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Direct Comparisons of the NBS Absorbed Dose Calorimeters Irradiated with 20 and 50 MeV Electrons

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ABSTRACT

Two NBS absorbed dose calorimeters were compared in 20 and 50 MeV electron beams that were scattered with lead foils of various thickness. The internal structures of the calorimeters are identical. The non-portable model is enclosed in a 40 cm x 40 cm x 30 cm thick graphite medium while a 30 cm diameter x 15 cm thick graphite medium was used to enclose the portable model. Measured results indicate that the three internal bodies of the calorimeters and their measuring circuits were constructed with sufficient care to produce essentially identical calorimetric responses to about 0.1%.

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Steve R. Domen†, Tomohisa Mikado*, and Paul J. Lamperti†

I. Introduction

Two graphite calorimeters [1], one non-portable and one portable, were constructed at the NBS for use as standards for the measurement of absorbed dose produced by radiation beams. Calorimeters provide the most direct and fundamental means for measuring absorbed dose, that is, measurement of a heating effect produced in a small volume element of known mass. Therefore, they are the most accurate devices for measurement of absorbed dose, particularly when it is produced as a result of a complex and unknown radiation spectrum at the position of measurement. The absolute accuracy of these instruments is a primary concern. In general, it would appear possible to achieve good accuracy by careful design and construction. However, there would always be a possibility of some unknown constructional defects contributing to significant and measureable systematic errors. Therefore, a calorimeter cannot be considered a trustworthy standard until it has been compared directly or indirectly with at least one other instrument or method of measuring absorbed dose. Direct comparisons of calorimeters of different design and measurement procedure would provide a critical and valuable test of these instruments.

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Direct intercomparison of the NBS calorimeters with others has not been achieved. However, they have been compared indirectly with other calorimeters using ionization chambers as intermediary instruments and with theoretical calculations. Measurements of the quotient of absorbed dose to specific charge in air were made with the non-portable calorimeter. The results are in agreement (to within the limits of the uncertainties) with the experimental and theoretical results of other investigators [2-4]. The portable calorimeter was used to measure the absorbed dose in a graphite phantom and these results correspond well with the absorbed dose calculated from exposure measurements made with a cavity ionization chamber [5]. The portable calorimeter was also used to measure the product of the average energy expended per ion pair (in air) and the ratio of the average mass stopping power for carbon to that for air. A preliminary analysis shows that the results are in agreement, to within the limits of the uncertainties, with the results of other investigators [6].

Although the above results indicate that the NBS calorimeters are accurate, there is merit for a direct intercomparison of the calorimeters even though their operational and internal structures are identical. Their direct comparison would, therefore, be a sensitive test to determine if some unknown differences in constructional details are large enough to produce significant differences in their responses. This report describes high precision measurements which indicate that their responses are identical to about 0.1%.

II. Experimental Procedure

Figures 1 and 2 show the experimental setup which is the same as that described in reference 2 (except for the portable calorimeter). An aluminum vacuum window (not shown in fig. 1), a lead foil scatterer, and air all scatter an electron beam which is monitored by two offset ionization chambers that remained at a fixed position. The uncollimated beam passed through one of ten graphite absorbers mounted on a large wheel, and then through one of three detectors whose central planes were in a common plane indicated by A. The distance from the scatterer to plane A remained at a fixed distance of 190 cm. The three detectors were a parallel plate ionization chamber (PP), the non-portable calorimeter (NPC), and the portable calorimeter (PC). Details of the detectors and their alignment are shown in fig. 2. The detectors were mounted on a table that was moveable perpendicular to the beam so that the axis of each detector could be made to coincide with the beam axis. All motions were remotely controlled. The lead barriers, (a) and (b), remained at a fixed position.

