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ABSOLUTE DETERMINATION OF BREMSSTRAHLUNG DEPOSITION (HYDRA)

G. J. Lockwood, G. H. Miller

Sandia Laboratories

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ABSOLUTE DETERMINATION OF BREMSSTRAHLUNG DEPOSITION (HYDRA)

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Albuquerque, New Mexico

June 1975

ABSTRACT

A technique developed to measure electron energy deposition in metals has been applied to the determination of bremmstrahlung deposition. In this method a square-wave beam modulation is employed and the time-derivative of a calorimeter temperature is used to obtain the energy deposited. This paper presents the results of bremsstrahlung deposition measurements in gold and aluminum. Data are presented for dose to a material as a function of converter material, converter thickness, and angle of electron incidence for electron energies in the range from 0.2 to 1.0 MeV. In addition, measurements of dose as a function of calorimeter position as it was moved both laterally and axially with respect to the beam axis are reported. Utilizing the facility and technique developed to make these measurements, a thorough study of the bremsstrahlung measuring calorimeters used with the pulsed electron beam machine Hydra was accomplished. The goal of this study was to determine accurately the correction factor for the loading effect of the thermocouple wires. The loading correction factor was measured to be 1.72 with an uncertainty of ± 5 percent. This value should be used when determining true dose to gold with the standard Hydra calorimeters instead of the value of 1.5 obtained from data on Hydra, since there is a larger uncertainty in the latter value.

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CONTENTS

FIGURES

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ABSOLUTE DETERMINATION OF BREMSSTRAHLUNG DEPOSITION (HYDRA)

I. Introduction

In the field of electronic engineering, one of the requirements frequently placed on circuit design is a tolerance (or hardness) to various types of radiation. Testing of circuits or components in a radiation environment has little meaning without a quantification of the environment. One type of radiation for which a tolerance is often required is x-ray bremsstrahlung. An important technique for testing to prescribed levels of radiation makes use of pulsed electron beam machines, operated in the x-ray mode. In this mode the pulse of electrons is allowed to impact on a target (bremsstrahlung converter) to produce the required radiation environment. In this technology the radiation environment is partially quantified by determining the dose delivered to some material. For example, the "dose to gold" is the number of calories deposited by the bremsstrahlung in a gram of gold for each kilojoule of energy in the electron beam. This quantity depends on the location and dimensions of the test sample as well as the bremsstrahlung energy spectrum. The latter depends in a very complicated manner on the electron beam energy spectrum and geometrical characteristics. The process is further complicated by the dependence of the bremsstrahlung spectrum on the converter material and geometry as well as the material and geometry of anything between the converter and the sample. However, the term "dose" is useful, because it specifies an environment insofar as a particular material is concerned.

One of the machines used to produce a bremsstrahlung environment in Sandia Laboratories is the pulsed electron beam machine "Hydra." This machine has the following characteristics. The pulse duration is about [illegible] ns, the voltage is approximately [illegible] MV, and the resulting current is about 30 kA. However, the electrons are not monoenergetic, having an average energy near [illegible] MeV. Pinhole camera pictures indicate that the electron beam at the converter is about [illegible] cm in diameter having converged from the 5.[illegible] cm diameter cathode 1.1 cm in front of it.

A detailed description of the bremsstrahlung production on Hydra is given in Ref. 1 and will not be repeated here. However, a few pertinent facts are in order. Due to the harsh environment in the vicinity of the dose-measuring calorimeters when the machine fires, it is necessary that they be rugged. The calorimeter most generally used consists of a gold disc 0.64 cm in diameter and 2.8×10^{-3} cm thick which is supported by chromel and constantan thermocouple wires which are spot welded to the gold disc. Durability is achieved by using large wire diameter (2.5×10^{-2} cm). The penalty for this lies in the strong influence which the thermocouple wires exert on the results obtained. Two effects can be involved. First, the thermal capacity of the wires is not negligible compared to that of the disc. In fact, it is about twice as great for a one-cm length of wire as that of the disc. Second, there may be bremsstrahlung energy deposited directly in the wires, resulting in a differential dose effect. Using the Hydra machine, these effects have been treated together in the following way. Data were taken simultaneously (the same shot) with calorimeters of different wire diameter. In each case the results were normalized to that obtained on the same shot for the standard 2.5×10^{-2} cm wire diameter calorimeter. A plot was then made of the normalized dose as a function of wire diameter and this curve, taken to be an exponential function of diameter, was extrapolated to zero diameter. Here, it was reasoned, there can be neither radiation nor thermal loading. The normalized dose thus obtained is the factor by which the data obtained with the 2.5×10^{-2} cm wire diameter calorimeters should be multiplied to obtain the true dose. The factor measured this way was found to be 1.5.

Because of the size of the loading effect and the importance of this diagnostic, it was decided to undertake a more thorough investigation of this calorimeter under more carefully controlled conditions. To accomplish this goal, a high-stability electrostatic accelerator which operates in the voltage region up to 1.1 MeV was used as the electron source. In this case the beam is very narrow (0.2 cm diameter) so that the electron beam geometrical dependence differs from that of Hydra. Furthermore the electrons from this source are mononergetic, unlike the electron energy spectrum from Hydra. Because of these differences, it was decided to first build a laboratory calorimeter to measure the absolute dose to gold as a function of converter material thickness and angle of electron incidence for electron energies in the range from 0.2 to 1.1 MeV. This calorimeter was also used to measure dose as a function of position as it was moved both laterally and axially with respect to the beam axis. By this means the environment was at least partially documented. Finally, this laboratory calorimeter was used to determine the most accurate experimental technique for measuring the dose of gold and other metals.

With the facility and technique for measuring dose to gold developed with the laboratory calorimeter, a thorough study of the Hydra calorimeter was accomplished under laboratory conditions. The goal of this study was to determine accurately the correction factor for the loading effects of the thermocouple wires. Measurements were made of dose with the Hydra calorimeter as a function of converter thickness for 1.0 and 0.5 MeV electrons and as a function of energy for the standard (5.2×10^{-3} cm thick tantalum) Hydra converter. The dependence of apparent dose on thermocouple wire diameter was also studied. From these measurements, a correction factor was determined.

II. Laboratory Calorimeter Measurements

For dose to gold measurements, the laboratory calorimeter was constructed of 2.5×10^{-3} cm thick gold and had the shape shown in Fig. 1. It was supported from a heat sink by eight wires, each of 5×10^{-3} cm diameter tantalum, to minimize the thermal loading. The temperature was measured by a chromel-constantan thermocouple. Each wire was 5×10^{-3} cm in diameter and the couple was spot welded to one edge of the calorimeter. This calorimeter was used with the geometry shown in Fig. 2. Since the bremsstrahlung converter thickness was less than an electron mean range, it was necessary to place a low-Z (carbon) electron absorber between the converter and the calorimeter to shield the calorimeter from electrons not stopped in the converter. A sheet of ATJ graphite 0.762 cm thick was used for this purpose for all measurements made with laboratory calorimeters. The use of a low-Z electron absorber minimized bremsstrahlung absorption. Because the graphite absorbed the energy of the electrons which were not stopped in the converter, its temperature increased. To attenuate the thermal radiation coupling between the graphite and the calorimeter, two aluminum heat shields were used.[2] Using this experimental package, dose was measured using the modulated beam-time derivative method described in detail in Ref. 2. Since this experimental package differed slightly from the Hydra converter package, measurements were made with both packages. The results were the same within experimental error.

