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DRY THERMAL INSULATION OF THICK CLOTHING

by

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FOREWORD

This is one of a series of reports in the general field of wool type fabrics and alternates to conserve wool, with special reference to the physical features by which clothing structures contribute to the protection and effectiveness of the soldier.

This report was prepared by Harris Research Laboratories under Contract No. DA 19-129 QM 1336, Headquarters Quartermaster Research and Engineering Command, Quartermaster Research and Engineering Center, U.S. Army, Natick, Massachusetts. The contract, entitled "Investigation of Properties of Synthetic Fibers in Blends with Wool," was initiated under Project No. 7-93-18-020A, Development of Alternate Fabrics to Conserve Wool: Task: Development of principles to improve the insulating characteristics and "comfort" of textile fabrics combinations, and was administered under the direction of the Textile, Clothing and Footwear Division, Headquarters Quartermaster Research and Development Center with Mr. Constantin J. Monego acting as project leader.

This material is contractor's Report No. 31, for the quarter ending March 11, 1959, the first quarter of this contract.

INVESTIGATION OF PROPERTIES OF SYNTHETIC
FIBERS IN BLENDS WITH WOOL

Contract No. DA-19-129-QM 1336
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Contractor's Report No. 31

DRY THERMAL INSULATION OF THICK CLOTHING

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SUMMARY

This report presents a physical analysis of an insulated cylinder system in use in this laboratory and insulating values or thermal resistances per unit thickness obtained on certain types of clothing materials under dry conditions. The thermal measurements are made in terms of thickness while in place in the tests, and include the effect of thickness decrease and density increase brought about by bending to fit on the test cylinder. There is more change of thickness for thick foam or batt materials than for woven fabric layers, which is one factor involved in use in clothing that is not involved in tests on flat plates.

The over-all heat flow rates, or over-all thermal resistance of clothing assemblies, which have been used for greater-than-or-less-than comparisons in previous reports, have been refined to come closer to being

measurements of the thermal resistance of particular layers, by making more accurate corrections for heat losses through the insulated ends of the test equipment, and by measuring temperature gradients through the clothing itself. As a system for measuring thermal resistance, the cylinder used in this laboratory is best suited to layers ranging in thickness from 0.2 to 2.0 or 2.5 cm. This extends to heavy arctic or flying clothing. At the still greater thicknesses required for sleeping bag materials and building insulation, the effect of further insulation on the sides becomes small, and the results increase in variability. Since two independent methods of measuring rate of heat transfer, one in steady state, the other in cooling, are applied in each test, the accuracy of the methods can be determined by comparison, showing that within the optimum range, thermal insulation can be measured with $\pm$ 0.035°C m^2/watt or about $\pm$ 0.2 Clo unit as the root mean square deviation of the cooling method and the steady state method from their average, in one pair of tests. Since the variability is random from test pair to test pair, a modest replication can considerably improved the measurement.

The intrinsic thermal resistance of a polyurethane foam was found to be 0.30° C m^2/watt cm or 4.9 Clo per inch. This appears to be more insulation per unit thickness than for woven fabrics. Results obtained on thick layers of batting are much more variable, and are likely to error on the low side. Allowing for this, intrinsic resistance similar to foams is indicated. While the usual "practical" value for clothing plus air layers is 4 Clo/inch, the thermal conductivity for still air is close to 7 Clo per inch, so these thick, low density layers of foams or batts may offer a real increase in insulation over woven or knitted textile structures.

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DRY THERMAL INSULATION OF THICK CLOTHING

I. PURPOSE

The basic purpose of this report is to establish a more quantitative and accurate basis for comparisons of over-all rates of heat loss, and measurement of the effects of separate layers of material within the total system. With more accurate knowledge of dry clothing systems the heat loss by mechanisms involving water or water vapor can be more accurately compared with the mechanisms which operate in dry clothing. The tests involved in the present report were all with dry clothing.

In earlier reports, the combined or over-all cooling through clothing assemblies by all routes including evaporation, if this was involved, has been measured in either of two ways:

a. Steady state method, in which power supply is adjusted to secure a constant, selected internal temperature.

b. Cooling method, in which the power supply is reduced or cut off, and internal temperature is followed until a new steady state or final temperature is established. The exponential cooling law is used to determine the rate of heat transmission by all mechanisms combined.

Each of these methods can be used to make "greater, equal or less than" comparisons between the over-all heat loss rates for any pair of clothing assemblies or conditions. The comparisons are sharpened, however, if the losses through the clothing assembly itself can be isolated from the losses through the insulated ends of the test system, and if the thermal resistance of the clothing itself can be separated from that of other layers, including the air film outside the clothing, between it and the general environment.

In recent work on thick clothing it is especially desirable to determine the end losses with greater accuracy, since with thick clothing the total loss from the whole system comes to be not much larger than the end loss correction alone. The need for accuracy in the end loss correction is greater, of course, the larger the fraction which the end loss is of the whole loss. In Report 24 of this series (1) a calculation of the correction for the cooling method was made, using published values (2) for the thermal insulation of dry cotton. Subsequent work, reported here, gives general confirmation of this calculation.

The present purposes also include obtaining data on certain clothing materials, particularly batts of polyester fiber, and on polyurethane foam structures.

II. EXPERIMENTAL METHODS

Equipment, test procedure:

All of the work in this report deals with one test facility, the "cold box" or "cold wind tunnel" cell or "arm", a hollow brass cylinder two inches in diameter, with 7.4 inches working length for clothing cover. This is sketched in Figure 1. The two ends of the cylinder are insulated by rectangular blocks approximately 2 inches thick, 4 inches high, and 4 inches broad, into which the metal ends of the cylinder extend about one inch. One of these is simple insulation, a light but stiff foamed structure; the other is an air filled wood and plastic box used for support of the electrical connections. The chief feature is that both ends provide roughly an inch of rather good insulation, so that for relatively thin layers of clothing, the major path for loss is through the sides. In all tests discussed here, the wind tunnel was operated at

5 miles per hour air speed, with air at from -2 to -4° C., so that the environment into which heat is lost is constant. The cold environment is maintained by a deep freeze chest with thermostatic control.

As a preliminary to every cooling curve, a steady state period has been established, so that both methods of measurement are available for each test of each material. The first period corresponds to a period of activity at a high metabolic rate, and, when relations of clothing with water are being investigated, with evaporation of sweat from a water carrying chamois layer in immediate contact with the brass cell. During this period water vapor if present moves through and in part is condensed within the clothing layers. Since the area of the sides of the cylinder is 0.0315 m^2, each watt flowing through the sides corresponds to 27.3 Kg cal/m^2 hr.

Whether the test is one in which water is present or not, the first period operation continues until a steady supply of electric power maintains a steady body temperature, usually 30.0° C. at the point of measurement. The criterion of success in this adjustment, which is made manually and stepwise by the observer, is that the temperature should be steady within 0.1° C. for at least 5 minutes. The watts power supplied refer to this steady period, not to preliminary adjustments.

Following the steady state period of exercise or sweating, the power is reduced to a low level corresponding to metabolism of a man at rest or "pinned down," or the power may be cut off. If power continues at a lower level, the cooling observations must be continued for about 120 minutes to find the new steady state internal temperature; if the power is cut off, the final temperature is taken as that of the cold environment.

Site of temperature measurement:

One experimental detail which makes a degree of difference in the results is the site of temperature measurement, for the internal or body temperature. In most of the work, this has been a thermistor, in contact with the end of the metal cylinder, and protected by the insulation of the box carrying the electrical contacts. This temperature is designated as T_b.

In more recent work, the surface temperature of the chamois layer covering the brass cylinder has been measured, by a nickel wire resistance grid which averages the surface temperature. This surface temperature of the body under the clothing has been designated T_s. In the presentation of the experimental results, attention is drawn to which site is involved.

In general, T_b and T_s are not the same, but the differences do not exceed a few degrees in some 33° C. temperature span from body to air. The range of these differences is shown in Figure 2a. These differences arise because the two temperature measuring sites are analogous to the galvanometer terminal points in a Wheatstone bridge electrical circuit, as diagrammed in Figure 2b. There is a pair of internal thermal resistances, between each site and the source of heat, and another pair of external thermal resistances, between each site and the cold environment. The external resistance of the ends, E_b, is constant, but that of the sides, E_s, varies with the amount of clothing used in the tests. Since the internal resistances I_b and I_s are also constant, there is only one amount of clothing for which the "bridge" can be in "balance", that is, $T_b = T_s$ only when

$$\frac{I_b}{E_b} = \frac{I_s}{E_s} \qquad (1)$$

The variation between T_b and T_s is kept at a small value because the internal resistance are quite small relative to the external ones, and because, unlike the electrical analogy, there is practically a "short circuit" between T_b and T_s, through the metal test cylinder.

Grid arrangements for layer measurements:

Another experimental detail which matters in determining the resistance of given layers is the location of the grid of wire used for measuring temperature, with respect to the fabric layer which supports the wire, and with respect to the layer of clothing material. The temperature measuring grids were made of No. 38 high purity nickel wire with double enamel insulation, this material being chosen for its high temperature coefficient of resistance (7). The supporting fabric for the grids is 9 oz. cotton sateen in all the tests involved in this report. Other support materials have been used in later tests. The wires were attached by feeding from the shuttle of a sewing machine, so that the regular sewing thread, carried by the needle, binds the wire to one surface of the fabric. Thus the thermal resistance of the fabric carrier is all on one side of the temperature measuring wires.

The arrangement used in all of the tests with grids in this report is that the wire sides were facing the layer of material to be tested so that the temperature difference from inside to outside, T_i-T_o, measures the gradient through the fiber assembly under test, plus only that of any air layers between test material and grid. Such air layers are kept to a minimum by firm wrapping and the use of rubber bands or pins to hold the layers securely.

It should be noted that a grid gives an average temperature at a particular level or radius in the assembly. While the work of Fonseca, Pratt, and Woodcock (8) shows that the temperature of the surface of a cylinder in wind is not uniform, a grid gives a closely spaced average over the whole area which is suitable for the present calculations. Measurements of individual layers which can be made in an individual test, are possibly more precise comparisons of layers than are the comparisons which can be made without grids, by means of differences in total resistance of the sides.

III. ANALYSIS AND CALIBRATION

Considerations from definition of thermal resistance:

In order to have better understanding in discussion of thermal resistance of materials such as fabrics or clothing layers, it is helpful to review the ideas of resistance and resistivity in application to textile layers. By analogy with Ohm's law for flow of electricity, the flow of energy, W, measured in watts, can be equated to the ratio of the potential, which is temperature difference, T_2-T_1, divided by thermal resistance, R_h:

$$W = \frac{T_2 - T_1}{R_h} \qquad (2)$$

The term "thermal ohm" has been proposed for resistance such that the flow rate is one watt for 1° C. temperature difference (3).

This defines R_h, the resistance in thermal ohms, as a characteristic of a physical system without regard to cross section or thickness, and is the sense in which thermal resistance is used in the discussion of the Wheatstone bridge analogy for the two temperature measuring sites. However, it is also desirable to define the thermal resistance of unit area of a layer of material. If we take R as the thermal resistance of unit area (1 square meter) of a layer, and recall that the heat flow will be proportional to the area, A, or the resistance of the system inversely proportional to the area, we have

$$W = \frac{(T_2 - T_1)A}{R} \quad \text{or} \quad R = \frac{(T_2 - T_1)A}{W} \tag{3}$$

This shows that the dimensions are (area x thermal resistance) and that it would be helpful to think of this property of layers as "area•resistance." The unit of area•resistance can be written as 1°C m^2/watt or 1 m^2 thermal ohm. The complexity of thinking and writing this area•resistance unit in terms of its basic quantities can be avoided by using more convenient practical or specially named terms. The "tog" unit proposed by Peirce and Rees (4) is 0.1° C. m^2/watt, one tenth of the square meter•thermal ohm unit. The "clo" unit (5) is 0.18°C m^2hr/Kg cal, or 0.155°C m^2/watt, or 1.55 togs. Conversely, 1°C m^2/watt or 10 togs is 6.46 clo.

We can further define, for a given material, a specific resistance, R_1, that of unit area and unit thickness, so that $R = x R_1$, where x is the thickness. R_1 is a unit of resistivity, °C m^2/watts cm thickness. Practical units of resistivity or specific resistance can be tog/cm or clo/inch. These units are related as follows:

1°C m^2/watt•cm = 10 tog/cm = 6.46 clo/cm = 16.4 clo/in.

0.061°C m^2/watt•cm = 0.61 tog/cm = 0.394 clo/cm = 1 clo/in.

In the discussion which follows, unless specially designated as specific resistance in resistivity units such as clo/inch we shall be concerned with area resistance, or resistance of unit area of some layer or series of layers, for example all the covering on the sides, R_s, or the air film between the outside of the clothing and the general environment, R_a, or of the clothing material, R_c.

<u>Analysis of steady state heat loss (dry)</u>:

In the absence of evaporation, the whole heat loss may be taken as proportional to the temperature difference. This is equivalent to asserting that radiation, conduction, and convection all combined are proportional to the first power of the temperature difference, which is approximately true for small ranges of temperature.

If R_s is the total thermal resistance of unit area of the sides of the cylinder, with area A_s, and if the effective ratio of area of ends to resistance of ends is E, then for temperature difference $(T_b - T_a)$ from the "body" inside to the air outside:

$$W = (T_b - T_a)\left(E + \frac{A_s}{R_s}\right) \qquad (4)$$

where W = watts supplied, while the system is operating at constant internal "body" temperature T_b. Similar relations hold if T_s, the body surface temperature, is used.

The effective equivalent area of the ends, and the thermal resistance of the ends, or their ratio, E, can be taken as constants. The resistance of unit area on the side, though, is composed of R_a, the resistance of unit area of the air layers outside the clothing, plus nR_g, the resistance of unit area of any layers, n in number, carrying temperature measuring grids, such as are used in some of the tests, plus R_c the resistance of unit area of the clothing. With different thicknesses of a given material, in which the intrinsic thermal resistance of unit area is R_1 per unit thickness, the clothing resistance becomes $(r_2-r_1)\ R_1$, where r_2 is the outer radius of the clothed assembly, and r_1 the inner radius of the clothing, or outer radius of the cylinder itself.

