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A Calorimeter for Measuring the Power in a High-Energy X-ray Beam*

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The design and calibration of a calorimeter to measure the power in X-ray beams having peak energies between 1 and 180 million electron volts are described. The calorimeter included two thermally balanced lead cylinders, 4 centimeters in diameter by 7.5 centimeters long, one irradiated by an X-ray beam. The lead cylinder was large enough to absorb almost completely the X-ray beam. The absorbed energy resulted in an unbalance of temperature of the two cylinders, which was measured by the change in resistance of embedded thermistors.

Calibration of the calorimeter consisted in observing the temperature rise due to a measured quantity of electric energy dissipated in the same cylinder. The results are given for five calibration runs, each using about 70 microwatts of power for approximately 20 minutes. The probable error of the mean was about ±1 percent. Separate reports of measurements of X-ray-beam powers at 1.4 and 36 million electron volts are in preparation.

1. Introduction

The interpretation of physical and medical experiments with high-energy X-rays has been greatly hampered by the uncertainties in the measurement of X-ray-beam power. The conventional method of determining beam power has been to measure the ionization current in the gas of an ionization chamber placed in the X-ray beam. To calculate the relationship between the beam power and the ionization current, one must make various assumptions concerning the spectrum of the incident photons, the production of electrons and positrons by the photons in the chamber walls, the values of the stopping power for these electrons in the wall and the gas, and the energy required for an electron or positron to produce an ion pair in the gas of the ionization chamber. Because these assumptions and quantities are difficult to evaluate, the calculated response of an ionization chamber to X-rays may contain unknown errors of the order of 5 to 10 percent.

In order to avoid these uncertainties, apparatus was constructed at the National Bureau of Standards for measuring the X-ray-beam power calorimetrically. Such measurements were made by comparing the temperature rise of a lead cylinder irradiated by the X-ray beam with the temperature rise of the same cylinder heated by a measured quantity of electric energy. After making suitable corrections for the small proportion of X-ray energy that was not absorbed, an electrical equivalent of X-ray energy could be obtained.

The first published measurements of this type were made by Laughlin et al. [1].[2] His later publication [2] described an improved calorimeter used to measure beam power from a 22.5-Mev betatron and a 400-kev [3] X-ray unit. Laughlin's calorimeter consisted of twin lead cylinders, one of which was irradiated. The resulting temperature difference between the two cylinders was used to determine the total energy absorbed.

Calorimetric measurements of X-ray-beam power were also made by Edwards and Kerst [3] for X-ray peak energies ranging between 150 and 300 Mev. Their calorimeter was similar to Laughlin's in design, but, due to the higher energy X-rays, more consideration had to be given to the power escaping from the cylinders.

One of the projects of the Betatron Section at the National Bureau of Standards was to develop an instrument to measure the power in X-ray beams with peak energies between 1 and 180 Mev. This report describes the construction and operation of a calorimeter designed for this purpose. X-ray-beam power measurements at 1.4 and 36 Mev with this calorimeter have been made, and the results are now being prepared.

2. General Method of Operation of the Calorimeter

The calorimeter consisted, essentially, of two similar lead cylinders, thermally insulated from their surroundings and from each other. The X-ray beam, emerging from an aperture in the shielding wall around the X-ray source, was directed axially into the end of one of the lead cylinders. The X-ray energy absorbed in the cylinder was converted into heat energy, resulting in a rise in temperature of the lead cylinder. The temperature-sensing elements were thermistors embedded in the two cylinders and connected in a Wheatstone-bridge circuit. Thermistors have a large negative temperature coefficient of resistance, thus providing high sensitivity to small temperature changes in the cylinders. Absolute

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[2] Figures in brackets indicate the literature references at the end of this paper.

[3] Mev and kev are energy units referring to "million electron volts" and "thousand electron volts", respectively.

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calibrations were made by determining the temperature rise when a measured quantity of electric energy was dissipated in a resistor embedded in the cylinder.

3. Construction of the Calorimeter

Figure 1 shows the vacuum chamber containing the two lead cylinders. The cylinders appearing in the background are reflections in the chrome lining of the chamber. The vacuum chamber was supported in a temperature-regulated water bath. Figure 2 is a schematic front view showing the position of the vacuum chamber in the water bath. A detailed description of the various components follows.

