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APPARATUS FOR CALIBRATING NET RADIOMETERS IN THE LONG WAVELENGTH REGION

BY

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DESCRIPTION D'UN APPAREIL SERVANT A ETALONNER LES RADIOMETRES DE FLUX NET DANS L'INFRAROUGE

SOMMAIRE

Les radiomètres de flux net mesurent les différences des flux énergétiques émis par le soleil et par le sol. Ils devraient être étalonnés séparément dans la région pertinente du spectre. Le principe fondamental de l'étalonnage des radiomètres pour le rayonnement infrarouge absolu du sol est très simple, mais l'irradiation des aires adjacentes par un flux réglable et calculable constitue un problème complexe. L'auteur explique en détail l'élaboration d'un corps conique rayonnant. On a construit ce corps et une chambre d'étalonnage dans les laboratoires du Conseil national de recherches, et on y a adjoint les appareils de mesure et de réglage nécessaires. L'étalonnage de quatre différents types de radiomètres de flux net indiquent que l'appareil fonctionne parfaitement avec une précision atteignant quelques unités pour cent. L'auteur propose quelques améliorations qui pourraient réduire la marge d'erreur à environ 1 pour cent.

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ABSTRACT

Net radiometers measure the net flux of both solar and terrestrial radiation, and should be calibrated separately in each of these wavelength regions. The basic principle of the absolute calibration of radiometers for terrestrial or long-wave radiation is very simple, but the problem of providing adjacent areas with controlled and calculable radiation fluxes is rather complex. The design of a conical radiating cavity has been developed in detail.

A radiating cone and a calibration chamber have been built at the National Research Council and the necessary controlling and measuring apparatus assembled. The calibration of four different types of net radiometers indicates that the apparatus functions satisfactorily and yields calibration factors with precision and accuracy within a few per cent. Several improvements are suggested that might reduce errors to about 1 per cent.

APPARATUS FOR CALIBRATING NET RADIOMETERS IN THE LONG — WAVELENGTH REGION

by
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I. INTRODUCTION

The net radiometers considered here are instruments for measuring the net vertical flux of both solar and terrestrial radiation at elevations of a few metres above the surface.

The essential parts of the net radiometer are a pair of black horizontal surfaces, one facing upwards and the other downwards, and some system of measuring the difference in temperature between these surfaces, or some quantity proportional to the temperature difference. Thermopiles are commonly used, with the output measured in millivolts rather than in degrees of temperature. The black surfaces reach a steady-state temperature by exchanging energy by radiation, conduction, and convection with their surroundings, and by conduction through the material separating them. If surrounding conditions are kept constant these energy transfers will be proportional to the temperature differences involved and hence the equilibrium temperature difference between the black surfaces will be proportional to the difference between the upward and down-radiation fluxes.

The temperature of the surrounding air can easily be measured and allowed for. Air movement can be kept constant by placing a polyethylene shield over the black surfaces or by directing a constant draft over them. The output voltage is, therefore, proportional to the net radiation, but the construction of the instruments is such that it is difficult, if not impossible, to compute the constant of proportionality. This constant, or calibration factor, can be obtained by comparing a net radiometer with another instrument that has already been calibrated, but sooner or later an absolute calibration will be needed.

If the black surfaces of the net radiometer are perfectly black, that is, if they absorb all the radiation falling on them, then the calibration factor will be the same throughout the range of wavelengths from 0.2 to about 40 microns. Most of the radiation falls into one of the two main bands: solar radiation, which is mostly in the visible and near-visible region from about 0.2 to 1.5 microns, and terrestrial radiation, which is mostly in the region from 5 to 40 microns. If the calibration factor is determined for each of these two ranges it need not be checked at other wavelengths.

When the work described herein was started, the Meteorological Branch of the Department of Transport seemed to have the problem of absolute calibration in the short-wavelength region well in hand. It was considered satisfactory to calibrate our net radiometers in the short-wavelength region by comparing them with Eppley pyrheliometers calibrated at the Scarborough, Ontario, research station. It was decided, therefore, to concentrate on the long-wavelength calibration. The apparatus described is for the sole purpose of obtaining an absolute calibration factor for net radiometers for wavelengths from around 5 to 40 microns, which are typical of terrestrial radiation.

2. PRINCIPLE OF THE APPARATUS

The basic principle of the absolute calibration is very simple. The net radiometer is placed in an enclosure for which the temperature and emissivity of all the surfaces are known. The radiation falling on each of the black surfaces can be computed and the millivolt output measured, thus yielding the required factor.

The temperatures above and below the radiometer must be different to produce a vertical flux of radiation and hence an output from the radiometer. This means that reflected radiation must be computed unless it is negligibly small. If reflections have to be considered the calculations become extremely complex, even in a simple enclosure. To avoid reflections the enclosure is usually painted black so that the reflectivity will be near zero and the emissivity near unity.

The calculations will also be simplified if the number of different temperatures is reduced, if possible to two. The usual arrangement is to have a relatively large enclosure at room temperature and to provide for a relatively small temperature controlled area facing one side of the radiometer.