With increasing thickness, A_s the area of the sides increases, so that the appropriate area for heat transfer using radius difference as a measure of thickness is the logarithmic mean area, A_m, as discussed by McAdams (6):

$$A_m = \frac{2\pi L(r_2-r_1)}{2.3 \log_{10} (r_2/r_1)} \qquad (5)$$

In this, L is the length of the clothed side of the cylinder. Combining:

$$\frac{W}{T_b-T_a} = E + \frac{A_m}{(r_2-r_1)\ R_1 + nR_g + R_a} \qquad (6)$$

With relatively thick layers of clothing, the clothing resistance R_c or $(r_2-r_1)\ R_1$, becomes large compared with the grid resistances nR_g and the air resistance, R_a. R_a is kept at a low value by the constant air stream past the cylinder. Hence with thick clothing, we have:

$$\frac{W}{T_b-T_a} = E + \frac{A_m}{(r_2-r_1)\ R_1}, \text{ approx.} \qquad (7)$$

Hence, if $A_m/(r_2-r_1)$ is plotted against $W/(T_b-T_a)$, an approximate straight line should result, which is more straight for large values of (r_2-r_1), and hence for small values of $A_m/(r_2-r_1)$. This also involves the assumption that R_1 is constant throughout the thickness, and, if more than one material is involved, for all the materials. The intercept at $A_m/(r_2-r_1) = 0$ gives a value for the end loss correction, in watts per degree,

$$E = \frac{W_e}{T_b - T_a} \qquad (8)$$

Hence Eq. 6 can be rewritten

$$\frac{W-W_e}{T_b-T_a} = \frac{A_m}{R_s}, \text{ or } R_s = A_m \frac{(T_b-T_a)}{W-W_e} \qquad (9)$$

End loss calibration, steady state:

End loss calibrations have been carried out using both T_b and T_s as indicators of body temperature. For calibration purposes, only tests in which both T_b and T_a were available have been used, so that both calibrations are based on the same group of tests. For parallel presentation, figure numbers are followed by b for data based on T_b, and by s for data based on T_s.

Figures 3b and 3s show data obtained with a number of materials in a wide range of thicknesses, from one layer of wool serge to more than an inch of batting. The least mean square deviation line has been drawn on each chart, giving the extrapolated values for W_e, based on T_b, of 0.114 watts/°C. and based on T_s, of 0.0864 watts/°C. However, owing to the approximations involved in using different materials, and in using the radius difference, (r_2-r_1) instead of the whole resistance these are not regarded as the best values for calculations of resistance. It may be noted, however, that a fairly linear relation is found. Comparison with the cooling method provides a basis for more precise choice of a "best" value, as is developed in further discussion.

Analysis of heat loss during cooling:

During cooling tests, the power supply is either low or zero, so that T_b, the body temperature of the system cools from T_w, the steady state temperature with full power, to T_f, the final steady temperature. With a low supply of power this is the temperature reached after about two hours of cooling, that is, when no change is observed in 10 minutes. With the power completely off, it is the temperature of the cold wind tunnel.

Making the same assumption that the rate of heat loss is proportional to the temperature difference, T, we have

$$\frac{dH}{dt} = -a\,T \qquad (10)$$

where a is a constant of proportionality, the over-all rate of heat loss. Furthermore

$$dH = 4.186\ C_p dT \qquad (11)$$

where C_p is the heat capacity of the "body," in gram calories per degree. The factor 4.186 converts the heat capacity to watt seconds per degree. Combining, integrating, and evaluating the constant of integration at t = o, the time the cooling starts,

$$2.3 \log (T_t - T_f) = \frac{-at}{4.186C} + 2.3 \log (T_w - T_f) \qquad (12)$$

where T_t is temperature at any time, T_f is final temperature, and T_w is original steady state temperature, when heat flow = W watts.

Hence, by plotting the logarithm of the difference from the final temperature, log $(T_t - T_f)$, against time in minutes, one can determine the slope, m, of this line, which corresponds to $-a/4.186C_p$. Since m from such a plot is in reciprocal minutes, a factor of 60 is required to convert it into seconds, the unit of time in Eq. 12.

Hence

$$\frac{m}{60} = \frac{a}{2.3\ C_p\ 4.186} \qquad (13)$$

However,

$$a = E + \frac{A_m}{(r_2 - r_1)\ R_1 + nR_g + R_a} = E + \frac{A_m}{R_s} \qquad (14)$$

So

$$\frac{2.3 \times 4.186\ mC_p}{60} = E + \frac{A_m}{R_s} \qquad (15)$$

By the same approximations as for the determination of end loss in the steady state, m can be plotted against $A_m/(r_2-r_1)$ to determine m_e at $A_m/(r_2-r_1) = 0$.

Thus the over-all thermal resistance of unit area of the sides, R_s, can be calculated in units of °C m^2/watt

$$R_s = \frac{60\ A_m}{2.3\ (m-m_e)\ C_p\ 4.186} = \frac{A_m\ 6.224}{(m-m_e) C_p} \qquad (16)$$

and compared with the values derived from the steady state by Eq. 9, providing that C_p is known. The effective value of C_p can be determined by comparison of the steady state method with the cooling method, and is discussed after considering the calibration of the cooling method.

<u>End loss calibration, cooling</u>:

The plots of log of temperature difference against time for individual tests do give good straight lines, indicating that the exponential cooling process is a good empirical description, that is, that within this range heat loss is proportional to temperature difference. From these plots, m is determined for each cooling test, on the basis of change of body temperature measured at the end of the cylinder, T_b, or, when the grid was used, on the basis of change of surface temperature, T_s. Figures 4b and 4s show m plotted against $A_m/(r_2-r_1)$ for the same sets of tests that were used to establish W_e. For Figure 4b, the temperatures are body temperature T_b measured on the end by a thermistor, and for Figure 4s, body surface temperatures.

As in Figures 3b and 3s, least square deviation regression lines have calculated and drawn on the charts, to determine the intercepts, for m_e based on T_b, 0.00604, for m_e based on T_s, 0.00555.

From comparison of these values, and the extrapolated values of W_e obtained earlier, with the general relation of steady state and cooling methods, best values for calculation are obtained.

Correction of calibration by comparison of the two methods:

In each individual test, data on a given insulating system are obtained by both the steady state and the cooling method. From one individual test to another, the insulation on the sides is varied, but not that on the ends. Hence the whole range of tests permits comparison of the two methods at a series of points corresponding to the various amount of insulation used on the sides.

The comparison of the two methods can be carried out by noting from Eq. 4 and Eq. 15 that in all the tests E is constant, and in any one test under dry conditions A_m/R_s is constant for the two portions, steady state and cooling, so that a linear relation exists

$$\frac{W}{T_b - T_a} = m \frac{C_p}{6.224} \tag{17}$$

which should pass through the origin.

Such comparisons, plotting W/°C. against m, are presented in Figure 5b for data based on $(T_b - T_a)$ and in Figure 5s for data based on $(T_s - T_a)$, for the set of tests in which both T_b and T_s are available. The data do fall on good straight lines in each case, and do seem compatible with a line through the origin. The regression line, passing through the origin, for least mean square deviation, has been drawn in each figure.

These comparison charts can be used to improve the extrapolations for W_e, from Figures 3b and 3s, and for m_e, from Figures 4b and 4s, since the point W_e, m_e should also fall on the straight line. The extrapolated values for W_e and m_e are shown in each figure by a cross, which is near but not on the line.

Standard error of estimation has been calculated for the regression lines in Figures 5b and 5s: for Figure 5b, the standard error of estimating m from W is 0.00070; for Figure 5s, 0.00058. The displacement of the extrapolated points in each figure falls close to one standard error of estimate. Hence the approximations involved in the extrapolations fall well within the statistical group defined without such approximations. With the guidance of the approximate values from extrapolation, it is possible to take the nearest rounded values on the line as calibration values. The values so chosen are:

Basis	W_e	m_e
T_b	0.11	0.0065
T_s	0.09	0.005

The values for m_e are in general agreement with the calculation from the thermal insulation of dry cotton, $m_e = 0.005$, discussed in Report 24 of this series (1).

Heat capacity of the system:

The heat capacity, C_p, of the portion of the system for which the temperature change is being measured in cooling, is an important part of the calculation of thermal resistance, by the cooling curve method.

The heat capacity is made up of that of the brass cylinder and heater, the chamois skin and any water used in the cover. In dry conditions, calculation from weights and published heat capacities gives an estimate of 100 g calories per degree. This value has been used in calculations for dry conditions in earlier reports.

A check on effective heat capacity can be obtained by comparison of thermal resistances by the two methods. The comparisons of the two systems of measurement, in either Figure 5b or Figure 5s, give the ratio of m to $W/(T_b-T_a)$ or $W/(T_s-T_a)$. Equation 17 can be rewritten:

$$C_p = \frac{W/(T_b-T_a)}{m} \quad \frac{60}{2.303 \times 4.186} \tag{17}$$

Taking the slope of the lines as establishing the ratio $W/(T_b-T_a)$ divided by m, we have, based on T_b, that C_p = 105.3 gram calories per degree, and from T_s, that C_p = 109.5 calories per degree. These calculations are in general agreement with the estimate of 100 g cal per degree from weights and published specific heats. Thus the heat capacity of the thermal reservoir appears to be nearly the same for either site of temperature measurement, with 107 g cal/°C. a useful rounded value for either method. Hence the constants in Eq. 16 can be completely evaluated, and this equation used to determine R_s, the whole resistance of unit area on the sides of the cylinder.

<u>Thermal resistance calculations, steady state:</u>

The most convenient measurement of thermal resistance of a clothing layer, given the calibration factors, is to use the end loss corrections on the basis of T_b measured at the end of the cylinder, (or from T_s, measured at the surface) and from this establish the watts through the sides:

$$W_s = W - W_e \tag{18}$$

$$W_e = 0.11\ (T_b-T_a) \qquad (19b)$$

$$W_e = 0.09\ (T_s-T_a) \qquad (19s)$$

Then the thermal resistance of the sides can be calculated from the temperature gradients between levels through which W_s must pass in series:

T_s = surface temperature of cylinder

T_i = interior grid beneath clothing, outside the grid support

T_o = outer grid, outside clothing, inside the grid support

T_a = air temperature

Because the wire grids are arranged to be next to the clothing material, the temperature difference T_s-T_i corresponds to the thermal resistance of the inner sateen which carries the wires of the inner grid, and the temperature difference T_o-T_a corresponds to the thermal resistance of the outer sateen layer plus that of the air film outside the clothing.

In calculating thermal resistance, an appropriate area must be used. If we consider thick clothing, or the sides as a whole, the appropriate area is A_m as defined in Eq. 5. For the air layer outside, R_a, plus the outer grid carrier, R_{g2}, a better approximation is obtained by using A_2, the area corresponding to r_2, the outside radius of the clothing measured over the outer grid. For the innermost grid the appropriate area is A_1, corresponding to r_1, the radius over the inner grid. On this basis, the whole resistance on the sides, for unit area (1 sq. m), is:

$$R_s = \frac{(T_b - T_a)}{W_s} A_m, \text{ (approx.)} \tag{20}$$

If T_s is available by direct measurement or by calculation from T_b and the total power, W, a better measurement is obtained

$$R_s = \frac{(T_s - T_a)}{W_s} A_m \tag{21}$$

The empirical relation of T_s and T_b, for the data shown in Figure 2a, in which T_s was held constant at 30.0° C. in all cases, is

$$(T_s - T_b) = 5.6 - 0.51W \tag{22}$$

The resistance for unit area of the first or inner grid, and the air layers associated with it, is

$$Rg_1 = \frac{T_s - T_i}{W_s} A_1 \tag{23}$$

The resistance for unit area of the clothing

$$R_c = \frac{T_i - T_o}{W_s} A_m \tag{24}$$

The resistance for unit area of the outside air plus the outer grid carrier is

$$R_a + Rg_1 = \frac{T_o - T_a}{W_s} A_2 \tag{25}$$

IV. RESULTS FOR MATERIALS

Results for two kinds of layers are contained in the data. One is the measurement of a clothing layer, by means of the grids on each side of it which is directly related to the general interest, the evaluation of clothing materials. Another set of layers which are measured in the tests are the constant layers, the inner grid and the outer grid plus air film. The results on these are only indirectly concerned with the general evaluation of clothing materials. However, since one would expect the inner and outer resistances to be independent of the total resistance, that is, of thickness, a check of this point indicates whether the actual performance of the equipment corresponds to the theory as developed in the analysis. In principle, resistances of grid and air film could be subtracted from the whole resistance of the sides, to obtain the resistance of the clothing alone. However, the experimental results indicate that these grid and air film resistance as calculated are not in fact independent of thickness, so, while empirical relations are available, it is better to limit the results to the more direct measurement of clothing layers between grids, or to the whole resistances of the assemblies.

<u>Resistance of inner grid</u>:

The measurement of T_s at the chamois surface and T_1 at the inside of the fabric permits direct calculation of Rg_2 for the inner grid. The upper part of Figure 6 shows this in comparison with radial thickness, indicating that Rg_1 appears to increase with increasing assembly thickness. The regression line for least mean square deviation, is:

$$Rg_1 = 0.0148 + 0.0277\ (r_2 - r_1) \qquad (26)$$

The exact reasons for this lack of independence from thickness are not known, although some of the possibilities can be considered after examining the results for the outer layer, which should also be independent of thickness of assembly.