3.1. Cylinders

The absorbing cylinders were made of lead because the absorption per unit heat capacity for high-energy X-rays is greater for a material of high atomic number than for one of low atomic number. The cylinders were 7.5 cm long and 4 cm in diameter. Figures 1 and 2 show their location in the evacuated chamber. The surface of each cylinder was gold plated to limit radiation losses, and the cylinders were suspended by nylon threads to limit conduction losses. The cylinders were cut in planes through their axes to simplify the insertion of the thermistors and calibrating resistors. Figure 3 shows one of the cylinders partly opened. The end of the cylinder that received the irradiation was called the front surface. When X-rays are absorbed by lead the maximum density of energy dissipation is at a position a few millimeters behind the front surface. This position depends upon the energy of the incident X-rays. The resistors for calibrating were, therefore, placed near the front surface. The position of these resistors was not critical because the heat from them was transmitted throughout the lead cylinder in a time that was short compared with the irradiation time. The resistors were located near the end of the cylinder in order to be out of the X-ray beam where they would not affect the absorption of the X-rays by the lead. One resistor was located in each half of the cylinder. Commercial 1,000-ohm ½-w carbon resistors were used. The resistors were coated with a liquid cement, placed in a groove in the lead, and surrounded with Wood's metal. The cement provided electrical insulation, and the Wood's metal filled the air gaps, thus providing better thermal contact.

The thermistors were located near the back surface and near the edge of the cylinder, so that they also were not in the primary X-ray beam. One thermistor was located in each half of the cylinder. They were embedded in the lead in the same manner as the resistors.

Number 43 enameled copper wire was used to connect the thermistors and the calibrating resistors to the outside. The wires were about 10 cm long, and small enough to limit conduction losses to a low value, yet large enough that their resistances were small compared with those of the thermistors and calibrating resistors.

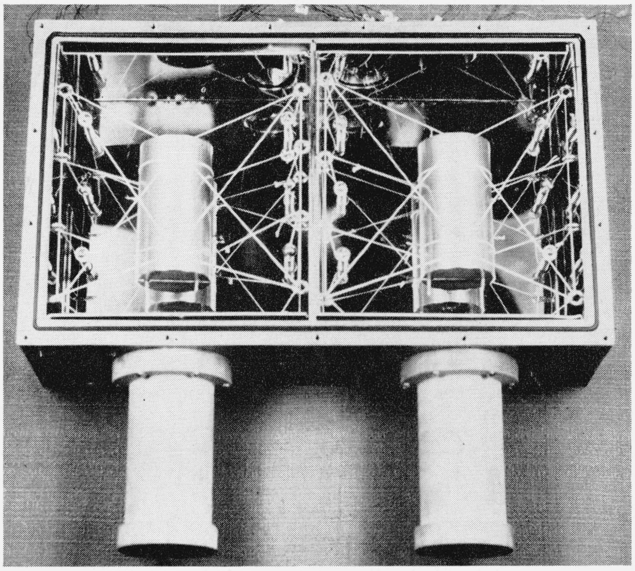


FIGURE 1. *Top view of the twin lead-cylinder calorimeter for measuring X-ray-beam power.*

The lead cylinders in the background are reflections in the chromium-plated surface.

3.2. Vacuum Chamber

The lead cylinders were suspended inside a brass vacuum chamber by means of 16 nylon threads. The chamber had ½-in.-thick walls and ¼-in.-thick bottom and top plates. Its inside dimensions were 6 by 11 in. and 2½ in. high. The inside surface was lined with $\frac{1}{32}$-in. plates, the surface of each of which had been chromium plated to limit thermal radiation effects on the cylinders. A chromium-plated metal partition separated the two cylinders. The chamber was evacuated to a pressure of about 10^{-5} mm Hg by means of an oil-diffusion pump and a mechanical forepump. A 1½-in.-diam hole was located just in front of each cylinder to permit the X-ray beam to enter without penetrating the ½-in. wall of brass. These holes were sealed with 0.003-in. brass foil as its absorption for high-energy X-rays is negligible. The electric connections were made through a glass-to-metal seal containing eight small metal tubes. The wires were threaded through but insulated from the tubes and then sealed with a liquid cement.

3.3. Water Bath

As shown in figure 2, the vacuum chamber was immersed in a temperature-controlled water bath. The water container, 15 by 21 by 12 in. high, was made of Bakelite reinforced with angle iron to prevent warping due to water absorption. There was at least 3 in. of water on all sides of the vacuum chamber. Two stirrers, placed diagonally opposite one another, circulated the water. The stirrers were geared to synchronous motors in order to help maintain a constant temperature distribution throughout the water bath. Air-filled Bakelite tubes extended through the water bath in front of the entrance ports of the vacuum chamber in order to