The emissivity and reflectivity of this small temperature controlled area are more critical than the emissivity and reflectivity of the rest of the enclosure. If the whole of an enclosure is at the same temperature, then the emissivity and reflectivity of the surface do not affect the radiation flux because a decrease in emissivity is compensated by an increase in reflectivity. If most of an enclosure is at a uniform temperature, then the emissivity of the surface is less important than the emissivity of a small area at a different temperature. The small critical area can be replaced by a cavity, which will increase its effective emissivity. The optimum shape of the cavity will be considered under the construction of the cone. The main enclosure is described in the next section.

3. THE BOX

The main enclosure, which is kept at room temperature, is essentially a rectangular copper box 16 in. square and about 36 in. long. Figure 1 is a photograph of the box showing the support and some of the thermojunctions before the insulation was added. Figure 2 shows the right side and top of the box, which is nearly the same shape as that used by MacDowall (1). The sensitive surfaces of the net radiometer are mounted in the centre of the box — that is, the centre of the radiometer is 8 in. from the top, bottom, and sides, and 12 in. from the rear. The rear end is one of several panels that slide into place and have holes in them to accommodate the supporting structures of the various radiometers. (It would have been more convenient if the rear end had been bolted in place (instead of sliding), so that it could be removed with the radiometer still mounted on it.

A circular hole 8 in. in diameter was cut in the top (or bottom depending on how the box was set) of the box, with the centre of the hole directly above the centre of the radiometer. The conical cavity described in the next section was mounted at this hole.

A ventilated net radiometer is equipped with a motor and fan which blows air over the sensitive surfaces. To accommodate such a radiometer in the box and to avoid air currents that would be unlikely under field conditions, it was necessary to have an adjustable opening at the front end of the box. The construction is shown in the drawings. To adjust the opening to the best width for a particular radiometer a sheet of thin paper was placed over the hole in the top of the box, as suggested by MacDowall (1). With the radiometer in place the fan was turned on and the opening at the front of the box adjusted until the thin paper showed no tendency to be either blown off or sucked in.

The interior of the box was painted with Parsons' optical black lacquer,* which is said to have an emissivity of 0.98 or more. It is estimated that when the cavity is hot the excess radiation reflected from the bottom of the box to the cooler side of the radiometer would never be as much as one-half of 1 per cent of the net radiation at the radiometer. This error could have been reduced by increasing the area of the radiometer so that it shielded the bottom of the box from radiation directly from the cavity.

The box was made of fairly heavy copper in the hope that the high thermal conductivity would prevent significant temperature differences over its surface. To check the temperature differences, constantan wire was soldered to several more or less

* *The optical black lacquer was obtained from Thos. Parsons and Sons, Ltd., Church Road, Mitcham, Surrey, England.*

randomly selected locations on the box and a single copper wire was used to complete the several thermocouples. A multipoint recorder was used to read each temperature in turn. Differences of over 5F deg and fluctuations over a few minutes of about 2 deg at a single thermocouple were measured. These differences were reduced by closing the laboratory window and covering the box with a blanket. Later the box was covered with ¾-in felt and ¼-in plywood and removed to a windowless laboratory where the air temperature was more closely controlled. The part of the box closest to the cavity was still influenced by the cavity temperature, but other differences and fluctuations disappeared. The remaining temperature differences, although still a nuisance, could be accounted for and allowed for as shown in the section on computations.

4. THE CONE

The cavity is the most critical part of the apparatus, because it is the source of radiation that must be calculable accurately from temperature measurements alone. The opening to the cavity must be effectively a surface with emissivity negligibly different from unity, and the temperature of the cavity walls must be controllable and measurable.

To design such a cavity, one must study the reflections of radiation within cavities of various shapes and calculate or estimate the amount of radiation that ultimately escapes through the opening. Consider first diffuse reflection, which does not depend on the direction from which the incident radiation comes. The reflected radiation obeys Lambert's law that the flux density from a unit area in any direction at an angle α to the normal to the surface is proportional to the cosine of α.

For an opaque surface the emissivity (ξ) is equal to the absorptivity, and the reflectivity (ρ) plus the absorptivity is unity.

$$\xi + \rho = 1.$$

If the reflectivity of a surface or the effective reflectivity of an opening can be found, then the emissivity will also be known. It is commonly easier to work with reflection.

Consider a cavity of any shape with a small opening of area a at point A (Figure 3). Suppose that diffuse radiation with flux density I enters the cavity at

A. It can be shown that the flux density at B at a distance r from A in a direction making an angle α with the normal at A will be:

$$\frac{I\ a \cos\ \alpha}{\pi r^2}$$

If the line AB makes an angle β with the normal at B, then the radiation falling on a small area b will be:

$$\frac{I\ a \cos\ \alpha\ b \cos\ \beta}{\pi r^2}$$

The reflected flux will be the same expression multiplied by ρ, the reflectivity of the interior surface. The reflected flux that will escape through the opening at A will be:

$$\frac{I\ a \cos\ \alpha\ b \cos\ \beta}{\pi r^2} \cdot \rho \cdot \frac{\cos\ \alpha\ a \cos\ \beta}{\pi r^2}$$

If b is replaced by ds and integrated over the interior surface of the cavity, then the total flux escaping after one reflection will be:

$$\frac{I\ a^2 \rho}{\pi 2} \int \frac{\cos^2 \alpha \cos^2 \beta}{r^4}\ ds.$$

Since the incoming flux is Ia, the effective reflectivity (ρ_0) of the small opening at A due to one internal reflection will be:

$$\rho_0 = \frac{a\rho}{\pi 2} \int \frac{\cos^2 \alpha \cos^2 \beta}{r^4}\ ds.$$