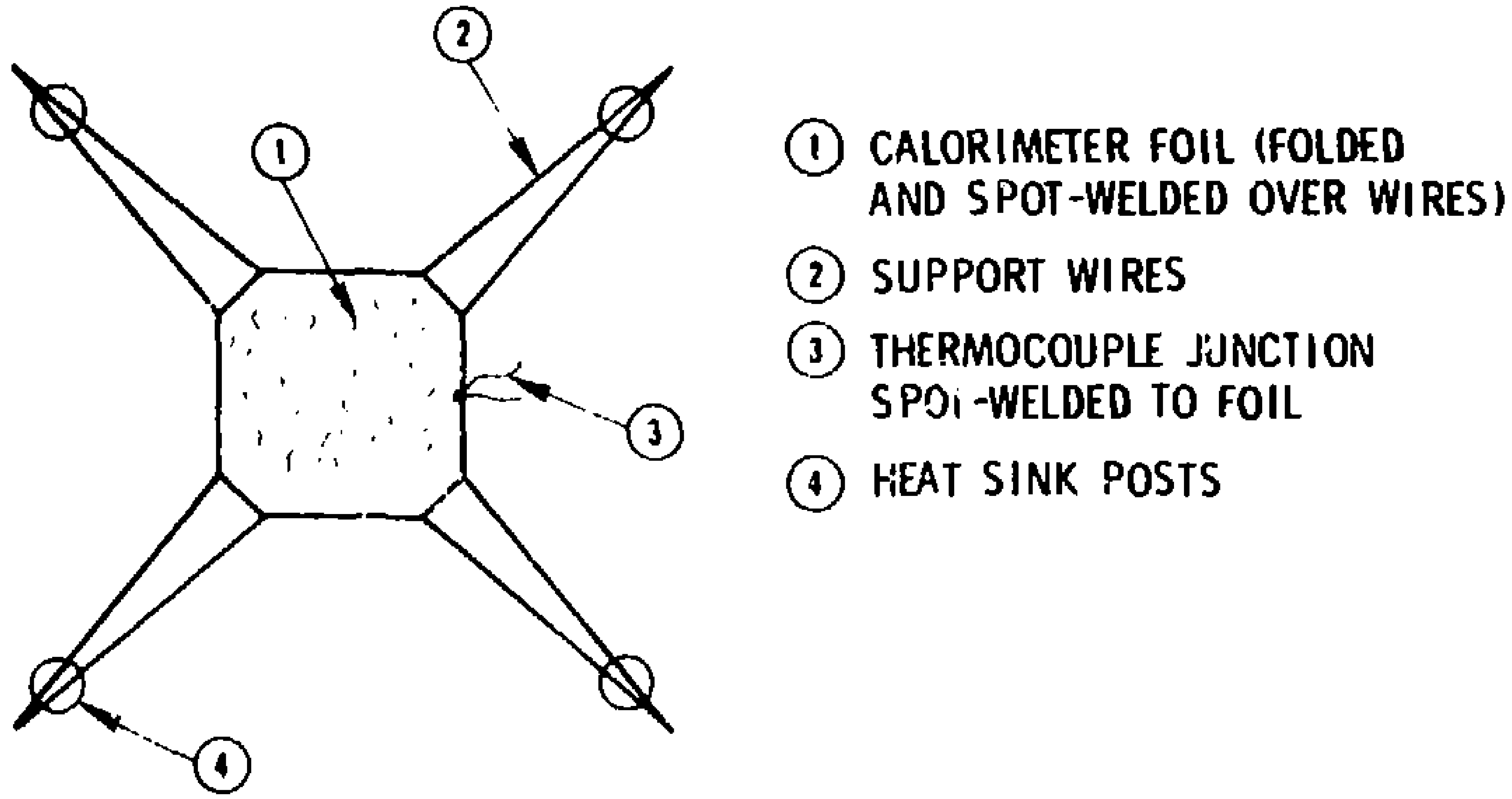

Figure 1. Gold laboratory calorimeter

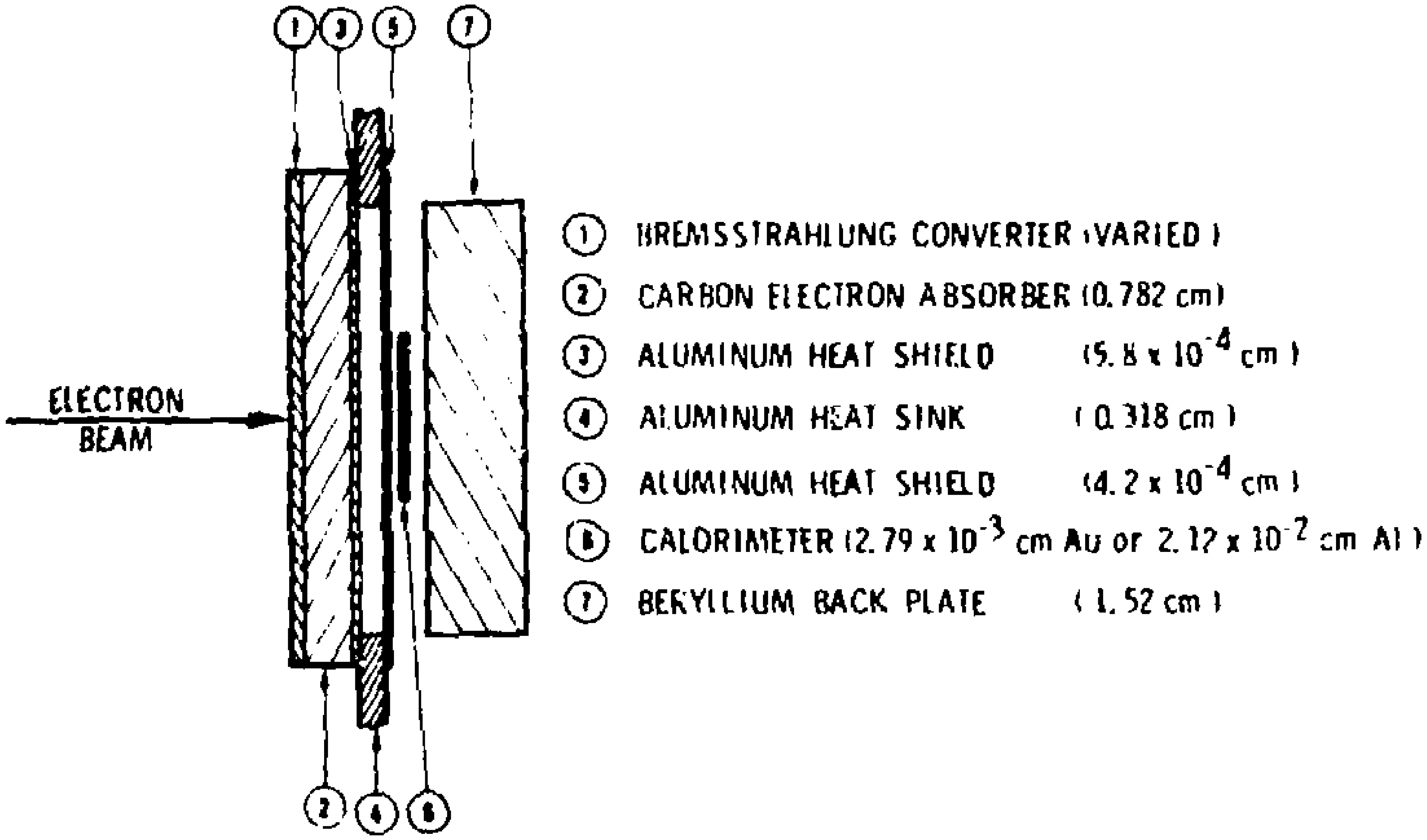

Figure 2. Experimental package with laboratory calorimeter

This method of measuring dose proved to be so successful that it was decided to try to measure dose to aluminum also. Aluminum is of interest for two reasons. First, it is used in packaging and mounting electronic components. Second, it is next to Si in the period table, thus measurements in aluminum are useful in predicting dose to Si. The aluminum calorimeter shown in Fig. 3 was 2.5 cm in diameter and 2.12×10^{-2} cm thick, and was supported by sixteen 1.6×10^{-2} cm diameter aluminum wires. However, in this case, it was necessary to use eight chromel-constantan thermocouples (8×10^{-3} cm diameter wire) in series to obtain sufficient signal. This calorimeter was used with the same geometry used to measure dose to gold (see Fig. 2). For all measurements, the incident electron beam current was measured with a Faraday cup which surrounded the experimental package.[3] The Faraday cup wall thickness was greater than the range of the most energetic electrons used. Electrons could escape only by being backscattered through the small entrance hole in the Faraday cup. The small solid angle which this hole subtended with the electron impact region of the converter made this a very small effect.

The calorimeters were calibrated using a heavy-ion accelerator. The ion beam was modulated in the same manner as the electron beam. In this case the calorimeter thickness was much greater than the range, so that, except for a negligible amount of backscattered energy, all of the ion energy was deposited in the calorimeter. Thus a careful measurement of the accelerator potential (which was kept between 20 and 30 kV) along with the Faraday cup measurement permitted an excellent determination of the input power. The effect of the aluminum heat shield was checked during calibration by placing an aluminum shield, with a small hole for the ion beam to pass through, in front of the calorimeter. No difference was found in calorimeter temperature for a fixed power input with or without the aluminum shield.

The results of these measurements are shown in Figs. 4 through 11. Fig. 4 shows the measured dose to gold and aluminum as a function of converter thickness for 1.0 MeV electrons normally incident upon a tantalum converter. The dose measured at zero thickness is due to bremsstrahlung produced in the graphite. The initial increase in dose with converter thickness is due to the increased production of bremmstrahlung as the energy deposited in the converter increases. This dose does not increase indefinitely as the converter thickness is increased, because of self-absorption in the converter and the

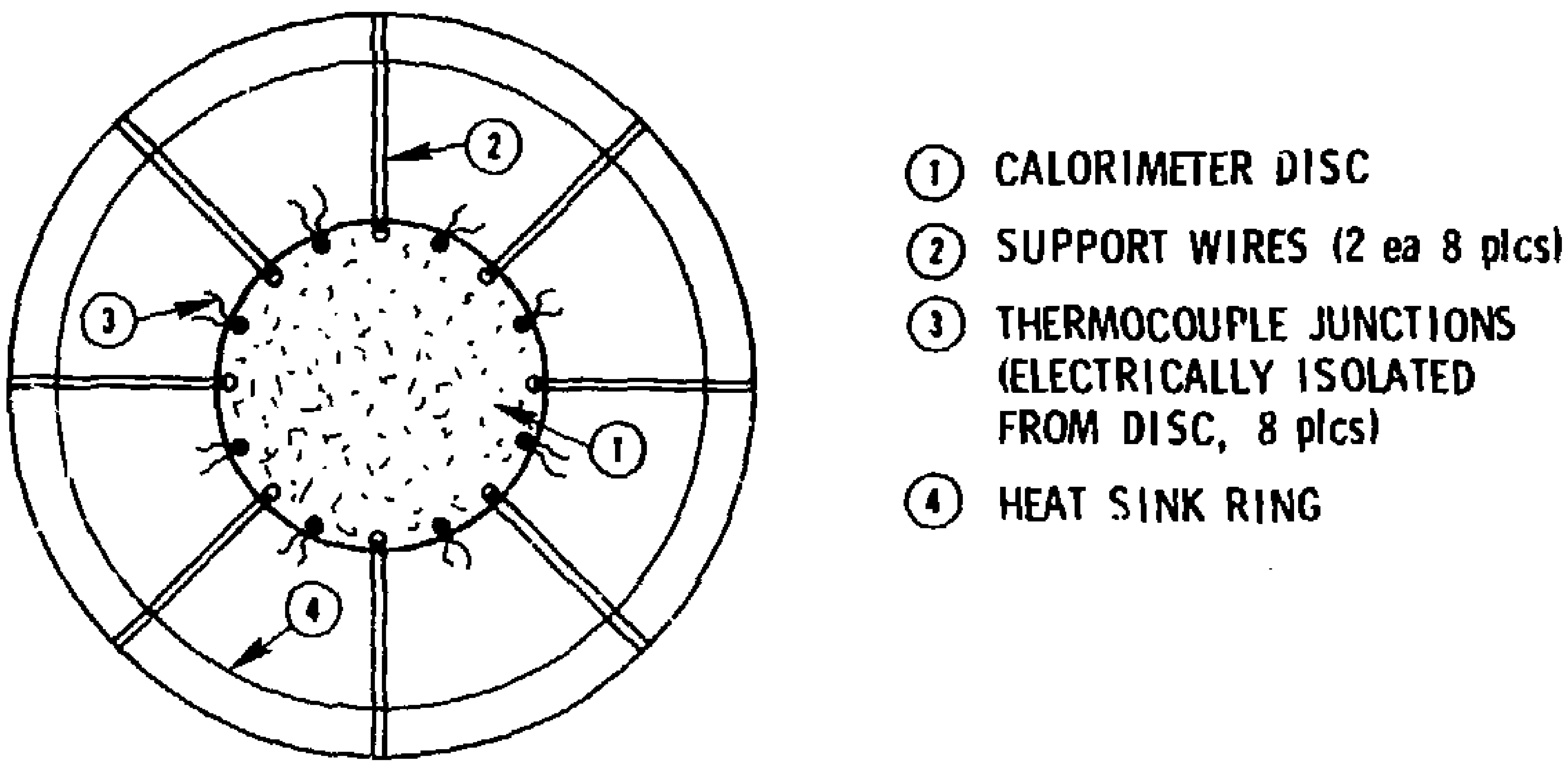

Figure 3. Aluminum calorimeter

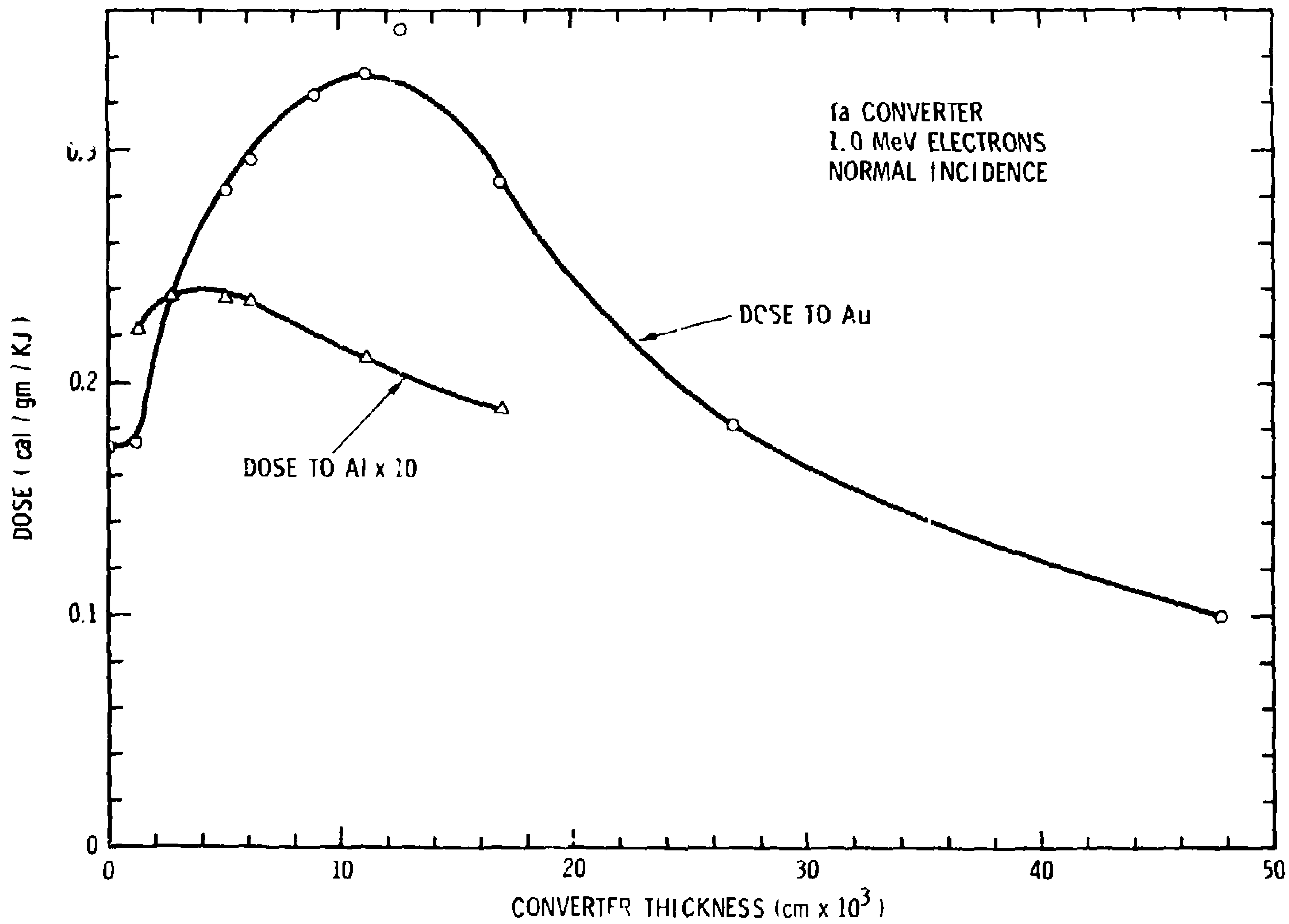

Figure 4. Dose to gold and aluminum as a function of converter thickness for 1.0 MeV electrons normally incident upon a tantalum converter