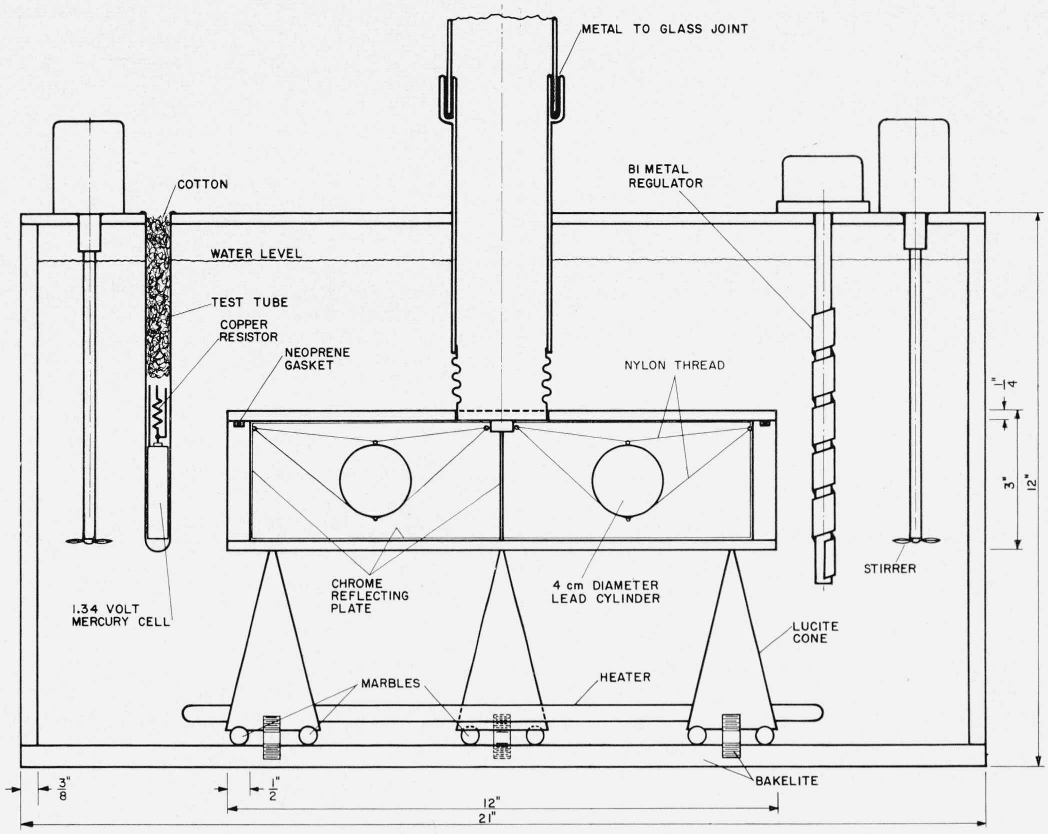


FIGURE 2. *Schematic diagram of a vertical cross section of the calorimeter with the associated water bath and equipment.*

keep the water from absorbing energy from the X-ray beam. A 0.001-in. aluminum foil was placed at the external end of the tubes to limit exchange of heat either by convection of air or by radiation to the inner foil.

The vacuum chamber was supported inside the water bath on the points of three Lucite cones, each of which rested on three marbles. The vacuum connection to the top of the chamber consisted of a 2-in.-diam glass tube on top of a metal sylphon soldered to the vacuum chamber. The purpose of this construction was to provide high insulation between the chamber and the outside, and to provide good thermal contact between the chamber and the water bath, so that outside temperature fluctuations would have as small an effect as possible on the temperature of the vacuum chamber.

The temperature of the water bath was regulated by means of an immersed helical bimetallic strip with an electric contact at one end. The electric current through the contact actuated an electric relay that controlled the "on" and "off" time of the electric heater at the bottom of the water bath. Thermal regulation under optimum conditions was estimated to be ± 0.005 deg C. The heater was operated at 24 w and maintained the temperature at 33.4° C.

It was found necessary to surround the Bakelite box with a larger plywood box to prevent temperature fluctuations due to convection currents in the room. The temperature of the air in the plywood box was controlled by a thermostat to within ± 0.3 deg C of 32.4° C.

The entire calorimeter was mounted on an adjustable hydraulic lift table for convenience in lining up the calorimeter with the beam from the X-ray source.