This expression can be integrated for several cavities of simple shape such as those in Figures 4 and 5. For a hemisphere centred at A:

$$\rho_0 = \frac{2}{3} \cdot \frac{a\rho}{\pi R^2}.$$

For a pair of infinite parallel plates separated a distance H:

$$\rho_0 = \frac{1}{3} \cdot \frac{a\rho}{\pi H^2}.$$

For a semi-infinite cylinder with a small opening in the end:

$$\rho_0 = \frac{1}{16} \cdot \frac{a\rho}{R^2}.$$

For a cone with a small opening at the centre of the circular base the integration becomes more complex. If γ is the half-angle at the apex then:

$$\rho_0 = \frac{2\,a\rho}{R^2 \cos^2\gamma}\left\{\frac{1}{6\pi}\sin^3\gamma + \frac{3}{32}\sin^2\gamma\cos\gamma + \frac{1}{4\pi}\sin\gamma\cos^2\gamma + \frac{1}{32}\cos^3\gamma\right\}$$

To compare cones with different apex half-angles the dimensions of the cones must be kept within reasonable limits. If the radius of the base is kept constant, the cone becomes very shallow for large apex angles: If the height is kept constant, the cone becomes very narrow for small apex angles. The form of the above equation suggests keeping R cos γ constant. (R cos γ is the distance from the opening in the base to the nearest point (or circle) on the cone itself.) If this is done the cylinder and the pair of parallel plates are included as special cases when γ is zero and 90 deg, respectively.

Figure 5 shows the variation in the value of the part in brackets for apex half-angles from zero to 90 deg. If the area of the opening, the value of R cos γ, and the reflectivity of the interior surface are all kept constant, then this is proportional to the effective reflectivity of the opening.

It should be noted that in this derivation of the effective reflectivity the total flux escaping from the cavity (after one diffuse reflection) was considered, and no account was taken of the direction in which this radiation was moving. In general, this escaping radiation will not obey Lambert's law, that is, it will not be proportional to the cosine of the angle from the normal to the plane of of the opening. This means that the effective reflectivity will seem to vary with this angle. For large apex angles the escaping radiation will be more concentrated towards the axis of the cone; for small apex angles it will be more concentrated towards the plane of the base of the cone. The radiometer will be placed on or near the axis of the cone and, therefore, the reflected radiation in this area should be kept to a mininum. This suggests the use of a small apex angle in the hope of keeping the effective reflectivity as low as that indicated in Figure 5, or perhaps even reducing it slightly below that value.

The cavity that was finally built was a copper cone with an apex half-angle just over 20 deg. The height from the plane of the opening to the apex was 19 in. and the opening was a circle with radius 4 in. Such an opening is admittedly rather large to be considered as a point, as was done in the derivation of the equation above. The effective reflectivity for points near the axis, however, would not differ greatly from the value for the point on the axis, and it is believed that the equation will give reasonably good values. If these values are substituted in the equation one obtains:

$$\rho_0 = 0.143\ \rho\ .$$

No attempt has been made to compute accurately the amount of radiation that would escape from a cavity after two diffuse reflections on the interior surfaces. It is assumed, however, that it would be about ρ times the amount escaping after one reflection. With ρ about 2 per cent this additional reflected radiation would increase the effective reflectivity to:

$$\rho_0 = 0.146 \rho .$$

This means that if the reflectivity of a flat plate is about 2 per cent, then the effective reflectivity of this cone is less than one-third of 1 per cent for diffuse reflections.

So far only diffuse reflections within the cavity have been considered. Part of the reflection, even from a matte black surface, is probably specular; that is, the reflected radiation will be in the form of a ray in the plane of the incident ray and the normal to the surface, and make an angle with the normal equal to the angle made by the incident ray, but on the opposite side of the normal.

In designing the cavity to minimize specularly reflected radiation one must be sure, first of all, that no radiation escapes from the cavity after only one internal reflection. The hemisphere (Figure 4) is immediately ruled out because any ray entering at A will be reflected back along the same path and hence will escape. Only cones and their two limiting forms need be considered.

In any cone there will be a ring where the normals to the surface pass through the opening in the base of the cone. Radiation entering along any of these normals will escape after one reflection. This cannot be avoided in a simple cone, but to minimize its effect one can ensure that the radiometer is not on any of these rays.

In dealing with specular reflection by tracing individual rays it will be easier to consider a cavity designed for use with the box or main enclosure described earlier instead of trying to treat the problem generally. The openings in the box and in the cavity have to be fairly large so that the flux from the cavity will produce an output from the radiometer that is comparable to its output when in use in the field. A smaller opening would require a larger range of temperatures in the cavity. In this case a radius of 4 in. was chosen, and it seems to have been a good compromise. The radiometer is placed in the centre of the box and hence is 8 in. from the plane of the opening. It will be assumed that no point on the sensitive surface of the radiometer is more than 2 in. from the axis of the cone.

