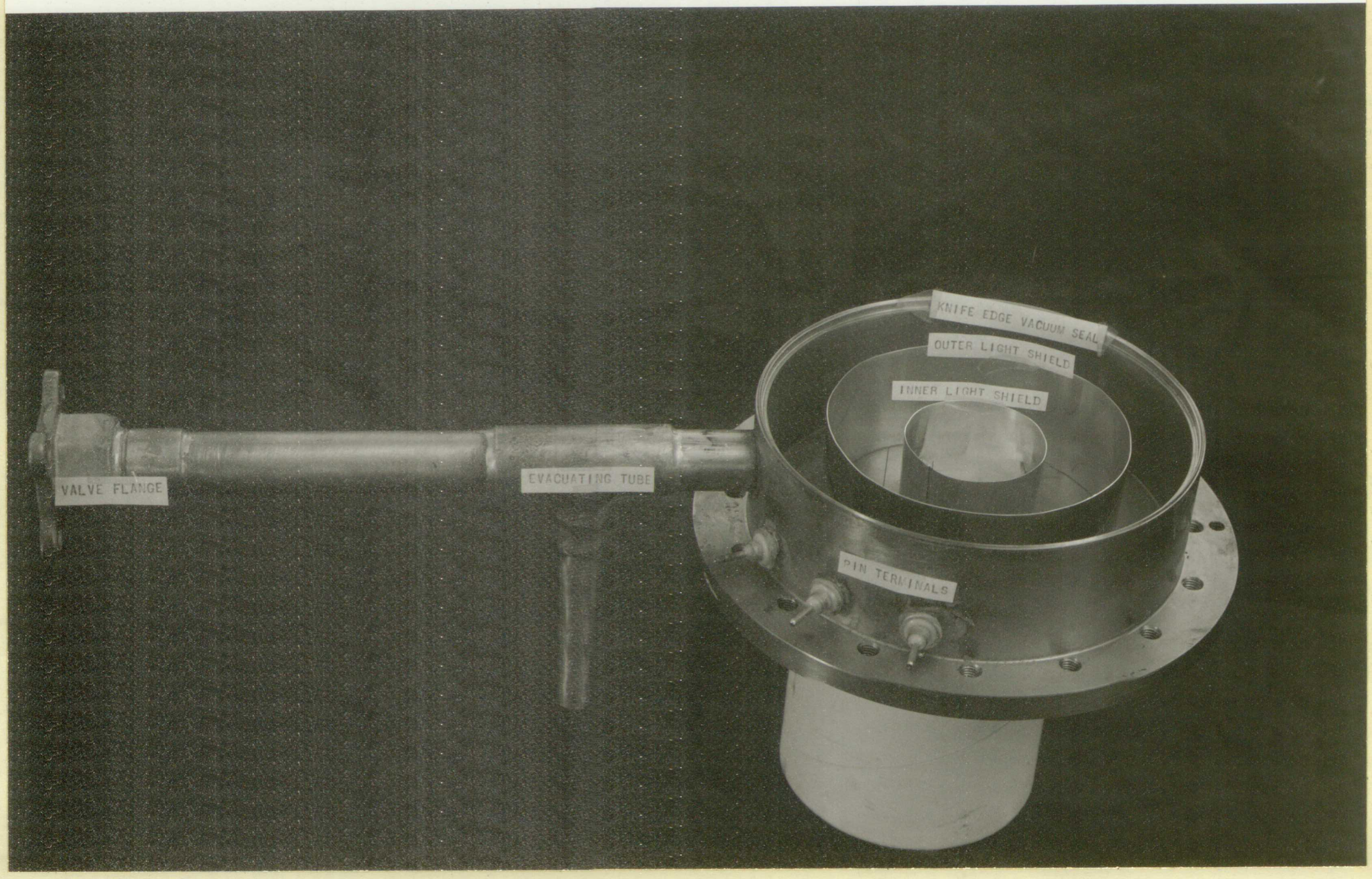


Fig. 12(a). Cavity without target plate attached, which was evacuated after assembly with target plate, valve, and vacuum gage.

A-1 adhesive. A 3-3/4 inch diameter light shield with 0.010-inch wall thickness was glued to the bottom plate and it extended to about 1/64-inch from the aluminum surface. Three timing pins were glued to a piece of glass which in turn was glued to the bottom plate. One pin end was located near the top of the inner light shield, one was located midway between the two light shields and within 1/32-inch of the plate, and the third was located near the top of the outer light shield. The two pins near the light shields were the same heights as their respective light shields. The leads from these pins passed through a hole in the outer light shield to insulated terminals that were soldered to the side of the cavity. Except for the window and the aluminum plate all the inside surfaces were coated with lamp black by playing an acetylene flame over them. The cavity also had a 3/4-inch evacuating tube welded to it. A Philips ionization vacuum gage and a ball valve were attached to the tube.

The 1100 aluminum plate, as shown in Figure 12 and used in the latest shots, had been changed considerably from the plates used in the earlier shots. The earlier plates were of 3/8-inch uniform thickness and for shots through No. 16 were supported on an O-ring seal on the top surface of the water jacket, which was not removed. The volume between the plate and the window behind the barricade was evacuated at the firing site after the calibration runs were completed. Because of the difficulty and time required to secure a good

vacuum under these conditions, a small vacuum assembly like that described above was adopted, except that the cylindrical diameter of the can was 4.5 or 3.9 inches for several experiments. For shots starting with No. 22 the 5-3/8 inch diameter cavity was again used to support the plate. The results of experiments employing the flat plates finally indicated that the signal detected by the phototube was emitted from some area outside the inner light shield, probably from the discontinuity in the planeness of the shock wave at the outer diameter of the high explosive. To make this signal appear at a later time than that emitted from the center of the plate, the top surface of the plate was contoured so that at the outer diameter of the high explosive the shock would be delayed by about 3.5 microseconds when a 1/4-inch brass plate was placed between the high explosive and the aluminum plate as shown in the figure. The light shields which were first used on Shot 29 and the nonreflective coatings were to reduce to a negligible level any signal emitted outside the center portion of the plate. The vacuum, too, was to reduce any radiation that gas in the system might emit when the strong shock wave from the plate reached the gas-aluminum interface.

Before clamping the aluminum plate to the knife edge, the surface of the aluminum plate was carefully treated. First it was lapped and polished, then it was dipped in caustic soda to remove a

few thousandths of an inch of material from the surface and thus uncover any voids that may have been closed over in the previous operations. The surface was then electropolished. Just before making the vacuum seal, the plate was placed in a bath of hot chromic and phosphoric acid to remove the oxide coating. The surface was then washed in acetone and before it could dry it was clamped to the cavity through which argon gas had been flowing. After clamping the plate tightly against the knife edge seal the argon supply was turned off and the evacuation process started. This was accomplished by pumping with a mechanical vacuum pump through a liquid nitrogen trap until the pressure was low enough so that an oil diffusion pump could do the pumping. A helium leak detector was invaluable in detecting small sources of leaks in the system.

The evacuation was started two to four days before the scheduled firing date. After the vacuum reached about 10^{-4} millimeters of Hg, a heat lamp was directed through the window and a torch was played on the opposite side of the aluminum plate for just a few minutes. This quickly heated the center portion of the plate. By doing this several times during the evacuating period, it was hoped that a good proportion of the gas adhering to the surface could be dislodged. The organic materials in the assembly could not stand high temperature baking. Subsequent heatings produced progressively

smaller changes in the vacuum, and lower vacuum readings when the system cooled back to room temperature, indicating that this procedure was somewhat effective.

After the outgassing operations were stopped, the ball valve was closed. The Philips gage was then capable of pumping the cavity down to about 2×10^{-5} mm Hg in a tight system with a minimum of adhesive and Apiezon compound exposed to the vacuum. Upon completion of the calibration runs at the firing pit the vacuum assembly was disconnected and taken to the pit. The Philips gage was reconnected and in a few minutes time the vacuum would be below 5×10^{-4} mm Hg. After placing this assembly on the brass can in place of the water jacket and the other parts that were removed, the pin leads were plugged into the mixing network (Figure 13) and checked for shorts and discontinuities.

The high explosive that was then assembled consisted of two parts. First, 60 inches of primacord with a detonator on each end was wrapped two or three times around the thin walled brass tube on the light pipe leaving 15 to 18 inches of free primacord on each end. Pressure-sensitive tape held this in place. The primacord was detonated simultaneously with the other high explosive assembly. By the time the 15- to 18-inch lengths had burned at the rate of one inch per microsecond, the other high explosive had produced the shock wave required for the experiment and the radiation from the plate surface

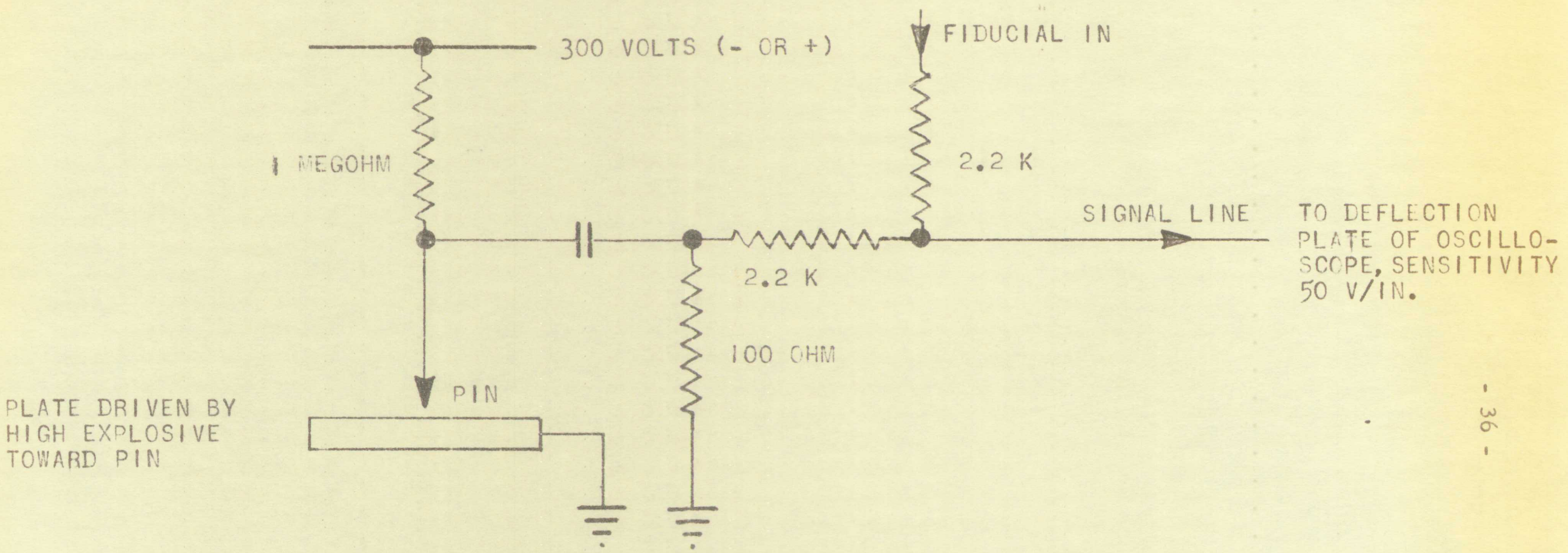


FIG. 13. TYPICAL CIRCUIT FOR AN ELECTRICAL CONTACTOR (PIN) AS USED IN THE MIXING NETWORK

had reached the phototube. The primacord then closed off the light tube preventing a strong shock and debris from the high explosive from breaking the quartz window.

The high explosive assembly that drove the aluminum plate consisted of several elements. A detonator detonated a six-inch length of primacord. (The detonator did not detonate the high explosive directly because of the possibility that electrical noise from the firing unit might appear on the phototube signal line at the time the signal should appear.) The primacord would detonate a tetryl pellet which would in turn detonate a plane wave lens in contact with it. The plane wave lens, through a combination of fast and slow burning explosives, was capable of converting a spherically diverging detonation wave into a plane wave traveling parallel to the vertical axis of the lens. Eastman 910 adhesive held the plane wave lens against a four-inch cylinder of high explosive two inches thick. For most of the experiments Baratol was employed, but Composition B and TNT were also used. A brass tube with a 0.015-inch wall thickness held around the outside diameter of the high explosive with a hose clamp reduced the edge effects of the detonating explosive. A 1/4-inch thick brass plate was cemented to the cylinder of explosive. This brass plate had an electrical contactor attached one inch from its center and to its bottom surface with pressure-sensitive tape. This contactor

consisted of the bare center conductor of some shielded lead which bridged a 1/32-inch gap between two pieces of cellophane tape 0.003-inch thick. The sudden motion of the surface of the brass would cause the contactor to become grounded against the plate, producing a signal which would indicate the time at which the brass plate surface started to move.

After assembling the high explosives the hand operated shutter was checked to be sure it was in the open position, and the temperature, T_0, of the aluminum plate was measured with a thermometer which was taped to the assembly. A piece of canvas was thrown over the back of the tubular blast shield on the barricade and dirt was shoveled over it to protect the electronic chassis assembly from blast damage.

The explosives were then detonated from the control room. A block diagram of the control room equipment used for this operation is shown in Figure 14. One microsecond timing markers were placed on the film below the signal trace. The traces on the charts in the "Results" section show the records photographed on the control room oscilloscopes.

After firing the shot the apparatus behind the barricade was disassembled. After cleaning, most of these parts were reused on subsequent shots.

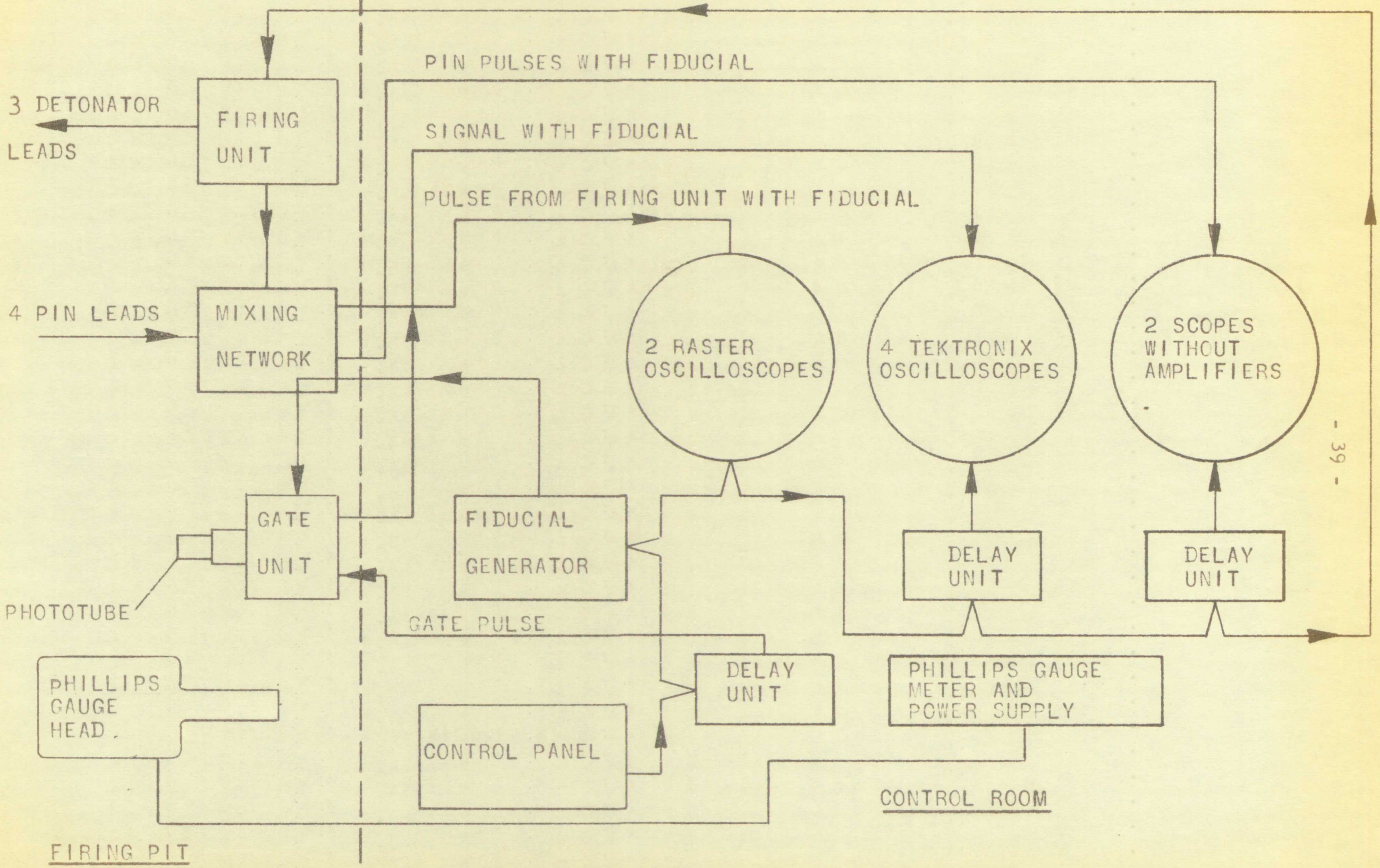


FIG.14. DIAGRAM FOR FIRING A PHOTOTUBE SHOT

Two of the experiments with the uniform thickness aluminum plates are of special interest. For one experiment an RCA type 6199 multiplier phototube was substituted for the 7102 tube. The bases of these tubes are identical so the same circuitry could be used on the substituted tube. The 6199 tube is sensitive to wavelengths between 0.30 and 0.70 micron wavelength (compared to 7102 sensitivity between 0.42 and 1.2 microns). Although the 6199 tube was sensitive to light admitted through the window in the brass can, it did not respond to the calibrating procedure used for the 7102 tube. The shot was fired and the 6199 remained intact and responded after the shot to white light. No signal appeared on the oscilloscope trace at the time a signal would have appeared if an infrared sensitive tube were used.