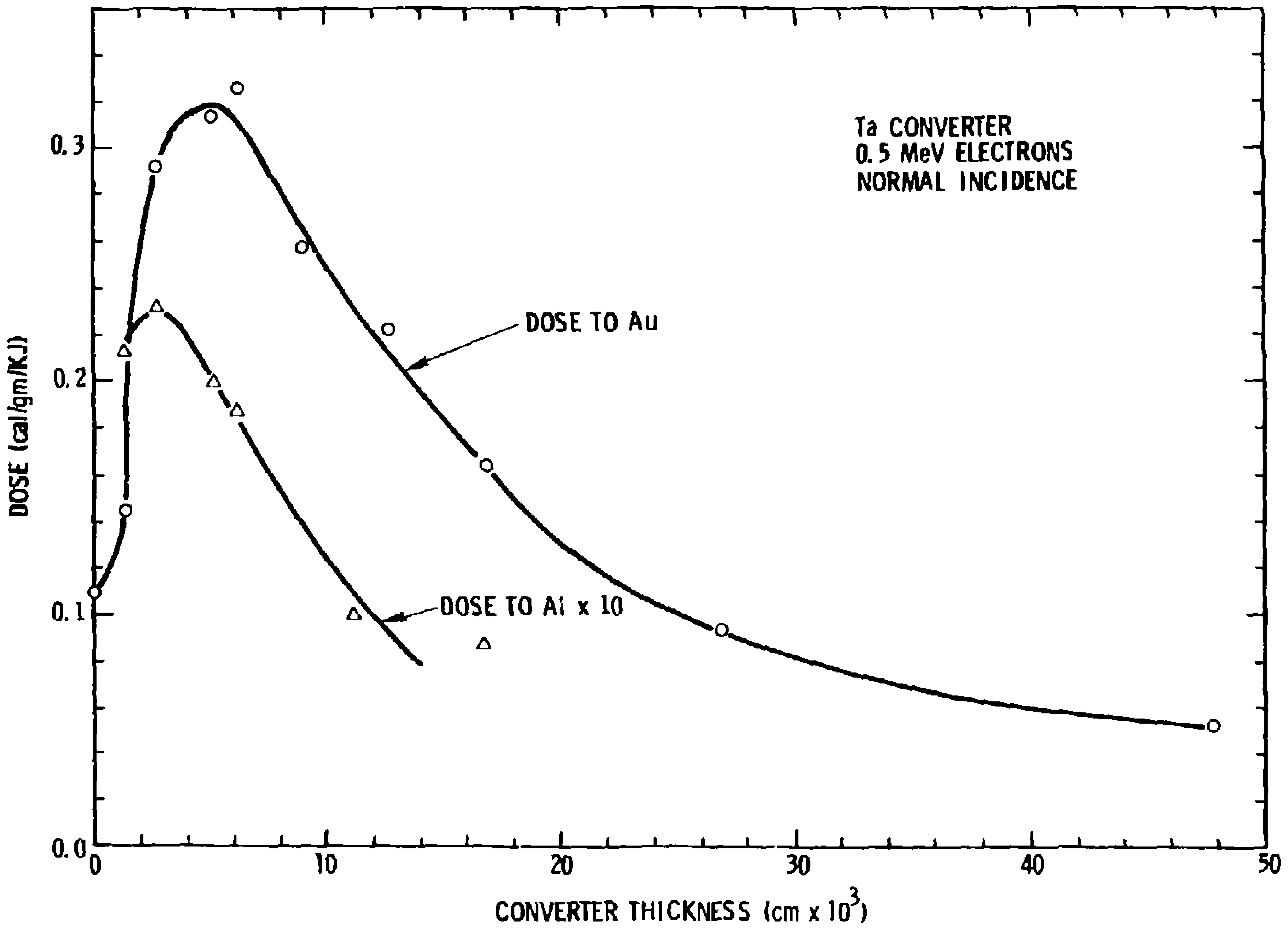

Figure 5. Dose to gold and aluminum as a function of converter thickness for 0.5 MeV electrons normally incident upon a tantalum converter

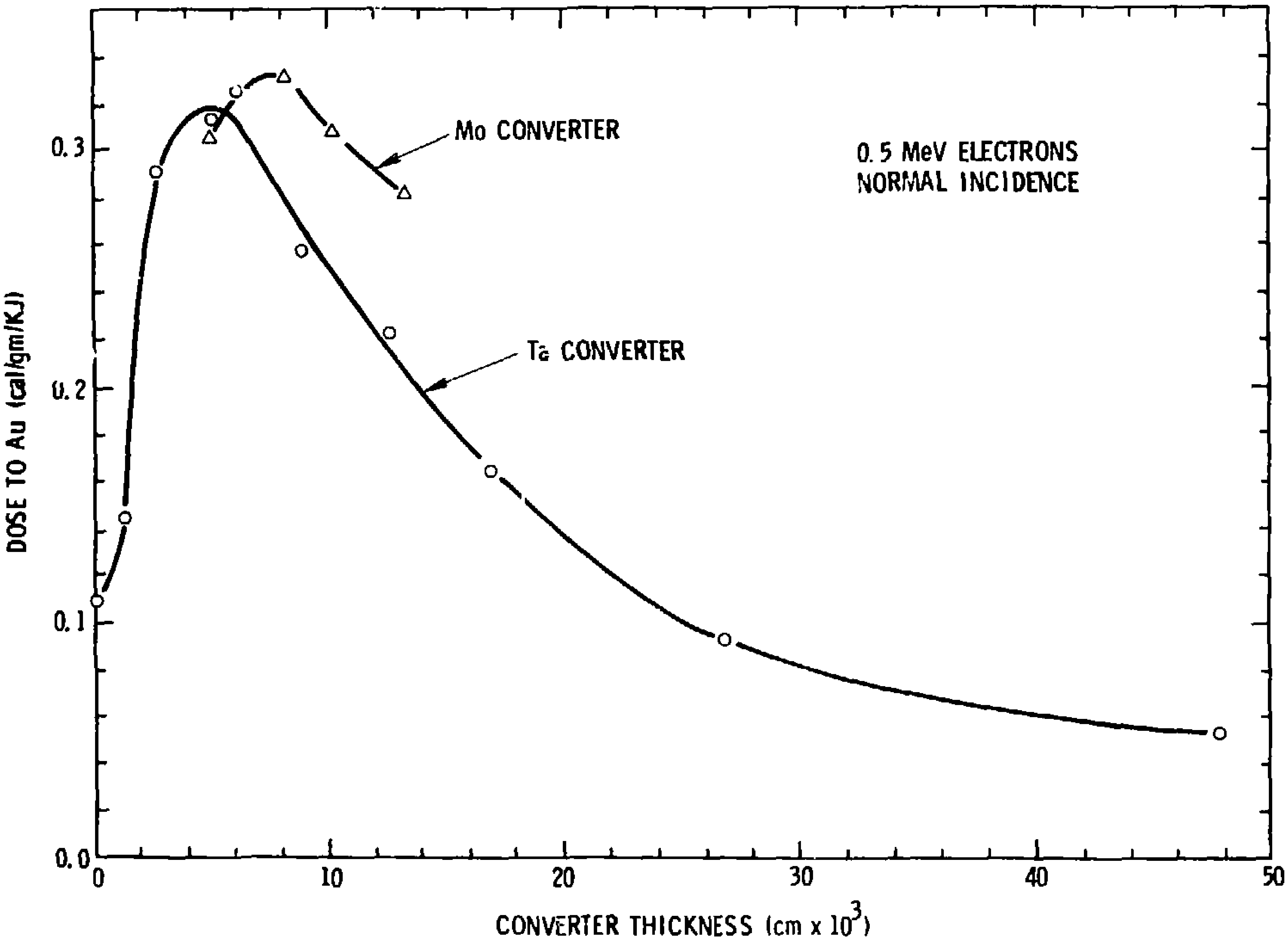

Figure 6. Dose to gold as a function of converter thickness for 0.5 MeV electrons normally incident upon tantalum and molybdenum converters

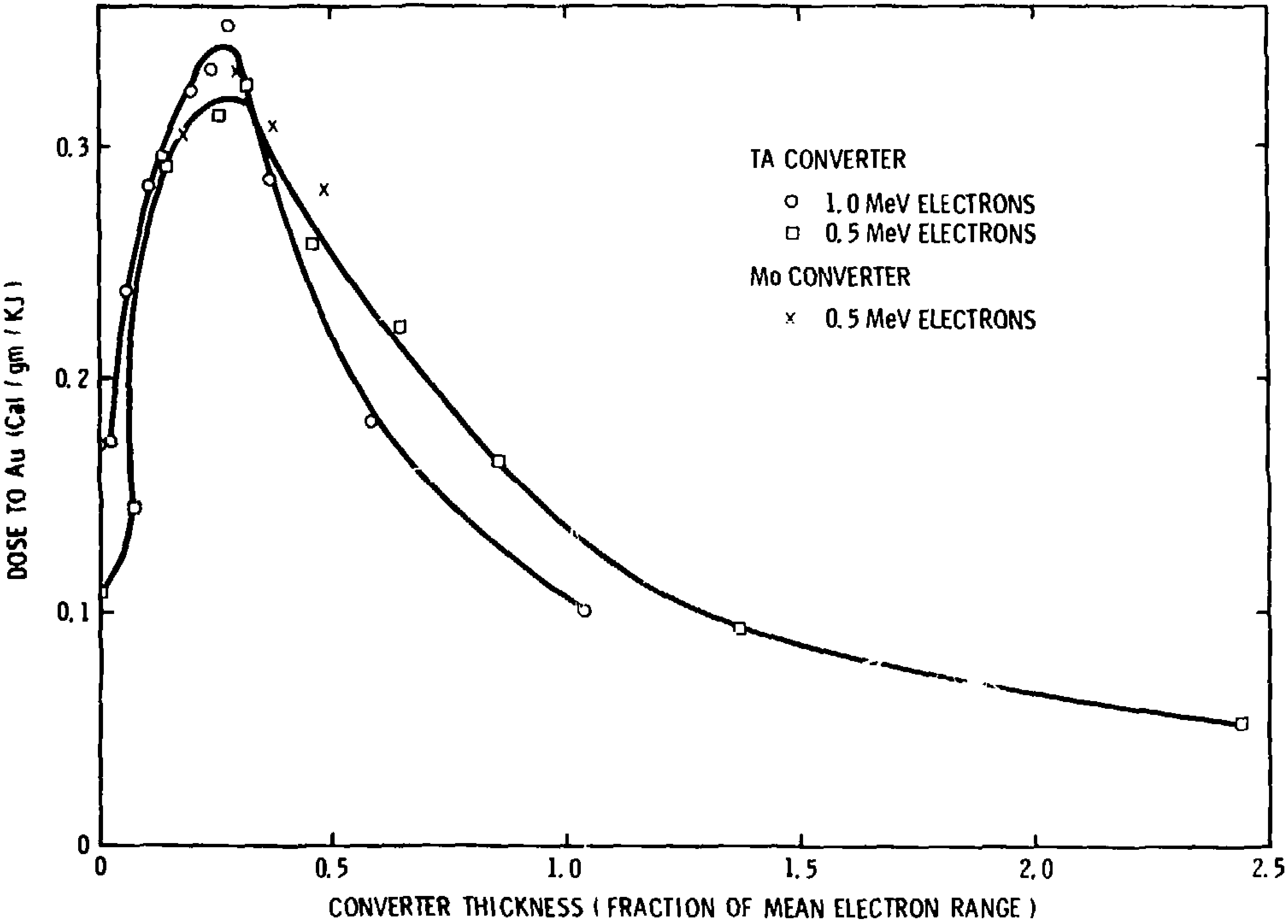

Figure 7. Dose to gold as a function of converter thickness expressed as a fraction of the mean electron range. Data are for 1.0 and 0.5 MeV electrons incident on a tantalum converter and 0.5 MeV electrons incident on a molybdenum converter.