The geometry of individual rays depends also on the apex angle and the radius of the cone. Many variations were tried, but the details need not be repeated here. A few qualitative remarks should suffice. If a reflected ray is to fall on any part of the radiometer, then its angle from the vertical must be less than about 37 deg. For a cone with a base radius of 8 in. and an apex half-angle of 35 deg such a ray could occur after only one reflection. A smaller apex angle is therefore necessary. It was found that it was possible to prevent all rays with two reflections from reaching the radiometer without making the cone unreasonably long. The dimensions finally chosen were: height from the plane of the opening to the apex, 19 in.; radius of the base, 7 1/8 in.; apex half-angle, $20^\circ\ 33'$ (Figure 6).

The opening in the base of the cavity and the opening in the top of the box must be in the same or very nearly the same plane. If they were appreciably separated there would be some radiating surface between them at an indeterminate temperature, which would invalidate the radiation calculations. On the other hand, the base of the cone cannot be placed in contact with the box because it would be impossible to control its temperature. The lowest 3 in. of the cone was, therefore, replaced by an inverted, truncated cone having the same radius as the main cone at the 3-in. level and a radius of 4 in. where it would be almost in contact with the top of the box. The angle of this truncated cone was such that no radiation from it would reach a radiometer whose radius was less than 1 1/3 in. The interior of the copper cavity was painted with Parsons' optical black lacquer.

To measure the temperature of the cone three thermocouples were glued to its outside surface. They were encased in a water resistant glue and were placed so as to be in good thermal contact with the copper cone, but insulated from it electrically. The temperature of the cone was controlled by encasing it in a cylindrical copper can and circulating water (or ethylene glycol solution) through the volume between the can and the cone. To allow for insulating material between the can and the box it was necessary to allow the truncated cone to extended about 1 in. below the base of the encasing can. Half-inch copper pipes were let into the can near the bottom and top to supply and remove the temperature-controlled water. These pipes were set inwards at an angle (instead of towards the axis of the cones) so that the water would have a circular motion and provide more uniform temperatures to the cone. The thermocouple leads were brought out through a separate opening.

The circulating water was introduced near the bottom of the can, and as it rose slowly to the outlet at the top some heat was lost (or gained) through the walls of the cylindrical can. The temperatures sometimes differed by a few degrees. The can was, therefore, insulated and the temperature gradient was reduced to an acceptable level.

Apparatus for controlling the temperature of the water surrounding the cavity might have been built into the cylindrical can. It would probably consist of a heater (and possibly cooling coils) and a stirrer. This would make the apparatus more compact but less flexible. In this case, there was another reason for having the temperature-controlling apparatus separate. A cubical tank about 20 in. to a side built for an entirely different purpose was available. The tank was filled with ethylene glycol solution and was equipped with refrigerating apparatus and a circulating pump. It was easy to add heaters. With this tank connected to the can it was possible to obtain cone temperatures anywhere to the range from about zero to 140°F.

The thermocouple temperatures of several points on the surfaces of the box and the cone were recorded on a multipoint recorder arranged to read directly in degrees Fahrenheit. The output of the radiometer being calibrated was recorded on a millivolt recorder. The box and cavity were mounted in a wooden frame so that the whole apparatus could be turned upside down with the cavity below the box.

5. PROCEDURE AND CALCULATIONS

Each radiometer that was calibrated required a new rear panel for the calibration box and some method of supporting the radiometer. A complete set of calibration positions included four cases:

1. radiometer erect and can above;
2. radiometer inverted and can above;
3. radiometer erect and can below;
4. radiometer inverted and can below.

In all cases the temperatures of the box and the radiometer were near room temperature, although the proximity of the hot or cold cone did modify the temperature to some extent. Box temperatures actually varied from about 60 to 85°F. A run in one position ordinarily covered a range of cone temperatures from around 10°F up to around 130°F. and lasted for several hours. Sometimes the apparatus was left running overnight on the cooling part of the cycle.

A set of readings was ordinarily taken from the charts every 20 min. The cone and box temperatures at a particular time were obtained by interpolating between the two nearest values for that particular point. It was originally assumed that the three cone temperatures would be close enough that averaging would not be necessary and that the ten box temperatures would also be almost the same. Actually there were differences of up to 2 F deg in the cone and 4 deg in the box.

The effect on the radiometer of the radiation from a particular part of the box is proportional to the angle of incidence on the sensitive surface of the radiometer. Temperatures of areas directly above and below the radiometer are therefore of greatest importance, while areas near the plane of the radiometer can almost be neglected. If the necessity of averaging the thermocouple readings had been realized sooner it would have been possible to place them on the box so that each was representative of an area exerting equal influence on the radiometer. As it was, they were placed more or less at random and a complex weighting system had to be devised to yield reasonable average temperatures. Strictly speaking the fourth powers of the temperatures should be averaged, but since the temperature differences are small this refinement is not necessary. Three average temperatures were obtained for each time: the cone; the top of the box; and the bottom of the box.

These temperatures were used to obtain values of σT^4 from tables published by Shirtliffe and Stephenson (2). The following values were used for computing the tables:

$$\sigma = 81.2619 \times 10^{-12} \text{ cal/cm}^2 \text{ min } {}^\circ\text{K}^4$$

$$^\circ\text{C} = {}^\circ\text{K} - 273.16.$$

The net radiation falling on the radiometer from these three sources must be found by weighting them in much the same way as the box temperatures were weighted above. This case is simpler and will, therefore, be considered in detail.