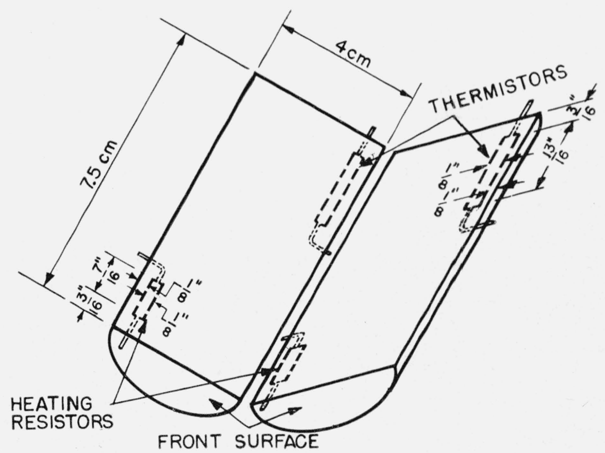


FIGURE 3. *Schematic diagram of one of the lead cylinders split in the plane along its axis to show the location of the thermistors and the heating resistors used for calibration.*
The X-ray beam was incident axially on the front surface.

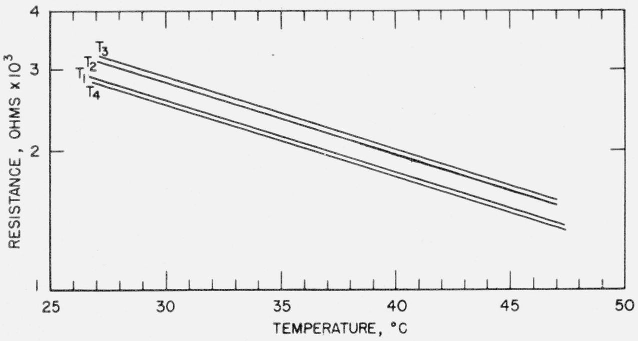


FIGURE 4. *Resistance of thermistors used in the calorimeter as a function of temperature.*

The temperature coefficient of resistance was −0.0363 for all four thermistors.

4. Characteristics of the Thermistors

The temperature-sensing elements in the lead cylinders were Veco 33S1 thermistors, about ⅛ in. in diam by 13/16 in. long. They were made of a mixture of the oxides of cobalt, manganese, and nickel. Figure 4 shows a plot of their resistance versus temperature over the range of about 30° to 45° C. Over this range the logarithm of the resistance is approximately a linear function of the temperature. Over a large range the resistance, R, at Kelvin temperature T, can be expressed as

$$R = R_0 e^{B(1/T - 1/T_0)},$$

where R_0 is the resistance at temperature T_0 (304° K), and B is a constant of the material. Table 1 shows the characteristics of the four thermistors used.

TABLE 1. *Thermistor characteristics*

Thermistor	R_0	B
	Ohms	° *K*
1	2,479	3,355
2	2,719	3,359
3	2,776	3,362
4	2,420	3,353

5. Wheatstone-Bridge Circuit

Two thermistors were embedded in each lead cylinder and connected in a Wheatstone bridge, as shown in figure 5. The 24-ohm copper resistor compensated for the adjustable resistance of the resistance box and provided an adequate range. A mercury cell supplying 1.34 v was used because of its stable output voltage with time. A variation in the cell voltage would affect the currents in the thermistors. These currents affect the temperatures of the thermistors, which in turn affect their resistances, resulting in a possible unbalance of the Wheatstone bridge. This effect was small because of the similarity of the thermistors, the symmetry of the bridge, and the magnitude of the bridge current used. The compensating copper resistor

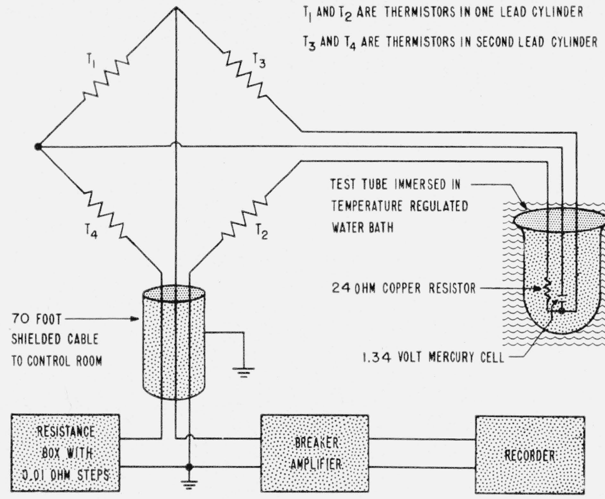
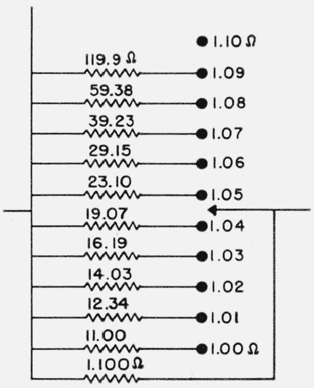


FIGURE 5. *Wheatstone-bridge-circuit diagram showing location of electric components.*

FIGURE 6. *Arrangement of resistors to give 0.01-ohm steps in resistance box and to reduce variations at the output of the bridge circuit due to contact resistances and emf's originating in the switch.*



and the mercury cell were located in a glass tube immersed in the water bath. The tube was stuffed with cotton to inhibit temperature variations due to convection from above. A 0.01 deg C change in temperature of the 24-ohm copper resistor could create the same bridge unbalance as a 5×10^{-6} deg C change in the thermistors in one of the lead cylinders.