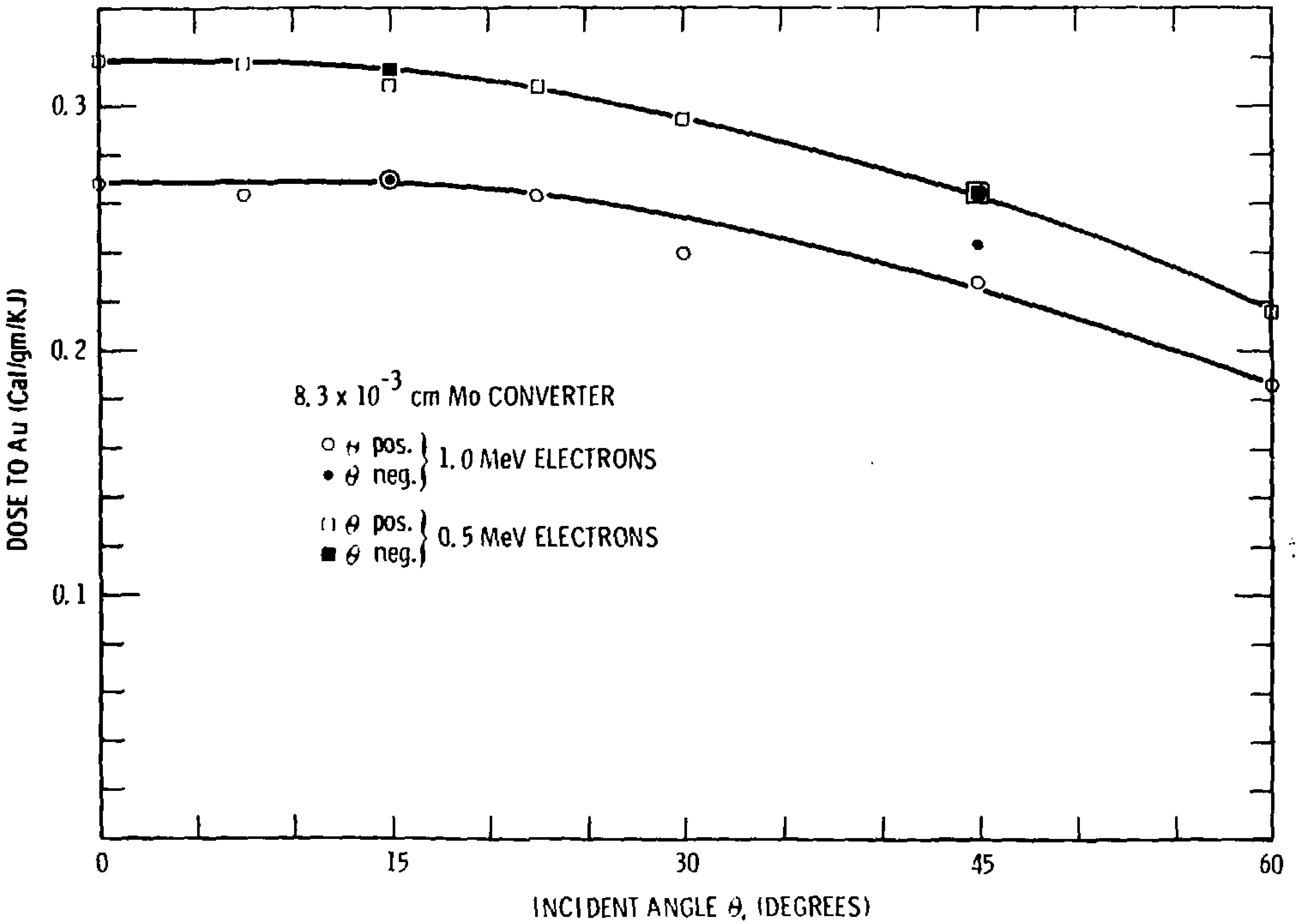

Figure 6. Dose to gold as a function of angle of electron incidence upon a molybdenum converter for 1.0 MeV and 0.5 MeV electrons

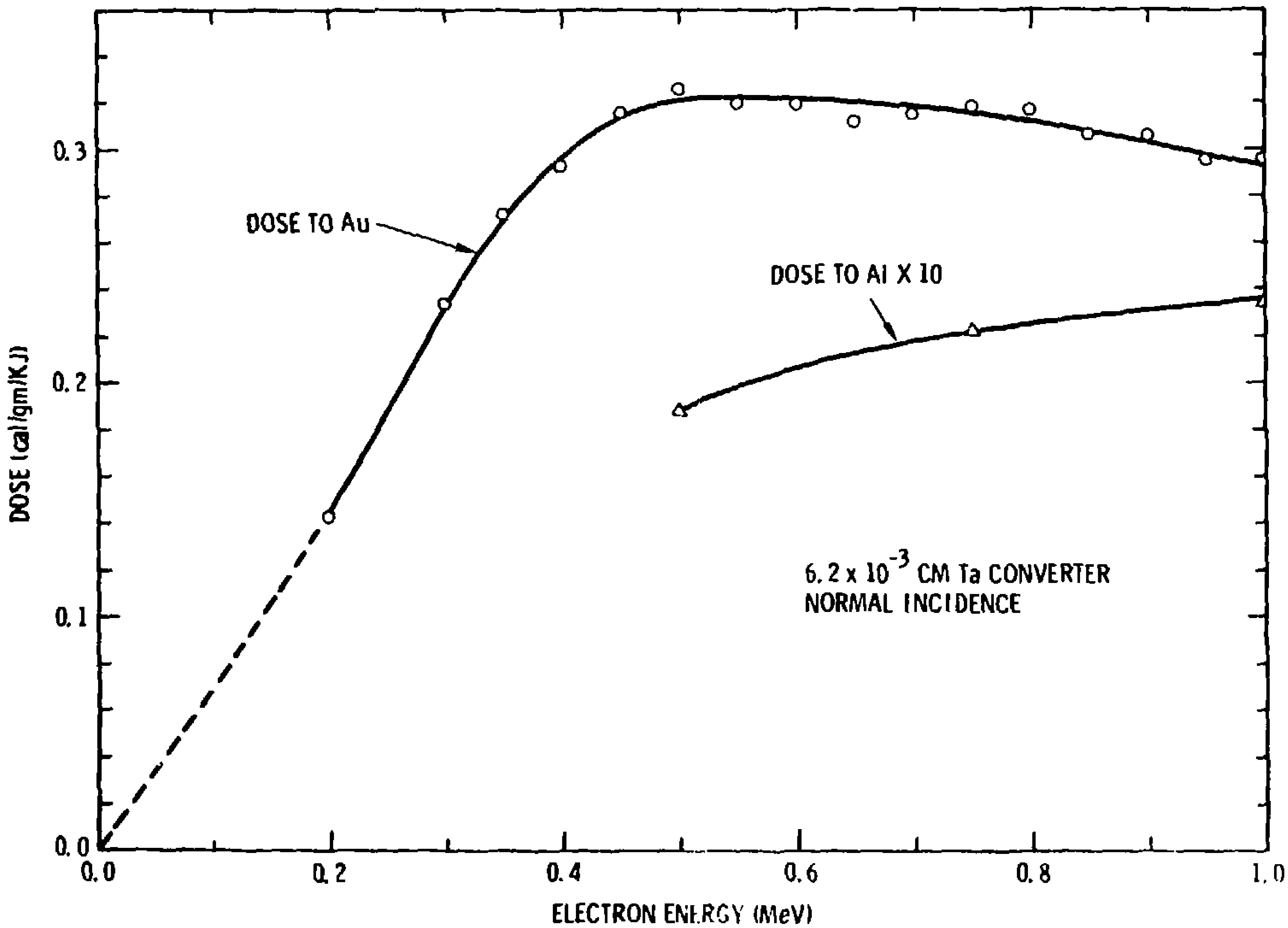

Figure 9. Dose to gold and aluminum as a function of electron energy for a 6.2×10^{-3} cm thick tantalum converter

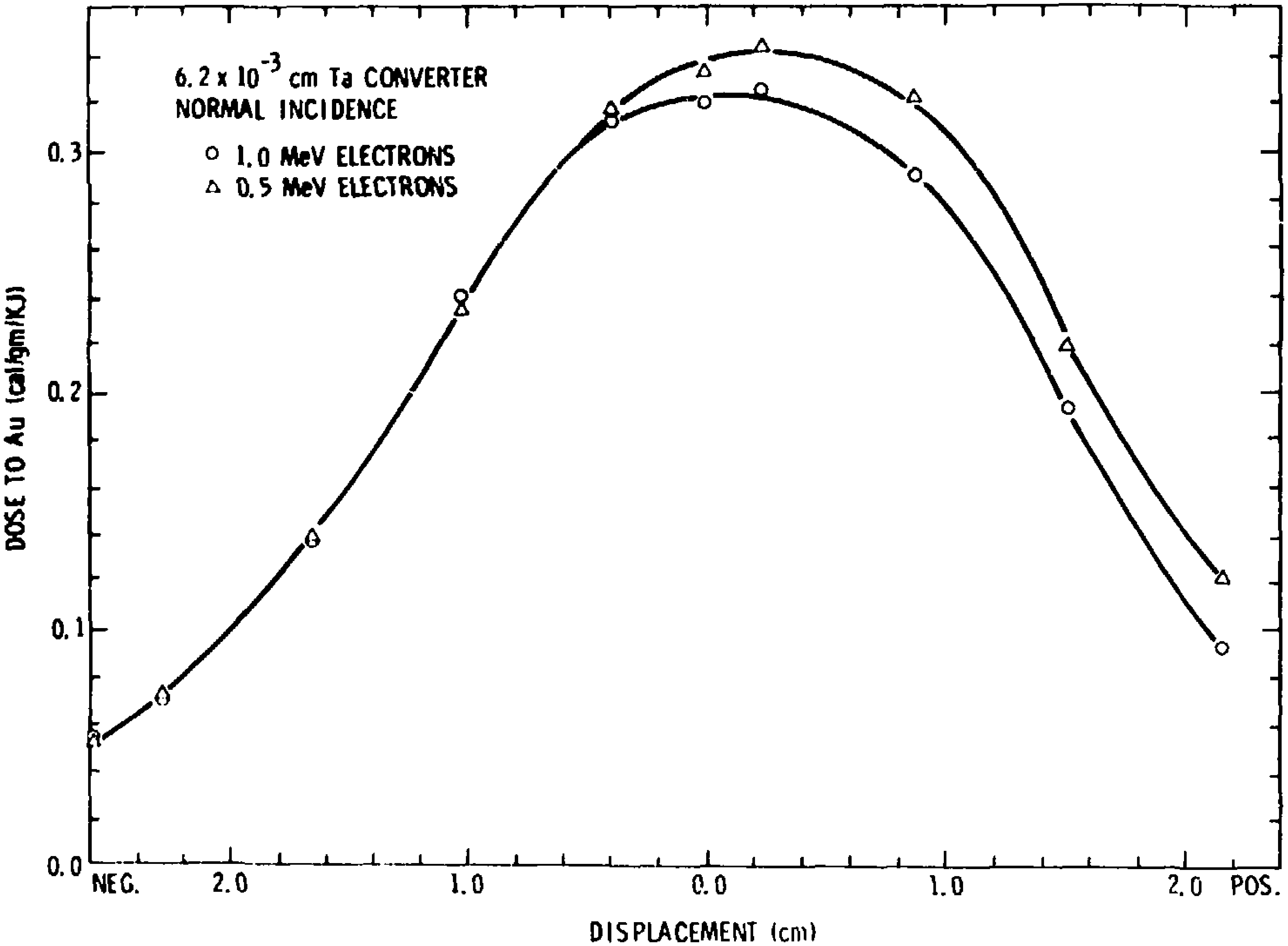

Figure 1. Dose to gold as function of lateral displacement of the experimental package for 1.0 MeV and 0.5 MeV electrons incident on a 6.2×10^{-3} cm thick tantalum converter