In order to minimize the small effects of possible beam instabilities on the precision of the measurements, the ion chamber and the two calorimeters were moved into the beam in rapid succession. A set of measurements began with a comparison of the parallel-plate ionization chamber to the monitor response (PP/M), while heating of the two calorimeters by scattered radiation was avoided by shielding them with the lead barriers (a) and (b). Immediately following the ionization chamber measurements, the non-portable calorimeter was placed on the beam axis. A measurement of this calorimeter response to the monitor (NPC/M) was made. As soon as this was completed, the portable calorimeter was moved from behind lead barrier (a) and was placed on the beam axis for a measurement of its response to that of the monitor (PC/M). To complete the series, another measurement of the ion chamber response to that of the monitor (PP/M) was made. In the meantime (as soon as the PC/M measurement was completed), a small amount of air, at a pressure of < 0.13 kPa (< 1 mm Hg), was injected into the common vacuum system of both calorimeters so that temperature recycling could take place during the final series of PP/M measurements. The difference between the PP/M ratios before and after the calorimeter runs was of the order of a few tenths of a percent, indicating good beam stability during the important short interval of time between the two calorimeter comparisons. The time between the two sets of PP/M ratios was about 20 minutes.

A Wheatstone bridge circuit was used to determine the response of each calorimeter, expressed as a fractional resistance change ($\Delta R/R$) of a balancing arm which is the same as the fractional resistance change of a thermistor embedded in a calorimetric core. The ratio of the fractional resistance change per unit monitor response of the NPC to that of the PC is:

$$\frac{\left(\frac{\Delta R}{R} / M\right)_{NPC}}{\left(\frac{\Delta R}{R} / M\right)_{PC}} \quad . \tag{1}$$

This ratio will indicate a difference from unity if the sensitivities of the embedded thermistors are different. To cancel out the effect of any difference in their sensitivities, the radiation runs must be related to electrical calibration runs so that the response of each calorimeter can be expressed in terms of absorbed dose per unit monitor response. Hence, the proper expression (X) to be used in comparing the response of the non-portable calorimeter to that of the portable calorimeter is:

$$X = \left[\frac{(E/m)_{NPC} \cdot (\Delta R/R)^{-1}_{NPC}}{(E/m)_{PC} \cdot (\Delta R/R)^{-1}_{PC}}\right]_{calibration} \cdot \left[\frac{\left(\frac{\Delta R}{R} / M\right)_{NPC}}{\left(\frac{\Delta R}{R} / M\right)_{PC}}\right]_{irradiation}, \qquad (2)$$

where the first expression is derived from electrical calibration runs in which $(E/m)_{NPC}$ is the electrical energy divided by the known mass of the core in the non-portable calorimeter, and $(E/m)_{PC}$ is the electrical energy divided by the known mass of the core in the portable calorimeter. An inspection of the above expression shows that differences in thermistor sensitivities are cancelled.

III. Graphite Media Enclosing Detectors

The parallel plate ionization chamber and non-portable calorimeter were enclosed by graphite media of identical dimensions, 40 cm x 40 cm x 30 cm thick. These differed from the graphite medium enclosing the portable calorimeter which was 30 cm in diameter and 15 cm thick.

Indications are that the difference in thickness of the surrounding media produced a negligible effect (< 0.01%). This conclusion was derived from comparisons of depth dose measurements in graphite irradiated with electrons and cobalt-60 gamma rays. To illustrate, refer to fig. 3 which shows two normalized dose curves. The curve for 20 MeV initial energy electrons was determined with the setup shown in fig. 1. The parallel plate ionization chamber remained at a fixed distance of 190 cm while graphite absorbers of various thicknesses were positioned in the beam in front of the chamber. The curve for cobalt-60 was also determined with the detector at a fixed distance (1 m) from the source while absorbers of various thicknesses were positioned in the beam in front of the detector embedded in the 30 cm diameter medium. The detectors for the cobalt-60 dose measurements were the same parallel plate ionization chamber as used in the electron beam measurements and a small spherical graphite ionization chamber. Both chambers produced the same normalized dose results. The position A' in fig. 3 is at 1.5 g/cm^2, the minimum thickness in front of the spherical ionization chamber for the cobalt-60 measurements. Position A indicates the depth of the detectors during the 20 MeV electron beam measurements. The position B (in figs. 1 and 3) corresponds to the back surface plane of the portable calorimeter (at a depth of 17.3 g/cm^2) where the cobalt-60 dose rate fell to 60% from the peak near the surface. The cobalt-60 measurements showed that when an additional thickness of graphite (BC, 4.3 g/cm^2) was placed against the back surface (plane B), the response of the ionization chamber at A' (which corresponds to the response of the calorimetric core at A') increased about 0.1%. An additional increase of the same thickness (CD) showed no further change. Hence, a comparison of the two dose curves show that an increase in thickness beyond that depth during the 20 MeV electron beam measurements would show much less of a back-scattering effect. Position B is beyond the range of the 20 MeV electron (11.3 g/cm^2) and into the bremsstrahlung tail where the dose rate was found to be 1.8% of the peak, lower by a factor of 30 from the dose rate produced by cobalt-60 at position B. Therefore, during the 20 MeV runs, an increase of plate thicknesses against the rear surface (B) of the calorimeter would have increased the response of the detector at A by approximately 1/30 of 0.1% or < 0.01%. The effect would have been even further attenuated since the back surface of the medium was at D, a depth of 26.8 g/cm^2 for the 20 MeV measurements. At 50 MeV, the rear surface was at D', a depth of 31.3 g/cm^2, beyond the electron range of 28.3 g/cm^2.