The resistance box was a six-decade box with steps of 0.01 ohm. Because of unpredictable variations in contact resistances and emf's originating in the switch, the decade was modified as shown in figure 6, involving a variation of several methods described by Mueller and Wenner [4]. As the contact was moved from one end of the decade to the other, the total resistance changed from 1.00 to 1.10 ohms. Because the variable contact resistance was always in series with a relatively large resistor, it contributed less variation to the over-all resistance.

The four thermistors, selected from a group of 12, had the most similar characteristics. This was desirable in order to reduce drifts and fluctuations at the output of the Wheatstone bridge produced by ambient temperature fluctuations and changes in bridge working currents that affected the temperature and hence the resistance of the thermistors.

For the small temperature changes occurring in these experiments, the first two terms of an expansion of the exponential formula were sufficient, so that R could be expressed as

$$R=R_0[1-(B\{T-T_0\})/(T_0^2)],$$

and the resistance could be assumed to be a linear function of the temperature. The temperature coefficient of resistance was $-0.0363/°$ C for the four thermistors used. As the temperature rise during any set of runs did not exceed 0.01 deg C, the error introduced by assuming linearity and neglecting the next term in the expansion was less than 1 part in 10 million.

Because of the small voltages detected in the Wheatstone bridge (order of microvolts), it is necessary to take every possible precaution to avoid variable voltages due to thermoelectric effects when conductors of different materials are used. Copper connecting wire was used throughout, and a special solder with small thermal electromotive force with respect to copper was used to minimize thermoelectric effects. Difficulty was originally observed with the use of solid metal leads through the glass seal to the vacuum. Although copper wires were attached to both ends, the variable thermal electromotive forces due to temperature differences between the inside and outside of the vacuum chamber were too great to work with. For this reason metal tubes were substituted, and the copper connecting wires were run through the axes and insulated from the metal to form a circuit of copper alone.

About 0.26 ma of current flowing through each arm of the Wheatstone bridge supplied about 0.35 mw of power continuously to each lead cylinder. This caused the equilibrium temperature of the cylinders to be of the order of 0.03 deg C above the surrounding temperature. As long as this temperature difference was constant and all heat losses were approximately linear functions of the temperature difference, this effect could be disregarded.

The detector employed in the bridge circuit was a d-c breaker amplifier. Its input impedance was 1,000 ohms. In the breaker amplifier the d-c input voltage was converted to an 8-cps signal by a mechanical breaker contact. The amplifier, tuned to 8 cps, amplified the signal, which was then converted back to direct current by a second breaker synchronous with the first. In this way the background noise was kept low. The observed noise level (maximum fluctuations peak to peak) corresponded to about 0.1-μv input, and the voltage gain was of the order of 500,000.

The temperature data were taken by either of the following methods: (1) The output of the amplifier was connected to a recording milliammeter. The amplifier and recorder were used as a null detector, so that variations in gain in the amplifier were not of primary importance. As the thermistors changed resistance due to a temperature change of the lead cylinder, the resistance box was adjusted, as required, to bring the bridge back into balance. The required balancing resistance was then plotted against time to provide the data. (2) The second method consisted in connecting the output of the amplifier to a recording d-c potentiometer (0 to 30 mv) with an 11-in.-wide chart and recording the unbalance of the Wheatstone bridge without changing the balancing resistor. Although this system eliminated the transient voltages caused by switching the balancing resistor, it had the disadvantage of depending upon the constancy of the amplifier gain. Periodic checks were made of the amplifier gain by adding a 1-μv signal to the input and observing the deflection; yet no evidence of a change in gain was observed.

6. Operating Characteristics

The smallest short-time signal detectable was limited by the noise level of the output signal. This noise had an over-all amplitude of about 0.0008-ohm equivalent, and corresponded to about 5×10^{-6} °C.