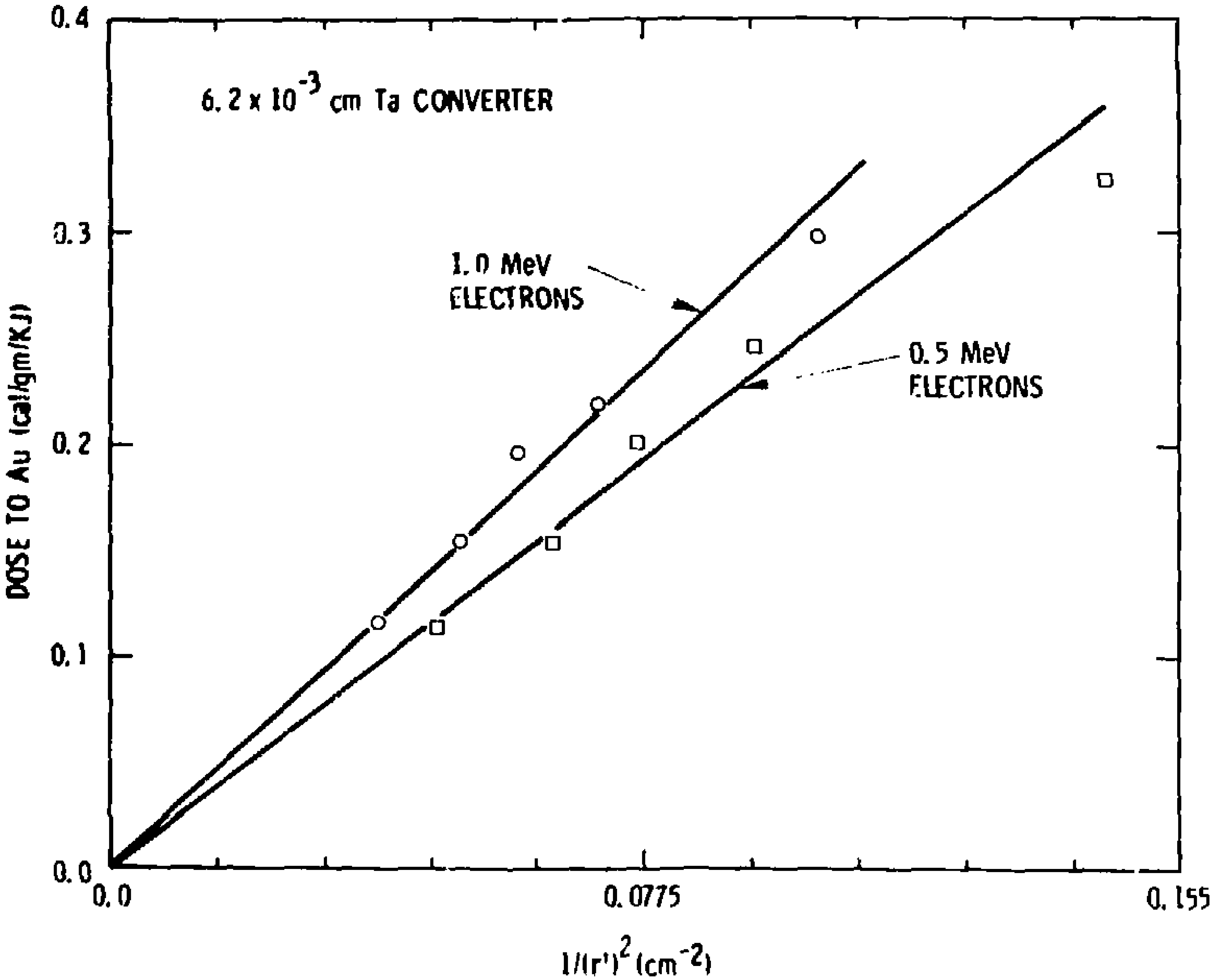

Figure 11. Dose to gold as a function of axial displacement of the converter for 1.0 MeV and 0.5 MeV electrons incident on [illegible] x 10^{-3} cm thick tantalum converter

resulting shift in the bremsstrahlung spectrum to shorter wavelength. Thus, after some optimum thickness is reached, the dose decreases. A similar behavior is seen in Fig. 5 where dose to gold and aluminum as a function of converter thickness is shown for 0.5 MeV electrons normally incident upon a tantalum converter.

The dependence of the dose to gold on the converter material was examined. Figure 6 shows the dose to gold as a function of converter thickness for 0.5 MeV electrons normally incident upon tantalum and molybdenum converters. The optimum converter thickness for molybdenum is greater than that for tantalum but the two are approximately the same if the converter thickness is measured as a fraction of the mean range (FMR) as obtained from the continuous slowing-down approximation. This is shown more dramatically in Fig. 7 where dose to gold is plotted as a function of FMR for 1. and 0.5 MeV electrons normally incident on a tantalum converter and [illegible] MeV electrons upon a molybdenum converter. In all three cases the converter thickness for maximum dose is about [illegible] percent of the mean electron range.

Figure [illegible] shows the dose to gold as a function of angle of electron incidence for 1.0 MeV and .5 MeV electrons incident upon a molybdenum converter. There is very little dependence on angle of incidence for 1. MeV electrons out to about 22.5° and for .5 MeV electrons out to about 1[illegible]°. For larger angles the dose decreases. This decrease in dose with angle could be caused by the increased number of backscattered electrons with increasing angle and the electron energy being deposited closer to the front surface thus increasing the self-absorption for a fixed thickness calorimeter. The energy dependence of the dose to gold and aluminum for a fixed converter thickness is shown in Fig. [illegible]. In this case the converter was tantalum [illegible] cm thick. This thickness corresponds to an FMR of [illegible] and [illegible] for 1. and .5 MeV, respectively. Thus for dose to gold it is close to optimum thickness for .5 MeV electrons and less than optimum for 1. MeV electrons. The energy dependence is as expected, rising slightly as the energy is reduced from 1. MeV to .5 MeV and falling rapidly below .5 MeV. This same tantalum converter was also used with electrons of 1. and .5 MeV to examine dose to gold as a function of calorimeter position as it was moved laterally and axially with respect to the beam axis. The results of these measurements are shown in Fig. 1[illegible] for lateral displacement and in Fig. 11 for axial displacement.

During the lateral position measurements, the entire package was moved along an axis perpendicular to the beam axis as shown in Fig. 12. The shape of the curve is consistent with what would be expected for a photon flux with a cosine distribution.

It might be expected that the axial dependence would follow an r^{-2} function, where r is the distance from the converter to the calorimeter. However, two factors affect this. First, the source (electron deposition volume) is not a point, but has finite extent. Second, the bremsstrahlung angular distribution is not isotropic, but is forward-peaked. Both of these tend to make the source appear to be further from the calorimeter. Data obtained by measuring dose as a function of distance from the converter were plotted in the form of $(\text{Dose})^{-2}$ versus r. The correction to r was obtained from the intercept, and Fig. 11 shows a conventional plot of dose as a function of r', the value of r modified by the addition of this correction. The fit is reasonable.

III. Hydra Calorimeter

Having demonstrated the facility for measuring dose to gold with the laboratory calorimeter and having determined the best measurement technique (time derivative with modulated beam), we undertook a thorough investigation of the Hydra calorimeter. The prime objective was to determine a correction factor for the loading effects of the thermocouple wires.

The Hydra calorimeter is shown in detail in Fig. 13a. The thermocouple wires of the standard Hydra calorimeter were 2.5×10^{-2} cm in diameter. However, during the course of this study, measurements were also made for calorimeters supported by thermocouple wires of smaller diameter. Measurements with the Hydra calorimeter were made using the geometry shown in Fig. 13b. This package is the same one used to make measurements with the laboratory calorimeter with the exception that the beryllium backplate has been replaced by the aluminum support.

The measurement technique, incident electron beam current determination, and calibration were the same ones developed and used with the laboratory calorimeter.

Measurements of dose to gold with the standard Hydra calorimeter were made as a function of converter thickness and as a function of energy for the