The differences in the lateral dimensions of the media appear to be of greater concern than the differences of thickness described above. An estimate of their relative importance can be obtained by considering the dose rates at the boundaries of the medium (enclosing the portable calorimeter) compared to the dose rates at the calorimeter core. The radius and thickness of the graphite medium enclosing the portable calorimeter are both 15 cm, and it has been shown above that the thickness of 15 cm, 25 g/cm^2, where the dose rate for 20 MeV initial electrons was less than

2% of that occurring at the core, was essentially an infinite thickness. At the radial boundary, at the distance of 15 cm from the core and in the vicinity of plane A, the minimum dose rate was estimated to be at least 50% of that at the core. This radius is still of infinite width even for 50 MeV electrons scattered at that or at any greater radii, since its distance from the core exceeds the range of those scattered electrons. However, that radius is not infinite in width for bremsstrahlung generated at radii greater than 15 cm, and at small depths into the medium. This again may be a small effect, but it must be considered. Another thing that must be taken into consideration is that bremsstrahlung production is more efficient at the higher energies than at the lower energies. Therefore, if the additional width of material around the non-portable calorimeter had any effect, it would have contributed more to the response of the calorimeter at higher beam energies than at lower beam energies. Increasing the degree of scattering in this additional material, by interposition of greater thicknesses of lead foil, will produce an increased NPC/PC response that may be detectable. These considerations led to the following bases under which the irradiation measurements were made: a 0.13 mm and a 0.38 mm Pb foil were used for scattering 20 MeV electrons, and a 0.25 mm and a 0.76 mm foil were used for scattering 50 MeV electrons, thus tripling the mean-square scattering angle at each energy. The depth at which the measurements were made were just before the peak of the dose curve, 2 g/cm^2 for 20 MeV electrons and 6 g/cm^2 for 50 MeV electrons.

IV. Results

Table I shows the results of the irradiation runs. The irradiation conditions are shown in columns 2 and 3, and the measured ratios are shown in column 5. Columns 6 lists the standard deviation, and the standard deviation of the mean, respectively, of the number of runs shown in column 4. About five runs at each irradiation condition were sufficient to produce good precision of measurement, from 0.04% to 0.25% standard deviation of the mean. This good precision of measurement was the result of a number of conditions, mainly the good stability of the linac beam, the short interval of time between the two calorimeter comparisons, a large delivered dose (∿1700 rad), and the high sensitivity of the calorimeters. Columns 7 and 8 list two small corrections. The front wall correction was determined from the depth dose curves at 20 and 50 MeV to correct for a small difference (36 mg/cm^2) in the front wall thicknesses of the two calorimeters. The detector positioning correction was a result of the central planes of each calorimetric core being slightly displaced from each other by 0.18 mm out of a scatterer to detector distance of 190 cm and applying an inverse square correction. The corrected measured ratios are listed in the last column, derived by multiplying columns 5, 7, and 8.

Table II shows the results of the electrical calibration of the calorimeters. Column 3 lists the measured values. The large number of runs shown in column 4 were made in preparation for efficient and rapid operation of the calorimeters during the irradiation measurements. The statistical fluctuations of the measurements as shown in the last two columns indicate a high degree of measurement precision. The measurement of electrical calibrating power in each calorimetric core required the measurement of two potentials: across an accurately known fixed resistor in series with the core heater, and across the heater. It can be shown that an accurate determination of expression (2) can be made without knowing the absolute accuracy of the potential measuring instruments, but depends on an accurate comparison of those instruments in measuring the same potential sources and making a correction for any difference. This was done and a small correction was applied, 0.12% ± 0.04% (standard deviation), as a result of 21 comparisons.