The smallest sustained input power detectable was limited by the long-time drifts in the balance point of the bridge. These could have been due to drifts in the thermistor resistance, drifts in the battery voltage, or changes in the water-bath temperature that affected the bridge output due to asymmetry of the bridge. The observed drift during good operation was less than 0.005 ohm/hr, and corresponded to approximately 3×10^{-5} °C/hr. The temperature rise due to the 100-μw input power in one cylinder was approximately 2×10^{-3} °C/hr and could readily be observed and measured.

7. Heat Losses

It was desirable to keep the heat losses small for several reasons: (1) it put less stringent requirements on the constancy of the water-bath temperature and led to a greater stability of the bridge balance, (2) a larger over-all temperature rise could be accumulated if the time constant were longer, and (3) linear approximations for heat-loss calculations could be used. The associated disadvantage was the long time required for the calorimeter to attain thermal equilibrium. The cooling time constant was determined from data taken of the required balancing resistance versus time before and after the cylinder was heated with 14.03 mw for 10 min. The data are shown in figure 7. Assuming Newton's law of cooling and linearity between R and T, the cooling constant K was determined in the following manner:

$$dR/dt=-K(R-R_e)$$

$$K=-(dR_i/dt-dR_n/dt)/(R_i-R_n),$$

where dR_i/dt and dR_n/dt are the slopes at R_i and R_n, respectively, and R_e is the equilibrium resistance that the exponential curve was approaching. K was determined at five points on the decay curve and found to average about 0.00548 $\pm$0.00002 min^{-1}, when the bath temperature was 33.4° C. This corresponded to about a 3-hr time constant. As is shown below, most of the heat losses were due to radiation. Therefore, this decay constant should

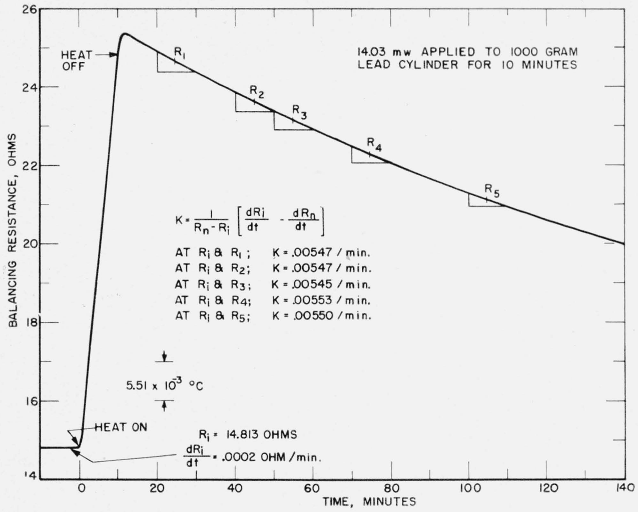


FIGURE 7. *Data from which the cooling constant was calculated.*

vary directly as the cube of the absolute temperature of the water bath. Four measurements of the decay constant over a temperature range of 5 deg agreed with the cube-law dependence on the absolute temperature.

The heat capacity of each cylinder was calculated from its dimensions and material to be about 136 j/°C. The heat loss per unit time per degree temperature difference between the cylinder and its surroundings is equal to the product of the cooling constant, K, and the heat capacity. Using these values, one obtains 12.8 mw/°C as the rate of heat loss by the cylinder to its surroundings. This heat loss is believed to be due, primarily, to radiation. Because of the roughness of the gold surface on the cylinders, the emissivity was not known, but must be considerably larger than 0.02, which is the emissivity for a polished gold surface.

The rate of heat loss per degree Celsius due to conduction was calculated and found to be small compared with the observed rate of heat loss. The loss due to conduction along the wires was 0.065 mw/°C, which is only about 0.5 percent of the observed value.

The rate of heat loss per degree Celsius by conduction through the air was 0.017 mw/°C, which is only about 0.1 percent of the observed value. The pressure used in this calculation was 10^{-5}mm Hg, as measured with an ion gage.

Assuming the entire observed rate of heat loss is due to radiation, the effective emissivity of the lead cylinder in the vacuum chamber can be calculated from the formula

$$dQ/dt = cAe_{eff}(T^4 - T_0^4)$$

where c is the Stefan-Boltzmann constant [5.673×10^{-12} w/cm^2 per (deg K)^4], A is the surface area of the cylinder (120 cm^2), e_{eff} is the effective emissivity of the cylinder in the vacuum chamber, and T and T_0 are the absolute temperatures of the cylinder and surroundings, respectively. Assuming $(T-T_0)\ll T_0$ and solving for e_{eff}, one obtains

$$e_{eff} = \frac{1}{4cAT_0^3(T-T_0)}\times\frac{dQ}{dt}$$

Substituting the measured value of 12.8 mw/°C for $(1/\{T-T_0\}\times dQ/dt)$, 303° K for T_0. and the above values for c and A, one obtains a value of 0.17 for the effective emissivity. This is a reasonable value, considering the matted appearance of the gold surface of the lead cylinder. It also indicates that a considerable improvement is possible if the gold surface were highly polished.