The radiation falling on the top of the radiometer can be considered as if it all came from a hemisphere centred at the centre of the radiometer and having a radius equal to the distance to the lip of the opening to the conical cavity (i.e., $\sqrt{8^2 + 4^2}$ in.). The flux density from the cavity will be σT_c^4 and from the rest of the hemisphere σT_b^4, where T_c and T_b are the average temperatures of the cone and the top of the box, respectively. If β is the angle of incidence measured from the normal to the radiometer surface, then the total radiation per unit area at the centre of the top of the radiometer will be:

$$\int_{\beta=0}^{\beta_1} \frac{\sigma T_c^4 \cos \beta}{\pi r^2} . \; 2 \pi r \sin \beta \, . \, r d \beta + \int_{\beta_1}^{\pi/2} \frac{\sigma T_b^4 \cos \beta}{\pi r^2} . \; 2\pi r \sin \beta \, . \, r d \beta$$

where $\sin \beta_1$ is the radius of the opening divided by the radius of the hemisphere mentioned above, or:

$$\sin \beta_1 = 1/\sqrt{5} .$$

Integration yields $\sigma T^4 \sin^2 \beta$ in each case, and substituting the limits gives:

$$0.2 \, \sigma T_c^4 + 0.8 \, \sigma T_b^4 .$$

The box was not designed to make these factors work out to exactly 0.2 and 0.8; the final result was fortuitous. Points on the top of the radiometer slightly removed from the centre will have weighting factors differing from 0.2 and 0.8 by negligible amounts.

The radiation falling on the lower side of the radiometer must be subtracted to give the net radiation. The weights applied to the computed fluxes from the cavity, the top of the box, and the bottom of the box were, therefore, 0.2, 0.8 and minus 1.0, respectively. The millivolt output from the radiometer, recorded separately, was plotted against the computed net radiation. The several points from a single run always lay close to a straight line through the origin. Least squares were used to compute the slope, which was the required calibration factor. Since the calibration factor is to be used to obtain net radiation from millivolt readings, the millivolt readings were assumed exact and the radiation values minimized. The slope was therefore given by:

$$b_o = \Sigma V^2 \div \Sigma R V$$

where V and R are the individual millivolt and net radiation values, respectively.

6. RESULTS

Four different types of net radiometers have been calibrated with the apparatus described. The results of each of the individual runs are given in Table 1, together with summaries for runs that could be combined. A few comments about each instrument may be useful.

An old Beckman and Whitley ventilated net radiometer, which had been used in the field several years ago, was calibrated mainly to gain experience in the use of the calibration apparatus. In the first four runs the cavity was facing the side of the radiometer that is normally upwards, while in the last four runs the cavity was facing the lower side. The difference is obvious. If the radiometer and the interior of the box had always been at the same temperature as the ventilating air then the calibration factors would represent the separate factors for the two sides of the radiometer. Since these temperatures, in general, where somewhat different the results merely indicate a serious difference in the two sides. The most probable cause of this difference is non-equal ventilating rates on the two sides, but it was not investigated further.

Run D is not significantly different from runs A, B and C. This means that no gravity effect was detected. Run H was the only one conducted in the air-conditioned laboratory. It is not significantly different from runs E, F and G; and this means that drafts from open windows in the earlier runs had little effect on the final results, although they did make the estimation of chart readings more difficult. The rear end of the calibration box was not blackened until after run E. The value for run E is somewhat lower than those for the later runs but hardly enough to be significant. One can conclude that no effect was detected as a result of blackening the end.

The second instrument to be calibrated was a shielded net radiometer of the type developed by Funk (3) of the CSIRO and manufactured in Australia. During the first run, dry nitrogen from a high pressure tank was delivered through reducing valves to keep the plastic domes inflated and dry. This is the method suggested by the manufacturer. For all the later runs a small aquarium pump was used to recirculate air through a drier to the domes. This worked satisfactorily in the laboratory and was later used in the field. The change from nitrogen to air had no noticeable effect on the calibration factor. Run C, as originally calculated, gave a factor of 26.25, but a fault was found in the radiometer support that placed the radiometer about ¼ in. closer to the cavity when it was inverted. When this was allowed for by changing the weighting factor from 0.20 to 0.21 the calibration factor was reduced by about 4 per cent. This emphasizes the importance of careful placement of the radiometer.

As with the Beckman and Whitley instrument, gravity had no measurable effect on the calibration. It was noted, however, that when the cavity was below and much warmer than the box the output of the CSIRO was unsteady. This effect is probably caused by convection currents rising from the heated cavity. If so, it raises the interesting problem of whether a small part of the upward heat flux is the result of convection instead of radiation. This might also occur in the field under very unstable conditions. The sensitive black surfaces of the CSIRO instrument were repainted following run E. Runs F and G indicate an increase in the output which is probably significant. The calibration supplied by the manufacturer was 24.28 mv/cal cm^{-2} min^{-1} at 20° C.

With the assistance of Mr. Graeme Wilmot of McGill University a Schulze shielded net radiometer that had been used on an expedition to Axel Heiberg Island was calibrated. The first run was quite short, but the results were more consistent than those made with the other instruments. Some additional observations indicated a difference of about 4 per cent in the sensitivity of the two sides, but this was not serious. It was not possible to compare this long-wave calibration factor with any other value because the short-wave calibration, investigated elsewhere, was done with a microammeter to record the output.