Table III shows the desired ratios of the calorimetric responses. The initial beam energies are listed in column 1 and the lead beam scatterers are listed in column 2. The ratios of the calorimetric responses, NPC/PC, were derived from expression (2) into which was substituted the appropriate values from tables I and II. The uncertainties were derived by combining in quadrature appropriate uncertainties listed in the first two tables while ignoring other insignificant uncertainties.

The results show that the responses of the calorimeters are essentially equal. The average of the results at 20 MeV shows no significant change when the beam scattering is increased by increasing the scatterer thickness from 0.13 mm to 0.38 mm. Those results are essentially the same (within 0.2%) as that measured with the narrower beam at 50 MeV, with the 0.25 mm scatterer. These three irradiation conditions produced average values of NPC/PC that are less than unity, which is opposite to what would be expected if bremsstrahlung production in the additional graphite material around the NPC was scattered to cause significant heating in its core. The data at 50 MeV, however, suggests that with the broader beam produced with the thicker scatterer the increase in bremsstrahlung generated in the additional graphite at radii greater than 15 cm may have contributed to that average being greater than unity (by ∿0.2%). If this last ratio is excluded, which would be proper if the additional graphite produced a significant effect, then the average of the first three differs from unity by 0.11%. That is within the experimental uncertainties shown in table III. If all four ratios are averaged, then the difference from unity is only 0.03%.

In conclusion, the results of these comparisons seem to indicate that the constructional details of the bodies of the two calorimeters, and their measuring circuits, were fabricated with sufficient care to produce essentially equal responses of those instruments.

V. Acknowledgment

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Table I. Iradiation Summary

1 Type of Measurement	2 Electron Energy MeV	3 Pb Scatterer Thickness mm	4 No. of runs	5 Measured Ratio	6 Percent Uncertainty		7 Front Wall Correction	8 Detector Positioning Correction	9 Corrected Measured Ratio
					σ	σ_M			
Ratios of Fractional Resistance Change per Monitor Response, eq. (1)	20	0.13	5	1.0051	0.55	0.25	0.9981	1.0002	1.0034
	20	0.38	5	1.0057	0.30	0.14	0.9981	1.0002	1.0040
	50	0.25	6	1.0019	0.26	0.10	0.9999	1.0002	1.0020
	50	0.76	5	1.0061	0.09	0.04	0.9999	1.0002	1.0062

Table II. Electrical Calibration Summary

Calorimeter Model	Type of Measurement	Measured Value	No. of runs	Percent Uncertainty σ	σ_M
Non-portable	Electrical energy per unit mass per fractional resistance change	21.967	48	0.20	0.03
Portable		22.060	32	0.11	0.02