<u>Resistance of outside air film and outer grid</u>:

The differences between the temperature of the outer grid layer and the external air furnish an indication of the combined resistance of the fabric carrying the outer grid plus the resistance of the film layer of air outside the assembly. The lower chart in Figure 6 shows $Rg_2 + R_a$, and the difference between this and the corresponding observation of Rg_1, which is an estimate of R_a. The least mean square regression lines are:

$$Rg_2 + R_a = 0.1170 + 0.0422\ (r_2 - r_1) \qquad (27)$$

$$R_a = 0.1022 + 0.0145\ (r_2 - r_1) \qquad (28)$$

Another set of data for $R_{g2} + R_a$ is available, with end loss corrections based on T_b instead of T_s. The additional tests for which only data based on T_b are available, including ones at greater thickness, are shown in Figure 7, along with the regression line determined for the data based on T_s, from Figure 6. The regression equation for the "T_b only" data shown in Figure 7 is:

$$(R_{g2} + R_a)_{T_b} = 0.021 + 0.076\ (r_2 - r_1) \qquad (29)$$

The fact that there is a rising trend of apparent resistance of the inner grid, and of the outer grid plus air film, with increasing thickness or total resistance, indicates that the analysis of the heat flow in the test system is only approximate. However, where the resistance of the clothing material is a major part of the whole resistance on the sides, useful estimates of resistance of materials can be obtained. While the variation of resistance of grid layers and the air film layer could in principle be accounted for by the empirical equations, and the clothing material layer resistance estimated by difference from the whole resistance, this is a less desirable double approximation.

Some of the factors which may contribute to this lack of constancy for the "constant" layers are:

1. Changes of thermal resistivity with temperature. Thermal resistance of air and of fiber-air systems increases with decreasing temperatures, and thus one could expect the outer layers of thicker assemblies, which are colder, to show increased thermal resistance. This is in accord with observation for the outer layer, but the opposite relation holds for the inner layer, which rises in temperature as the insula-

tion is increased. Thus while this factor could help explain the observations for the outer layers, its influence is contrary to observations for the inner layers.

2. The outer air film may be thicker over thicker assemblies with larger surface area. This would be in the direction observed.

3. The outer grid carrier is of constant length, and overlaps less on thicker assemblies. This is, however, in the direction opposite to the observation.

4. The partition of heat flow between the ends and the sides may not be a simple function of the temperature difference between one point of measurement and the environment, as assumed. If relatively more heat escaped through the ends, as the insulation on the sides is increased, the results would show an apparent increase of thermal resistance on the sides, as observed. This suggests that the best results are those obtained by using T_b for end loss corrections, and temperature differences from grids for the material layer itself.

<u>Types of clothing materials examined</u>:

The component of the assembly which can be expected to vary in resistance with its thickness, and possibly with the nature of the material, is the resistance of the clothing material, R_c. The data on dry systems covers three types of material: wool serge, polyurethane foams, and polyester fiber batts, with thicknesses increasing in that order. The thickest group, the polyester fiber batts, contains two types, a thinner group of higher density firm batts, and a thicker group of lower density loose batts corresponding to different degrees of needling.

Resistance of whole system: limits of thickness:

Figure 8 shows the resistance of the whole system, determined by the steady state method, based on T_b, so that the widest range of thicknesses can be considered. Figure 9 shows the whole system resistance determined by the cooling method for the same range of materials, also based on T_b. The two charts agree in showing a generally linear relationship for serges, and foam layers, and some fiber batts, up to between 2 and 3 cm radial thickness, with an increased scatter at greater radial thicknesses. From this it is concluded that the best range of thickness for the method is below 2.5 cm or one inch.

Foam materials:

The polyurethane foam materials examined cover a sufficient range of thickness within the optimum range to warrant calculation of a regression equation, based on observations below 2 cm thickness. Figure 10 shows R_c determined from grid temperatures T_i and T_o in the steady state method, with end loss corrections based on T_b. The smaller number of tests for which end loss corrections could be based on T_s also fall in the same pattern. The least square deviation regression equation is

$$R_c = 0.10 + 0.30\ (r_2 - r_1) \qquad (30)$$

This line has been drawn in Figure 10, and has an intercept at a positive value of thickness.

This indicates that the radial thickness appears to have a definite value, 0.33 cm, at zero resistance of clothing material, a type of relation which should be expected, since the radial thickness includes the two grid layers, which are not contributing to the thermal resistance, R_c.

As a check, the radial thickness of the two grid layers alone, wrapped on the cylinder, is found to be 0.30 cm, a good agreement.

The slope of the regression line establishes R_1 for this material, as 0.30° C m^2/watt cm or 1.94 Clo/cm, 4.92 Clo/inch. This foam material, in different thicknesses, is similar to that identified as VEI-188, which was used in Report 25 of this series (9), which weighs 4.0 oz./yd.^{2}, or 135 g/m^2, and has a density of 0.033 g/cm^3 at 0.01 lb./in.^{2}, 0.069 g/cm^3 at 1.0 lb./in.^{2}. The density during the tests varies with the number of layers used because of folding to small radius but the average is near to 0.03 g/cm^3.

For comparison, similar foam material has been measured on the guarded hot plate at Natick (10) with results ranging from 3.7 to 4.7 clo/inch.

Wool serge

Figure 11 shows, on a larger scale than Figure 10, the resistance observed for single and double layers of Army 16 oz. wool serge fabric. The points lie near or below the regression line determined for foam.

If we take the base thickness as 0.33 cm, one layer of serge, centering around 0.45 cm, has a thickness increment of 0.12 cm, and two layers, averaging 0.52 cm total radial thickness, have an increment due to the two serge layers themselves of 0.19 cm.

The averages for one or two layers work out:

Layers	Average Resistance °C m^2/watt	Average Thickness Increment	R_1 °C m^2/watt cm	R_1 Clo/in.
1	.0256	0.12	.213	3.5
2	.0290	0.19	.152	2.5

This may be compared with representative values for "ordinary" fabrics in the effective range of the Cenco-Fitch and guarded hot plate measuring systems used at the Quartermaster Textile Engineering Laboratories at Natick, of about 3.0 Clo/inch and 3.2 Clo/inch, respectively. (10a, 10b)

The scatter of the results on serges suggests that, as with the guarded hot plate, there is a lower as well as an upper limit of thickness for best accuracy using this equipment and method. The lower limit is probably set by the relation between variation in the included air spaces between layers, in the wrapping, in relation to the total thickness, and appears to lie above 0.2 cm fabric thickness. In this system there are air spaces between the cell and the inner grid, the inner grid and fabric, and the fabric and the outer grid--at least three for one relatively thin layer of fabric. With more fabric and no more air spaces, better accuracy can be obtained, up to the point where scatter becomes large relative to the measured quantity, for a different reason, as will be shown in discussion of thick batts.

It may be noted that by omitting the grid layers, and using comparisons between separate tests, as has been done in earlier reports it is possible to make "greater than" or "lesser than" comparisons of fabric plus outer air which can show smaller differences, and may be less affected by variation in tightness of winding and closeness of layering.

Thick polyester fiber batts:

The two types of polyester fiber batt were successive stages in the compacting of a given card web by increased needle felting. The more firm batt, identified as VEI 70, weighed 9.1 oz./yd.^{2}, and had a density of 0.023 g/cm^3 at 0.01 lb./in.^{2}, 0.091 g/cm^3 at 1.0 lb./in.^{2}. Its thickness, free standing, is about 5/8 inch or 1.60 cm; the density about 0.019 g/cm^3. The loose batt had a thickness near 2 inches, free standing, and a density of about 0.006 g/cm^3. In use on the test cell, however, both forms of batt were considerably compressed by bending:

Batt	Layers	Radial thickness (less 0.33 for grid) cm	Average Density g/cm^3
Firm	2	1.4	.044
	3	2.4	.039
Loose	1	3.6	.009
	2	4.2	.015

Figure 12 shows the thermal resistance of the two sorts of batts, in comparison with the regression line established for the foams, using the steady method with end corrections from T_b.

The considerable scatter suggests that while there is a tendency to continue the general trend set by assemblies below 2 cm thickness, it is difficult to tell from this data whether these low density, thick assemblies exceed in thermal insulation, as suggested by points above the line, or fall below it. The end correction, W_e, is as much as 2 or 3 fold larger than the residue for loss through the sides, in these tests, so any heat leakages due to poor arrangement such as poor contact between assembly and insulated ends would be very influential in lowering the apparent thermal resistance. In addition, any inaccuracy of calibration has maximum effect at this level. For these reasons, the upper useful limit of clothing thickness on this equipment appears to be near 2.5 cm.

Comparison with cooling method; accuracy:

All of the thermal resistances discussed to this point have been obtained by the steady state with grids on each side of the fabric. The overall resistance of the whole assembly can be compared in each test, using the cooling method. Figure 13 shows the deviation between the whole resistance, R_s for steady state, minus that for cooling, as based on T_b. This omits the measurements on low density, loose batts, for which the variations were very large.

Figure 12 shows that up to 2 cm radial thickness the differences between the two methods are randomly distributed on each side of zero. For assemblies thicker than 2 cm, the cooling method tends to give resistance values much larger than the steady state method, which may reflect a difference in the accuracy of the end loss calibrations for m_e used in the cooling method and W_e used in steady state.

In the 18 sets below 2 cm radial thickness, the combined positive deviation is 0.448, the negative 0.442°C m^2/watt, indicating a balanced randomness. The root mean square deviation in a given test from the average between the two methods, is 0.035°C m^2/watt or 0.2 Clo. With a modest replication, this can be considerably improved for any one material at one thickness.

V. DISCUSSION

Relation to other equipment:

In addition to the comparisons with the Cenco-Fitch and guarded hot plate methods as used at the Quartermaster laboratory at Natick, it is known that cylinder test systems with insulated ends have been constructed in other laboratories (11, 12). These have been used with the assumption that end loss is negligible compared with loss through the clothed sides, but this assumption could be tested by the method of extrapolation to zero value of $A_m/(r_2-r_1)$, using multiple layers of a given material. Such calibration would probably account for part of the systematic difference between different measuring systems which was noted by Backer and Winston (12).

Thermal resistance and density:

Changes in density arise in the present system both in going from one type of structure to another, and in changing from the greater, free standing thickness to the lesser thickness of a structure when bent around the cylinder.

A relation of thermal resistance to density has been suggested by many investigators, but as noted by Morris (13) other variables prevent a general comparison. In the present work the variation of type of material and increase of experimental error with both small and large thickness prevent one from determining a relation with density in the experimental results themselves. However, certain published results give an indication of the magnitudes which can be expected.

Baxter (14) measured the thermal conductivity of wool felt in the range of densities from 0.1 to 1.0 g/cm^3, the variation in density being obtained at nearly constant thickness by increased pressure on a greater number of layers. Figure 14 shows Baxter's data (as estimated from his graphic presentation as conductivities) recalculated as thermal resistance. In the range from 0.1 to 1.0 the thermal resistance decreases with increasing density, ranging from 0.34 to 0.09°C m^2/watt cm, or 5.6 to 1.5 Clo/inch.

Wool fibers were also packed at bulk densities below 0.1 g/cm^3, with thermal resistance decreasing as density decreased, down to the lowest observed density at about 0.017 g/cm^3, as judged from the graph of data in Baxter's publication. The thermal resistance at the lowest observed density was about 4.7 clo/inch. Baxter also measured the thermal conductivity of air in this apparatus, and reported 5.72 x 10^{-5} g cal cm/cm^2 sec °C, in good agreement with other investigators. This would correspond to 0.418°C m^2/watt cm or 6.85 Clo/inch for air itself, at the temperature of measurement, in good agreement with International Critical Tables values. (15)

Additional data is available from Speakman and Chamberlain's (16) measurements of loose fiber assemblies, in the same general range of density that Baxter used for felt. These results indicate a decrease in resistance of .15°C m^2/watt cm for unit change of density, in comparison with Baxter's result of approximately 0.27 for this slope. Speakman's results also suggest a small increase of conductivity or decrease of resistance at the very lowest packing density, below 0.1 g/cm^3.

Randolph (17), working entirely in the low range of density, 0.015 to 0.19 g/cm^3, found increasing resistance with increasing density. The range used by Randolph overlaps and doubles the range of density in which Baxter found increase of resistance with increasing density, and so may be compatible, since the structural arrangement of fibers in Baxter's tests was different at densities above 0.1 g/cm^3. However, the numerical values of resistances in Randolph's paper appear to be high.

Comparing the present tests with the results of others with regard to density, one notes that the wool serge had a density on the order of 0.2 g/cm^3 or more while the foam and the polyester fiber batts were well below 0.1 g/cm^3, in the range from 0.01 to 0.04 g/cm^3. Thus the foam and the batt were below the density of maximum resistance in Baxter's results. The value for intrinsic resistance of foam, at 4.9 clo/inch, does lie in the same region as Baxter's low density wool fiber aggregates, while the range of intrinsic resistance found for wool serge (2.5 and 3.5 clo/inch) is not out of the range of Baxter's values for felt.

Hence it seems likely that with the very low density foams and batts, where fairly large changes of thickness are brought about by bending to fit the test cylinder, the intrinsic resistances measured here may be higher than in the free standing condition, but that in general the direction of the effect of density change depends on whether the density is low or relatively high, and requires to be determined for each type of structure.

<u>Suggestions for improvement</u>:

The present equipment, with its relatively small diameter (2 inches) was originally designed for comparisons of one to four or six layers of fabric such as serge, poplin, or knit underwear. Such fabrics are not as much changed as are thicker materials, in being bent to this curvature, so that the scale of equipment is satisfactory for the ordinary woven or knit fabric range.

However, if equipment were to be specifically designed for thicker materials such as foam or batts, a general suggestion to the designer would be to use a larger radius of curvature to reduce the changes of thickness and density between the free standing condition and the condition during the test. A larger ratio of area of sides to area of ends, or more effective insulation or guard rings on the ends would also be helpful with the thicker materials which are higher in thermal resistance.