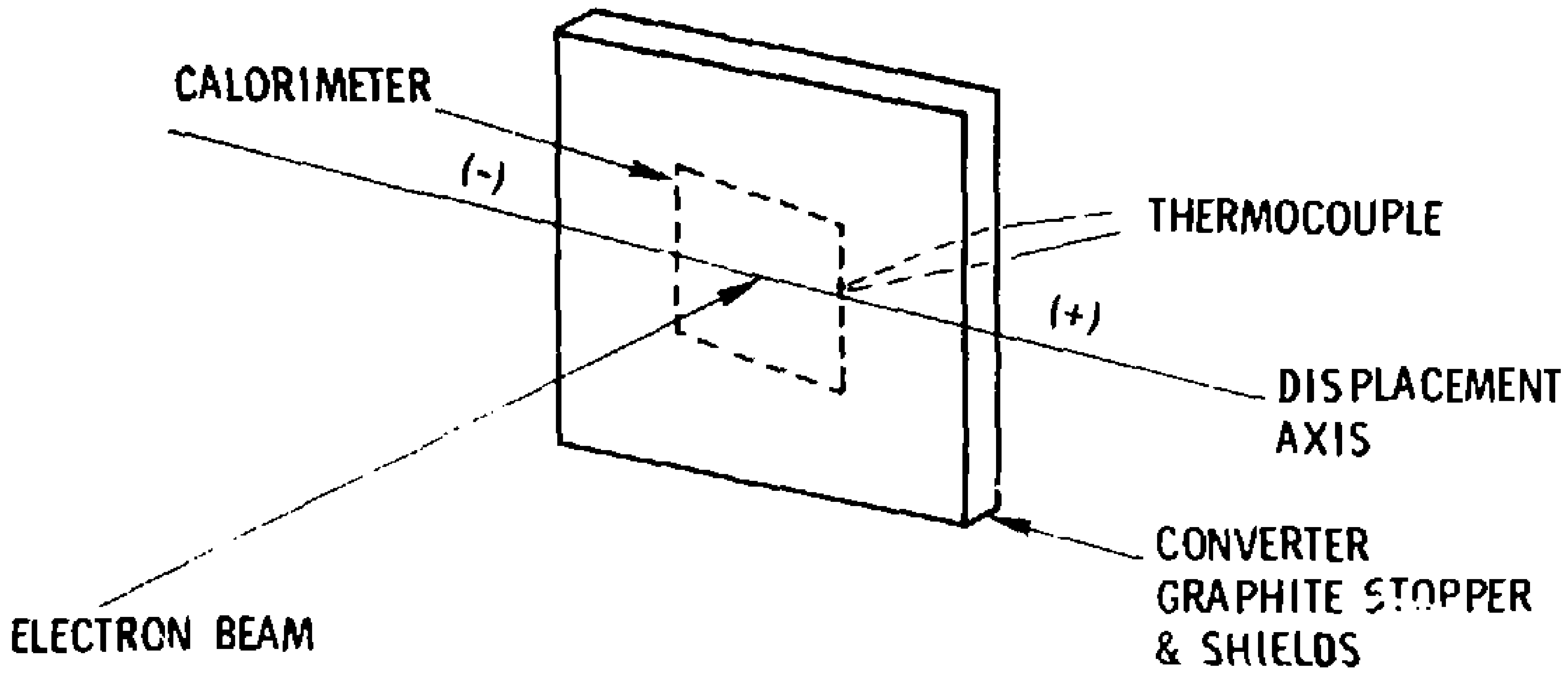

Figure 12. Geometry for lateral displacement measurements

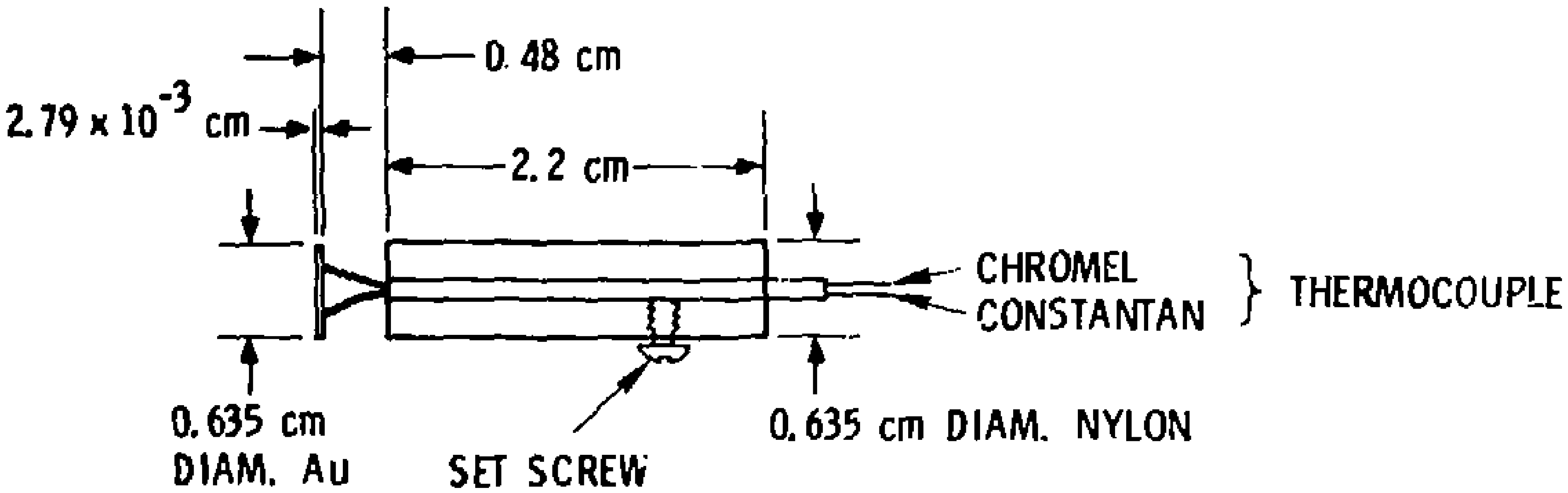

Figure 13a. Hydra Calorimeter

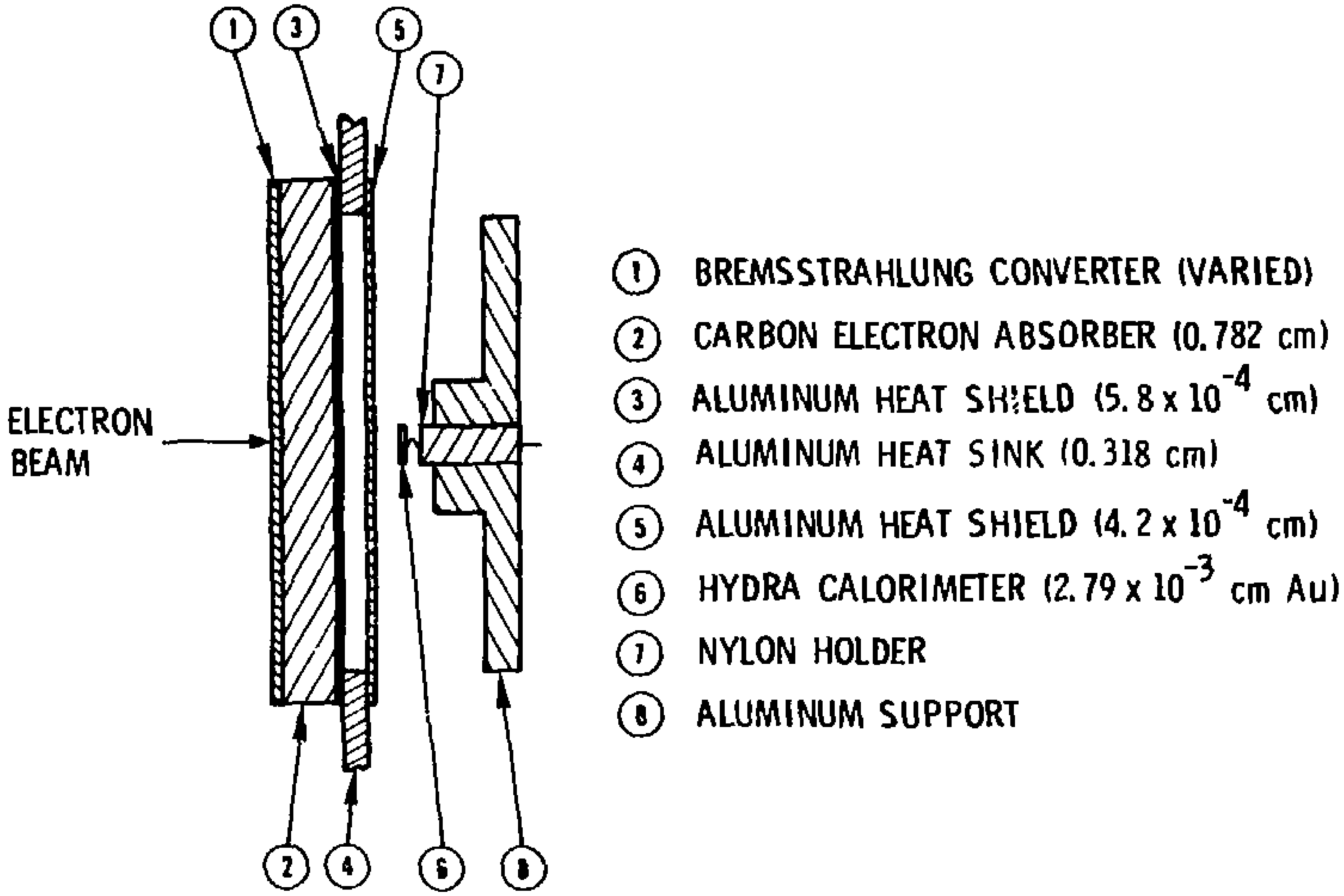

Figure 13b. Experimental package with Hydra Calorimeter

regular Hydra converter (5.2×10^{-3} cm thick tantalum). The results of these measurements, corrected for loading effect, are shown in Figs. 14 and 15. The basis for this correction will be indicated later in this Section and in the following Section. Figure 14 shows the measured dose to gold as a function of converter thickness for 1 MeV electrons normally incident upon a tantalum converter. For comparision, results of both the Hydra and laboratory calorimeters are plotted. The curve for the Hydra calorimeter has the same general shape as that for the laboratory calorimeter discussed earlier. The dose to the Hydra calorimeter was larger because it subtended a smaller solid angle. Since the dose decreased as the polar angle increased (see Fig. 10), the smaller calorimeter was in a region of higher average dose. The converter thickness for optimum dose is the same for both calorimeters. Similar results are seen for 0.5 MeV incident electron in Fig. 15. Dose as a function of energy for a fixed thickness converter is shown in Fig. 16. Here, as in the case of the laboratory calorimeter (also shown), the converter thickness is near optimum for both 1.0 and 0.5 MeV and the dose is almost constant from 1.0 to 0.45 MeV. Then, as in the case of the laboratory calorimeter, the dose decreases rapidly with decreasing energy.

In addition to these measurements with a standard Hydra calorimeter, dose to gold was measured as a function of thermocouple wire diameter. The results are shown in Fig. 17 where relative dose is plotted as a function of thermocouple wire diameter. For these measurements a fixed 5.2×10^{-3} cm thick tantalum converter was used. It is apparent that the measured dose increases with decreasing wire size; however, the relationship is not linear and a meaningful extrapolation of this curve is not possible. It would be reasonable to expect that for some small but finite wire size the loading effect would be negligible and that the relative dose would be constant for all smaller size wires.

Finally, a crude but direct measurement of the contribution to the signal from bremsstrahlung deposition in the thermocouple wires (2.54×10^{-2} cm diameter) was made. This was done by exposing a bare thermocouple of the same wire size and material to the bremsstrahlung with the gold disc removed. In these measurements, a 2.8×10^{-3} cm thick gold foil was placed between the final aluminum shield and the thermocouple wires to produce the same shielding which the calorimeter disc would normally produce. The results of these measurements showed that approximately 7.0 percent of the signal came from

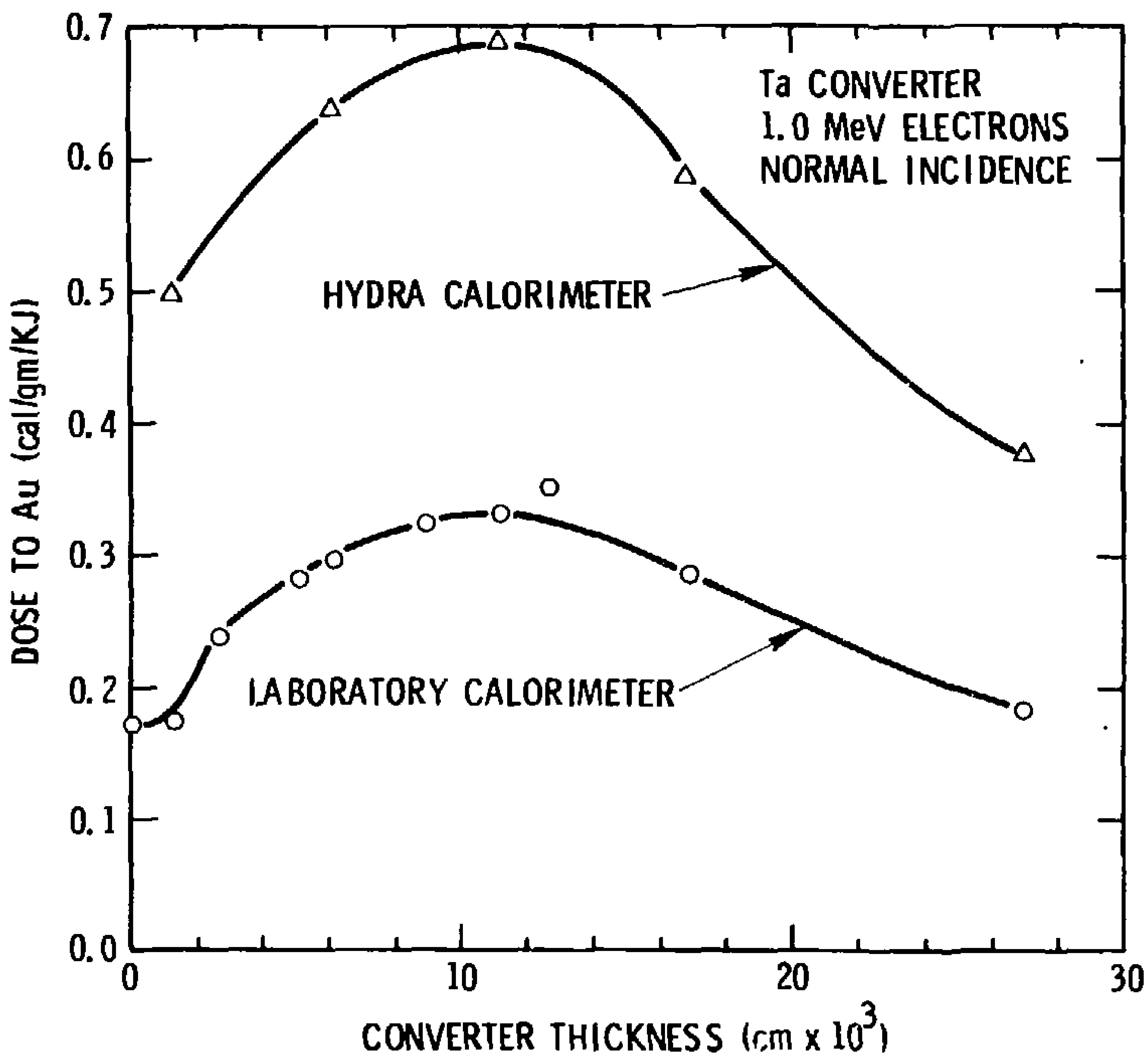

Figure 14. Dose to gold as a function of converter thickness for 1.0 MeV electrons incident upon a tantalum converter. For comparison, results of both the Hydra and laboratory calorimeters are shown.