In the other experiment a Kodak Wratten 87-C infrared filter was placed in front of the photocathode of the 7102 tube. This filter cut off all wavelengths of light below 0.8 micron wavelength which is the wavelength of peak response for the 7102 phototube. The signal from this shot was not unlike the signals from shots similar to this fired without the filter in the light system. The experiments with the 6199 tube and with the filter partially proved the design of the apparatus in that the signal observed was not of a visible wavelength as might be produced by a light leak, or ionized gas, and that the signal was not a strong electronic or magnetic noise signal picked up by the cables or multiplier phototube.

D. Other Testing

The calibrating apparatus described earlier and shown in Figure 4 (except that the barricade and tubular blast shield were not used) was assembled on a laboratory workbench (Figure 15). The brass can and water jacket assembly was turned upside down so that the calibration plates could be supported by the heavy brass plate and therefore heated to higher temperatures without distortion due to gravity. A number of different calibrating plate surfaces were used as well as several runs with different multiplier phototubes. A blackbody cavity, Figure 16, was calibrated so its radiation as detected by the phototube could be compared to that of the plate surfaces. The blackbody cavity was a copper can with an aperture in one end. Three thermocouples imbedded in the bottom, top, and side of the can indicated the temperature spread in the cavity. Two semicylindrical electric heaters around the cavity provided the heat. Layers of asbestos, glass wool, and aluminum foil around the heaters and over the top of the can kept all the surfaces of the cavity uniform in temperature to within about 2°C after the power was turned off as indicated by the thermocouples and the Brown millivoltmeter pyrometer. A five position Leeds and Northrup thermocouple switch allowed the three thermocouples to be connected to the single millivoltmeter.

The plate surfaces checked with this apparatus all had a 32 microinch finish or better. They are listed as follows:

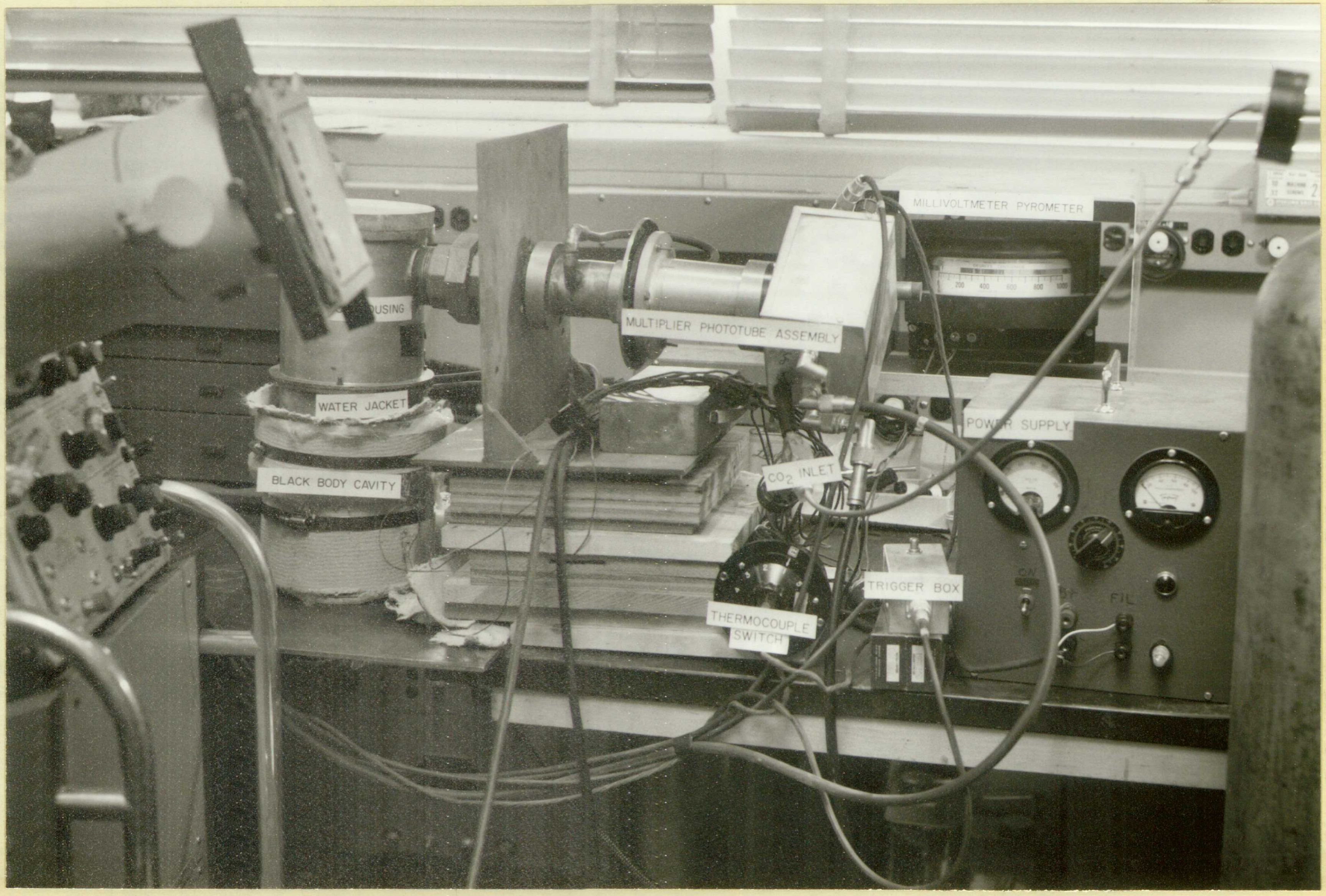


Fig. 15(a). Apparatus used in the laboratory to obtain data on the emittance of the artificial blackbody.

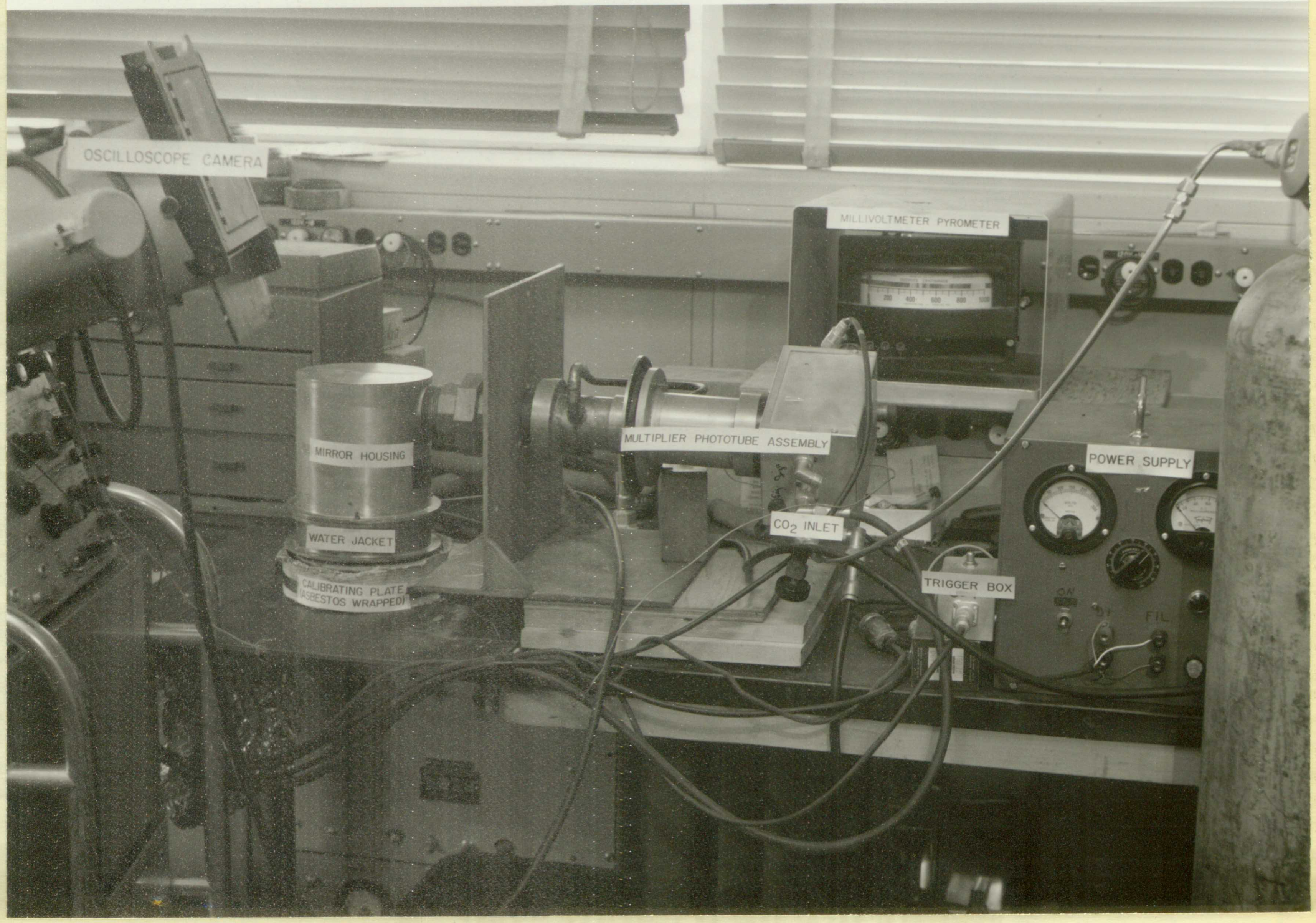


Fig. 15(b). Apparatus as used in the laboratory to obtain data on the emittances of various plate surfaces.

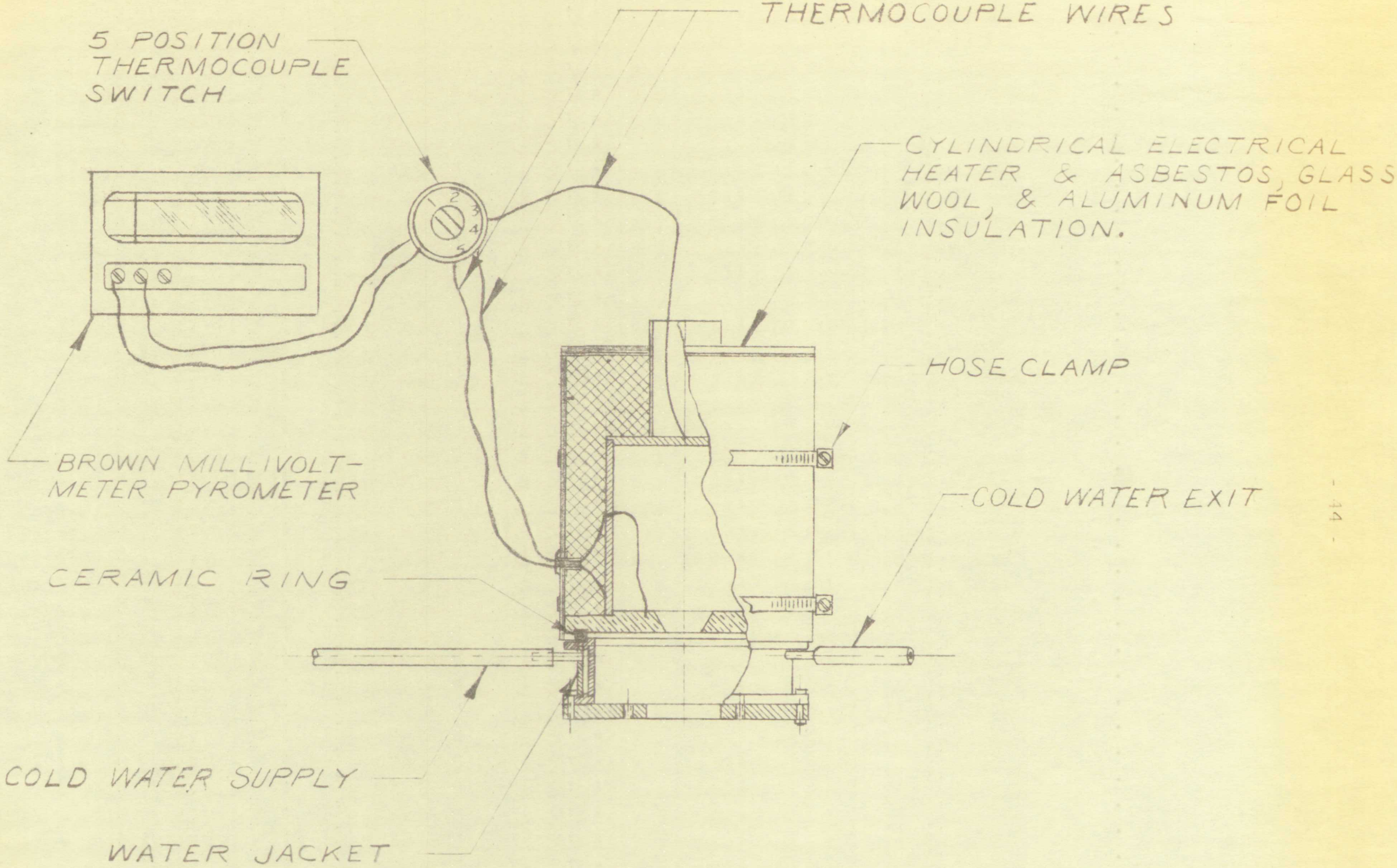


FIG. 16 BLACKBODY CAVITY & WATER JACKET

1. Lapped 1100 aluminum
2. Lapped and polished 1100 aluminum
3. Machined 1100 aluminum
4. Polished, then oxidized brass
5. Oxidized stainless steel, type 347

When the camera shutter was replaced by the gated circuit, tests with the same apparatus as that described above showed that the output of the phototube was not seriously affected by the change.