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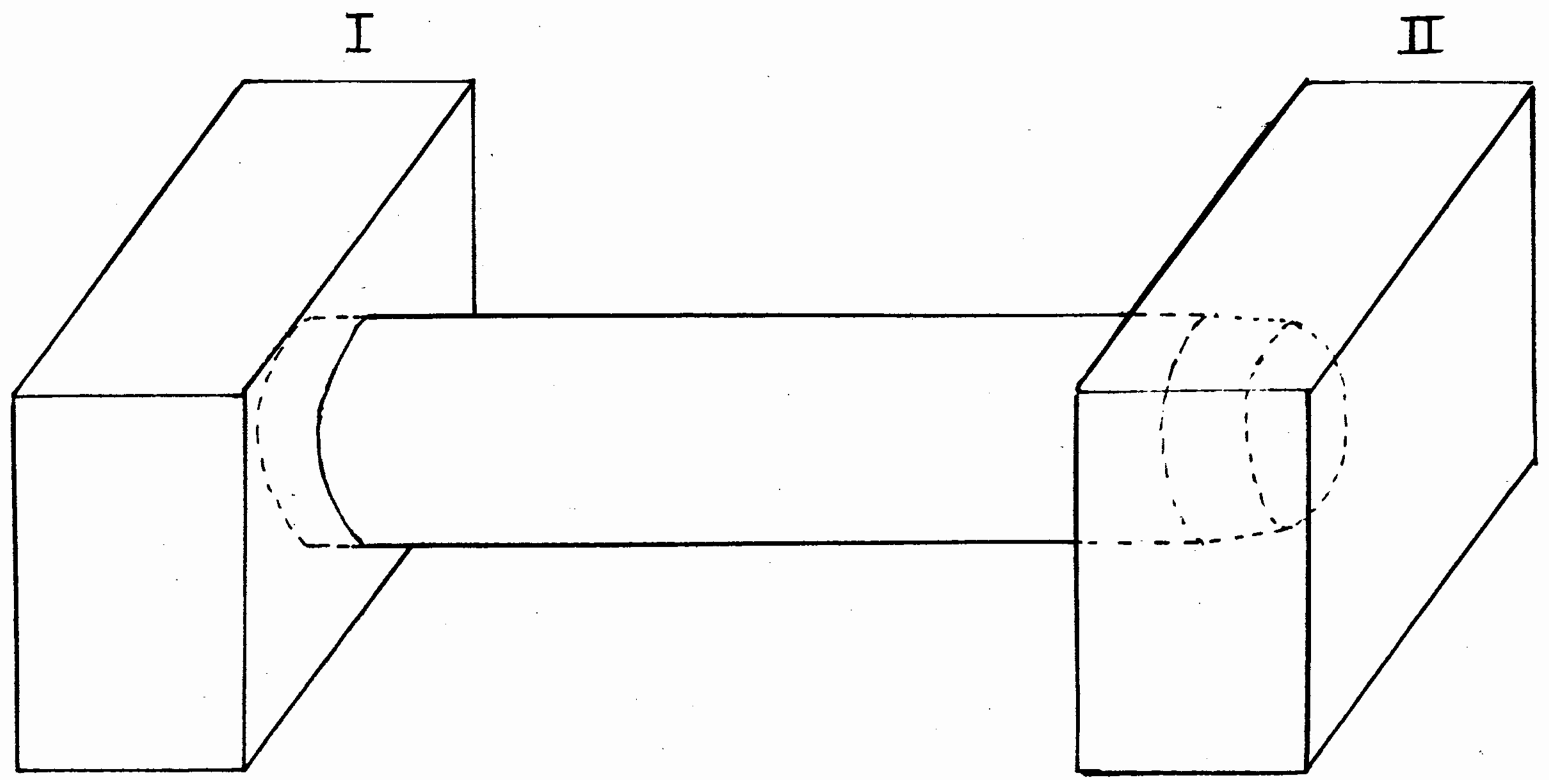

Figure 1, Report 31. Sketch of arm used in cold wind tunnel tests. I and II designate insulating blocks at each end of the brass cylinder, which extends into the blocks. Clothing is wrapped on the sides of the cylinder between the blocks.

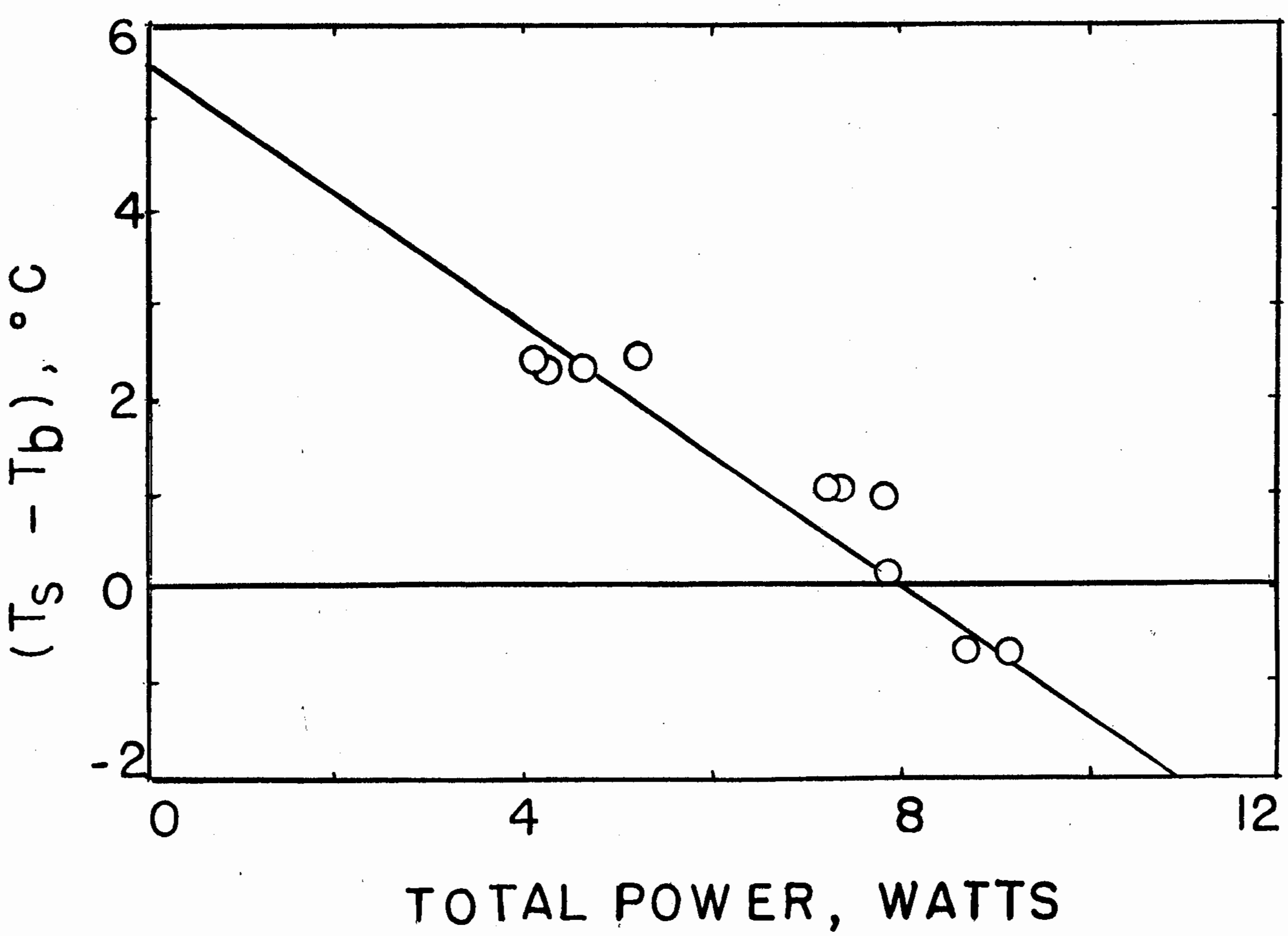

Figure 2a, Report 31. Difference between temperature measured at T_s on the side of the cylinder and T_b measured at the end of the cylinder.

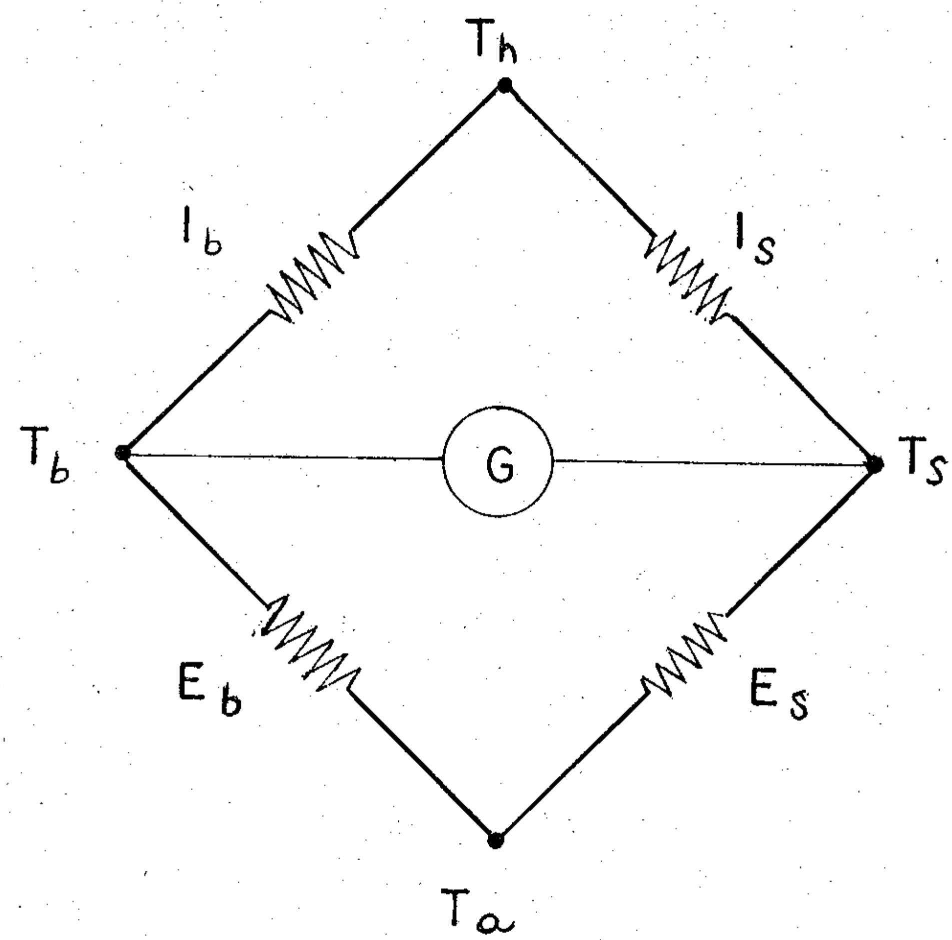

Figure 2b, Report 31. Analogy between flow of heat in the measuring system, and flow of electricity in the Wheatstone bridge. The highest potential, T_h, is the temperature of the heater; T_b is measured on the end, and T_s on the side of the cylinder; T_a is the temperature of the cold air. I_b and I_s are thermal resistances inside the system, between heater and points of temperature measurement; E_b and E_s are external thermal resistances. G, the galvanometer in the electrical analog corresponds to temperature difference T_s-T_b.

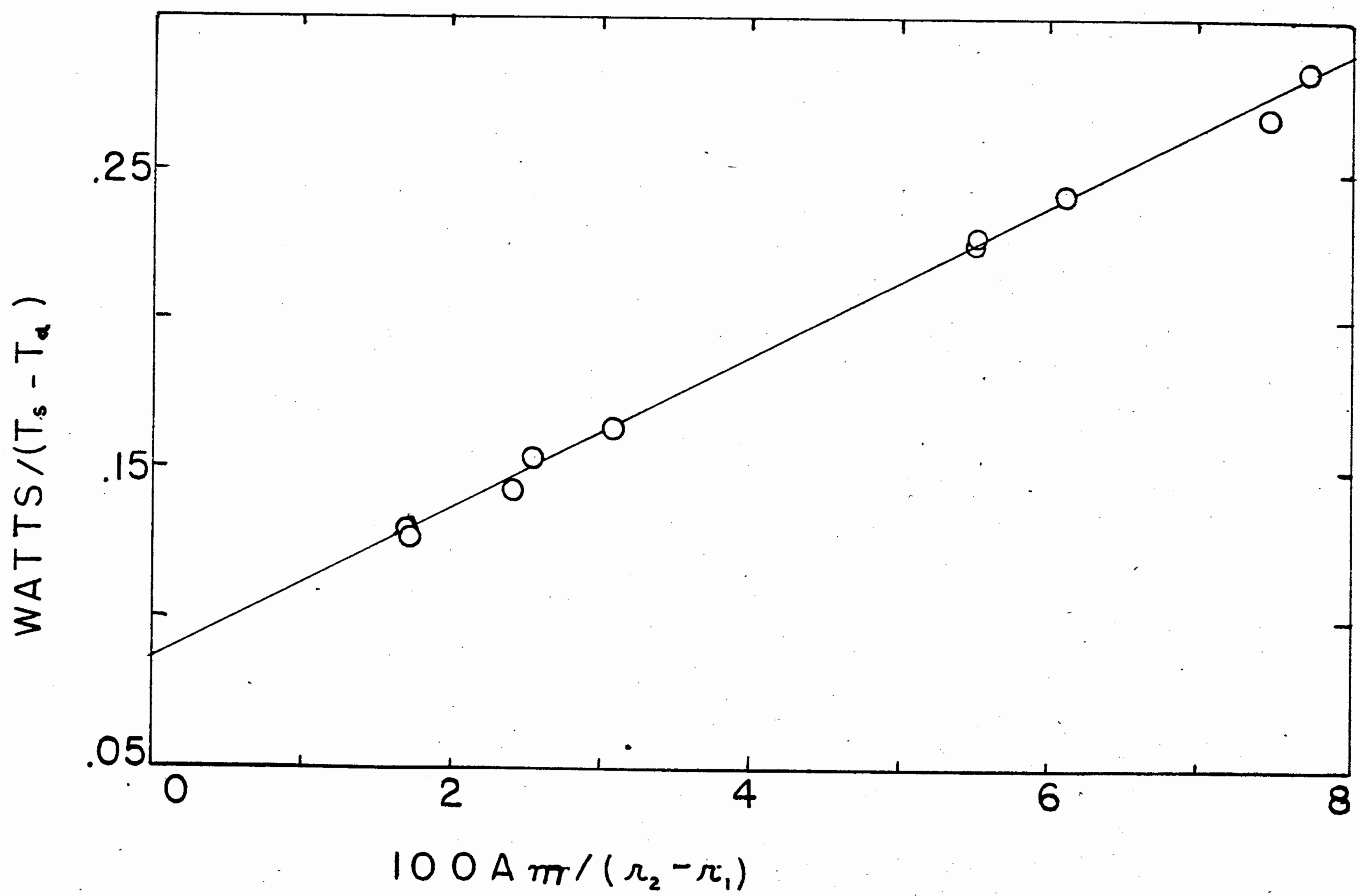

Figure 3s, Report 31. Extrapolation to determine rate of heat loss in steady state through insulated ends, as thickness of insulation on the sides increases and $A_m/(r_2-r_1)$ decreases. Based on T_s.