8. Calibration

The method used for calibrating the calorimeter was to supply a measured quantity of electric energy to the resistors embedded in the lead cylinder and to determine the resulting rise in temperature of the cylinder. The rate of heating and total temperature rise were chosen so as to duplicate as nearly as possible the conditions during the measurement of the X-ray-beam energy. This procedure partially eliminates some of the systematic errors in the calorimetric measurements. A potentiometer with an accuracy of about 0.1 percent was used to measure the voltage across the heating resistor, and a model 622 Weston d-c milliammeter with an accuracy of 0.5 percent of full-scale deflection was used to measure the current. The measurements involved about half-scale deflections, so the accuracy of the current reading was about 1 percent.

Figure 8 is a freehand sketch showing the output voltage of the Wheatstone bridge when method 1, described in section 5, was used. The vertical breaks represent manual changes of the resistance box of 0.01 ohm. The values between breaks indicate the

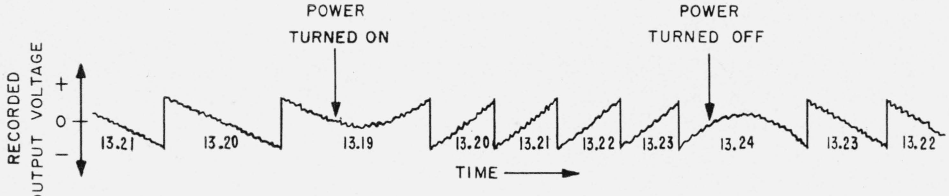


FIGURE 8. *Sketch showing a way of recording data by using method 1, described in section 5.*
The vertical breaks were caused by manual changes in the resistance box of 0.01 ohm. The resistance values are shown between breaks.

resistance of the box at that time. A change in slope of the output versus time in figure 8 follows any change in the power being applied to the cylinder.

The resistance required for exact balance could be determined at any instant by interpolation. This resistance was calculated at the instant before each vertical break in order to minimize the effect of transients that sometimes appeared after a change of resistance. Figure 9 shows a plot of the calculated balancing resistance as a function of time for a 1,400-kev X-ray run. Straight lines were drawn to represent the average data and to simplify the analysis. Linearity between the balancing resistance and temperature was assumed, and the observed temperature rise was calculated to be 4.0×10^{-4} °C.

Figure 10 is a graph of a calibration run, using method 2 described in section 5; 122.6 μw of power was applied for 12 min. Linearity between the bridge unbalance and the temperature was assumed, and the observed temperature rise during the heating period in this example was calculated to be 5.47×10^{-4} °C.

In figures 9 and 10 there is apparent an approximately 45-sec time lag between the application of heat to the cylinder and the detected temperature rise. This time lag was caused by a combination of two phenomena: (1) the time required for diffusion of heat through the lead (most of the heat energy was supplied near the front surface, whereas the thermistors were located near the back surface), and (2) the thermal time constant of the thermistor determined by its heat capacity and its insulation from the surrounding lead. The correction of the observed temperature rise for heat loss was made on the basis of Newton's law of cooling, using the observed curve of temperature as a function of time. This procedure makes the assumption that the average temperature throughout the cylinder is equal to the surface temperature, and that the time lag in the observed temperature is constant. It is recognized that these assumptions may not be strictly true when comparing the heating portion of the curve with the initial- and final-cooling portions. However, it is believed that the error arising from this assumption is small in comparison with the estimated over-all error, and will partially cancel out when comparing X-ray energy with electric energy.

The total energy absorbed by the lead cylinder can be expressed as a sum of two terms, one involving the observed temperature rise and the other involving the energy lost to the surroundings as a result of the temperature difference. The heat lost to the surroundings was calculated from the average of the observed cooling slopes before and after the heating period. Table 2 summarizes the results of five calibration runs over a period of 2 days, using method 1. The heat loss was computed for each run, so it was not necessary to wait each time for complete temperature equilibrium to be attained. It is seen that at times the heat lost through radiation was just about as large as the heat corresponding to the net temperature rise. The average calibration factor of this calorimeter was 80.5×10^{-6} ohm/μw-min, with an rms error of 1.0×10^{-6}.