Two sets of experiments were performed to determine the transient response of the detector system. For one of the sets the end of the calibrating apparatus with the gated circuit was placed in a light-tight box with a xenon flash tube capable of producing bright light pulses of less than one microsecond duration. A delay unit provided a pulse to gate the phototube at various times with respect to the light pulse; however, with the equipment available it was not possible to gate the phototube prior to flashing the light. The other set had a neon lamp which was flashed off and on by a bistable multivibrator. This apparatus was capable of more variation of the light flash time with respect to the phototube gate time. The neon flash time could not be reduced to a very short duration nor did it have a uniform intensity.

The calibrating apparatus was also modified so that the effect of a high temperature source outside the area monitored by the phototube could be noted. The calibrating plate was replaced

by an aluminum ring supporting a ceramic tube about four inches in diameter (Figure 17). An aluminum plate covered the inside area of the tube. A small step in the end of the tube contained a ring of No. 18 gage Nichrome wire. A variable power transformer was used to control the current in the Nichrome wire. The output of the phototube with the wire heated to a temperature above 1000°C was noted with a light shield around the aperture and without the light shield. The light shield did reduce the output of the phototube to a negligible level from the very high level noted without the light shield.

A simple arrangement of the brass calibrating plate and the stainless steel calibrating plate was made so that their thermocouple outputs could be compared. The two plates were placed face to face on a quartz ring. An electrical heating ring was tied to the back of the brass calibrating plate and a third thermocouple was inserted between the plates. This thermocouple and the one in the stainless steel plate were previously checked in a bath of freezing lead. Asbestos, glass wool, and aluminum foil insulation were wrapped around the assembly. The heating elements then brought the assembly up to about 800°C. Power lines were then disconnected and more insulation was wrapped around the assembly. The assembly then cooled slowly, taking four hours to cool to about 450°C. After disconnecting the power the three thermocouples soon indicated the same temperature within 5°C. The Leeds and Northrup thermocouple switch and Brown millivoltmeter pyrometer displayed the thermocouple outputs.

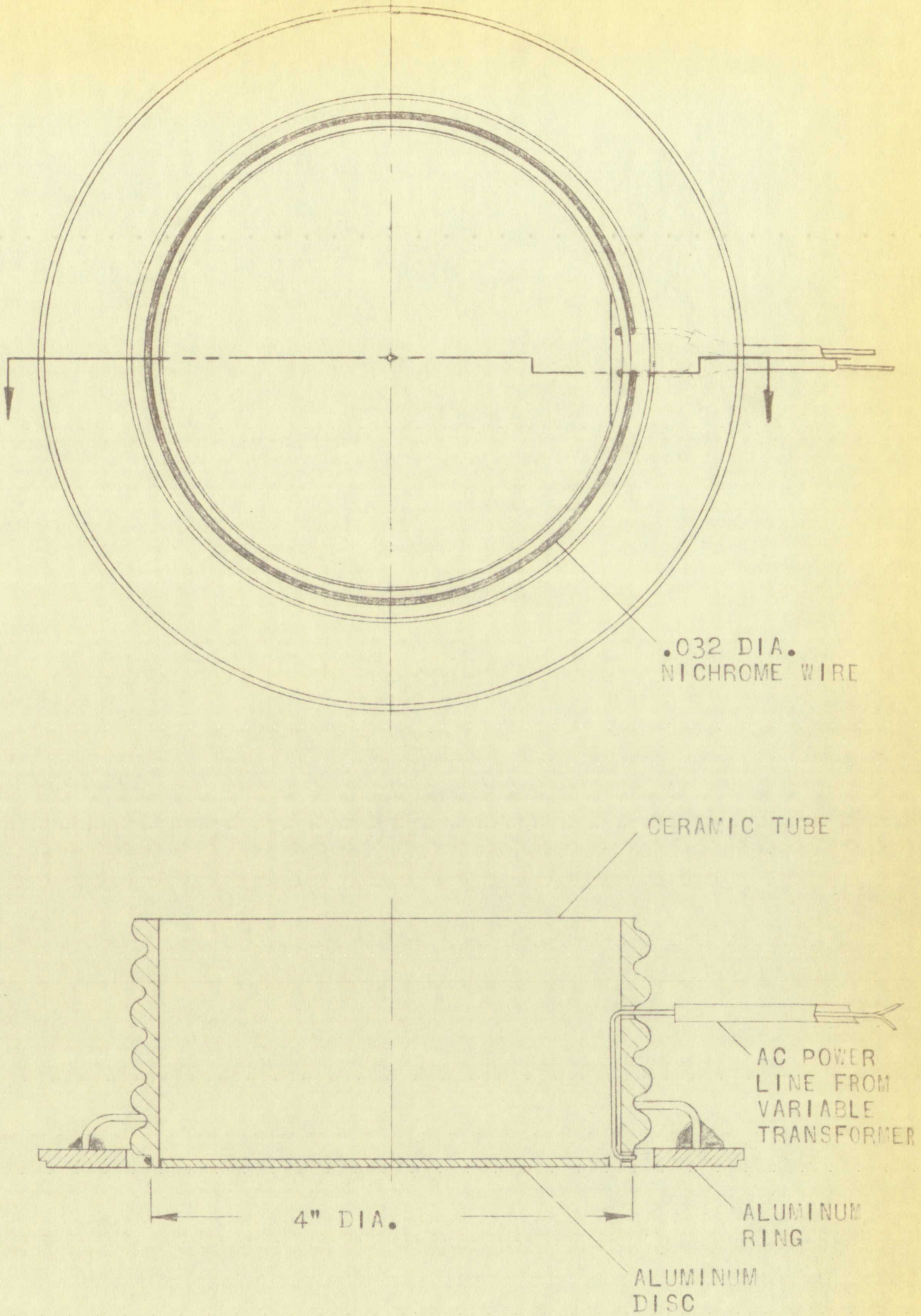


FIG. 17. APPARATUS TO TEST THE EFFECT OF A HEATED RING UPON THE OUTPUT OF THE PHOTOTUBE

II. Other apparatus for high explosive experiments

A. Electrical contactor (pin) experiments

The apparatus for measuring the velocity of the aluminum plate is shown in Figure 18. This consisted of a four-inch diameter plane wave lens, a cylinder of Baratol two inches thick, a 1/4-inch thick uranium plate, an aluminum plate of 3/8-inch uniform thickness, and 37 pins of various lengths mounted in a circular array on a textolite plate which was spaced 1-3/4 inches away from the aluminum plate. Shielded leads from these pins went into a mixing network where each lead was connected to an electrical network like that shown in Figure 13.

After the metal parts were assembled and the pin lengths measured, the space between the aluminum plate and the textolite plate was sealed from the atmosphere by wrapping masking tape around the outside of the plates. Before firing the shot methane was flushed into this cavity to displace the air around the pins. Methane does not ionize easily when compressed by a strong shock wave and, therefore, it would not discharge the pins before the aluminum plate contacted them.

A similar shot was fired except that a 1/8-inch thick steel plate was driven by seven inches of Composition B in order to determine how to effectively space the steel plate from the aluminum plate to achieve a high shock pressure. A pad of polyethylene 1/32-

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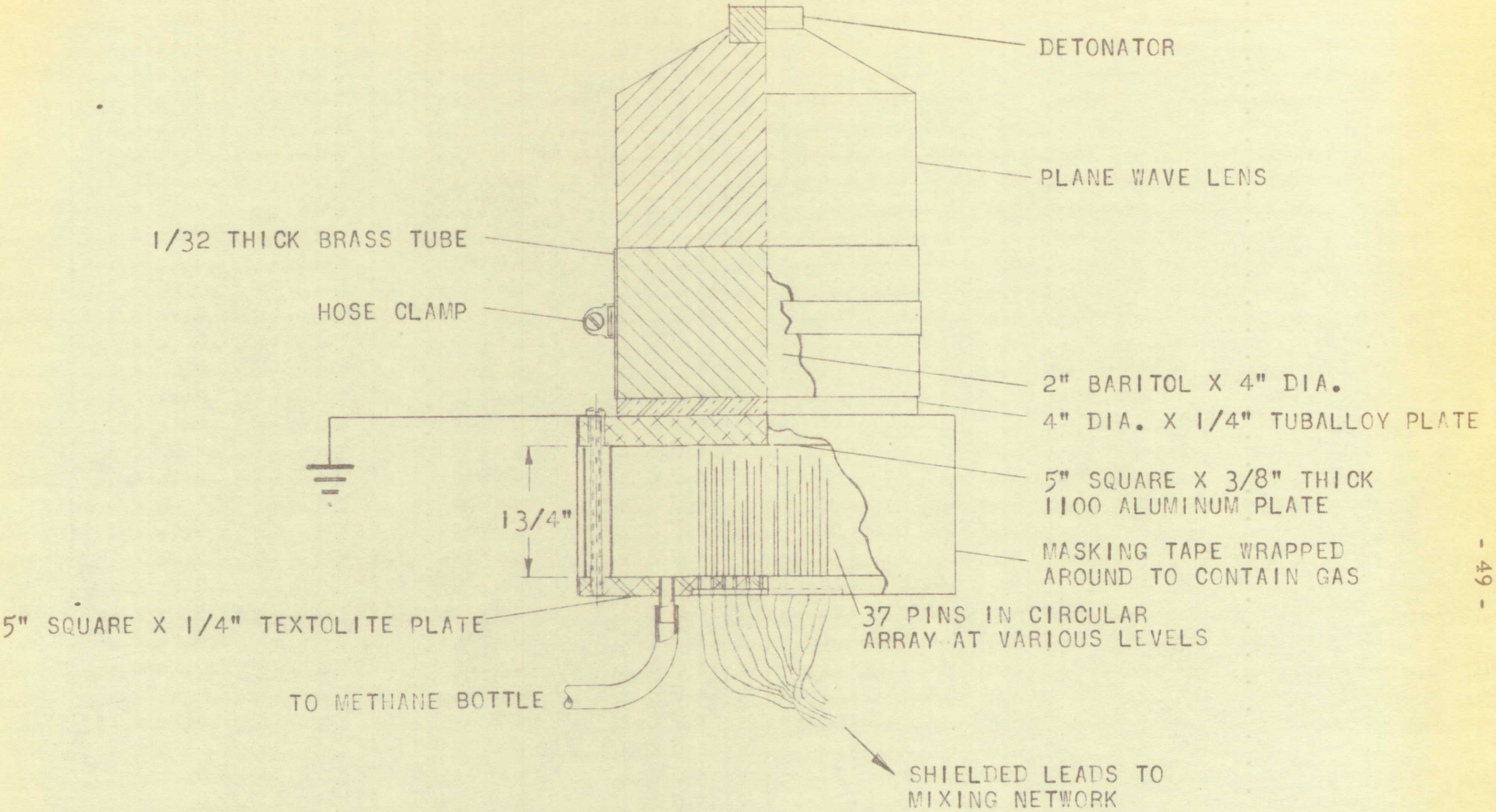

FIG. 18. EXPERIMENT TO MEASURE PLATE MOTION BY MEANS OF ELECTRICAL CONTACTORS

inch thick was placed between the steel and the explosive to stabilize the shock wave in the steel. The distance from the starting position of the plate that the velocity of the plate stopped increasing was considered the optimum distance at which to place the aluminum plate from the steel plate to achieve a maximum shock pressure in the aluminum. The first shot with the phototube assembly had a steel plate spaced at this distance from the aluminum plate.

B. Recovery shots

Another group of experiments were designed so that a small part of the aluminum in the center of the plate might be recovered after a strong shock wave traveled through the plate. The experimental hardware is shown in Figure 19. Both the aluminum and brass plates had a 1/2-inch hole through their centers which were filled with plugs of the same material. The high pressure waves would cause the outer portion of the plate to expand laterally and to tear apart, but the lateral stresses would not be transmitted to the plug, leaving it intact. To prevent another strong shock wave from being started in the plug when its free motion was stopped, 16 inches of foamed plastic grading from 1.5 lbs/cu. ft. density to 30 lbs/cu. ft. was placed against the opposite side of the plate from the high explosive. Finally a 30 gallon can of water stopped the motion of the plug and saved it for recovery.

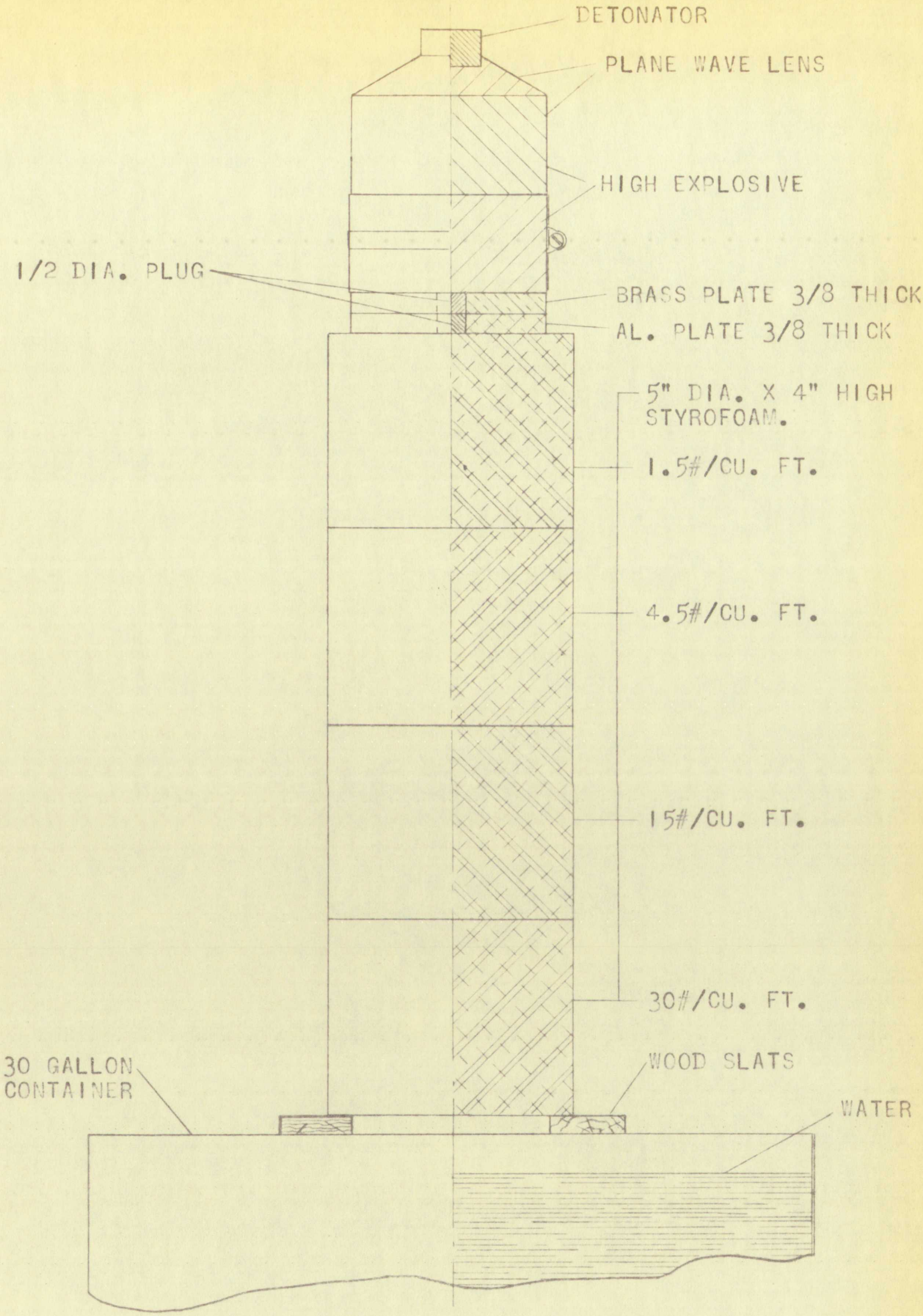

FIG. 19. RECOVERY SHOT APPARATUS

VI. THEORETICAL INVESTIGATION

A. Thermal Radiation Theory

Because the method of measuring temperatures adopted for this thesis was the detection and measurement of the heat that was radiated by metal plate, a knowledge of physical laws describing thermal radiation is important. Thermal radiation is the radiant energy emitted by a body as a function of its temperature only as distinguished from characteristic or spectral radiation which may be caused by electric discharge, bombardment by nuclear particles, exposure to radiation of a suitable wavelength, or shock waves. In the experimental investigation there should have been no characteristic radiation contribution to the radiation detected by the multiplier phototube.