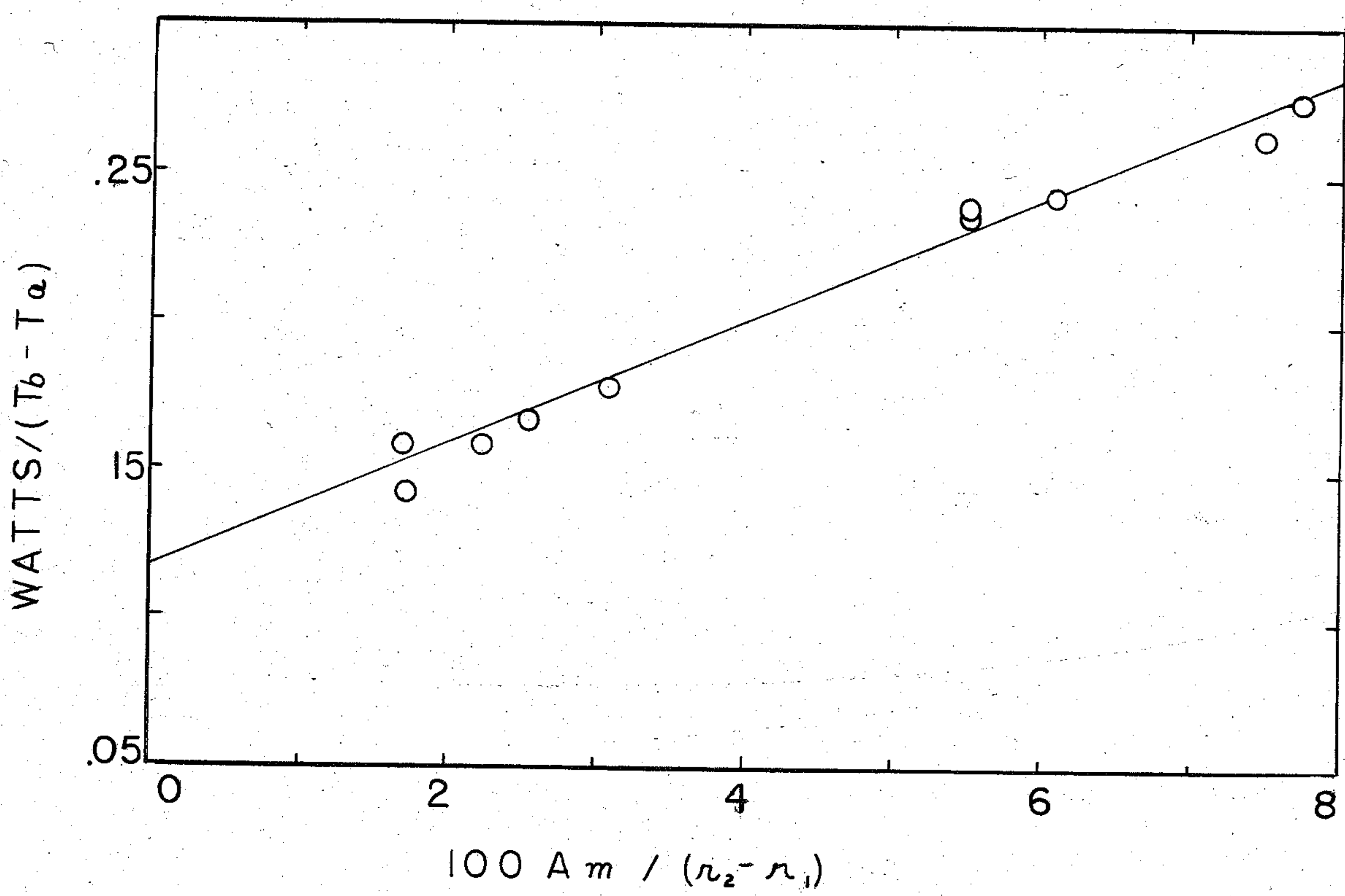

Figure 3b, Report 31. Extrapolation to determine rate of heat loss in steady state through insulated ends, as thickness of insulation on the sides increases and $A_m/(r_2-r_1)$ decreases. Based on T_b.

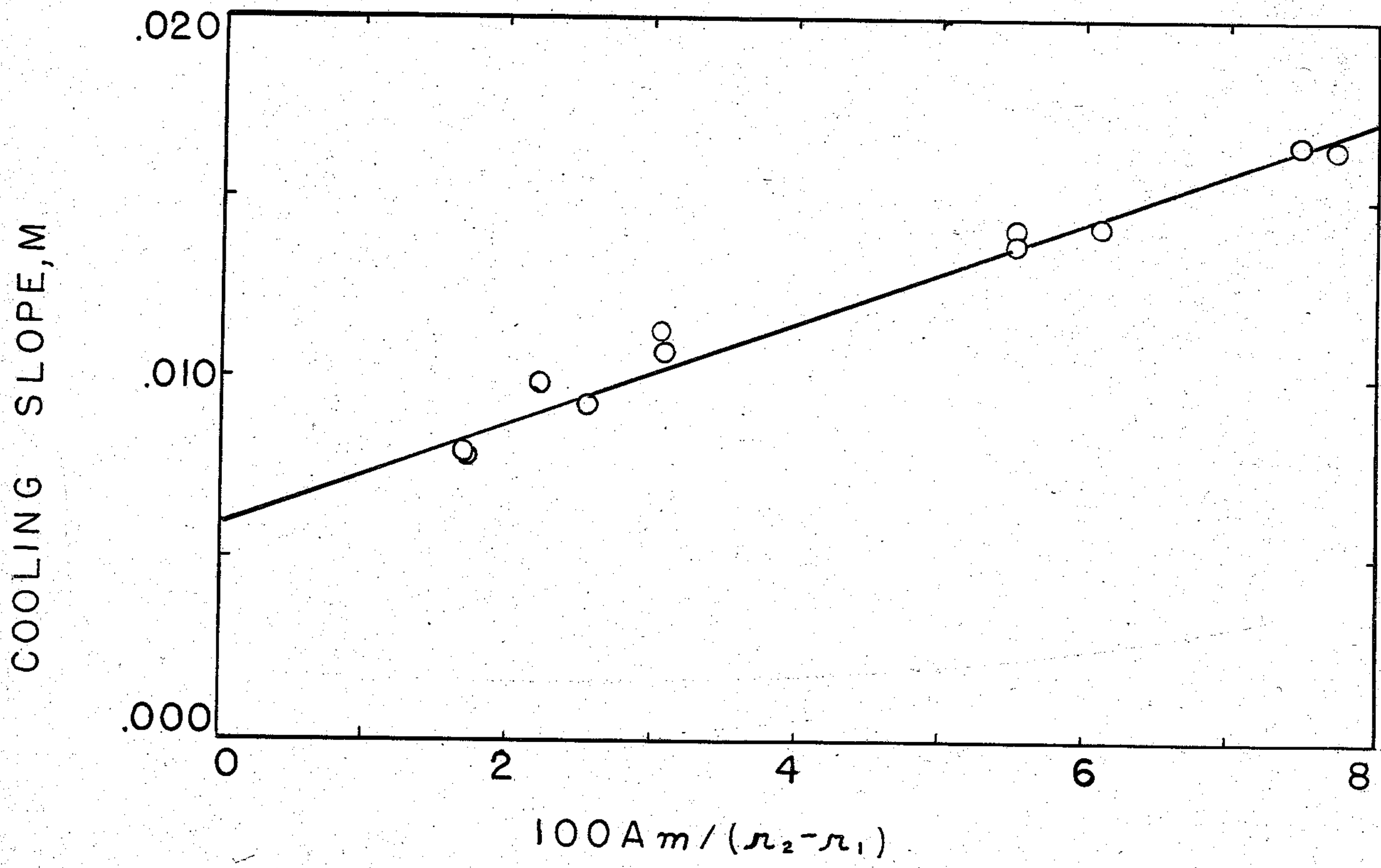

Figure 4b, Report 31. Extrapolation to determine rate of heat loss through insulated ends in cooling method, based on T_b.

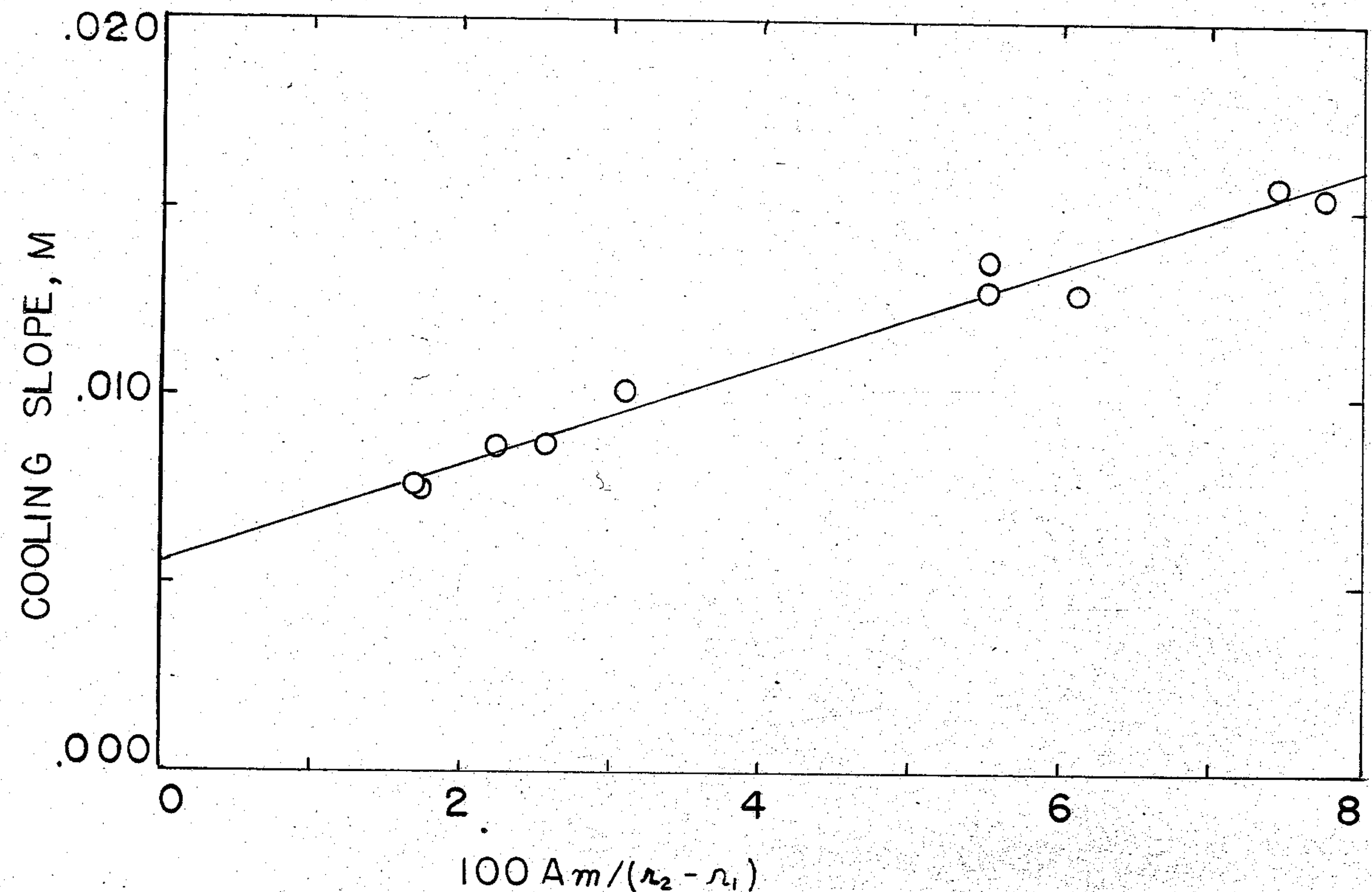

Figure 4s, Report 31. Extrapolation to determine rate of heat loss through insulated ends in cooling method, based on T_s.