TABLE 2. *Electrical calibration of calorimenter*

Resistance change corresponding to temperature rise	Resistance change corresponding to heat loss	Resistance change corresponding to total energy	Input power	Heating period	Calibration factor [1]
Ohm	*Ohm*	*Ohm*	*μw*	*min*	*Ohm/μw-min*
0.058	0.052	0.110	70.6	20	77.6×10^{-6}
.114	.008	.122	69.9	21	83.2
.095	.028	.123	70.5	22	79.4
.080	.033	.113	70.5	20	80.3
.080	.036	.116	70.7	20	81.9

[1] Average $=80.5\times10^{-6}\pm1.0\times10^{-6}$ ohm/μw-min.

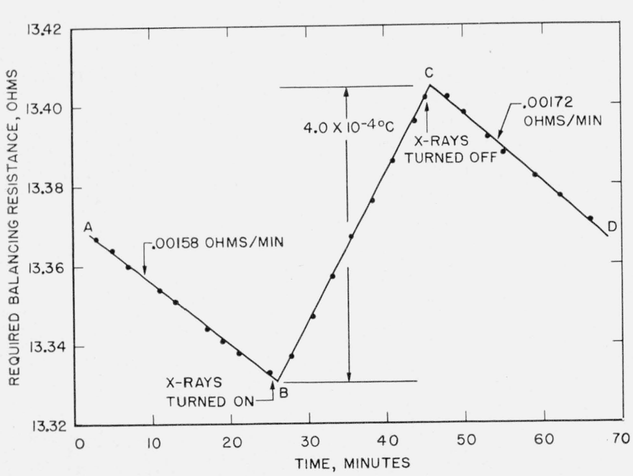


FIGURE 9. *Data calculated from recordings such as in figure 8.*
Straight lines were drawn through the points for aid in calculating the total relative heat absorbed.

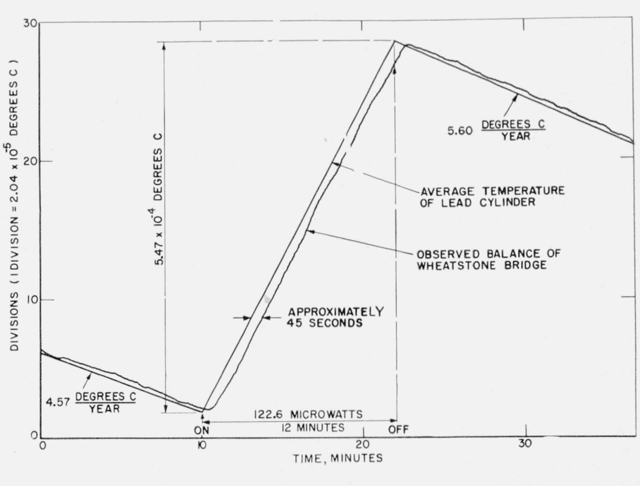


FIGURE 10. *Signal from Wheatstone bridge during a typical heat run when method 2, described in section 5, is used.*

9. Considerations in Measuring X-ray-Beam Power

The described calorimeter was designed for measuring X-ray beams in the range 1 to 180 Mev. The total beam power will be the sum of the power absorbed by the lead cylinder plus that which escapes by transmission, scattering, or by other means. As the escaping energy must be measured by auxiliary experiments, using ionization chambers or scintillation detectors (the very methods whose uncertainties make the calorimeter necessary), it is desirable to select X-ray-beam and lead-cylinder dimensions that limit the escaping energy to less than 10 percent. If an effort is made to reduce the escaping energy further by increasing the dimensions of the lead cylinder, the heat capacity would be increased, and thus the sensitivity would be decreased. To obtain maximum accuracy and sensitivity, a specific size and shape of lead cylinder should be chosen for each application, depending upon the beam power available and the X-ray energy of the source.

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[4] Fulbright Fellow from the University Fuad I, Cairo, Egypt. Deceased.

10. References

[1] J. S. Laughlin and J. W. Beattie, Calorimetric determination of energy flux of 22.5 Mev X-rays, Rev. Sci. Instr. **22,** 572 (1951).

[2] J. S. Laughlin, J. W. Beattie, W. J. Henderson, and R. A. Harvey, Calorimetric evaluation of the roentgen for 400 kv and 22.5 Mev roentgen rays, Am. J. Roentgenol. Radium Therapy Nuclear Med. **70,** No. 2 (1953).

[3] P. D. Edwards and D. W. Kerst, Determination of photon flux for energies between 150 Mev and 300 Mev, Rev. Sci. Instr. **24,** 490 (1952).

[4] E. F. Mueller and F. Wenner, The Waidner-Wolff and other adjustable electrical-resistance elements, J. Research NBS, **15,** 477 (1935) RP 842.

WASHINGTON, June 1, 1955.