The latest calibration was done on a Suomi type (4) of net radiometer manufactured by the Meteorological Service of Canada. The first two runs yielded values that were almost as poor as those for the Beckman and Whitley instrument. There was on this instrument, however, a means of adjusting the ventilation on the two sides of the plate. After adjustment, which was difficult to do accurately, the instrument was recalibrated in runs 3 and 4. These results were much better but still differed by about 10 per cent. The calibration based on both runs 3 and 4 was 4.09 mv per cal cm^{-2} min^{-1}, which agreed well with the short-wave calibration factor of 4.10 supplied by the Meteorological Service. When the cavity remained well below freezing for a considerable time frost sometimes formed on the inside. This would probably change the emissivity of the cavity, and when it was noted the run was stopped.

7. SUGGESTED IMPROVEMENTS

For greater convenience the rear door of the calibration box should be bolted on instead of sliding into place. The thermocouples on the box and cone should be carefully placed to simplify the calculations and perhaps increase the accuracy.

To improve the accuracy a rigid but adjustable support for the radiometers should be devised to ensure that they are properly placed in the box. A study of the variation in the radiation on different parts of the side of the radiometer facing the cavity might reveal a constant but significant error.

All the calibrations so far have been done at ordinary room temperatures. It is hoped that some of them can be repeated in a cold room to show the variation in calibration factor with ambient temperature. With the apparatus in the cold room and the heated cavity below the radiometer, the convection will be more vigorous and it may be possible to detect its effect on the calibration.

8. CONCLUSIONS

An absolute calibration is required for net radiometers in the long-wavelength region. Although the basic principle of such a calibration is very simple, the practical difficulties of obtaining reasonable accuracy lead to complex computations. The formulae which determined the shape of the radiating cone, have been developed in detail in this paper.

The radiating cone and the calibration chamber or box were built at the National Research Council and the necessary controlling and measuring apparatus was assembled. The calibration of four different types of net radiometers indicates that the apparatus functions satisfactorily and yields calibration factors with precision and accuracy within a few per cent. Several improvements are suggested that might reduce errors to about 1 per cent.

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TABLE I

RESULTS OF RADIOMETER CALIBRATIONS FOR LONG-WAVE RADIATION

RADIOMETER	RUN	CAVITY	RADIOMETER	N*	b_o**	REMARKS
B and W	A	Above	Erect	6	16.78	
	B	Above	Erect	20	15.59	
	C	Above	Erect	15	13.96	
	D	Below	Inverted	18	14.45	
	E	Below	Erect	15	5.98	End blackened
	F	Below	Erect	9	8.02	
	G	Below	Erect	24	6.57	Moved downstairs
	H	Below	Erect	16	7.53	
	ABCD			59	14.83	
	EFGH			64	7.03	
CSIRO	A	Above	Erect	11	24.87	Aquarium pump set up
	B	Above	Erect	13	25.21	
	C	Below	Inverted	9	25.17	
	D	Below	Erect	9	25.47	
	E	Below	Inverted	6	23.12	CSIRO repainted
	F	Above	Erect	10	26.24	
	G	Above	Inverted	11	26.52	
	ABCDE			48	24.69	
	FG			21	26.42	
Schulze	NO. 1	Below	Erect	4	19.25	
	No. 2	Below	Inverted	9	19.05	
	No. 3	Above	Erect	9	19.16	
	No. 4	Above	Inverted	12	19.34	
	Totals			34	19.22	
Suomi	No. 1	Above	Erect	18	6.13	
	No. 2	Below	Erect	19	2.85	Ventilation adjusted
	No. 3	Below	Erect	23	3.91	
	No. 4	Above	Erect	18	4.34	
	3 and 4			41	4.09	

* N: number of points.