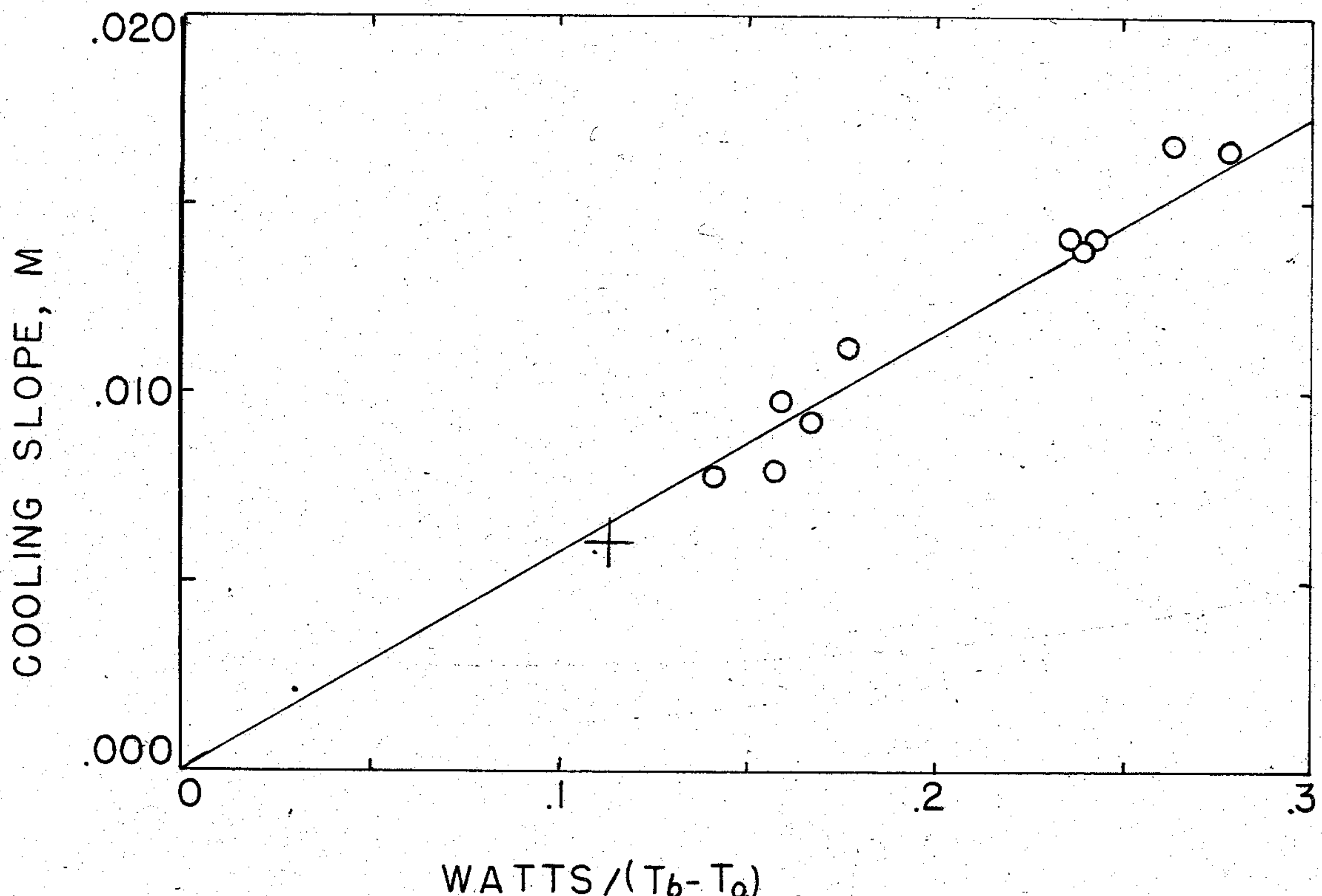

Figure 5b, Report 31. Comparison of cooling method (slope) and steady state loss rate in watts/°C., based on T_b, temperature at the end of the cylinder. Cross indicates end losses found by extrapolation.

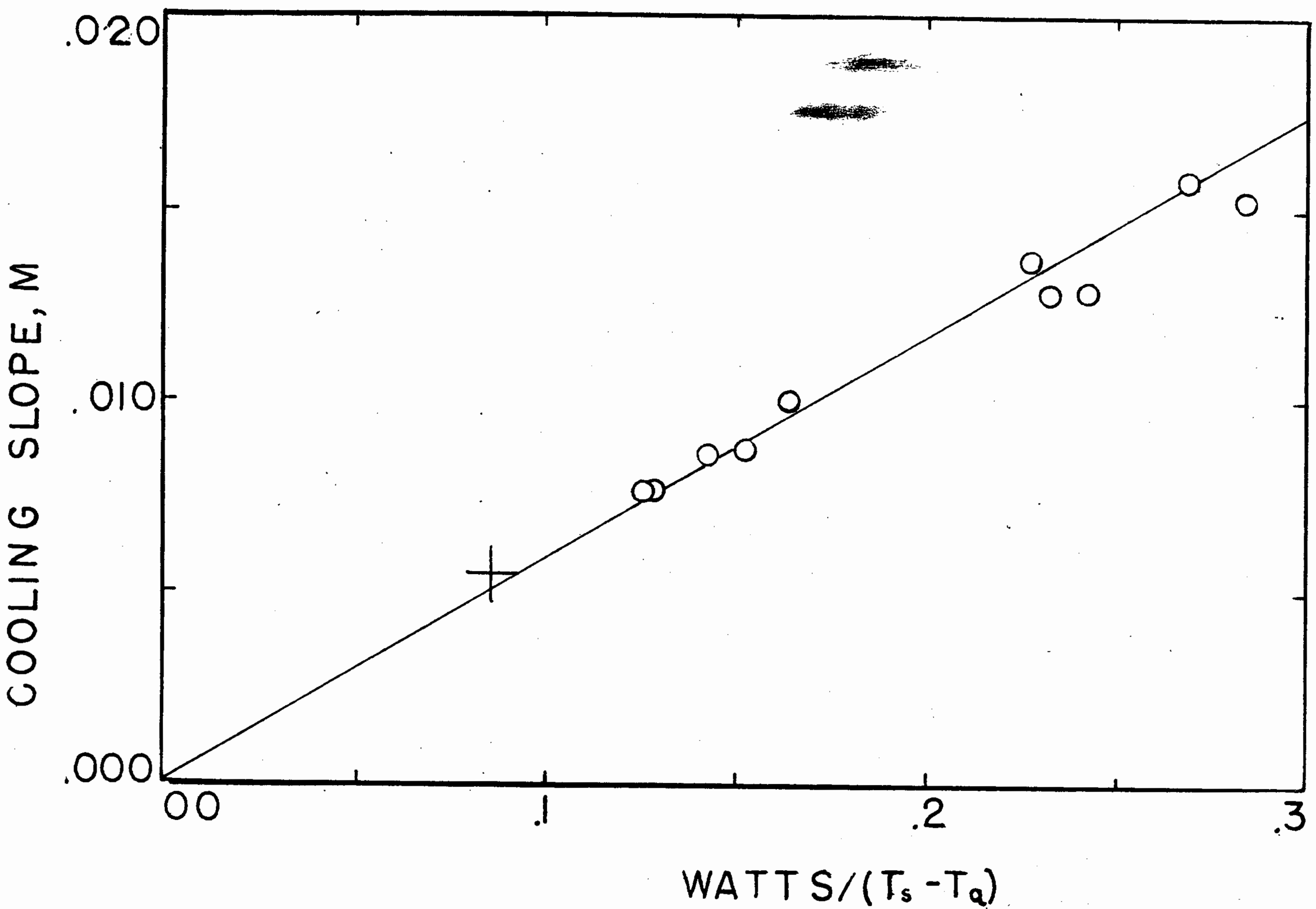

Figure 5s, Report 31. Comparison of cooling method slope and steady state loss rate in Watts/°C., based on T_S, temperature of side of cylinder. Cross indicates end losses found by extrapolation.

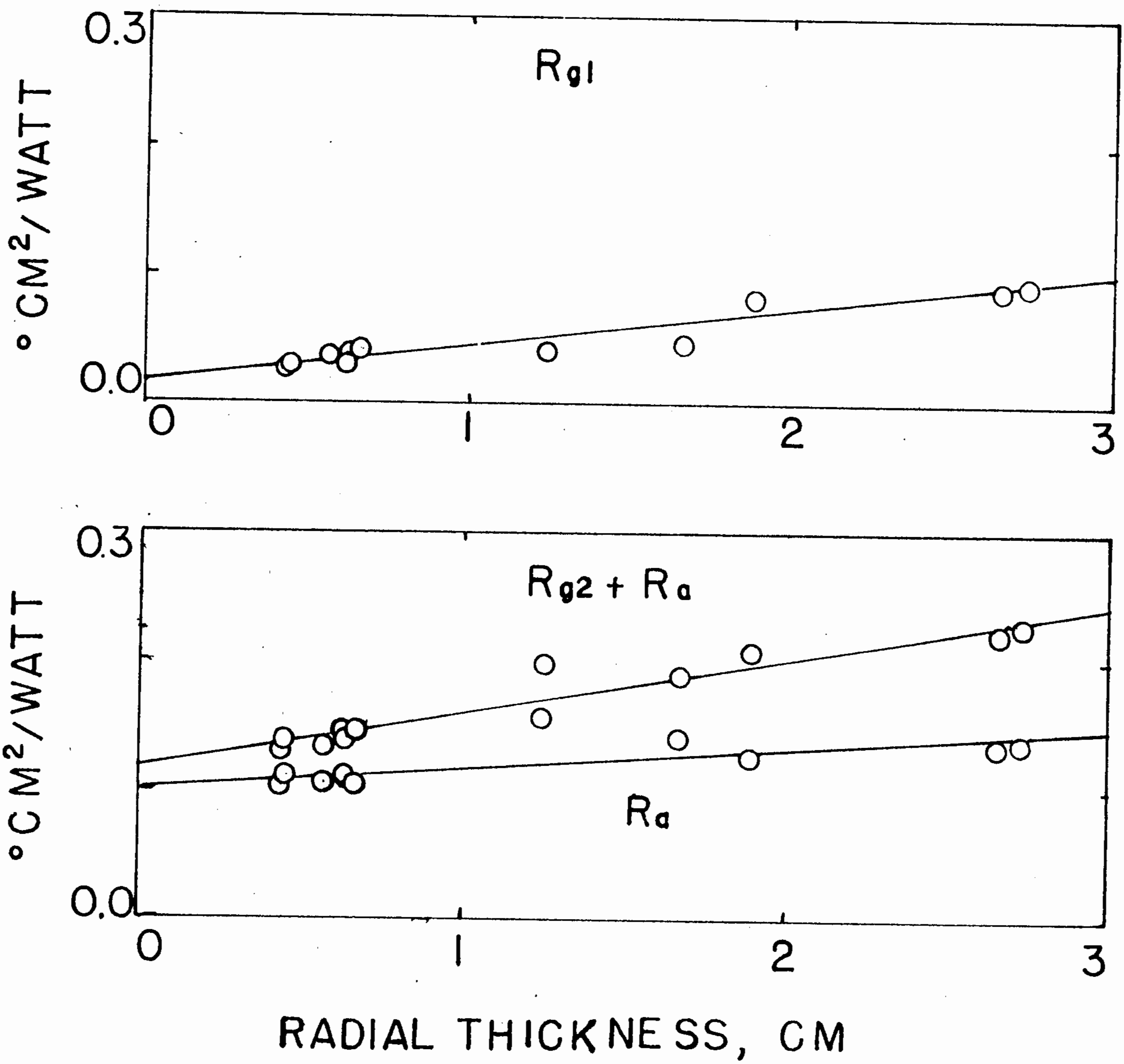

Figure 6, Report 31. Resistance for unit area of layers which in theory are independent of thickness of whole assembly or nature of clothing material. Upper chart shows inner grid, Rg_1; lower chart shows outer grid plus air film, Rg_2 + Ra. By subtracting Rg_1, an estimate of Ra is obtained. Least mean square regression lines are shown.

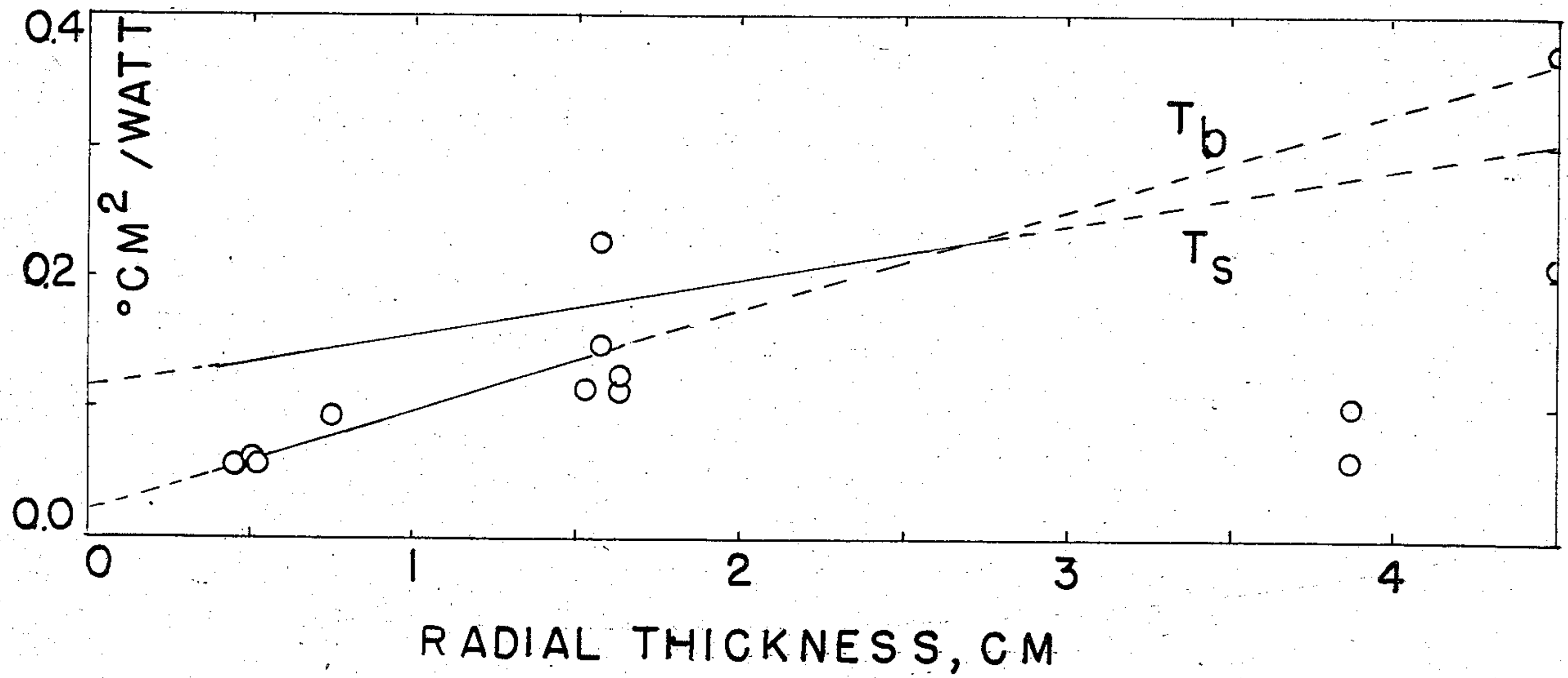

Figure 7, Report 31. Additional data on resistance for unit area of outer grid plus air film, based on end corrections from T_b. The regression line from Figure 6, for other data with end corrections bases on T_s, is also shown. Dashed lines extend beyond the range of data used for the regression lines.