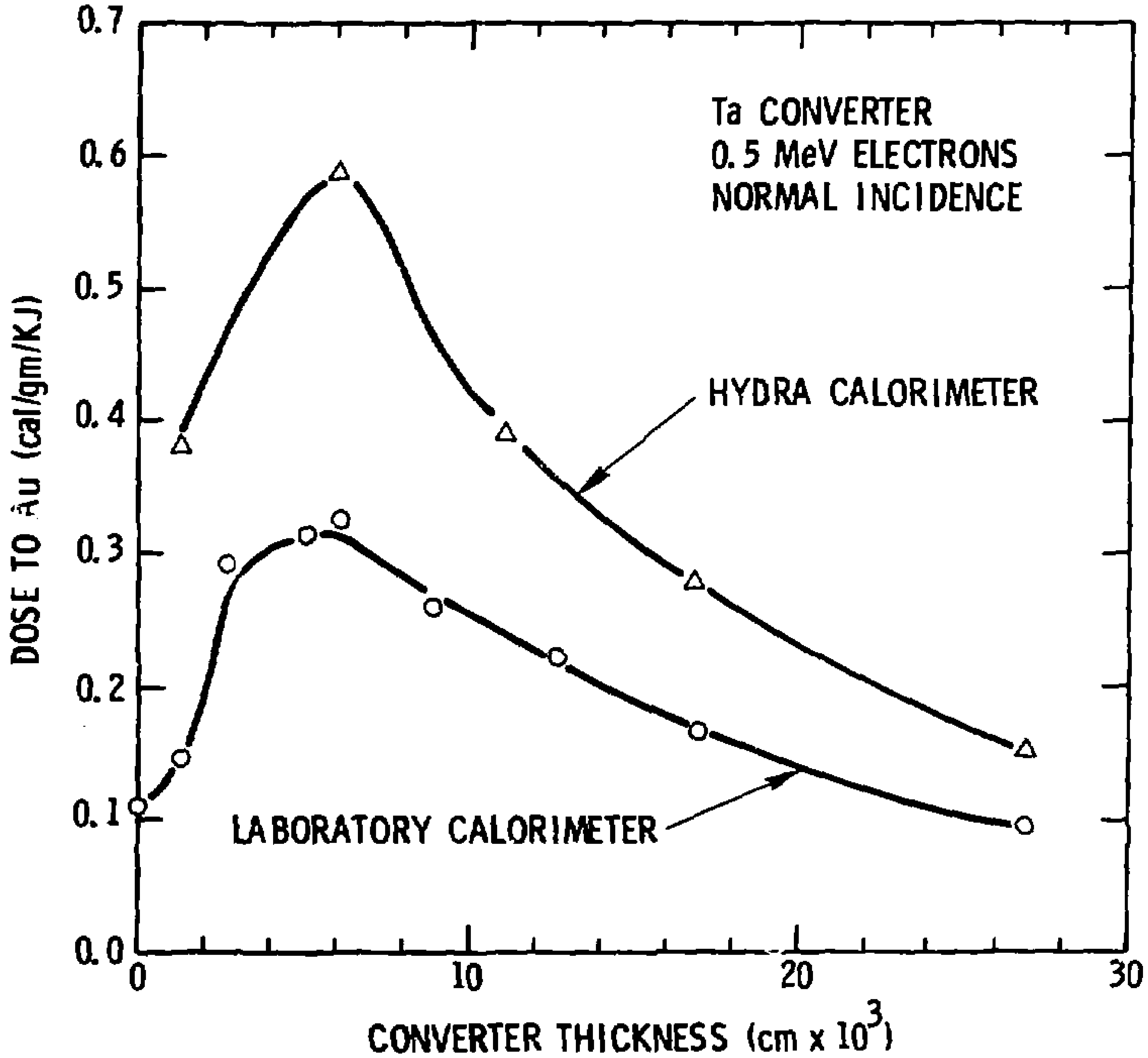

Figure 15. Dose to gold as a function of converter thickness for 0.5 MeV electrons incident upon a tantalum converter. For comparison, results of both the Hydra and laboratory calorimeters are shown.

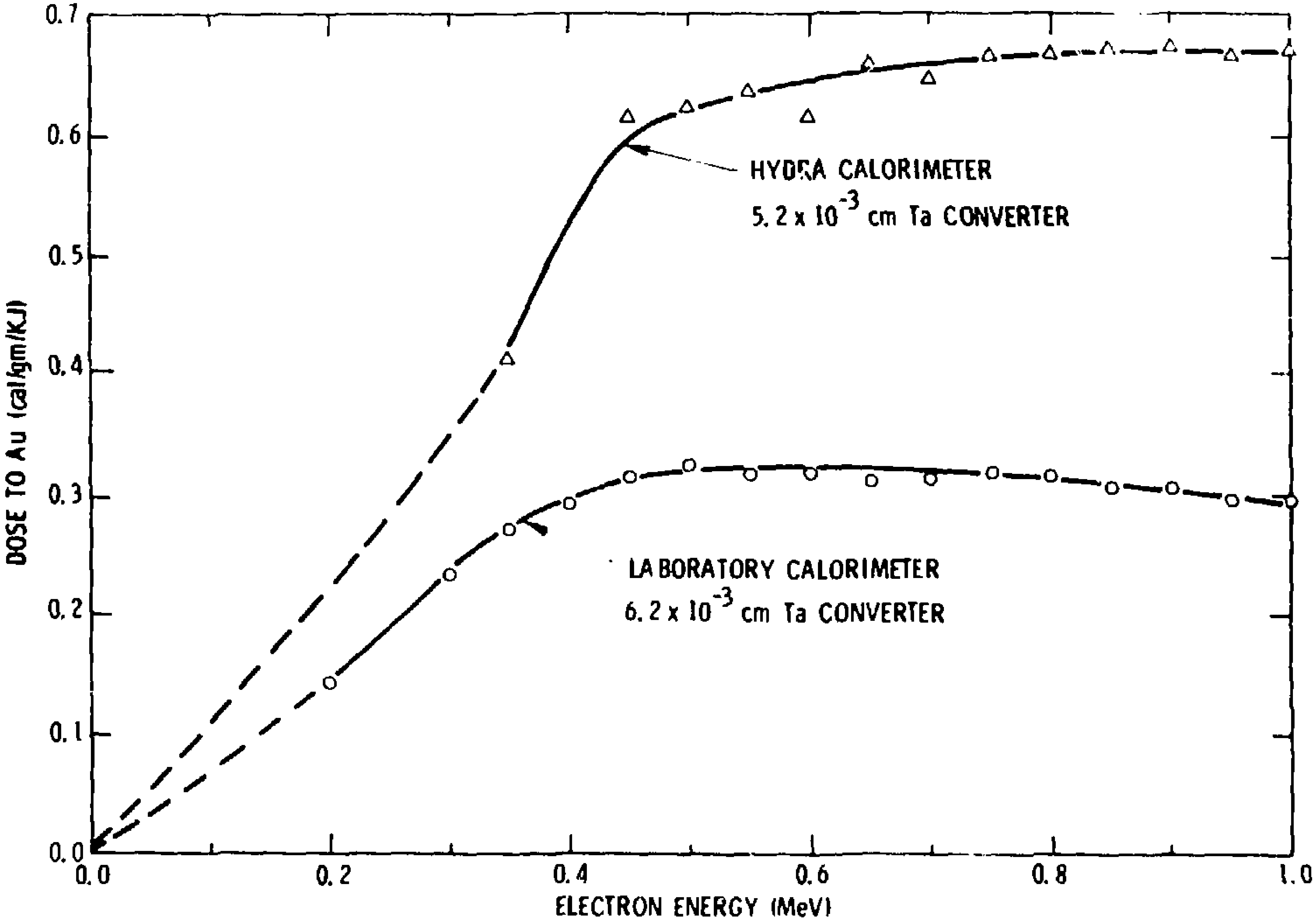

Figure 16. Dose to gold as a function of electron energy for a tantalum converter. For comparison, results of both the Hydra and laboratory calorimeter are shown.

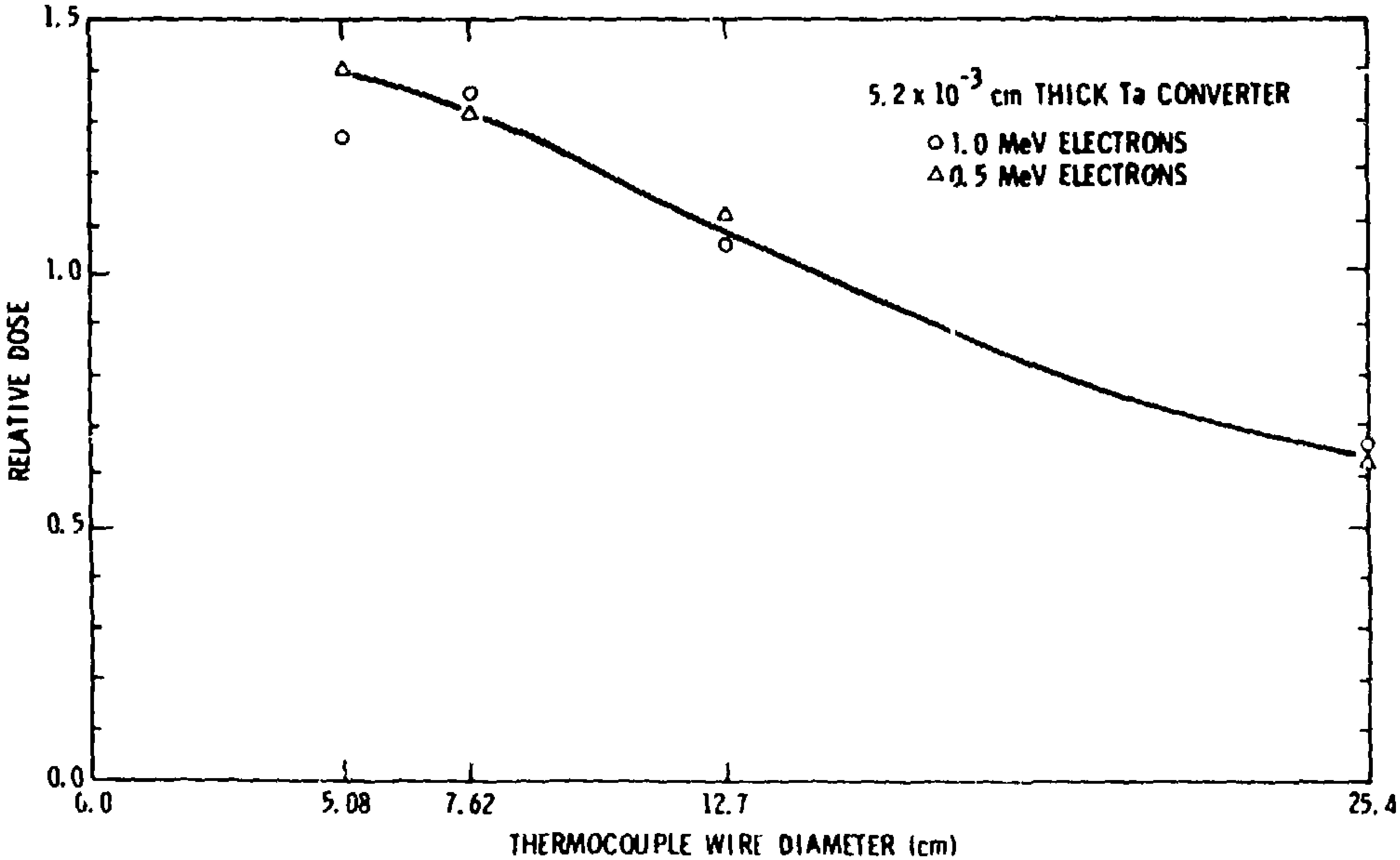

Figure 17. Relative dose as a function of thermocouple wire diameter for Hydra calorimeters

bremsstrahlung deposition in the thermocouple wires at both 1.[illegible] and [illegible].5 MeV. These measurements agree with a SANDYL[4] calculation which predicted 1[illegible] percent direct deposition in the thermocouple wires. Thus the loading effect of the thermocouple wires is due predominantly to thermal loading and radiation dose to the wires is minor.

The effects of thermal loading and dose to the wires for the standard Hydra calorimeter can also be separated using the data obtained from the combination of measurements with the ion-beam energy source and bremsstrahlung measurements. Both effects should be present in the case of bremsstrahlung deposition, while only thermal loading is present when the energy source is the ion beam. When these data were combined, it was found that the calorimeter wires receive very little radiation dose. This result is most important since the laboratory measurements which were used to determine the correction factor for the loading effect were made with an energy source, converter package, and bremsstrahlung spectrum different from that of the Hydra machine. However, because thermal load, which does not depend upon any of the differences mentioned above, is the predominant effect, the laboratory measurement should yield a valid correction factor.

IV. Thermal Loading Correction Factor

The correction factor was determined from the laboratory measurements in two ways. The results of the two different analyses are in excellent agreement. The first method involves calculation of the correction factor from the data obtained with the standard Hydra calorimeter. In the second method, the correction factor is obtained from an analysis of the data obtained when the thermocouple wire diameter was varied.

For bremsstrahlung deposition in the Hydra calorimeter, the expressions for dose to a metal with and without thermocouple wire loading are derived in Appendix I. For the case of no loading, dose to a metal calorimeter, D_c, is given by:

$$D_c = \frac{dv/dt}{(Vi)_e} \frac{C_c}{S} f(t)$$

where dv/dt is the change in thermocouple voltage with time, $(iV)_e$ is the power in the electron beam, C_c is the specific heat of the calorimeter foil, S is the thermocouple sensitivity, and $f(t)$ is a function involving the time constants of the system. Where loading is present, dose to the calorimeter is given by:

$$D_c = \frac{dv/dt}{(Vi)_e} \frac{C_c}{S} f(t) \frac{\left(1 + \frac{M_w C_w}{2M_c C_c}\right)}{\left(1 + \sigma \frac{M_w}{M_c}\right)}$$

where M_w and M_c are the masses of the thermocouple wires and calorimeter foil, respectively, C_w is the specific heat of the thermocouple wire and σ is the fraction of the dose received by the thermocouple wires. The quantity

$$1 + \frac{M_w C_w}{2M_c C_c}$$

is the factor by which the measured dose must be multiplied to correct for thermal loading and the quantity

$$1 + \sigma \frac{M_w}{M_c}$$

is the correction factor for the dose to the thermocouple wires. These factors were evaluated with the aid of an expression for M_w/M_c also derived in Appendix I from consideration of energy deposition by the ion beam during calibration: this ration is given by

$$\frac{M_w}{M_c} = \left[\frac{S}{C_c} \frac{(Vi)_{cal}}{(dv/dt)_{cal}} \frac{f(t)}{4.186\ M_c} - 1\right] \frac{C_c}{C_w}$$

where $(Vi)_{cal}$ is the energy in the ion beam and $(dv/dt)_{cal}$ is the change in thermocouple voltage with time during calibration. All quantities on the left side of the equation are either known, measured, or calculated. Solving this equation gives:

$$\frac{M_w}{2M_c} = [illegible].235.$$

Using this value along with the value of τ = [illegible].7 measured with the bare thermocouple wires, one obtains a correction for thermal loading of 1.75[illegible] and a correction for dose to the thermocouple wires of [illegible].33. Combining these gives a correction factor for the loading effect of the thermocouple wire of [illegible].7[illegible].