** b_o: calibration factor in mv per cal/cm^2-min.

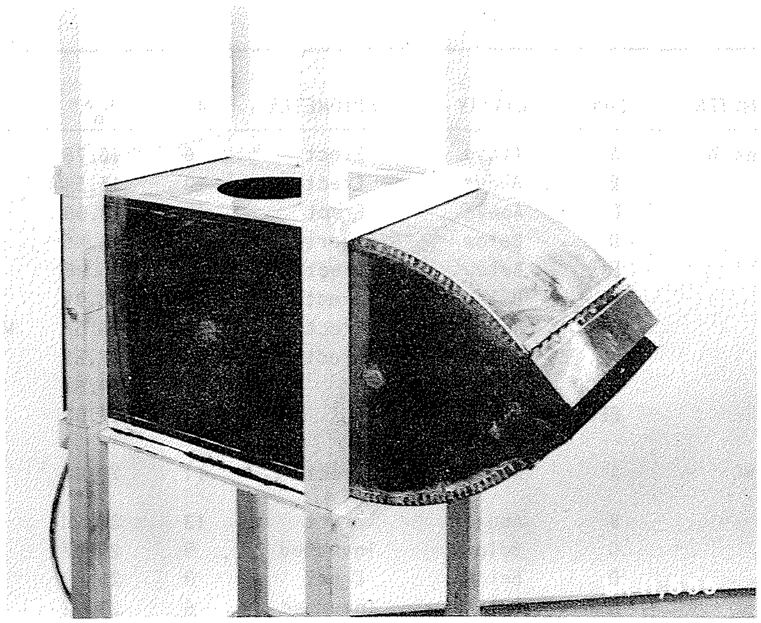

FIGURE I

COPPER CALIBRATION BOX BEFORE INSULATING

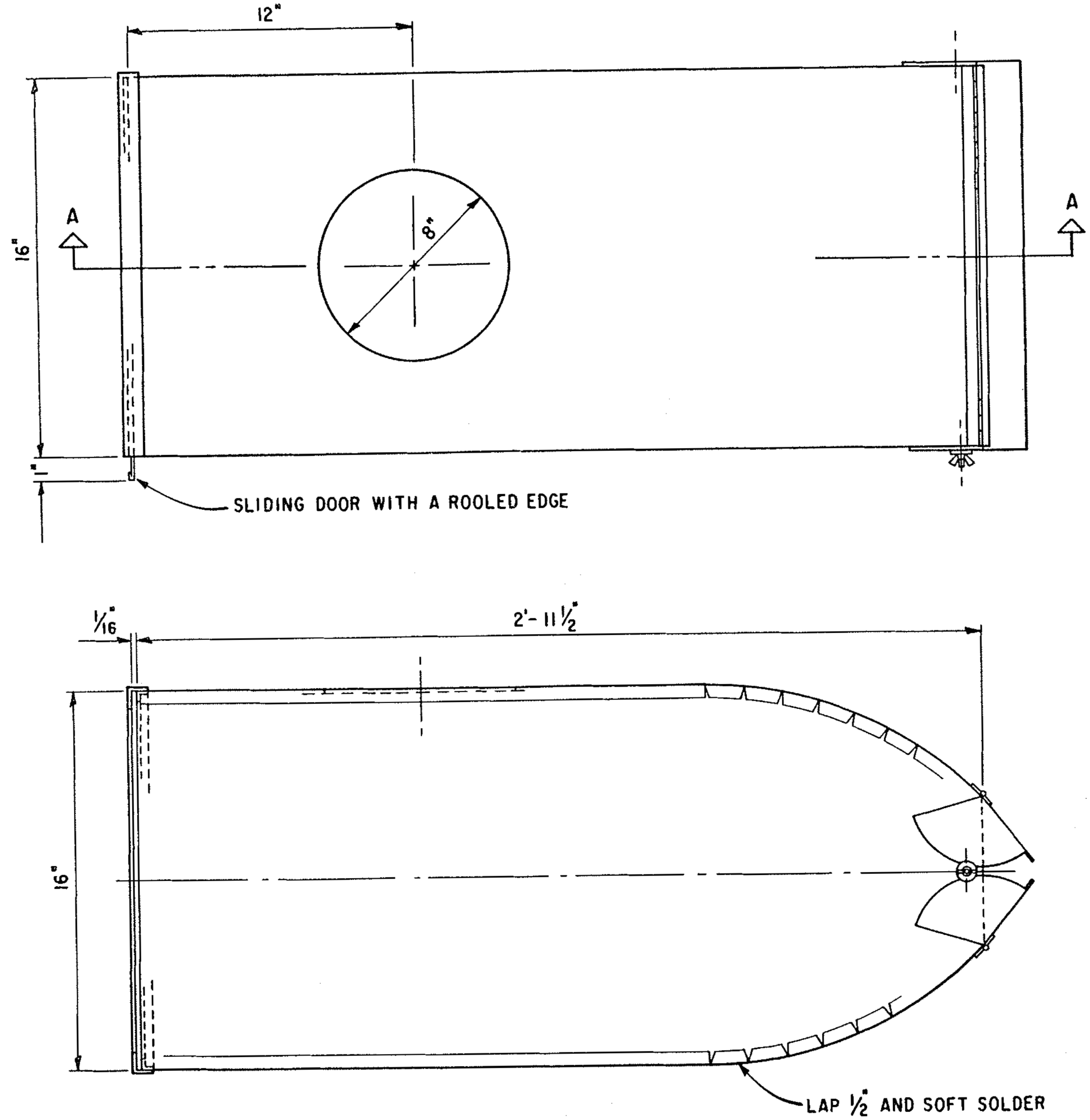

FIGURE 2 COPPER CALIBRATION BOX

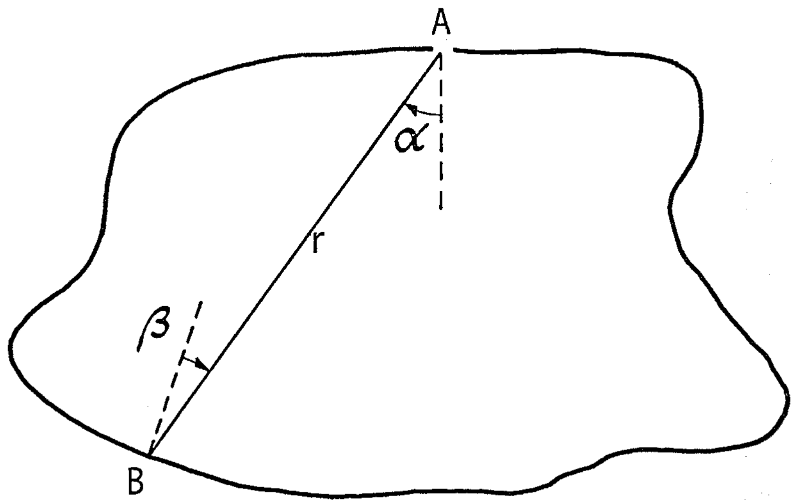