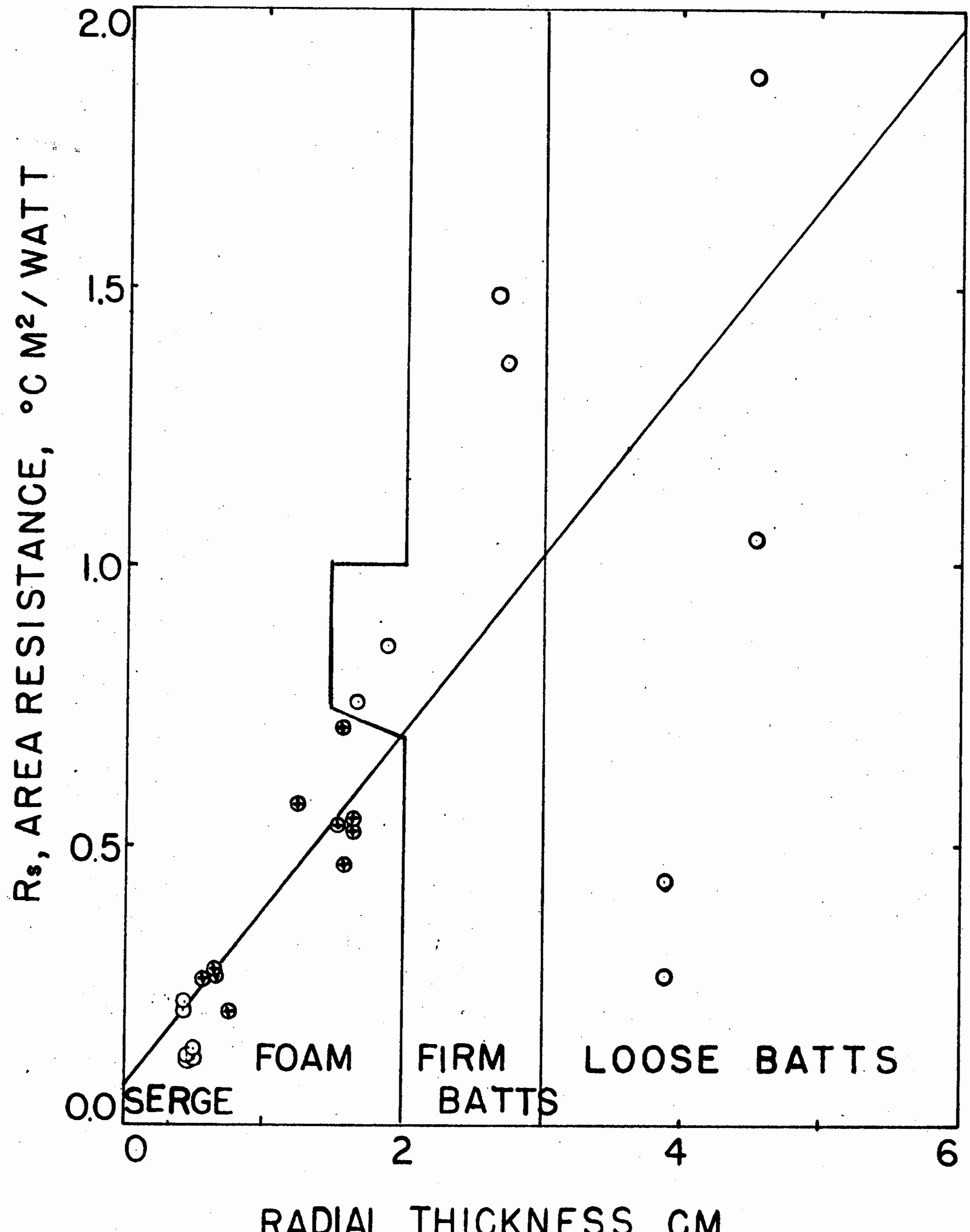

Figure 8, Report 31. Resistance for unit area of whole assembly, steady state method. Crosses mark the results for foams, for which the regression line, $R_s = 0.060 + 0.318\ (r_2 - r_1)$, is shown.

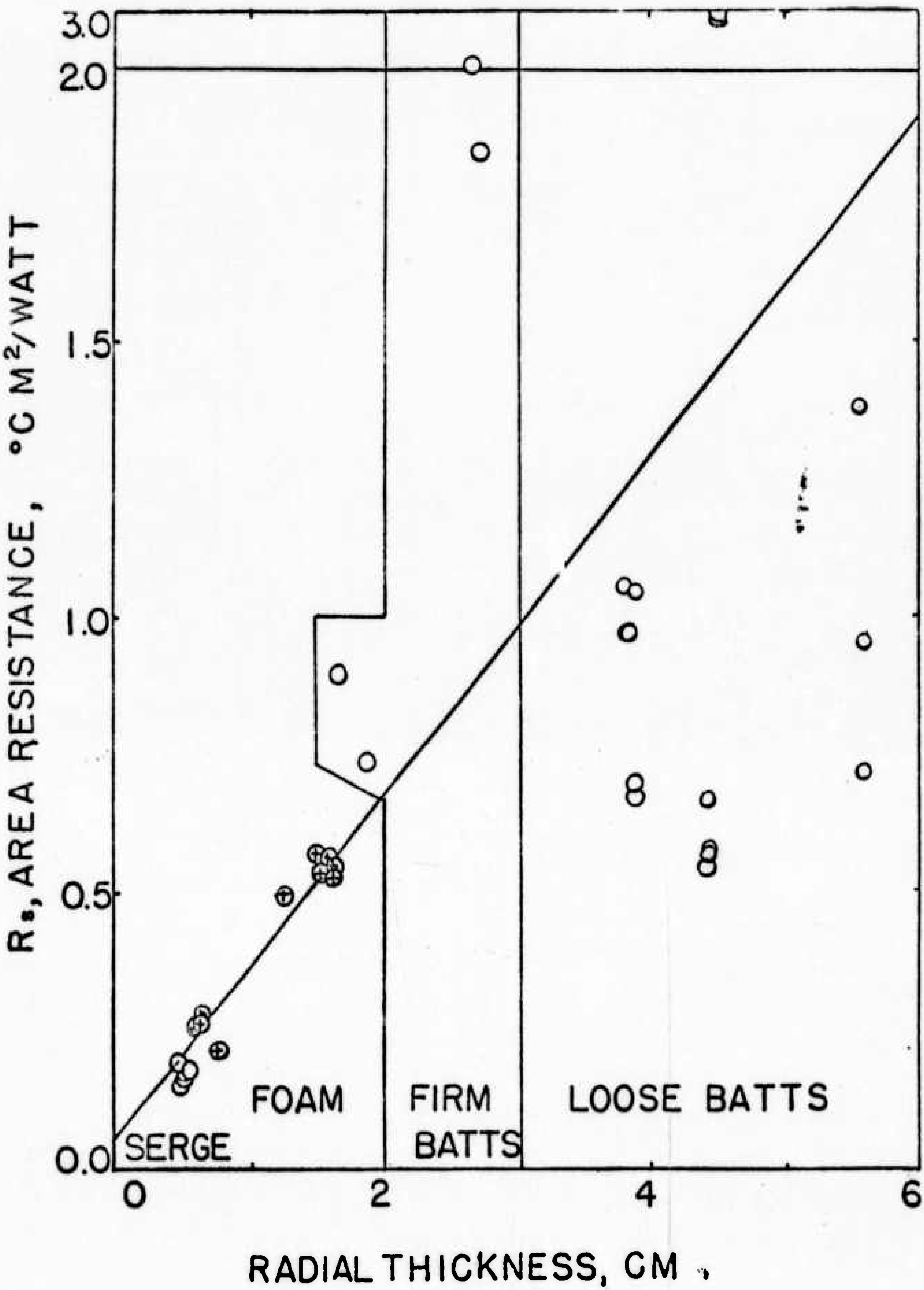

Figure 9, Report 31. Resistance of whole assembly measured by cooling method. Crosses mark results for foams, for which the regression line, R_S = 0.061 + [illegible]

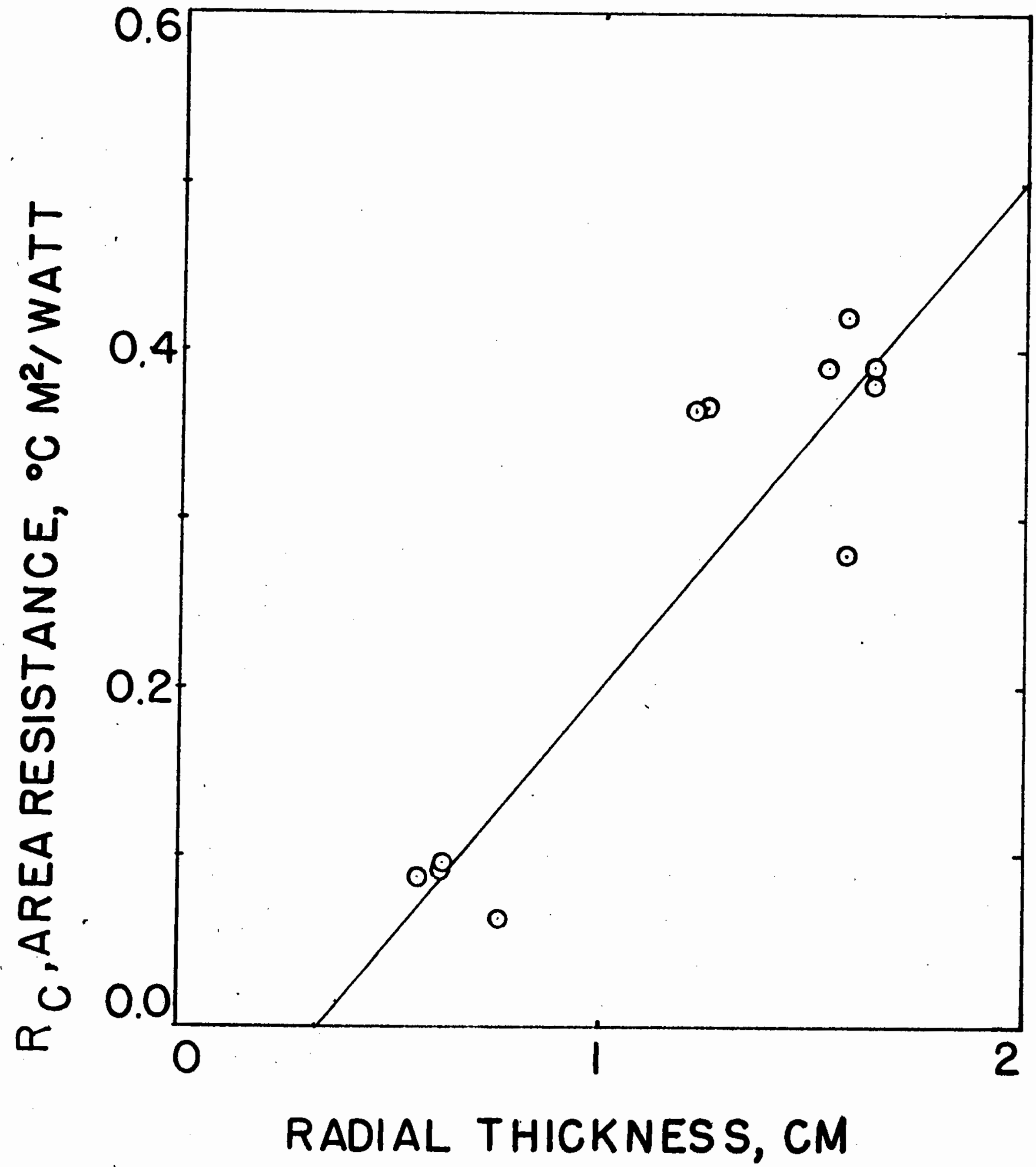

Figure 10, Report 31. Resistance for unit area of polyuretane foam assemblies of varying thicknesses as determined by grids on each side of the foam. The least squares regression line is $R_c = -0.10 + 0.30 (r_2-r_1)$.