Two small bodies of areas A_1 and A_2 at thermal equilibrium in a large evacuated enclosure will emit radiation at the rates A_1W_1 and A_2W_2 where W is the total emissive power, radiant flux density, or emittance with units of watts/cm^2. The intensity of radiation from the enclosure is I (watts/cm^2). The energy balance on the bodies will be $IA_1\alpha_1 = A_1W_1$ and $IA_2\alpha_2 = A_2W_2$ where α is the absorbtivity (fraction of incident radiant energy that is absorbed). From these relations

Kirchhoff's law can be derived:

$$\frac{W_1}{a_1} = \frac{W_2}{a_2} \quad ;$$

that is, the ratio of emittance of a surface to its absorbtivity is the same for all bodies. When $a \doteq 1$ (its upper limit) W has an upper limit W_b. Any surface for which $W = W_b$ is called a perfect radiator or a blackbody. Because $a = 1$, the reflectivity of the surface must be zero. The ratio of the emittance of an actual surface W', to that of a blackbody is called the emissivity ϵ, and must be equal to a under conditions of thermal equilibrium according to Kirchhoff's law.

An approximate blackbody can be realized by applying a coating of platinum black or other metallic black to a surface (17). The most nearly perfect blackbody is a small hole in a hollow body with walls at a uniform temperature. The radiant energy which enters the hole is repeatedly reflected from the walls of the body. Because the walls are not perfectly reflective only a small part of the energy is reflected out of the hole, and the smaller the hole the smaller the amount of energy reflected out of the body. Thus the hole becomes a nearly perfect absorber, and because $a = \epsilon$ it is also a nearly perfect emitter.

The emittance of a blackbody depends only upon its temperature. By application of the second law of thermodynamics the relation (17),

$$W_b = \sigma T^4 \quad ,$$

Kirchhoff's law can be derived:

$$\frac{W_2}{a_2} = \frac{W_1}{a_1}$$

that is, the ratio of emittance of a surface to its absorptivity is the same for all bodies. When a=1 (its upper limit) W has an upper limit W_b. Any surface for which $W=W_b$ is called a perfect absorber or a blackbody. Because a=1, the reflectivity of the surface must be zero. The ratio of the emittance of an actual surface W to that of a blackbody is called the emissivity (ε) and must be equal to a under conditions of thermal equilibrium according to Kirchhoff's law.

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The emittance of a blackbody depends only upon its temperature. By application of the second law of thermodynamics, the relation(17),

$$E_T = {}_{e}W$$

known as the Stefan-Boltzmann law, can be derived. The Stefan-Boltzmann constant σ, is equal to 5.669×10^{-12} watts $cm^{-2}T^{-4}$.

The relation among emittance, temperature, and wavelength is expressed by Plank's law (18),

$$W_\lambda \equiv (W_\lambda)_T = c_1\lambda^{-5}(e^{c_2/\lambda T} - 1)^{-1} \quad ,$$

where $c_1 = 2\pi c^2 h = 3.74126 \times 10^{-4}$ watts $cm^{-2}\mu^4$, and $c_2 = hc/k$ = $14,388\mu^\circ K$ when the emitting area is expressed in square centimeters and both the wavelength and the wavelength interval are in microns.

An error of less than 1 per cent in $(W_\lambda)_T$ for values of T below $3000\lambda^\circ K$ would be introduced by the use of Wien's law,

$$W_\lambda \equiv (W_\lambda)_T = c_1\lambda^{-5}e^{-c_2/\lambda T} \quad .$$

(The maximum value of λT of interest in the work for this thesis is about $1200\mu^\circ K$ for which the error is less than 0.001 per cent.) Figure 20 shows how the two equations differ at $600^\circ K$.

Figure 20 is a plot of Plank's law for seven different temperatures. The dashed curve is the locus of the maximum values of $(W_\lambda)_T$ at a given temperature and its equation is expressed by Wien's displacement law,

$$W_{\lambda_m} = (W_{\lambda_m})_T = b_1 T^5 \quad ,$$

where $b_1 = 1.2864 \times 10^{-15}$ watts $cm^{-2}\lambda^{-1}(^\circ K)^{-5}$.

known as the Stefan-Boltzmann law, can be derived. The Stefan-Boltzmann constant, σ, is equal to 5.6697 x 10^{-12} watt cm^{-2} ($°K$)$^{-4}$.

The relation among emittance, temperature, and wavelength is expressed by Planck's law (18),

$$W_\lambda = (W_\lambda)_T = c_1 \lambda^{-5}\left(e^{c_2/\lambda T} - 1\right)^{-1}$$

where c_1 = $2\pi c^2 h$ = 3.7413 x 10^4 watts cm^{-2} μ^4 and c_2 = ch/k = 14,388μ°K when the radiation is expressed in watts per centimeters and both the wavelength and the wavelength interval are in microns.

An error of less than 1 per cent in $(W_\lambda)_T$ for values of T below 3000°K would be introduced by the use of Wien's law,

$$W_\lambda = (W_\lambda)_T = c_1 \lambda^{-5} e^{-c_2/\lambda T}$$

(The maximum value of ΔT of interest in the work for this thesis is about 1200°K for which the error is less than 0.001 per cent.) Figure 20 shows how the two equations differ at 600°K.

Figure 20 is a plot of Planck's law for seven different temperatures. The dashed curve is the locus of the maximum values of $(W_\lambda)_T$ at a given temperature and its equation is expressed by Wien's displacement law,

$$W_{\lambda_m} = (W_{\lambda_m})_T = b_1 T^5$$

where b_1 = 1.2864 x 10^{-15} watts cm^{-2} μ^{-1} (°K)$^{-5}$

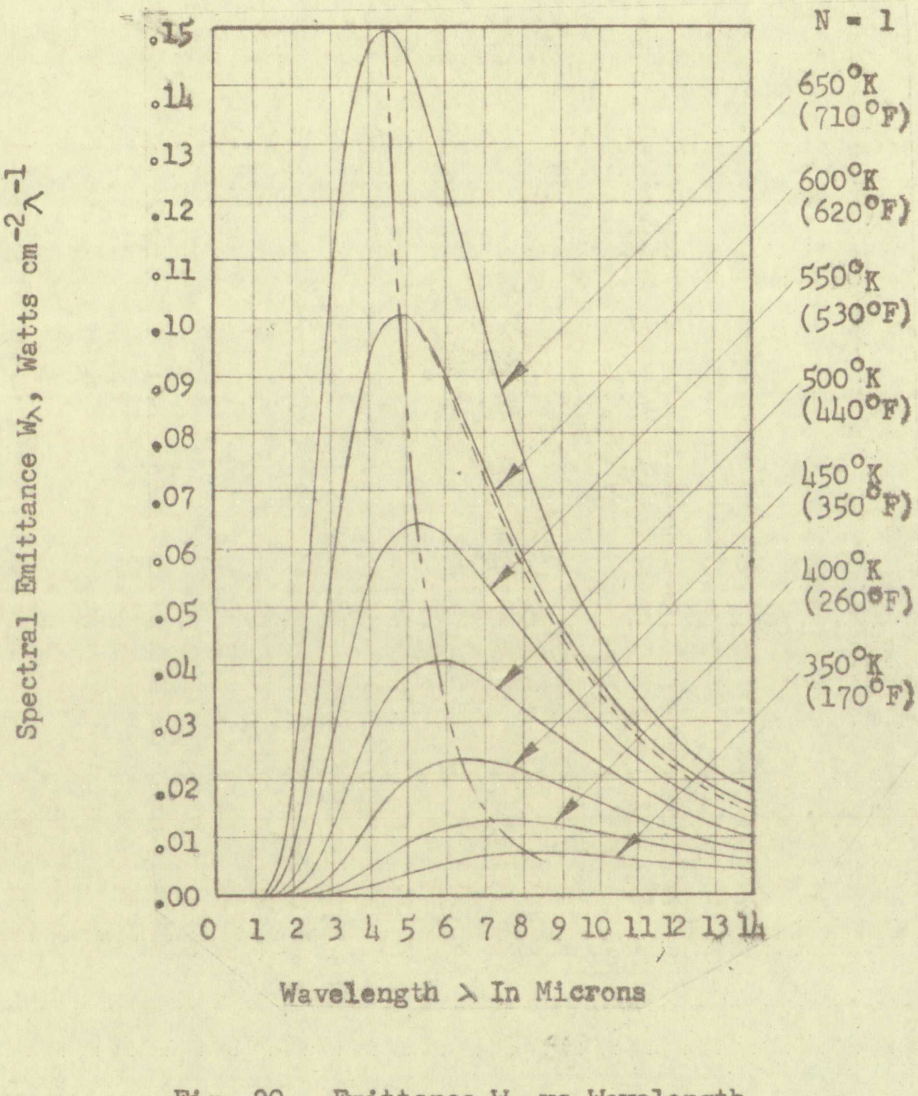


Fig. 20. Emittance W_λ vs Wavelength

Dashed curve by the 600°K curve shows how W plotted from Wien's law compares to W_λ from Plank's law both evaluated at 600°K. Curve through maximum points is a plot of Wien's displacement law.

The relative spectral response curve of the 7102 multiplier phototube is shown in Figure 21. Taking values of relative response from the curve for various wavelengths and multiplying them by values for W_λ calculated from Wien's law for these wavelengths and for a given temperature will yield values which will be the relative spectral response of the phototube to blackbody radiation at that temperature. Figure 22 shows W_λ from Wien's law as a function of λ for three temperatures in part of the region of phototube response. Also three curves representing the relative spectral response of the phototube to blackbody radiation is shown. The area under one of these curves, is proportional to the output of the phototube at the temperature represented by the curve. A plot of the areas under the curves for temperatures ranging from 700° to 1500°K is given in Figure 23. A calibration curve for one of the artificial blackbody experiments is also plotted in that figure. The slope of a curve at any temperature gives the sensitivity, theoretical or actual, of the phototube output to blackbody or artificial blackbody radiation at that temperature. At 850°K it can be seen from the theoretical curve that the relative phototube response or signal level E, doubles for about a 40° rise in blackbody temperature which implies that E is proportional to $T^{15.1}$ at this temperature. This high exponent is the result of the narrow band response of the phototube in the short

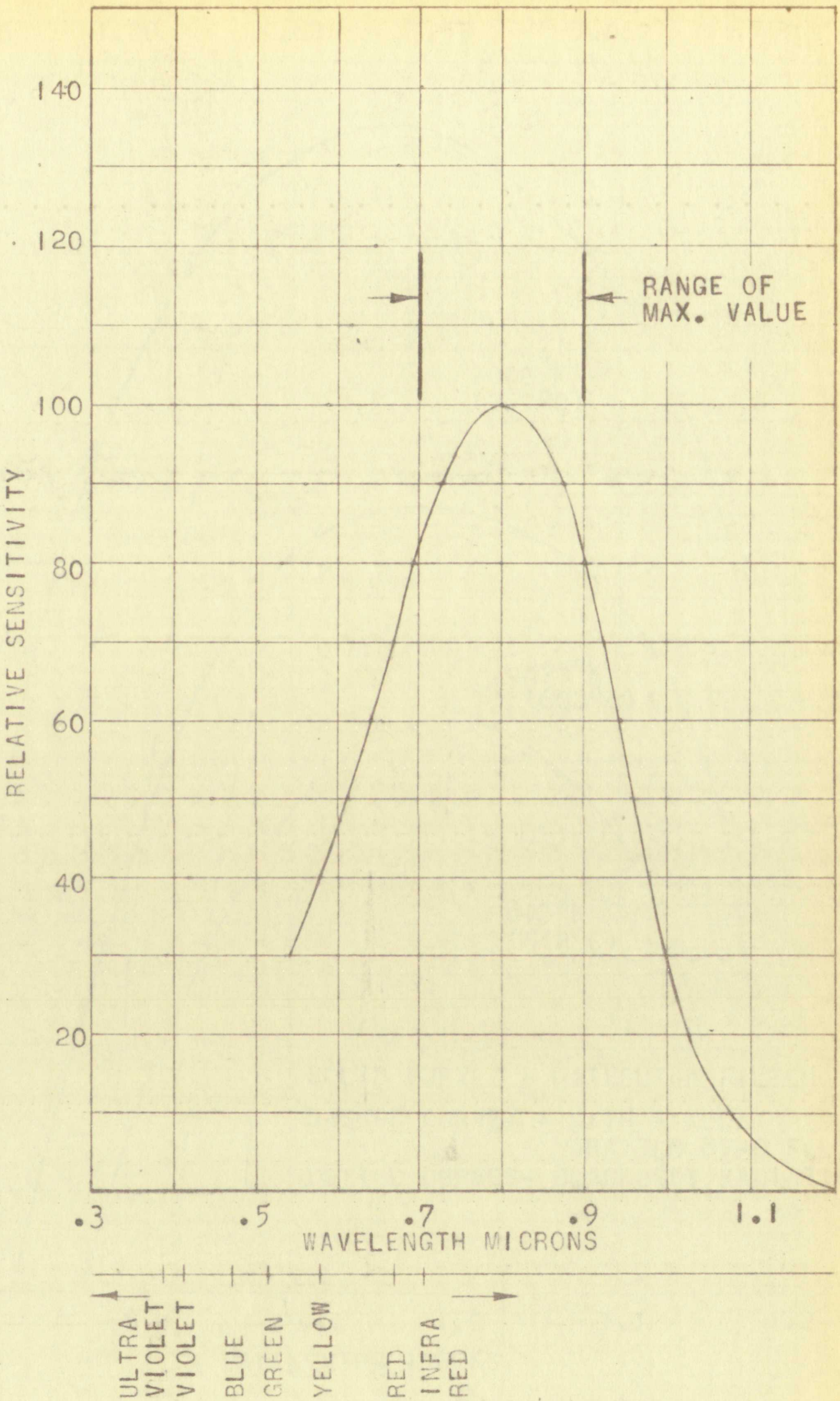
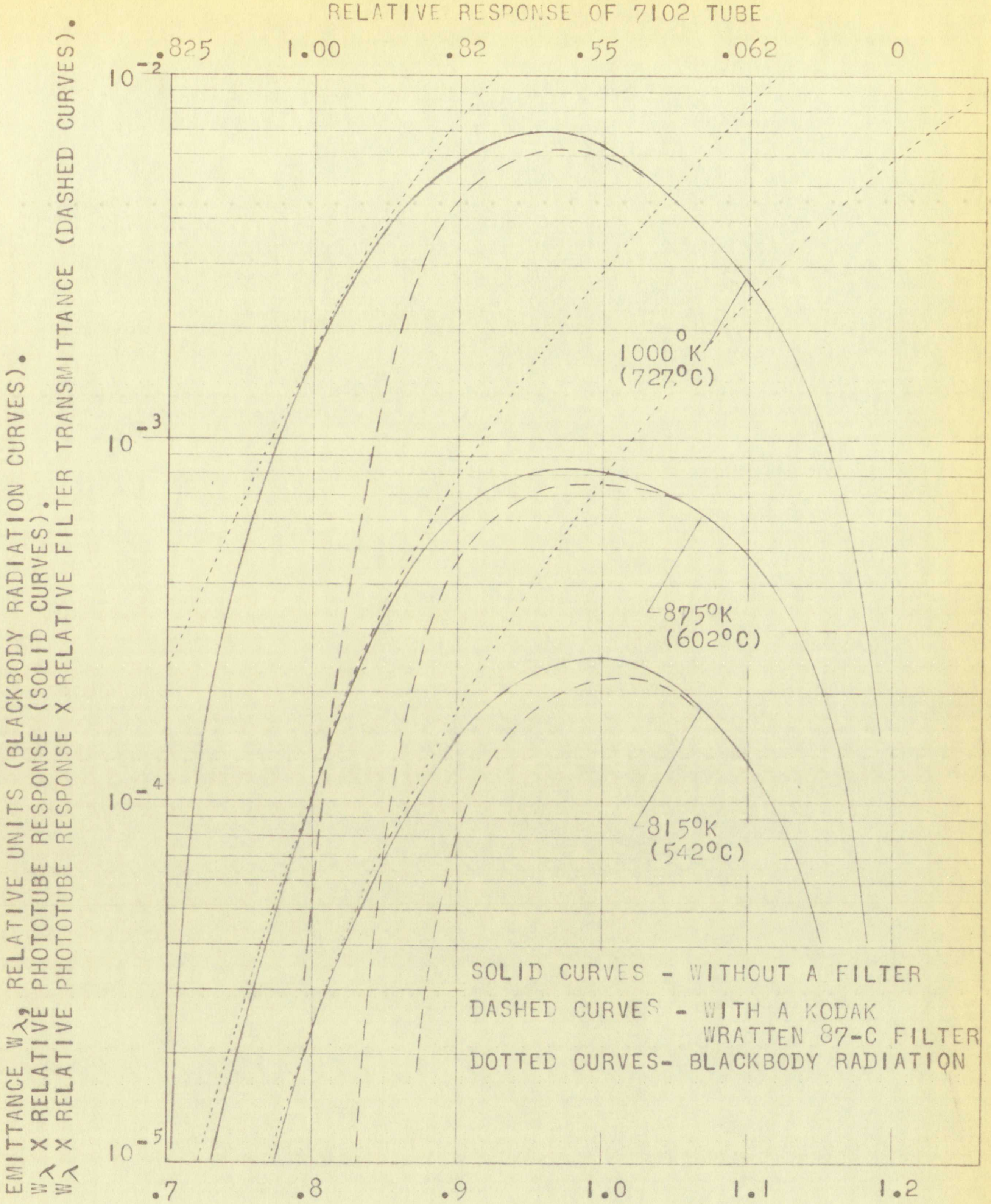