To obtain the correction factor from the data of dose versus thermocouple wire diameter, a relation between dose and thermocouple wire diameter is derived in Appendix II. This linear relation is

$$\frac{1}{D_a} = \frac{1}{D_t} + Kd^2$$

where D_a is the apparent dose (measured), D_t is the true dose, K is a constant involving physical properties of the calorimeter, and d is the diameter of the thermocouple wires. Thus, if the reciprocal of apparent dose is plotted as a function of thermocouple wire cross-sectional area, the true dose to the calorimeter foil can be obtained from the intercept. The ratio of the true dose to the apparent dose for the standard 2.54 x $10^{-[illegible]}$ cm thick wire calorimeter is the correction factor. A plot of this type is shown in Fig. 1[illegible]. The correction factor thus obtained is 1.72 which agrees well with the value calculated above. This method is considered to be more reliable than the method previously described, because of the large uncertainty in the value of τ in the other method. Thus the correction factor is taken as 1.72. An uncertainty of ± 5 percent should be attached to this value on the basis of statistical considerations.

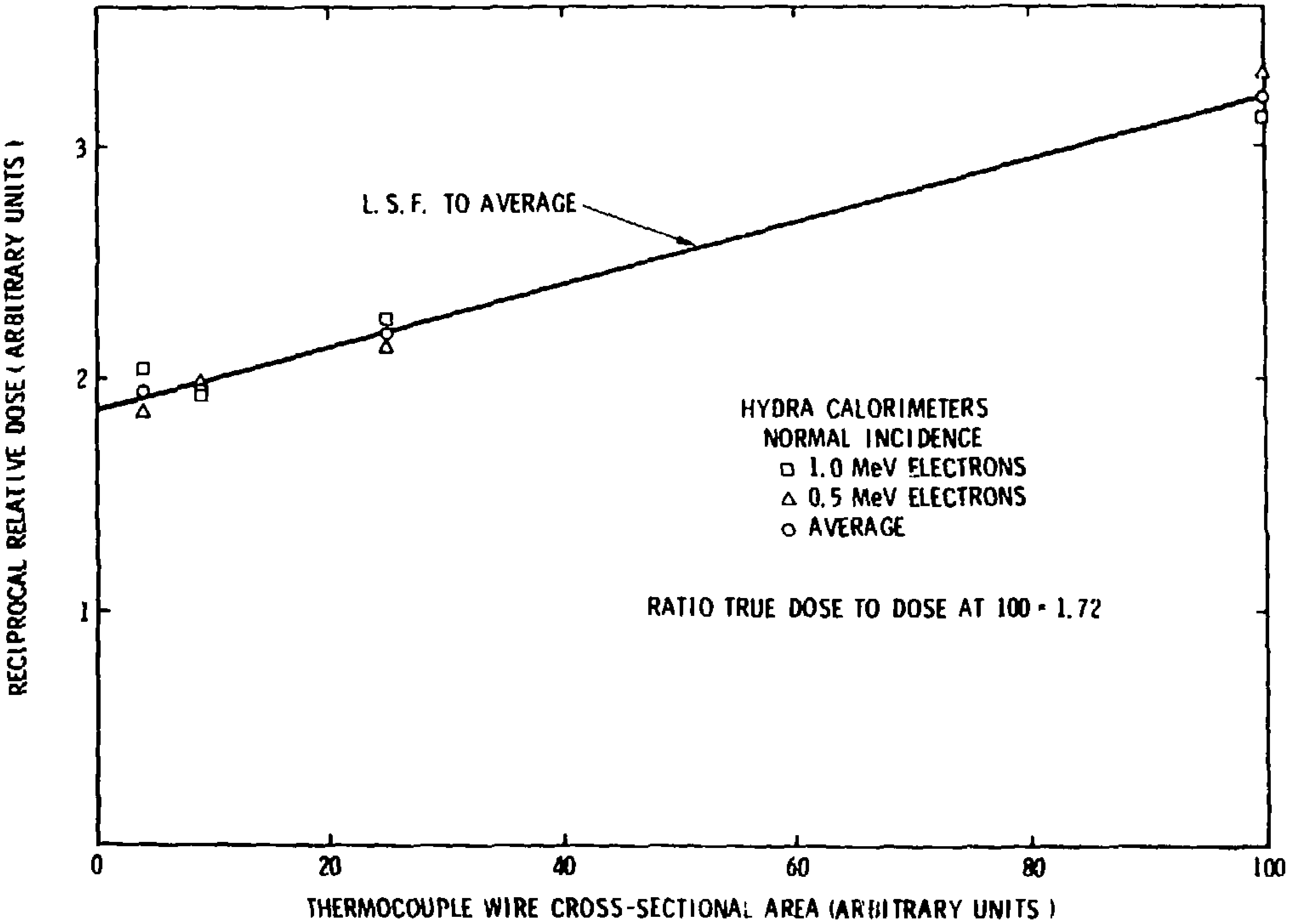

Figure 18. Reciprocal relative dose as a function of the thermocouple wire cross-sectional area for Hydra calorimeters

V. Conclusions

The loading factor correction of 1.72 determined from laboratory measurements is not in bad agreement with the value of 1.5 obtained from data on Hydra, since there is much uncertainty in the Hydra data. The correction factor of 1.72 should be used when determining true dose to gold with the standard Hydra calorimeters.

VI. Acknowledgement

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Appendix I

Loading Effects of Thermocouple Wires

The basic equation for the calorimeter output when used in the square-wave modulation, time-derivative mode is

$$\left.\frac{du}{dt}\right|_{t_o} = \frac{1}{S}\left.\frac{dv}{dt}\right|_{t_a} = \frac{\dot{Q}}{y} f(t_a) \quad , \qquad (1)$$

where:

u = temperature of thermocouple junction relative to heat sink, in degrees C,

S = thermocouple sensitivity, in microvolts per degree C,

v = thermocouple output, in microvolts,

$\dot{Q}$ = rate of heat input, in calories per second,

y = effective thermal capacity, in calories per degree C,

t_a = the time measured from beam switch at which the derivative is taken, and

$f(t_a)$ = the dependence on t_a, the time constant τ, and the modulation period, t_o.

The explicit form of $f(t_a)$ is:

$$f(t_a) = \left[1 + e^{-\frac{t_o}{2\tau}}\right]^{-1} e^{-\frac{t_a}{\tau}} \quad . \qquad (2)$$

The effective thermal capacity is made up of contributions from the calorimeter and the thermocouple wires. Thus:

$$y = (MC)_c + 0.5\ (MC)_w \quad , \qquad (3)$$

where subscripts c and w refer to the calorimeter and the wires, respectively.

The mass and specific heat are M and C. At this point, the mass of wire is unknown, since the length at which the temperature is effectively zero is not known. The factor of 0.5 in the second term results from the assumption that the temperature decreases linearly with distance along the wires.

During the calibration procedure (using the ion beam technique), the heat input rate is given by:

$$\dot{Q}_{cal} = \left(\frac{Vi}{4.186}\right)_{cal} , \tag{4}$$

where V and i are the accelerator voltage and current, respectively. Thus from (1), (3), and (4), one obtains:

$$(MC)_c + 0.5\ (MC)_w = \left(\frac{Vi}{dv/dt}\right)_{cal} \cdot \frac{S\ f(t_a)}{4.186} . \tag{5}$$

or:

$$\frac{M_w}{M_c} = \frac{2C_c}{C_w}\left\{\frac{1}{(MC)_c}\left[\frac{S\ f(t_a)}{4.186}\left(\frac{Vi}{dv/dt}\right)_{cal}\right] - 1\right\} . \tag{6}$$

Since all quantities on the right are either measured or known, the ratio can be evaluated, and in fact the effective wire length can be determined

In measuring the bremsstrahlung dose to the calorimeter, there is an additional effect due to deposition of energy directly in the wires. It is assumed in what follows that this makes very little change in the temperature distribution along the wires; i.e., that the energy deposited in the wires is small compared to that deposited in the calorimeter. With this assumption, Eq. (1 becomes:

$$\frac{1}{S}\frac{dv}{dt}\bigg|_{t_a} = \frac{\dot{Q}_c + \dot{Q}_w}{(MC)_c + 0.5(MC)_w} f(t_a) .$$

In terms of dose, $\dot{Q}_c = D_c M_c (Vi \times 10^{-3})$, where D_c is the dose in calories-gm^{-1}-kJ^{-1}, so that $Vi \times 10^{-3}$ is the electron beam power in kilowatts. In like manner, $\dot{Q}_w = D_w M_w (Vi \times 10^{-3}) = \alpha D_c M_w (Vi \times 10^{-3})$, where $\alpha = D_w/D_c$. We then obtain:

$$\frac{1}{S} \left.\frac{dv}{dt}\right|_{t_a} = \frac{Vi \times 10^{-3} \, D_c M_c \left[1 + \alpha \frac{M_w}{M_c}\right] f(t_a)}{(MC)_c + 0.5 \, (MC)_w} \quad . \tag{7}$$

The only quantity which is neither measured (in the experiment or in the calibration) nor known is α. Since it is expected to be small, an approximate value is all that is necessary. This can be obtained from a very crude experiment in which the thermocouple junction is thermally isolated (disconnected from the calorimeter) and the bremsstrahlung signal is measured. This must be done with the calorimeter foil in place, so that the same shielding effect is present. This tends to overestimate the dose, due to the reduction in thermal capacity. Thus the value of α obtained by this procedure should be considered as an upper limit. Combining (7) and (5), one obtains:

$$D_c = \frac{\left(\frac{Vi}{dv/dt}\right)_{cal}}{4.186 M_c \left(1 + \alpha \frac{M_w}{M_c}\right)} \cdot \frac{dv/dt}{Vi \times 10^{-3}} \quad , \tag{8}$$

which is the equation used to obtain the corrected dose.

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Appendix II

Effect of Wire Diameter on Thermal Loading

If one disregards the thermal loading effect of the wires, he obtains an apparent dose, D_a, which is contained in the following equation:

$$\frac{1}{S}\left.\frac{dv}{dt}\right|_{t_a} = \frac{Vi \times 10^{-3} \times D_a \times M_c}{M_c C_c} \cdot f(t_a) \quad .$$

Inclusion of wire thermal capacity, on the other hand, leads to the true dose D_t by the following equation:

$$\frac{1}{S}\left.\frac{dv}{dt}\right|_{t_a} = \frac{Vi \times 10^{-3}\, D_t \times M_c}{M_c C_c + \frac{\pi d^2}{4}\rho_w C_w \ell_w}\, f(t_a) \quad .$$

Here ℓ_w is the "effective" length of the wires, that is the length at which the temperature rise is negligible. The density of the wire is ρ_w and its diameter is d. Note that since the two wires are of different materials, the product $\rho_w C_w \ell_w$ is the average of that product for the two wires. The quantity on the left is observed experimentally, so the two expressions on the right side of the two equations may be equated. This gives

$$\frac{1}{D_a} = \frac{1}{D_t}\left[1 + \frac{\pi}{4}\frac{\rho_w C_w \ell_w}{M_c C_c} d^2\right] \text{, or}$$

$$\frac{1}{D_a} = \frac{1}{D_t} + Kd^2 \quad .$$

Note that D_t is a factor in K. Since it is a constant the linear relationship between $\frac{1}{D_a}$ and d^2 is preserved. While in principle D_t could be obtained from the slope, the intercept provides a more straight-forward determination.

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