Table III. Summary of Calorimeter Response Ratios

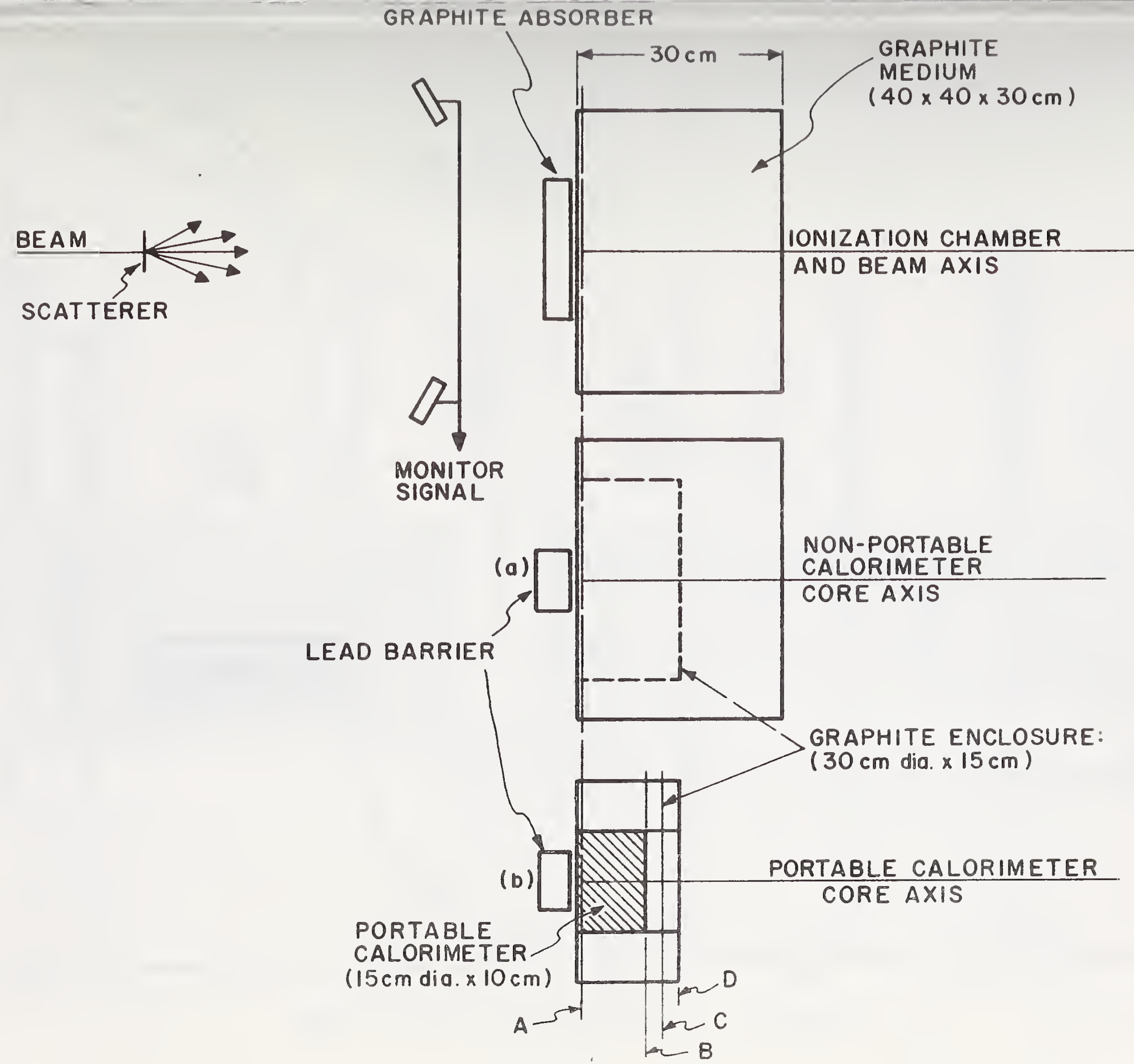
Electron Energy MeV	Pb Scatterer Thickness mm	Ratio	Difference Percent	Percent Uncertainty (combined)	
				σ	σ_M
20	0.13	0.9992	-0.08	0.60	0.25
20	0.38	0.9998	-0.02	0.38	0.14
50	0.25	0.9978	-0.22	0.35	0.11
50	0.76	1.0020	+0.20	0.25	0.05