FIG. 21. SPECTRAL SENSITIVITY CHARACTERISTIC OF TYPE 7102. CURVE IS SHOWN FOR EQUAL VALUES OF RADIANT FLUX OF ALL WAVELENGTHS.



RELATIVE PHOTOTUBE OUTPUT IN
RESPONSE TO BLACKBODY RADIATION

FIG. 22

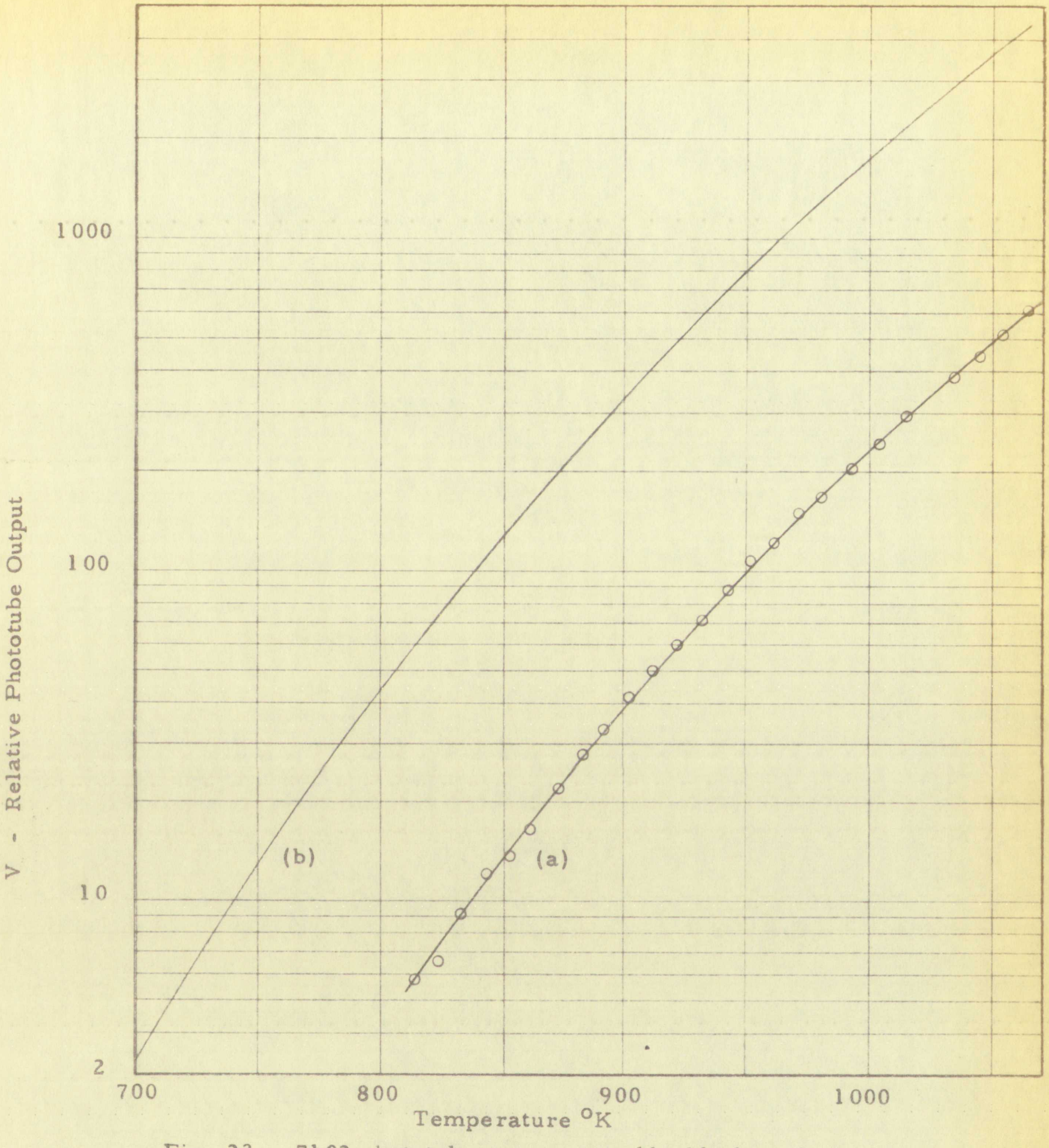


Fig. 23. 7102 phototube response to blackbody radiation
(a) Measured phototube output to artificial blackbody radiation.
(b) Calculated phototube output to blackbody radiation as predicted by $\int_{\lambda_1}^{\lambda_2} W_\lambda \times f(\lambda) d\lambda$ where W_λ is expressed by Wien's law and $f(\lambda)$ is relative phototube spectral response shown in Fig. 21.

wavelength region of the blackbody radiation curve which from Wien's displacement law allows W_m to vary as T^5, coupled with the fact that an increase in temperature moves the W_λ vs T curve to the left into the region of rapidly increasing phototube sensitivity, as can be seen in Figure 22.

The artificial blackbody and the target and calibration plates used in the experimental investigation could only approach blackbody radiation to varying degrees as are denoted by values of ϵ for these surfaces. The emissivity may vary with many factors including wavelength, temperature, angle of detection (neglible for angles from normal to surface $< 30^\circ$), and degree of surface roughness. The emittances W_λ and W may be modified to include nonblackbody emission by multiplying by the spectral emissivity ϵ_λ, or the total emissivity ϵ_t, as

$$W'_\lambda = \epsilon_\lambda W_\lambda \qquad \text{and}$$

$$W' = \epsilon_t W \quad .$$

ϵ_λ and ϵ_t are related by the formula

$$W' = \int_0^\infty \epsilon_\lambda W_\lambda d\lambda = \epsilon_t W = \epsilon_t \sigma T^4 \quad .$$

In order to eliminate as many as possible of the variables involved in emission and detection of the radiation the experimental

wavelength [illegible]
displacement [illegible]
an increase [illegible]
the region of [illegible]
in Figure [illegible]

[illegible]
used in the [illegible]
radiation [illegible]
surfaces. [illegible]
length, temperature [illegible]
to surface [illegible]
W_1 and W [illegible]
multiplying [illegible]
as

[illegible]

[illegible]

f_1 and f_2 are [illegible]

In [illegible]
involve [illegible]

investigation was made nearly empirical. Calibration for each shot was done in the geometry in which it was fired. Changes from the calibration apparatus to firing apparatus were kept at a minimum. It was not possible to control or eliminate probable changes in the character of the surface of the shock plates due to the reflection of the shock front from it, but results from some tests made it possible to determine an upper limit to the error involved.

B. Basic shock wave considerations.

A temperature change was produced on the free surface of the plate by the formation of a strong plane shock front by a high explosive charge, the transmission of this shock through a plate, and its reflection from the free surface of the plate. Therefore, some of the aspects of shock wave phenomena will be discussed.

When Composition B is detonated it produces a wave traveling at supersonic velocity (about 8 mm/μsec) (1). The effective pressure developed in the detonation front is approximately 270 kilobars (1 bar = 10^6 dynes/cm^2 = 14.5 psi). When this wave reaches the interface between the explosive and the plate it induces shock waves which are generically related to elastic and acoustic waves, but differ in that the equations for the shock waves are nonlinear.

The medium in which a shock wave, induced by high explosive, is traveling is considered an ideal fluid incapable of supporting shear. Experimental studies have indicated the state of shocked solids to be indistinguishable from a hydrodynamic state, and for plane shock waves the shock equations for solids are the same as for fluids.

If we consider a plane shock front that is uniform; i. e., the material behind the front has equal or uniform values of density ρ_1, pressure P_1, and particle velocity u_1, extending indefinitely from the front, the conservation laws for mass, momentum, and energy are

respectively, where D is the velocity of the shock front,

$$\rho_0 D = \rho_1 (D - u_1) \tag{1}$$

$$P_1 - P_0 = \rho_0 D u_1 \tag{2}$$

$$P_1 u_1 = \rho_0 D (E_1 - E_0 + u_1^2/2) \tag{3}$$

where E is the internal energy and the subscript 0 denotes quantities referring to the "undisturbed" substance in front of the shock wave, and 1 denotes quantities referring to material behind the shock wave.

Equations (1) and (2) may be used to eliminate u_1 and D from equation (3) resulting in the Rankine-Hugoniot equation:

$$\Delta E = \frac{1}{2}\left(\frac{1}{\rho_0} - \frac{1}{\rho_1}\right)(P_1 + P_0) \tag{4}$$

where $\Delta E = E_1 - E_0$.

This equation, because it does not include the velocities D or u, is suitable for a determination of the possible "final" states of the material behind the shock front when the initial conditions, in front of the shock wave are given (32). For a given ρ_0, E_0, P_0, and ρ_1, Equation 4 gives a linear relation between E_1 and P_1. Another relation between the same quantities is provided by the equation of state, which, if it is in the form $E = f(P_1, v_1)$ where $v_1 = \frac{1}{\rho_1}$, can be combined with Equation 4 to eliminate the internal energy. The resulting relation, known as the Hugoniot p-v relation, represents the locus of all points which may be reached by a shock transition

from the initial state. If the initial and the shocked states are equilibrium states they can be connected by a reversible path and the relation is

$$dE = TdS - Pdv.$$

The procedure of combining this with Equation 4 is discussed in detail by Rice and others (2).

The reflection that occurs when a shock wave encounters a change in the propagating medium is important in measuring the properties of the shock wave and is the mechanism which causes the temperature increase of the free surface of the medium.

For simplicity consider a uniform shock wave moving in a slab. After the front has reached the free surface of the slab a wave is reflected back into it. At this instant the particle velocity of the slab is u_1. From a coordinate system moving with particle velocity u_1, the slab would appear to be motionless under static compression P_1. At the next instant a rarefaction begins to move back into the compressed material allowing it to return to pressure P_0. A mean velocity R, can be assigned to the rarefaction velocity, and after a time t, the rarefaction has traveled a distance Rt, from the reflection boundary and the free surface has moved a distance Δx, in the other direction with the relative velocity u_2. The material between the free surface and the rarefaction has expanded to density ρ_2, at pressure P_0, where $\rho_2 < \rho_0$ because of irreversible heating by the shock wave.

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The free surface velocity relative to coordinates moving with velocity u_1, is:

$$u_2 = \Delta x/t = R\left(\frac{\rho_1}{\rho_2} - 1\right) = R\left(\frac{\rho_1}{\rho_0}\ \frac{\rho_0}{\rho_2} - 1\right)$$

$$= R\left(\frac{1}{(1 - \frac{u_1}{D})(1 - \beta\Delta T)} - 1\right)$$

where β is the thermal expansion coefficient and $\Delta T = T_2 - T_0$, and $\rho_0/\rho_1 = 1 - u_1/D$ represents the conservation of mass in the original shock (Equation 2) and $\rho_2/\rho_0 = 1 - \beta\Delta T$. If both u_1/D and $\beta\Delta T$ are small, then $u_2 \doteq (Ru_1/D) + R\beta\Delta T$. $\Delta T \propto (u_1/D)^3$ and since $R/D \simeq 1$ irreversible heating contributes to total free surface velocity a term the order of $(u_1/D)^3$ (1).

The free surface velocity in fixed coordinates, $u_{fs} = u_2 + u_1 \simeq 2u_1$ within one per cent at 500 kilobars for relatively incompressible materials, except where melting occurs (2).

VII. RESULTS

The results of the investigation are grouped into categories of similar experiments and are described as they relate to the main body of experiments where temperatures were measured under dynamic conditions.

A. Results of the phototube experiments with high explosives.

The results of these experiments are described in the three charts included in this section. The experiments are numbered in chronological order.

In the "Explosive System" column the type of high explosive is described. The materials or parts driven by this charge onto the target plate are listed in the order that they are acted upon by the shock wave traveling through them. For the first three experiments a free run technique was used to increase the shock pressure in the target plate and for a number of the other shots a uranium or a brass plate was used to attenuate the shock pressure.

In the "Target Plate" column are shown the target plate materials and special surface treatments, such as lapping, polishing, or the removal of metal or oxide by chemical means. The plates were flat on both sides with the exception of those plates used in the last three experiments which were contoured on the top surface.

The "Plate Support Diameter" column refers to the diameter of the cavity around the bottom surface of the plate. The reduced diameters of the cavity for Shots 17 through 21 seem to have a serious effect on the signal output for these experiments, with the possible exception of Shot 18. The lower initial apparent temperature for Shot 18 may indicate that the copper plate did not produce such a high temperature either at the uranium plate diameter discontinuity or at the cavity wall when the shock wave caused the free surface to move at these places.

The "Top Calibration Temperature" column indicates whether the apparent temperatures determined for each shot had to be extrapolated or interpolated from the calibration points plotted for that particular shot.

The "Calibration Plate" column shows whether the heated plate for the calibration runs for a particular shot was the same plate as that used with the high explosive, or another plate. In a few cases two different calibration plates were used so that the effect of different emissivities could be evaluated more easily.