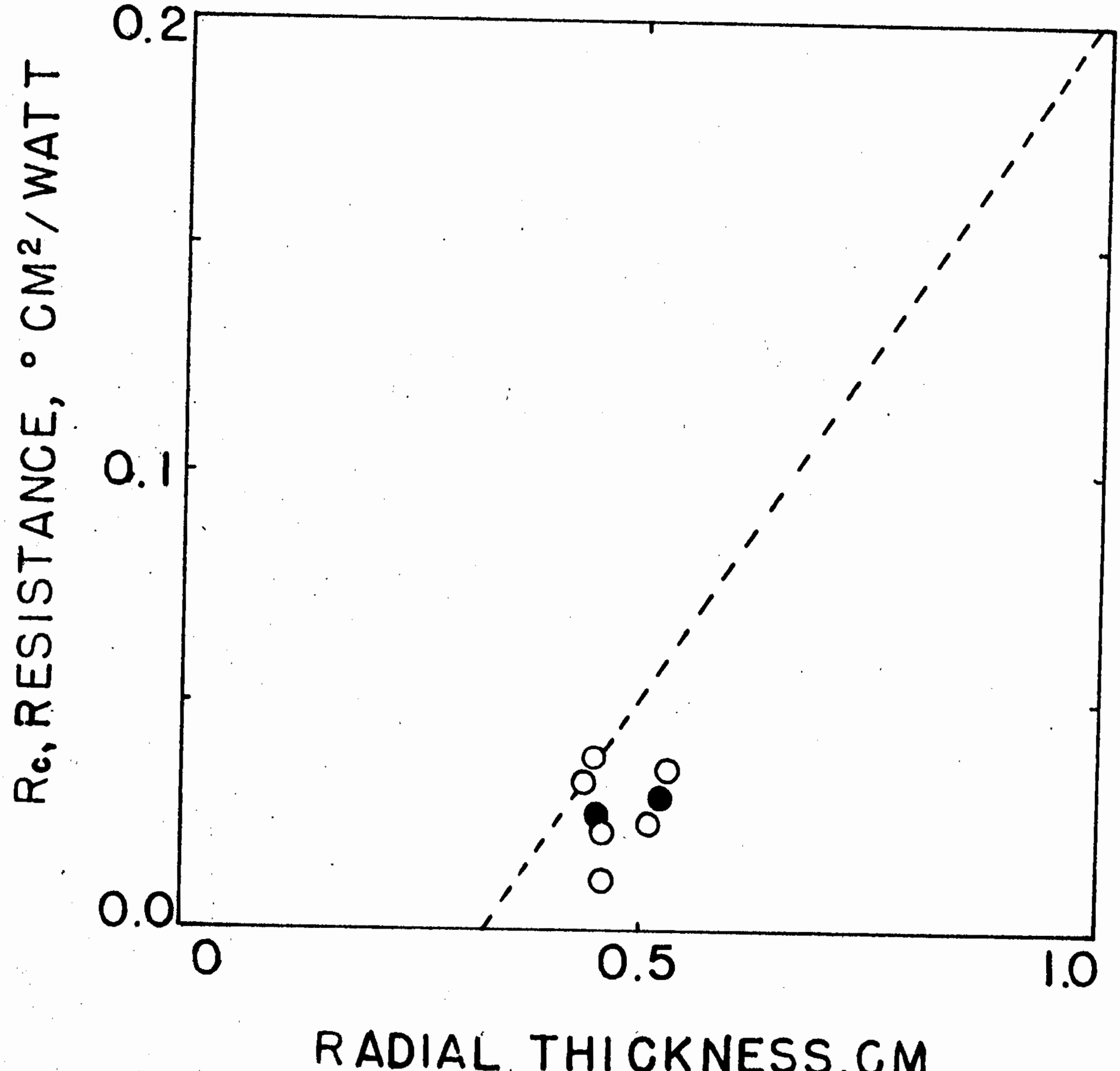

Figure 11, Report 31. Wool serge fabric, in one and two layers, measured between grids by steady state method. The line is the regression line determined for a wider range of thickness of foam structures; its intercept at 0.33 cm indicates the thickness due to measuring grids rather than to wool fabric. Solid circles indicate averages for 1 and 2 layers, open circles, individual tests.

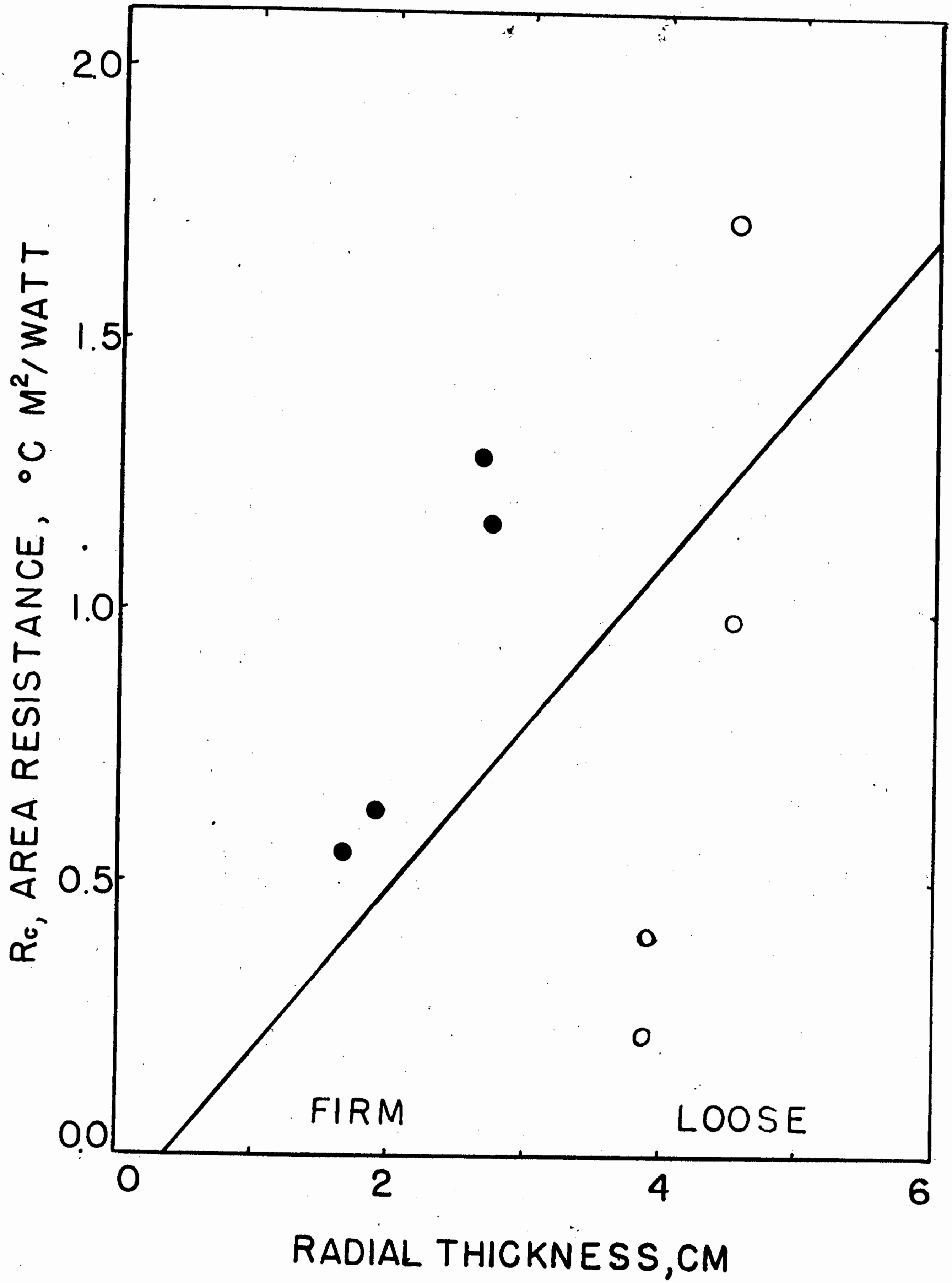

Figure 12, Report 31. Resistance of polyester fiber batts measured between grids. Regression line for foam structures has been added.

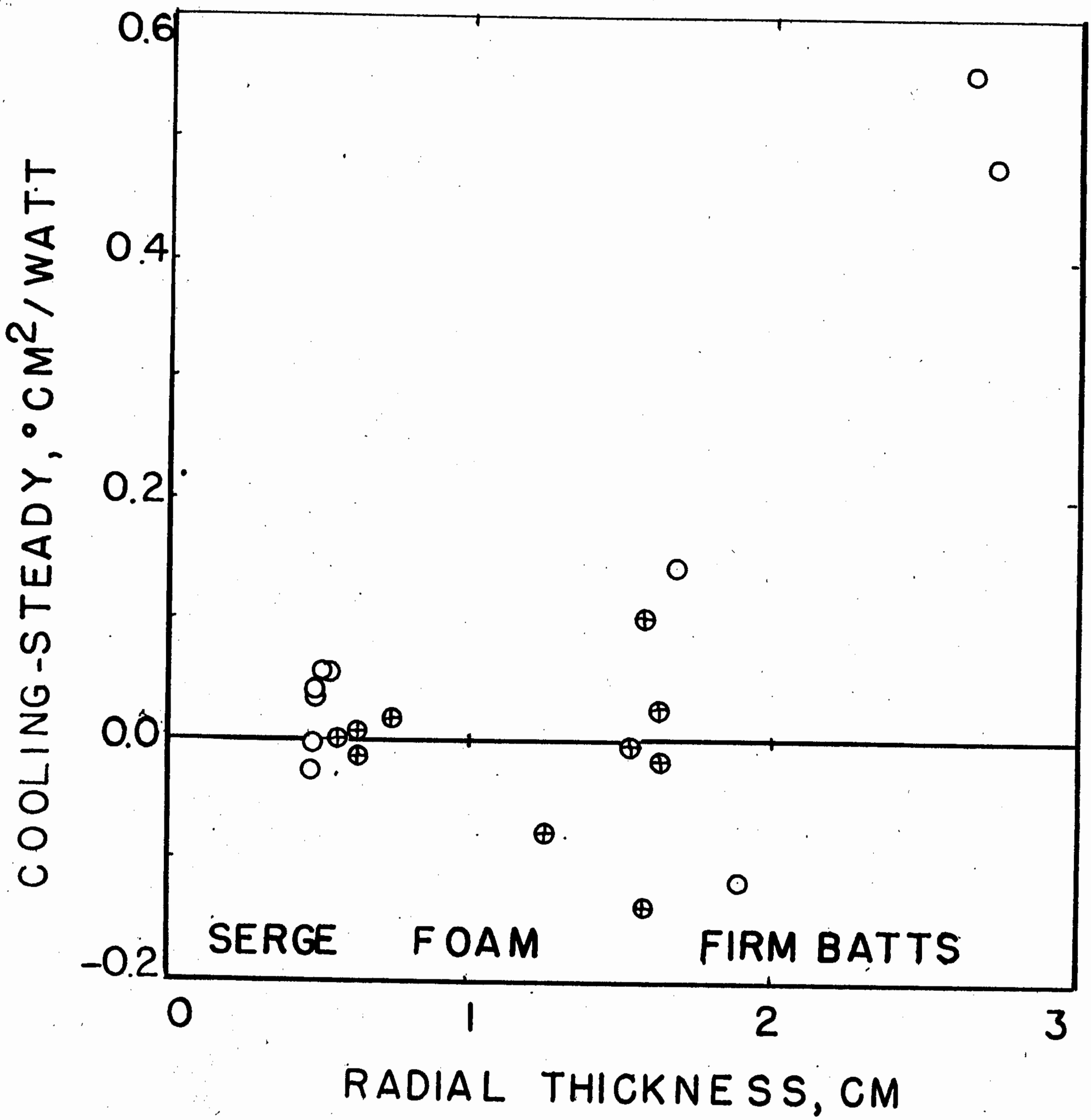

Figure 13, Report 31. Difference in whole resistance of sides, R_s, as measured by cooling method or by steady state method.

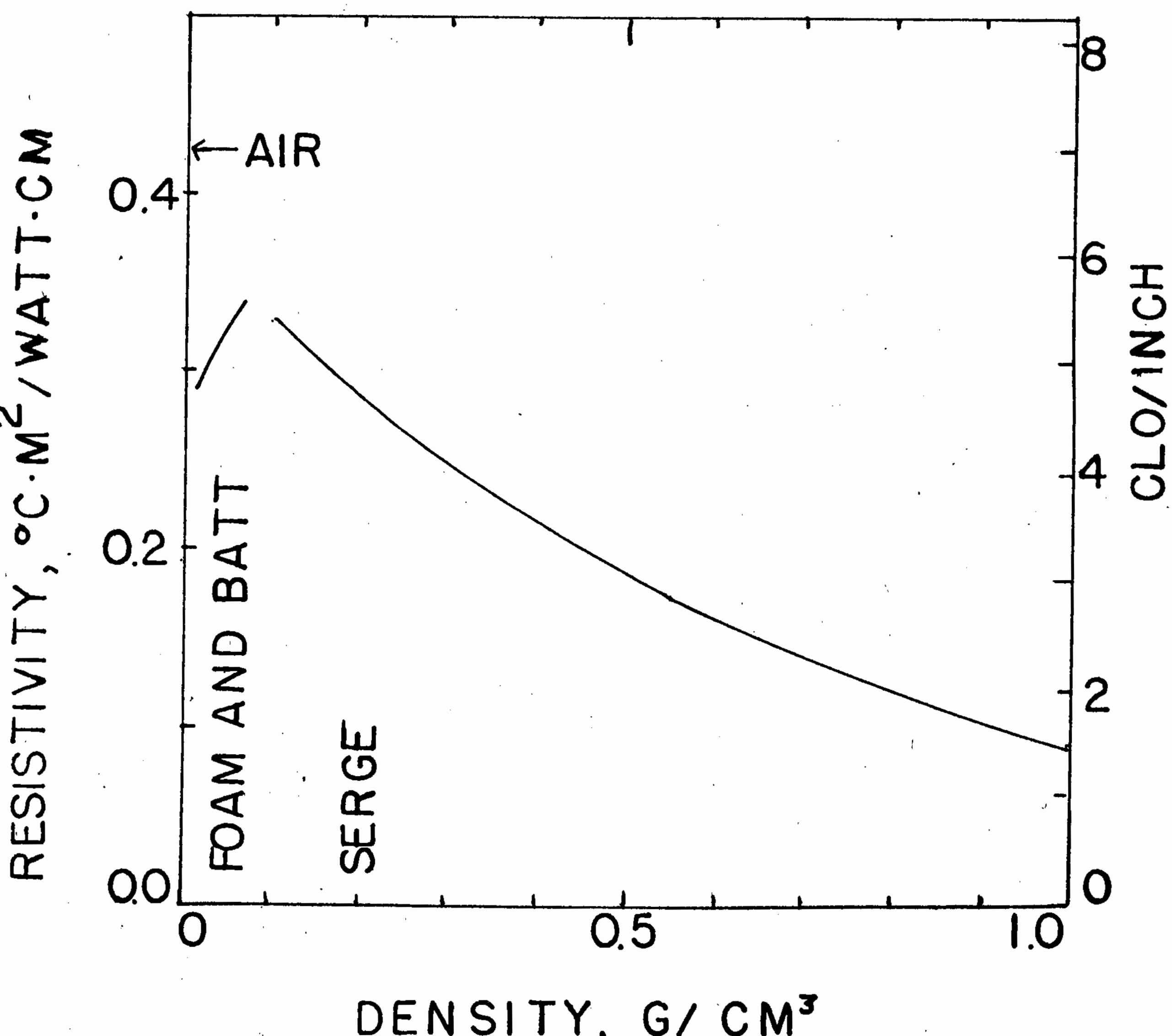

Figure 14, Report 31. Resistance of wool fiber in relation to density. Below 0.1 g/cm^3, loose fiber; above this density, wool felt. Data of S. Baxter, 1946, calculated as resistivity. The location of the materials of the present report is indicated on the range of densities.