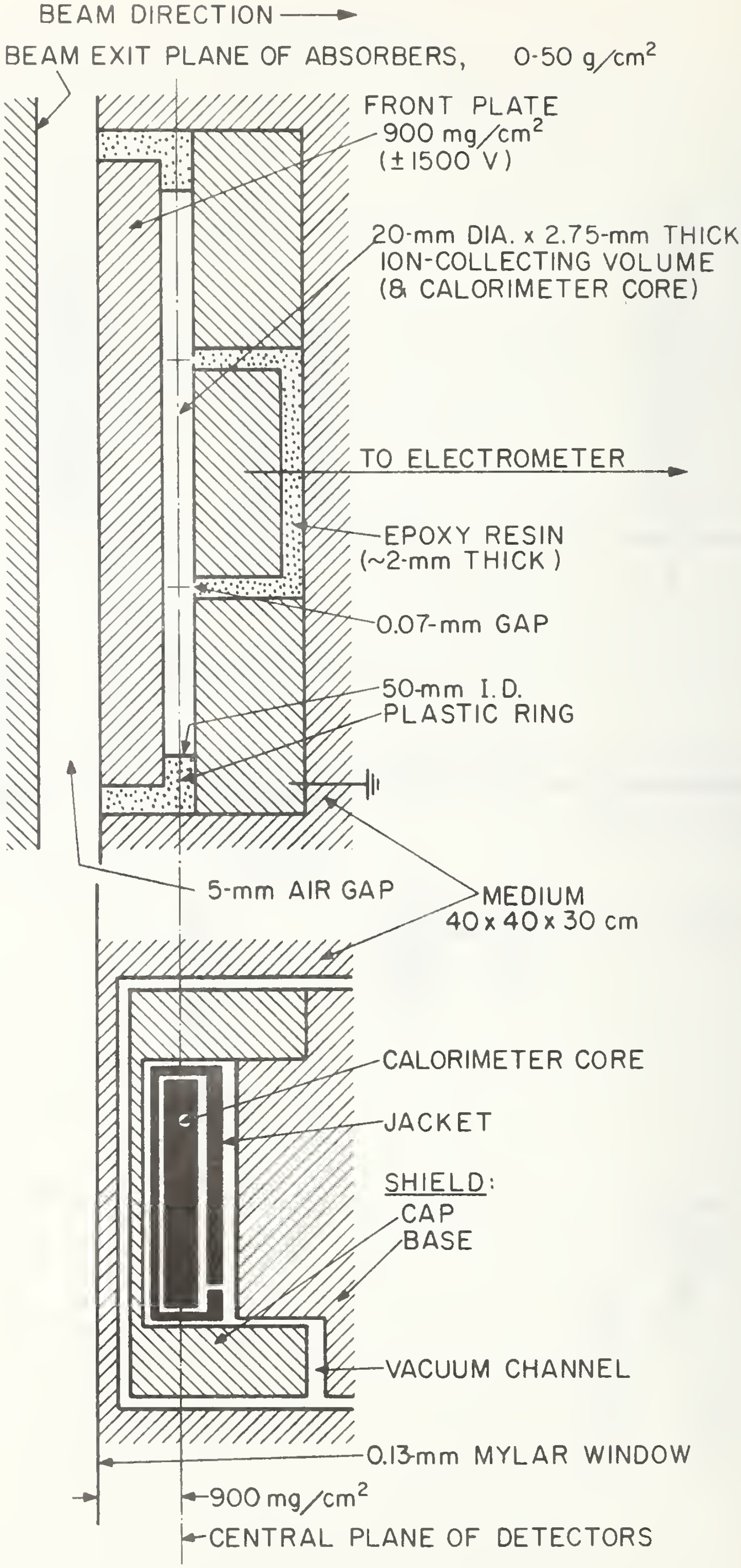
Figure Legends

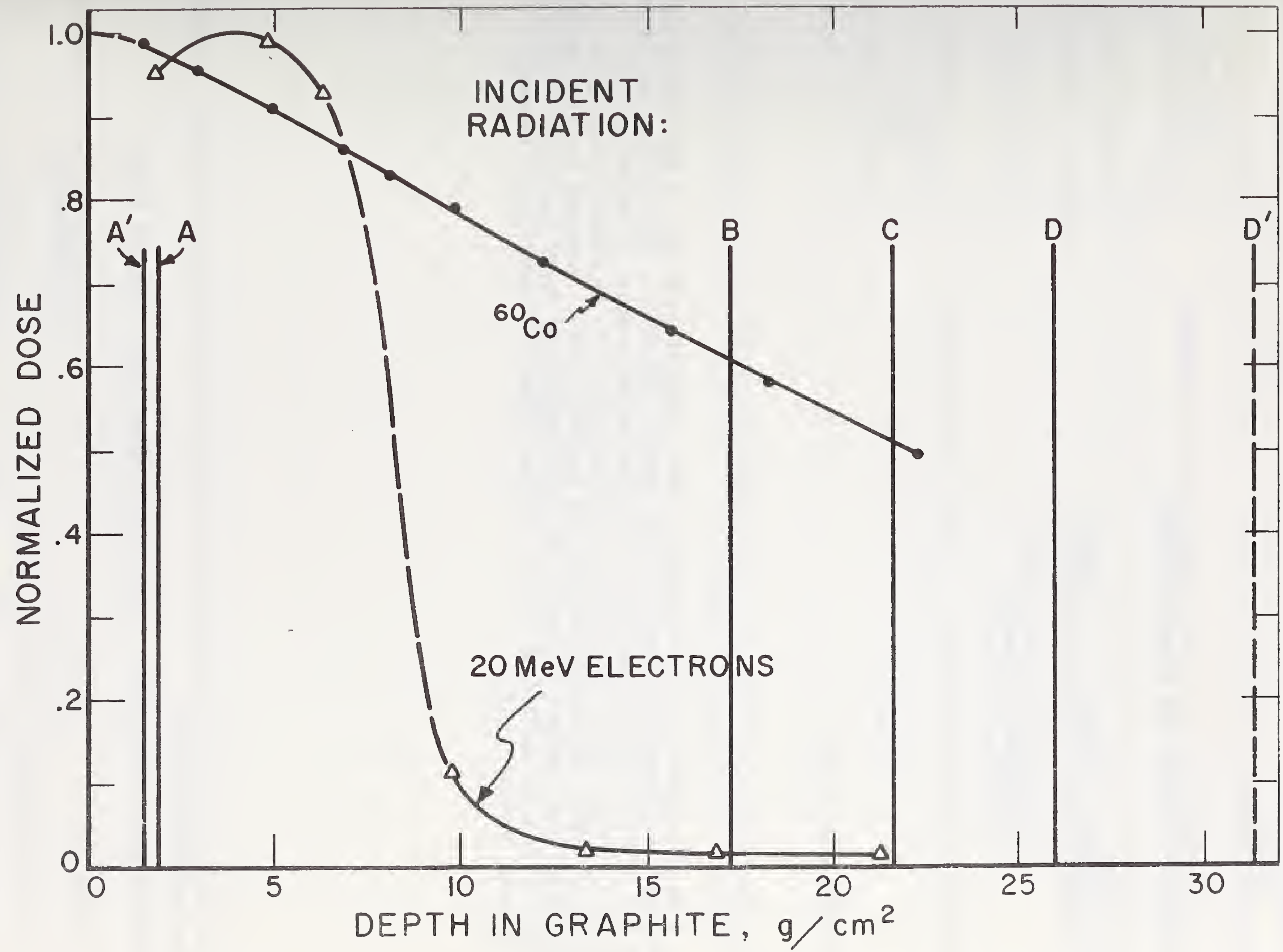
Fig. 1. Experimental setup for direct comparisons of the NBS absorbed dose calorimeters.

Fig. 2. Alignment and details of the calorimeter and parallel plate ionization chamber.

Fig. 3. Normalized dose curves for incident irradiation with cobalt-60 gamma rays and with 20 MeV electrons.


GRAPHITE ABSORBER
30 cm
GRAPHITE
MEDIUM
(40 x 40 x 30 cm)
BEAM
SCATTERER
IONIZATION CHAMBER
AND BEAM AXIS
MONITOR
SIGNAL
(a)
NON-PORTABLE
CALORIMETER
CORE AXIS
LEAD BARRIER
GRAPHITE ENCLOSURE:
(30 cm dia. x 15 cm)
(b)
PORTABLE CALORIMETER
CORE AXIS
PORTABLE
CALORIMETER
(15cm dia. x 10 cm)
A
B
C
D


BEAM DIRECTION
BEAM EXIT PLANE OF ABSORBERS, 0-50 g/cm²
FRONT PLATE
900 mg/cm²
(±1500 V)
20-mm DIA. x 2.75-mm THICK
ION-COLLECTING VOLUME
(& CALORIMETER CORE)
TO ELECTROMETER
EPOXY RESIN
(~2-mm THICK)
0.07-mm GAP
50-mm I.D.
PLASTIC RING
5-mm AIR GAP
MEDIUM
40 x 40 x 30 cm
CALORIMETER CORE
JACKET
SHIELD:
CAP
BASE
VACUUM CHANNEL
0.13-mm MYLAR WINDOW
900 mg/cm²
CENTRAL PLANE OF DETECTORS



INCIDENT
RADIATION:
^{60}Co
20 MeV ELECTRONS
A'
A
B
C
D
D'
NORMALIZED DOSE
1.0
.8
.6
.4
.2
0
0
5
10
15
20
25
30
DEPTH IN GRAPHITE, g/cm^2

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

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17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Absorbed dose; calorimeter; calorimetric comparisons; electron beams

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