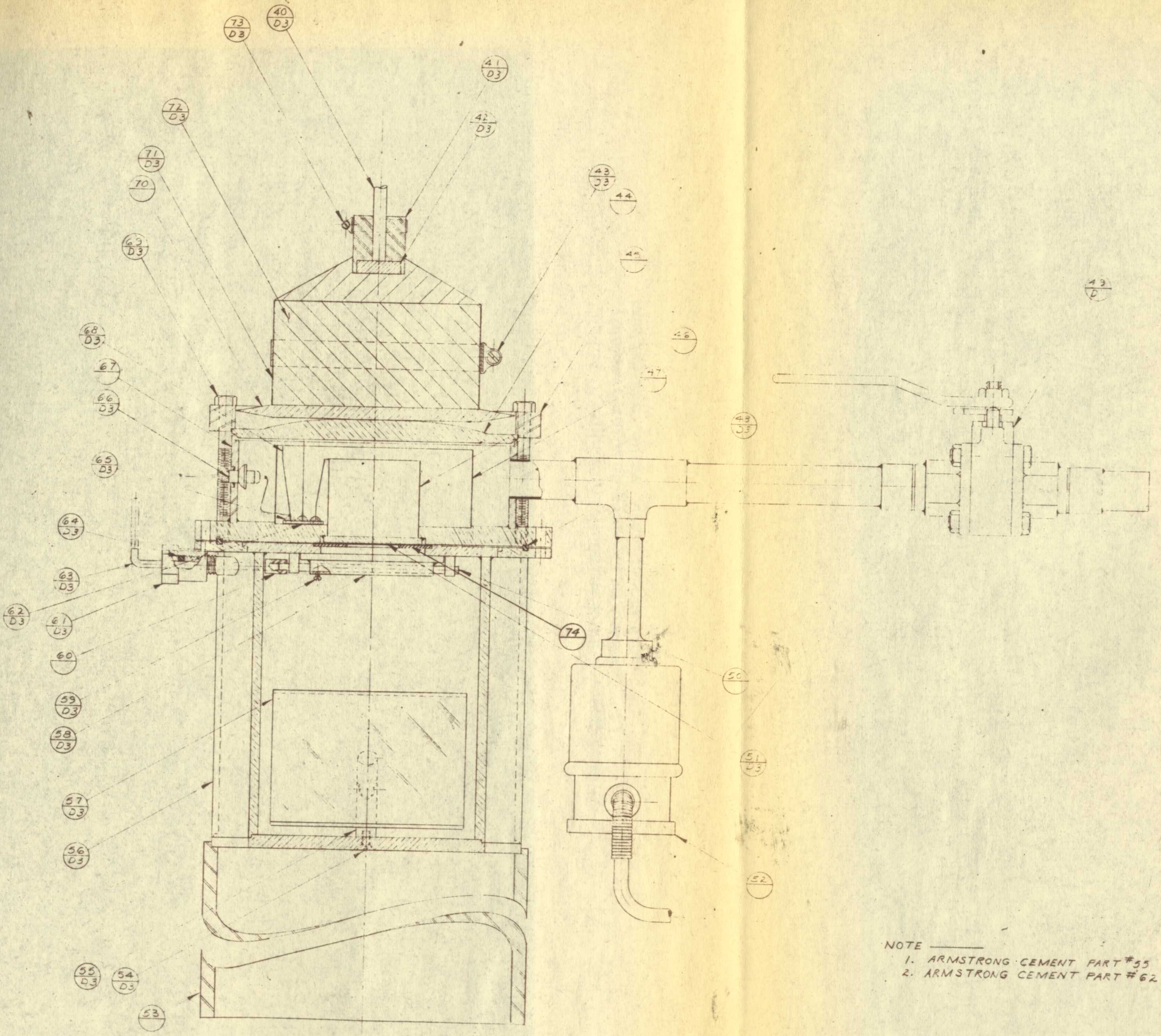
The last column shows how the signal traces appeared for those experiments which produced signals that did not saturate all the oscilloscopes. The vertical lines through the traces indicate one microsecond time intervals. The signal from the phototube is

C. Shot Firing

The validity of the temperatures reported for this work depends upon how closely the calibrating geometries and conditions are duplicated when the shots are fired. For this reason the calibration was always performed with the same jacket, electrical system, and apparatus setup as that used for the firing of the shots. As the experiments progressed there were some differences between the calibrating conditions and the firing conditions, but it was felt that these did not introduce excessive errors. The charts in the "Results" section indicate the differences between the experiments and between calibrating and firing conditions. Except as is mentioned, the following apparatus description applies to Shot 24.

After calibration the blackened tube and quartz window assembly, the water jacket, the calibration plate, and the ceramic ring (Figure 9) were replaced by the evacuated cavity (Figure 17). The aluminum plate that was to be fired was the cover plate for the cavity and it was sealed against a 1-3/8 inch diameter knife edge (15) on the lip of the cylindrical section by a steel ring bolted to the bottom flange. The bottom plate of the cavity had an opening covered with a quartz disc the same thickness as that used in the calibration apparatus. The seal was a small amount of Apiezon Q sealing compound. An aluminum tube the same diameter and height as the brass tube that was removed but with a 0.005-inch wall thickness, was glued to the quartz with a few spots of Armstrong

BILL OF MATERIAL			
PART NUMBER	NUMBER REQD.	PER	DESCRIPTION
40	1	ASS'Y	PRIMACORD 6" LG.
41	1		PRIMACORD ADAPTER
42	1		TETRAL PELLET
43	1		HOSE CLAMP - LASL STK. CAT #HF-6042
44	1		TARGET PLATE
45	1		CLAMP RING - STL.
46	1		.001 WALL X 1 1/2 LG. AL. CYL.
47	1		.010 WALL X 1 1/2 LG. AL. CYL.
48	1		5 15/16 O.D X 5 3/4 I.D. X .103 WALL O-RING {LASL STK. CAT. #GS-3162
49	1		FLANGE, BALL VALVE, 1/2" NOM. SRE.
50	1		BRASS SHAFT
51	1		PYREX GLASS
52	1		PHILLIPS GAUGE TUBE
53	1		STAND - 6 1/4 O.D. X 1/4 WALL STL. TUBING.
54	1		#8-32 X 3/8 LG. FLT. HD. SCR.
55	1		UNIVERSAL JOINT - LASL STK. #HF-1295
56	1		MIRROR HOUSING - SK #69809 PART #12
57	1		MIRROR - 4 X 4 X 1/8
58	1		SHUTTER - BRS. - SK #69809 PART #6
59	1		#1-72NF-2 FIL. HD. SCR 1/8 LG.
[illegible]	1		UNION - STL.
[illegible]	1		COMPRESSION GLAND - SK #69809 PART #7
62	1		GLASS INSULATOR - 3/4 X 1/2 X 1/16
63	1		SHUTTER HANDLE - SK #69809 PART #8
64	AS REQ'D		O-RING 1/4 O.D. X 1/8 I.D. X .070 WALL
65	3		ARMSTRONG CEMENT
66	3		KOVAR TO GLASS SEAL - LASL STK. CAT. #LG-2070
67	1		VACUUM CHAMBER - S.S.
68	3		.011 DIA. MUSIC WIRE
69	15		1/4-28NF-2 HEX. HD. CAP SCR. 2 1/2 LG. - STL.
70	1		PLATE - MAT'L AS SPECIFIED
71	1		.020 THK. BRASS CASE
72	1		HIGH EXPLOSIVE
73	2		HOSE CLAMP
74	1		APERTURE PLATE



SECTION B-B / D1

NOTE
1. ARMSTRONG CEMENT PART #55 TO PARTS #56 & #57
2. ARMSTRONG CEMENT PART #62 TO #67

FIG. 12 ASSEMBLY OF EXPLOSIVE, VACUUM CAVITY, & CAN

REV. LETTER	REVISIONS	DATE	CHANGED BY	CHECKED BY	APPROVED BY

LOS ALAMOS SCIENTIFIC LABORATORY
UNIVERSITY OF CALIFORNIA — LOS ALAMOS, NEW MEXICO

TOLERANCES - UNLESS OTHERWISE NOTED: FRACTIONAL ± DECIMAL ± ANGULAR ±

	SIGNATURE	DATE	GROUP & REP.
ORIGINATED			
DRAWN	TAYLOR	3-24-61	
CHECKED			
PROJ. ENGR.			
APPROVED			
RELEASED BY			

TITLE: PHOTO-THERMOMETER SUBASSEMBLY #2

PART No.

SCALE	TOTAL SHEETS	DRAWING NO.	SIZE	SHEET NO.
FULL		SK #697	D	3

The "Plate Support Diameter" column refers to the diameter of the cavity around the bottom surface of the plate. The reduced diameters of the cavity for Shots 17 through 21 seem to have a serious effect on the signal output for these experiments with the possible exception of Shot 18. The lower initial apparent temperature for Shot 18 may indicate that the copper plate did not produce such a high temperature either at the uranium plate diameter discontinuity or the cavity wall when the shock wave caused the free surface to move at these places.

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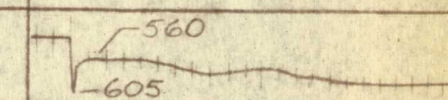
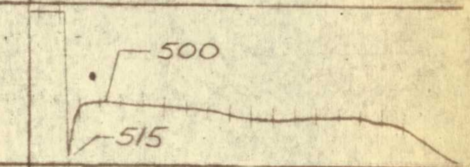
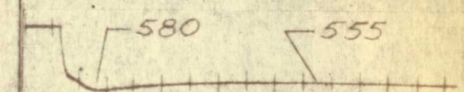
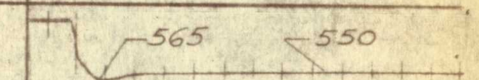
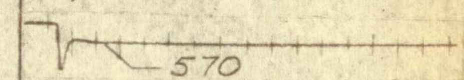
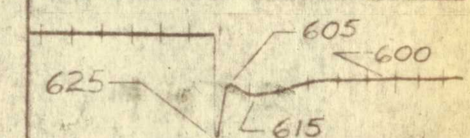
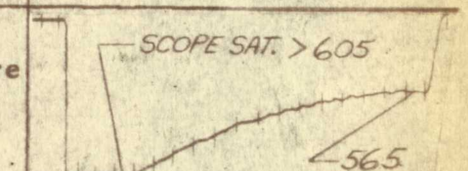
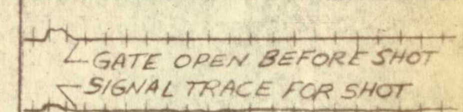
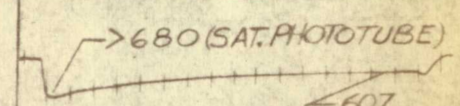
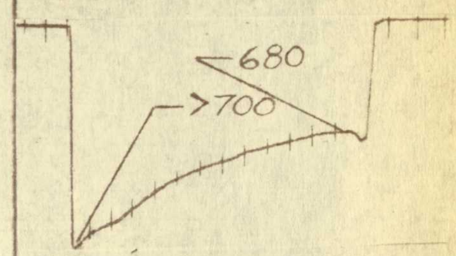
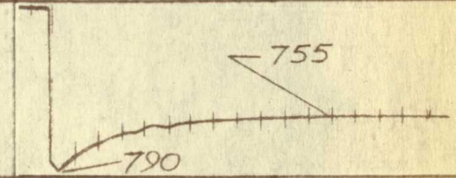
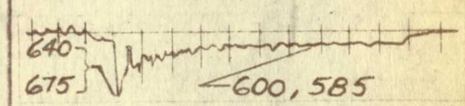
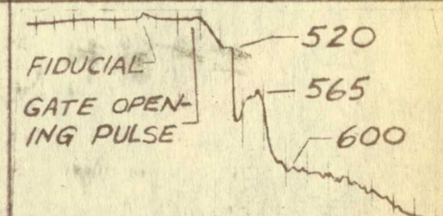
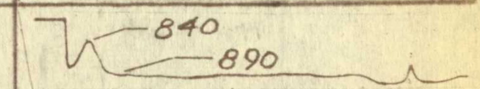
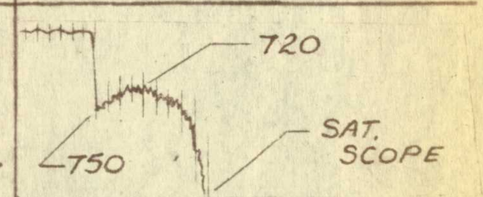
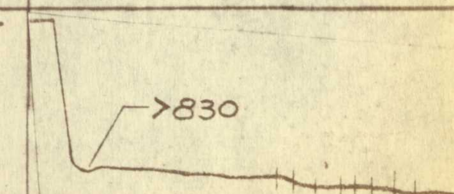
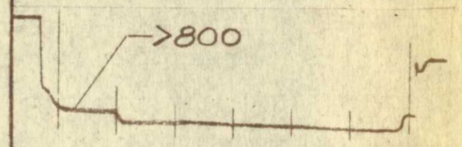
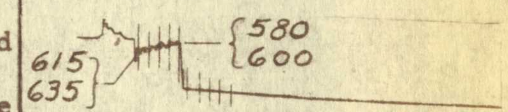
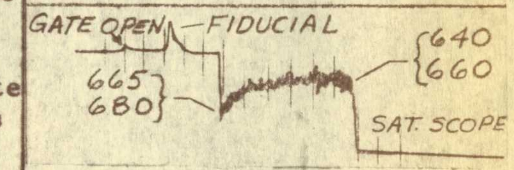
The last column shows how the signal traces appeared for those experiments which produced signals that did not saturate all the oscilloscopes. The vertical lines through the traces indicate one microsecond time intervals. The signal from the phototube is

Shot No.	Explosive System Above Plate	Plate	Plate Support Dia. inches	Phototube Circuit	Vac. µ Hg	Calibration Plate	Top Cal. Temp. °C	Remarks	
1	7" Comp B, 1/16" Lucite, 1/8 s. s., 3/4" Free Run	2024 Al med. lapped surf.	5-3/8	Standard with 7102 phototube	20	Shot Plate	490	Signal saturated oscilloscopes	
2	2" Comp B, .024" Polyethylene, 1/16 s. s., .200" Free Run	"	"	"	40	"	"	"	
3	Same as above, except .100 Free Run	"	"	"	20	"	"		
4	4" Comp B	"	"	"	45	"	"	Rise in signal at about 16 µsec after peak could be the breaking of the light pipe by the primacord.	
5	2" Comp B	"	"	.05 cap. added from signal output to ground.	15	1100 Al Plate	550		
6	2" TNT	"	"	"	30	"	"		
7	2" TNT, 3/8 brass plate attenuator	"	"	.05 µf cap. changed to .01 µf.	30	"	"		
8	"	1100 Al, med. lapped surf.	"	.01 µf cap. changed to .02 µf.	40	"	"	Signal came in about 6 µsec late, reason undetermined.	
9	2" Baratol, 1/4" uranium plate attenuator	"	"	Gate with .005 µf cap. on signal line to ground.	30	"	"	The decay of this curve (and of others where the uranium plate was used) and an apparent temperature higher than for the previous shots indicate some trouble in the experiment.	
10	2" Comp B	2024 Al, med. lapped surf.	"	Gate, .005 µf cap., 6199 phototube.	20	Brass, lapped surface	660	The two traces show the difference between the emission from a cold plate and a shocked plate.	
11	2" Baratol, 1/4" uranium plate attenuator	1100 Al, med. lapped surf.	"	Same as above except 7102 tube used.	35	Brass and 1100 Al, lapped	680	Calibration curves show phototube saturated at about 680°C.	

Shot No.	Explosive System Above Plate	Plate	Plate Support Dia. inches	Phototube Circuit	Vac. μ Hg	Calibration Plate	Top Cal. Temp. °C	Remarks	
13	2" Baratol, 1/4" uranium plate attenuator	1100 Al, med. lapped surf.	5-3/8	Gate, .005 μf cap., 7102 tube used.	30	Brass and 1100 Al, lapped	680		
14	2" TNT, 1/4" uranium plate attenuator	"	"	Gate, no cap. on signal line.	20	"	707		
15	"	"	"	Gate, .0005 cap. from signal to ground.	0.1	1100 Al plate, lapped	610	Signal saturated oscilloscopes.	
16	2" Baratol, 1/4" uranium plate attenuator	1100 Al, lapped then polished.	"	Gate, .001 μf cap. on signal line at oscilloscope.	0.035	1100 Al, polished; brass, polished	780	The higher apparent temp. of each pair is for the polished surface if it remains bright during the shock, the lower temp. is corrected for the dull surface.	
17	"	1100 Al, lapped heavily	4.5	Gate, .0015 μf cap. from signal to ground.	0.035	Brass, oxidized	740	Signal saturated all oscilloscopes.	
18	"	Copper, polished	"	"	0.2	Brass, polished	708	The gate opened after the signal arrived at the surface of the plate, and the lowest apparent temperature follows the 520° calibration curve closely. The sharp increase in signal seems to indicate some other disturbance probably due to the small support diameter.	
19	2" Comp B	1100 Al, lapped	3.9	Gate, no cap.	0.02	Brass, oxidized	780	The extremely large signal prevented the gate from closing effectively.	
20	2" Baratol	2024 Al, polished; cleaned in phosphoric and chromic acid solution.	"	"	0.02	Brass, polished	774	As the plate closed on a light shield the signal decreased until one side of the light shield contacted the plate, then the signal increased. This indicates that part of the signal was emitted by a source outside of the area monitored by the phototube, probably from the small diameter support.	
21	"	1100 Al, polished and cleaned as above.	"	Gate, but with .001 μf cap.	Atm. press.	"	770	Rounding off of signal and high apparent temperature probably indicates the effect of atmospheric air next to the plate. Wratten 87-C Filter used.	

Shot No.	Explosive System Above Plate	Plate	Plate Support Dia. inches	Phototube Circuit	Vac. µ Hg.	Calibration Plate	Top Cal. Temp. °C	Remarks	
22	2" Baratol, 1/4" brass plate attenuator	1100 Al, polished and cleaned in phosphoric and chromic acid solution and its top surface contoured.	5-3/8	Gate, but with .001 µf cap.	Atm. press.	Brass, polished	750	Rounding off of signal and high apparent temperature probably indicates the effect of atmospheric air next to the plate.	
23	"	"	"	Gate, no cap.	0.04	"	770	The higher apparent temperature in each pair is for a plate that remained bright, the lower is a corrected temperature for a plate surface that became dull like a lapped surface. The decay in the signal may be due to the closing of the gap between the light shield and the plate. The sudden increase in signal after about 6 µsec is probably caused by emission due to the plate contacting the light shield. Here the light shield was quite parallel to the plate.	
24	"	"	"	"	0.035	s. s. and brass	710		

negative with respect to the baseline and the trace travels from left to right. The numbers given for different parts of the traces are the apparent temperatures of the plate at the times indicated on the traces. The "Calculations" section shows how the apparent temperatures were calculated. Some of these temperatures may have very little significance except to show that there was some difficulty in the experiment. For example, the apparent temperatures shown for Shots 17, 19, and 21 when compared to the results of Shot 20 indicate that the radiation was emitted primarily from some source outside the small central area of the plate monitored by the phototube. The sudden rise from the 520°C temperature for Shot 18 also may indicate strong emission at the interaction between the copper plate and its support.

The "hash" that is apparent on the traces for Shots 20, 23, and 24 is statistical fluctuation in the emission from the photocathode of the phototube due to the incident photons. The fluctuations are most apparent when the oscilloscopes are set at high sensitivities and for those experiments where a capacitor was not added between the signal line and ground.

B. Results of the experiments in which the radiation from an artificial blackbody was compared to that from plate surfaces.

Two sets of experiments were performed to obtain these results. For the first set the apparatus was that shown in Figures 15&16

negative with respect to the baseline and the trace is read from left to right. The numbers given for different parts of the traces are the apparent temperatures of the plate as the [illegible] indicated on the traces. The "Calculations" section shows how the apparent temperatures were calculated. Some of these temperatures have [illegible] very little significance except to show that there were some difficulties in the experiment. For example, the apparent temperatures shown for Shots 17, 19, and 21 when compared to the results of Shot 8 indicate that the radiation was [illegible] primarily from some surface outside the small central area of the plate monitored by the [illegible]. The sudden rise from the 520°C temperature for Shot 10 also may indicate strong emission at the interaction between the copper plate and its support.

The "hash" that is apparent on the traces for Shots 20, 22, and 24 is statistical fluctuation in the emission from the photocathode of the phototube due to the incident photons. The fluctuations are most apparent when the deflections are not as high as other traces and for those experiments where a capacitor was not added between the signal line and ground.

D. Results of the experiments in which the radiation from an artificial blackbody was compared to that from plate surfaces.

Two sets of experiments were performed to obtain these results. For the first set the apparatus was that shown in Figure 15[illegible]

which did not have a tubular light shield in the cavity between the aperture and the heated plate or artificial blackbody. The results of these experiments apply to data obtained from the shots which did not have the tubular light shield and in which the signal was not obviously emitted from an extraneous source. These shot numbers are 3-9, 13, and 14. The second set of experiments was performed with a tubular light shield in the apparatus like that used in Shots 20, 22, 23, and 24. The signals in Shots 20 and 22 were extraneous in nature so the data apply only to Shots 23 and 24.

The curves plotted from these two sets of experiments indicate the maximum error that can be introduced by a plate's emissivity changing under shock conditions. It is felt, and GMX-6 photographs seem to show that a reflective surface tends to become less reflective (or more emissive) when a shock wave sets it in motion rather than more reflective. The maximum emissivity change in this direction is to that of a blackbody. The artificial blackbody constructed for these experiments had a calculated emissivity of at least 0.97 (10) which exceeds the emissivity that a metal surface could attain. The curves for the first set of experiments show that for a temperature of 540°C for a polished aluminum plate, if the plate became as emissive as the artificial blackbody, the apparent temperature obtained by using the polished plate curve would be about 60°C too high; i.e., instead of 540°C the temperature would be 480°C; or, between these two values

which did not have a tabular light shield in the cavity between the aperture and the heated plate or artificial blackbody. The results of these experiments apply to data obtained from the shots which did not have the tabular light shield and in which the signal was not obviously emitted from an extraneous source. These shot numbers are 3-9, 13 and 14. The second set of experiments was performed with a tabular light shield in the apparatus like that used in Shots 20, 22, 23, and 24. The signals in Shots 20 and 22 were extraneous in nature so the data apply only to Shots 23 and 24.

The curves plotted from these two sets of experiments indicate the maximum error that can be introduced by a plate's emissivity changing under shock conditions. It is felt, and CMX-8 photographs seem to show that a reflective surface tends to become less reflective (or more emissive) when a shock wave sets it in motion rather than more reflective. The maximum emissivity change in this direction is to that of a blackbody. The artificial blackbody constructed for these experiments had a calculated emissivity of at least 0.97 (10) which exceeds the emissivity that a metal surface could attain. The curves for the first set of experiments show that for a temperature of 540°C for a polished aluminum plate, if the plate became as emissive as the artificial blackbody, the apparent temperature obtained by using the polished plate curve would be about 60°C too high, i.e., instead of 540°C the temperature would be 480°C; or, between these two values

if the emissivity did not increase this much. Because the plotted curve of the nonreflective lapped aluminum surface lies closer to the blackbody curve, the true apparent temperature here could be as low as about 520°C.

The second set of experiments yielded data for higher temperatures (Figure 24). From these curves the maximum decrease in apparent temperature as indicated by the calibration curve for the surface due to possible emissivity changes can be seen to be about 10°C for a lapped aluminum surface and about 35°C for a polished aluminum surface at about 640°C. Because polished surfaces were used for Shots 23 and 24 the latter figure is the applicable possible decrease in apparent temperature.

Sources of other possible errors in the apparent plate temperatures are evaluated as follows:

(1) Thermocouple-millivoltmeter error

The maximum error of the thermocouple-millivoltmeter as determined by periodic observations of the temperature of the freezing point lead was about 4°C. The Instrument Society of America (25) gives an error for Chromel-Alumel thermocouples in the range of 530° - 2300°F which correlates with this observation. At about 640°C the thermocouple-millivoltmeter error might have been as much as 5°C.

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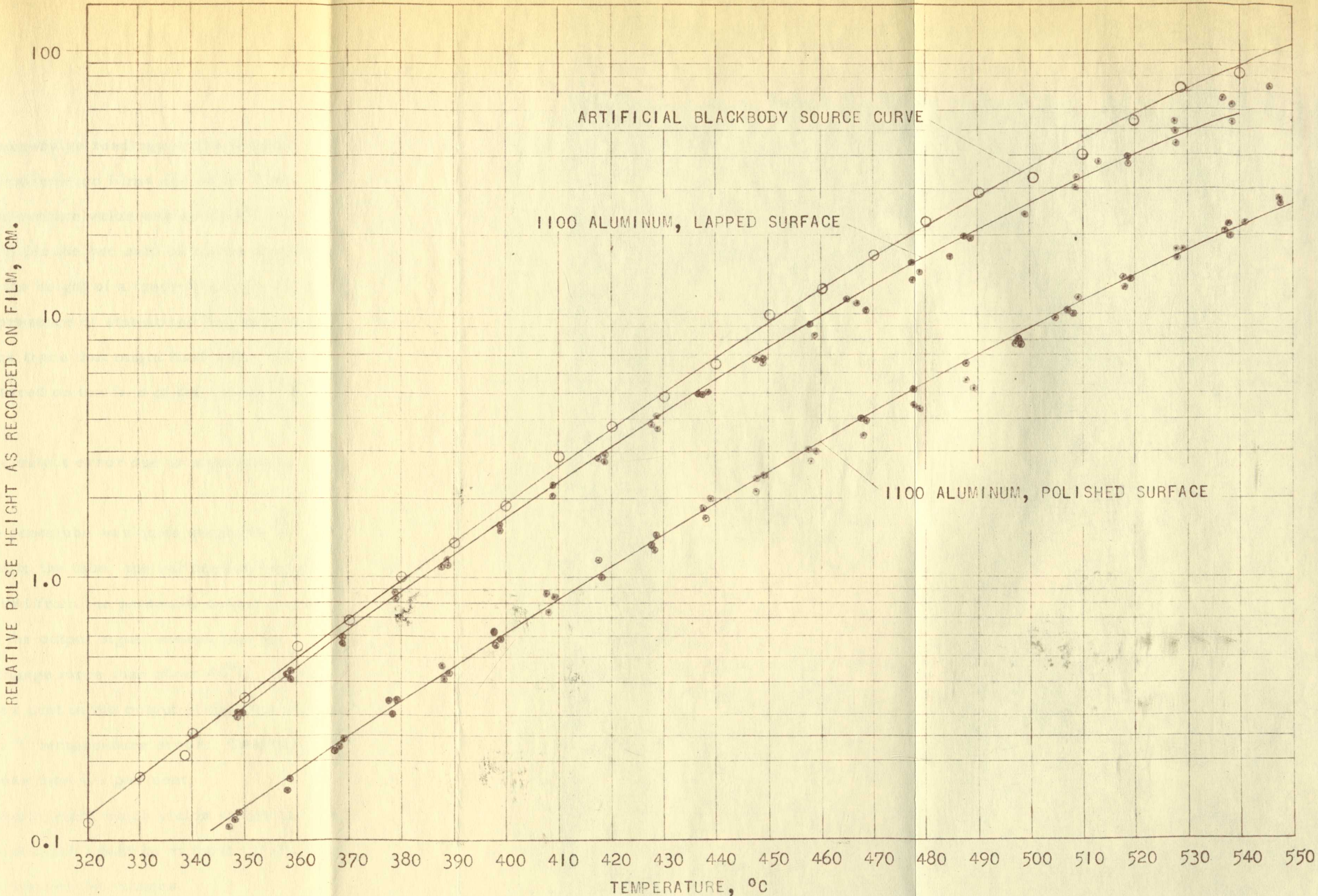

FIG. 24. PHOTOTUBE RESPONSE VS THE TEMPERATURE OF AN ARTIFICIAL BLACKBODY AND OF ALUMINUM PLATE SURFACES IN APPARATUS WITHOUT A TUBULAR LIGHT SHIELD

(2) Film reading error

The average error in successive readings of the largest, unsaturated pulse heights on the calibration films and on the shot records when converted to a temperature value was about 3°C for each trace read, or a total of 6°C for the two sets of traces that must be read for each shot. Reading the height of a trace from a base line was made more difficult by the presence of statistical fluctuations on the trace, and by curvature in the trace that might have been introduced by the trace not being centered on the face of the cathode ray tube.

(3) Multiplier phototube output error due to high voltage power supply changes

Although the gain of the phototube was quite sensitive to variations in the voltage supplied to the tube, the calibration curves show that the temperatures derived from the phototube output are not so sensitive; i. e., a doubling of the output signal means that the monitored temperature did not change more than about 40°C. Therefore, a possible change of 0. 1 per cent in the output of the high voltage power supply would mean about 1°C temperature error. The stability of the power supply is rated at less than 0. 1 per cent.

The total error for an experiment which yields values for the apparent temperatures of a plate surface would be at most ±11°C plus the error introduced by possible emissivity changes.

(2) Film reading error.

The average error in successive readings of the largest unsaturated pulse heights on the calibration films and on the shot records when converted to a temperature was about 2°C. for each trace read, or a total of 5°C for the set of traces that must be read for each shot. Reading the height of a trace from a base line was made more difficult by the presence of extraneous fluctuations on the trace, and by curvature in the trace that might have been introduced by the trace not being centered on the face of the cathode ray tube.

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The total error for an experiment which yields values for the apparent temperatures of a glass surface should be at most ±11°C plus the error introduced by possible emissivity changes.

C. Results of a comparison of the measured temperatures to calculated temperatures.

There is no correlation between the measured temperatures of the aluminum plates and the temperatures as calculated by GMX-6 for the shock pressures attained in the experiments. Examples of some of these temperatures are presented in the following table:

Shot No.	4	5	6	7	11	23	24
Calculated Temperature °C	240	225	130	120	45	125	125
Measured Temperature °C	500	555	550	570	607	590	650

D. Results of tests on the response of the phototube.

The RCA specifications for the 7102 phototube give an indication of its time response characteristics; i. e., the time spread of its response to a one millimicrosecond pulse in five millimicroseconds. How this response varies with the intensity of the pulse is not stated.

The tests with the xenon flash bulb and with the neon bulb controlled by a bistable multivibrator circuit showed that the output voltage of the phototube and gated circuit in response to a steady source of radiation was not measurably different for any of the following cases after the obvious transient effects had disappeared:

(1) Turning on the steady light source after gating the tube to a conducting state;

(2) Gating the tube on after the steady light source had been radiating to the photocathode of the tube for a few seconds;

(3) Gating the tube on while the steady light source was on and simultaneously flashing the one microsecond xenon source.

The obvious transient effects noted in the above operations were the response to the xenon flash and a small amount of overshoot in the rise of the signal when the gate was opened. Without modifying the apparatus it was not possible to flash the microsecond light pulse after gating the tube to a conducting state. When the radiation from the flash bulb was so intense that the output of the phototube circuit exceeded its design limit then the response became very erratic and the trace had the appearance of a damped oscillation.

E. Results of the recovery experiments.

Four recovery experiments were performed. Two shots had two-inch thick charges of Baratol driving a brass plate attenuator onto an aluminum target plate. Two-inch charges of TNT and Composition B were used with an aluminum plate for the other two shots. The Composition B experiment did not yield a recovery sample, which perhaps indicates that the temperature of the sample was indeed near the

melting point of the material, but more extensive tests would have to be conducted to establish this. The sample recovered from the TNT shot was quite deformed and its surface looked like the material had been close to its melting point, but a microscopic examination of the grain structure by Group CMF-13 was inconclusive. The samples recovered from the two Baratol shots were deformed, but not as radically as the one recovered from the TNT experiment.

F. Results from pin experiments.

The first pin experiments were fired to determine how to most effectively use the free run technique in order to achieve a high shock pressure in the aluminum plate. As later experiments showed, a high pressure was not necessary to produce a temperature above about 400°C, the lower limit of effective phototube response in the apparatus designed for the investigation. These experiments also indicated how uniformly the free surface of the aluminum plate moved as a result of the reflection of a plane shock wave. These experiments showed that when a charge of Composition B, four inches in thickness, detonated in a free run type geometry, imparted a free surface velocity of 4.6 mm/μsec to a 3/8-inch aluminum plate the material at a 1.5-inch diameter lagged the center material by 0.3 microsecond when the free surface had been traveling for about 2 microseconds. At this time the

melting point of the material, but more extensive tests would have to be conducted to establish this. The sample recovered from the TNT shot was quite deformed and its surface looked like the material had been close to its melting point, but a microscopic examination of the grain structure by Group CMF-13 was inconclusive. The samples recovered from the two Baratol shots were deformed, but not as radically as the one recovered from the TNT experiment.

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material at a one-inch diameter lagged the center less than 0. 03 microsecond. A charge of Baratol two inches thick on a 1/4-inch thick uranium attenuator plate which was against a 3/8-inch aluminum plate imparted a free surface velocity to the aluminum plate of 0. 92 mm/μsec. The material at a 1. 5-inch diameter lagged the center by 0. 01 microsecond after the surface had been moving for two microseconds. Except for Shot 3 all the shots that yielded temperature data were fired under the conditions which would produce free surface uniformity as good as that of the Baratol experiment. The variations in temperature over the surface that could be expected from variations of these magnitudes in free surface velocity are negligible in the region above 0. 92 mm/μsec free surface velocity as can be seen by noting that the slope of the temperature curve is not much different from the slope of the free surface velocity curve in Figure 25.

In the experience of GMX-4 free surface velocity from one shot might vary as much as 7 per cent from that of another supposedly identical shot with the explosive systems used in these temperature measuring shots. From Figure 25 one finds that a 7 per cent change in free surface velocity corresponds to a 30°C change in temperature at ~330 kilobars pressure, which was the approximate pressure of the shock wave in Shot 3. If the pressure-temperature slope is the same for the higher temperatures obtained in the experiments, the reproducibility of temperatures for shots having 330 kilobars pressure would

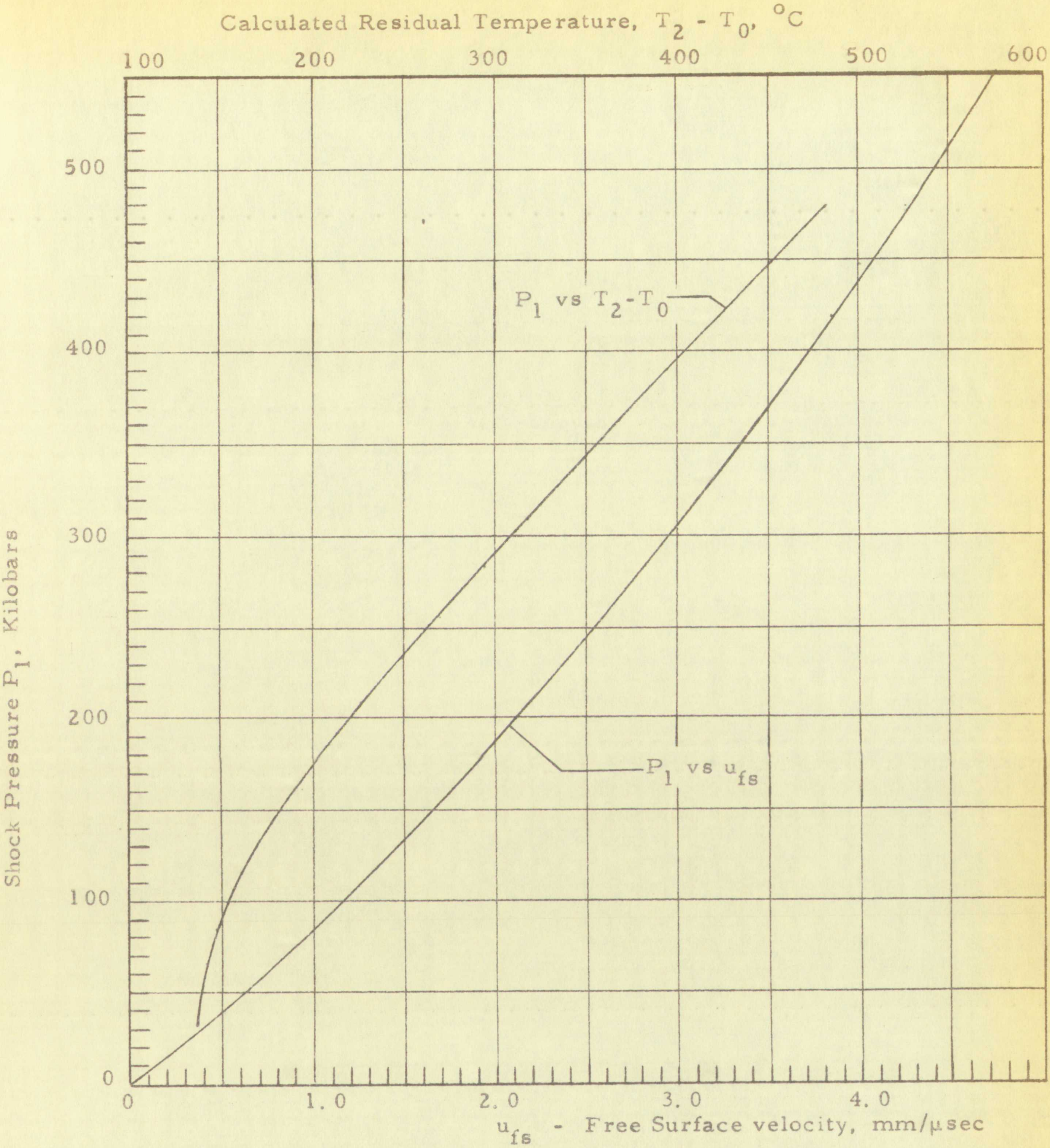

Fig. 25 Plots of Shock Pressure vs Residual Temperature and Free Surface Velocity for 2024 Aluminum (Plotted from GMX-6 Data)

be $\pm 30^{o}C$ which does not include the $\pm 11^{o}C$ from errors previously listed, nor the error caused by the change in the emissivity of the surface which is probably negligible for two identical experiments.

G. Results of a comparison of a blackbody calibration curve to a theoretical curve of phototube response .

Figure 23 in the theoretical investigation is a plot of an artificial blackbody calibration curve and a calculated theoretical curve of phototube response to blackbody radiation. Although the slopes of the curves represent the sensitivity of the phototube output to temperature changes the units of the axis of ordinates are only relative because no attempt was made to evaluate the geometrical factors and energy losses involved in the transmission of radiant energy to the phototube. Also the points plotted for the calibration curve are relative units because they simply represent the pulse heights of the oscilloscope traces as measured on the film. A voltage calibration of the oscilloscope used in this experiment showed that its response was nearly linear over the range of measurements covered by the experiment. The linearity of the phototube circuitry was not tested.

The difference in the slopes can partly be attributed to the errors in temperature measurements and film reading already

be $\pm 5^{\circ}C$ which does not include the $\pm 1^{\circ}C$ from errors previously listed, but the error caused by the change in the emissivity of the surface which is probably negligible for two identical experiments.

G. Results of a comparison of a blackbody calibration curve to a theoretical curve of phototube response.

Figure 22 in the theoretical investigation is a plot of an artificial blackbody calibration curve and a calculated theoretical curve of phototube response to blackbody radiation. Although the slopes of the curves represent the sensitivity of the phototube output to temperature changes the units of the axis of ordinates are only relative because no attempt was made to evaluate the geometrical factors and energy losses involved in the transmission of radiant energy to the phototube. Also the points plotted for the calibration curve are relative units because they simply represent the pulse heights of the oscilloscope traces as measured on the film. A voltage calibration of the oscilloscope used in this experiment showed that its response was nearly linear over the range of measurements covered by the experiment. The linearity of the phototube circuitry was not tested.

The difference in the slopes can partly be attributed to the errors in temperature measurements and film reading already

discussed, to possible nonlinearity in the phototube circuitry, and to errors in plotting the curves and determining the slopes. Probably the greatest contribution to the slope difference is a shift of the region of maximum response of the phototube selected for the calibration run that was plotted. The manufacturer's specifications permit the peak value of the response curve plotted in Figure 21 to shift ±0.1 micron from the nominal 0.8 micron wavelength specified for peak response.

VIII. CONCLUSIONS

It was concluded that the phototube apparatus developed for the shock wave experiments was capable of producing a signal which was related to the effect of the shock wave on the free surface of the plate. The experimental evidence for this conclusion may be summarized as follows:

A. The heights of the traces produced by the calibrating apparatus showed a sensitive and direct dependence upon the temperature of the surface of the plate, and these heights could be repeated from one calibration to another within a maximum error of 15°C, but more often within 10°C.

B. The times at which the signals appeared were consistent with the times as measured and as calculated for the shock waves to have reached the free surfaces of the plates. For two experiments where electrical contactors were employed the maximum uncertainty in the arrival time of the shock wave was 0.1 microsecond.

C. The signals were not electric or magnetic disturbances such as might have been generated in a field around the detonating high explosive. If the signals had been of this origin, Shot No. 10, a shot in which a phototube that was

insensitive to infrared radiation was used, would have produced a signal similar to the signals produced by the other shots.

D. Shot No. 18, in which a filter was used to absorb visible radiation, showed that most of the radiation in the signal reaching the photocathode was of wavelengths greater than 0.8 micron wavelength; i.e., in the infrared region. This ruled out the possibility that gas or other contaminants could have produced the signal by strong spectral emission at wavelengths shorter than 0.8 micron. An experiment to rule out the effect of such spectral emission over the rest of the phototube response region (0.8 to 1.1 microns) was not performed. Because the apparent temperature did not seem to vary with changes in the vacuum pressure over a wide range (3×10^{-5} to 4×10^{-2} mm of Hg), the experiments seem to be insensitive to any emission that may have been produced by the gas in the system, unless the gas was near atmospheric pressure as in Shots No. 21 and 22. If gases were confined somehow on the surfaces of the plates so that they could be compressed they would reach very high temperatures, and the possibility of emission from this source has not been entirely eliminated, although the treatment of the plate surfaces in Shots No. 23 and 24 was designed to reduce this

possibility. The lack of a noticeable effect as a consequence of this treatment seems to decrease the possibility of gaseous inclusions being the primary source of the signals.

E. In the experiments the magnitude of the signal corresponded directly to the pressure of the shock wave, with two exceptions: The assemblies with the small diameter support for the plate produced exceptionally large signals, which were probably caused by a strong interaction between the support and the plate. The assemblies with uranium plates produced disproportionately large signals, but the reason for this has not been determined.

It was concluded that the measured temperatures were probably not the residual temperatures of the target plates. It was not proved that other possible sources of high temperature radiation were not contributing to the observed signal. Such sources would include the microscopic pockets of compressed gas mentioned above, surface oxide or contamination, uneven highly strained areas on the surface of the plate near the monitored area, and spalling or scabbing phenomena.

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2. In the experiments the magnitude of the signal corresponded directly to the pressure of the shock wave, with two exceptions: The assemblies with the small diameter support for the plate produced unexpectedly large signals, which were probably caused by a strong interaction between the support and the plate. The assemblies with uranium plates produced disproportionately large signals, but the reason for this has not been determined.

It was concluded that the measured temperatures were probably not the residual temperatures of the target plates. It was not proved that other possible sources of high temperature radiation were not contributing to the observed signal. Such sources would include the microscopic pockets of compressed gas mentioned above, surface oxide or contamination, uneven highly strained areas on the surface of the plate near the monitored area, and spalling or scabbing phenomena.

IX. RECOMMENDATIONS

Work should be continued to determine the source of the measured temperatures of the target plates. The apparatus should be modified so that experiments could be performed to show if the possible sources of high temperature radiation mentioned in the previous section are contributing to the observed signal. Any effects of microscopic gas pockets and other contamination can be reduced by using vacuum cast target material and outgassing the surface at high temperature. A high frequency induction heating process might be devised for this so that only the surface would be heated and the rest of the system would not be damaged by the high temperature. Devising a technique for using a vacuum furnace is another possibility. High temperature sources caused by areas of large uneven strains on the surface of the plate can possibly be determined by photographing the surface of the plate under shock conditions. These experiments may also help to determine if there is any spalling of the plate surface.

Experiments for measuring the temperature of different surfaces may yield information which will help to explain the temperatures obtained so far as well as yielding their own temperatures. Such materials might be platinum or gold, or a liquid such as mercury.

If necessary the accuracy of the temperature measurements can be improved in several ways. The effect of variations in the

emissivity of the surface of the plate can be reduced by covering the monitored area with a highly reflective cavity. A small hole in the cavity would emit radiation to the phototube. This radiation would be nearly blackbody radiation and the emissivity of the plate surface would have very little effect on the amount of energy emitted through the hole at a given temperature. So that the hole size can be kept small, it may be necessary to move the phototube closer to the plate in order to maintain the signal amplitude, or to use a lens system. An infrared sensing device with a smaller area than the photocathode of the 7102 tube may have a good application here. More refined thermocouple techniques, such as using a sealed, sheathed junction, and providing more protection from the wind and sun for the millivoltmeter pyrometer would probably improve the accuracy of the calibration curves.

A fast light pulser, such as that described by Garbony and others (13), capable of producing pulses of 10^{-8} to 10^{-10} second duration could be used to make a more thorough study of the response characteristics of the apparatus. The device is essentially a rotating mirror which allows light sources of any wavelength and intensity to be used. For some of the semiconductor detectors a knowledge of the response time versus the temperature of the detector and the wavelength of the incident light may be quite important.

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XII. APPENDIX

A. Calculation of the shock pressure in the aluminum plate from the experimental data.

Charged electrical contactors or pins set at known distances from the free surface of a plate will discharge when contacted by a moving plate at ground potential and the time interval between pulses can be used to calculate the velocity of the motion of the plate. A large number of pins in various groupings are usually used for these experiments, but to illustrate the process only data from a pair of pins is used below.

Pin No.	Distance d from plate, inches	Contact time measured from reference time, μsec	$t_2 - t_1 = \Delta t$ μsec	$d_2 - d_1 = \Delta d$ inches	Velocity $\Delta d/\Delta t$ in/μsec	Velocity u_{fs} mm/μsec
1	0.066	53.140	12.026	0.439	0.0365	0.927
2	0.505	65.166				

The P vs u_{fs} curve (Figure 28) yields a shock pressure for u_{fs} = 0.927 mm/μsec of 86 kilobars and a calculated residual temperature of 45°C from the P_1 vs $T_2 - T_0$ curve in the same figure.

B. Formula for solution of phosphoric-chromic acid and process used to remove oxide from type 1100 aluminum plate surfaces.

35 ml. of 85 per cent phosphoric acid

20 grams of chromic acid

Water to make 1000 ml.

After cleaning the plate with acetone, it was immersed in the heated solution (150° - 190°F) for five minutes. The surface was then rinsed with acetone and the plate was attached to the vacuum system to keep the oxide layer thickness to a minimum.