FIGURE 3

CAVITY WITH A SMALL OPENING AT A

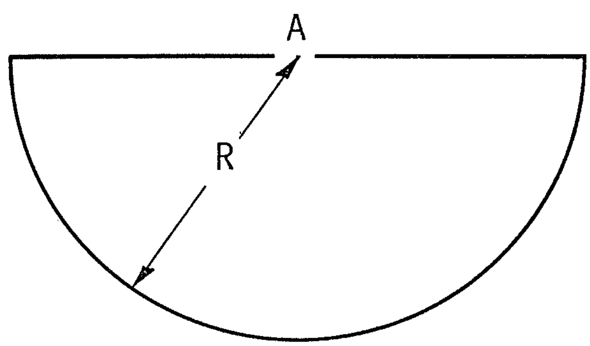

FIGURE 4

HEMISPHERICAL CAVITY

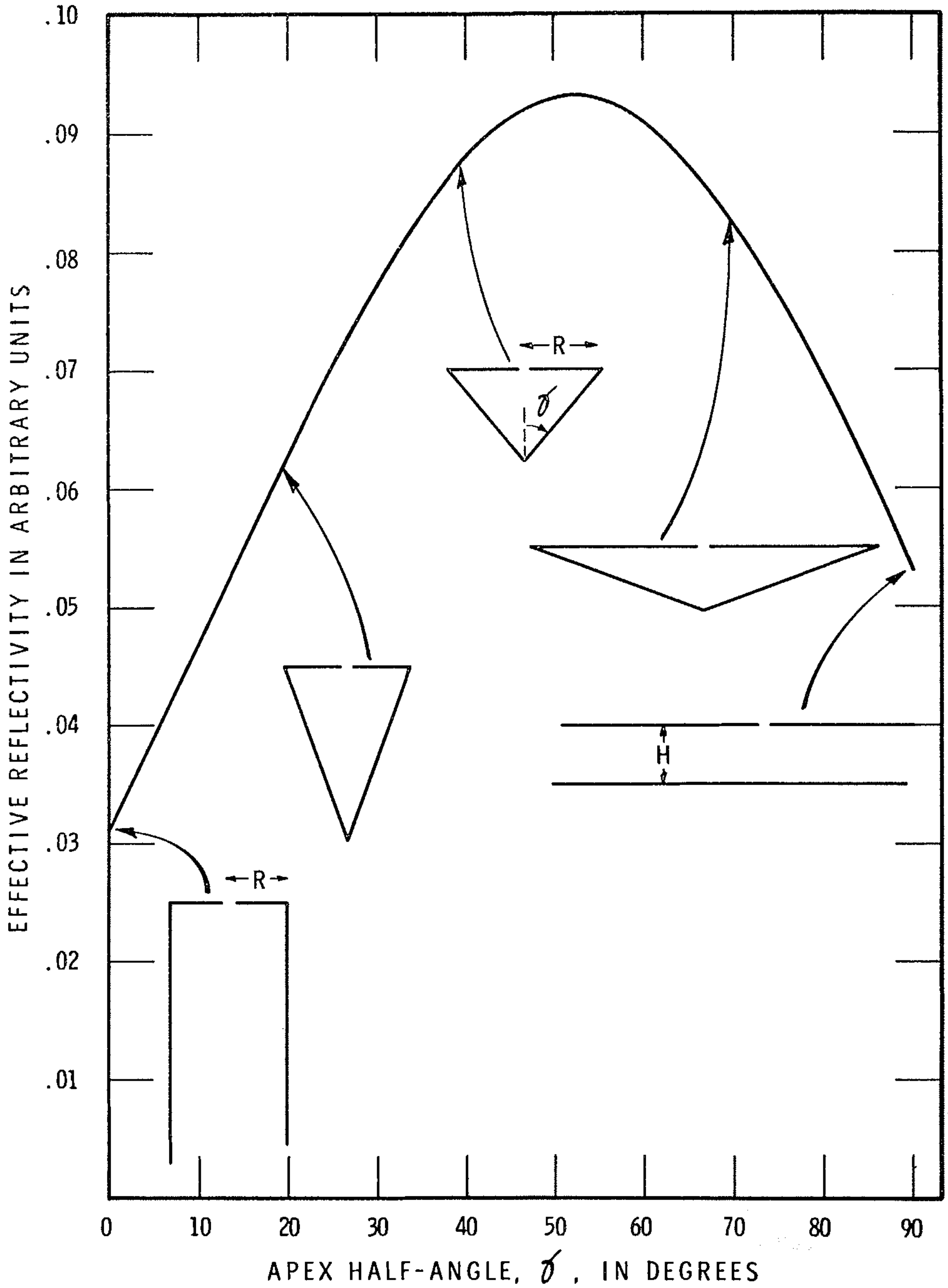

FIGURE 5

EFFECTIVE REFLECTIVITY OF CONES OF DIFFERENT SHAPES BUT WITH A CONSTANT VALUE OF R COS γ

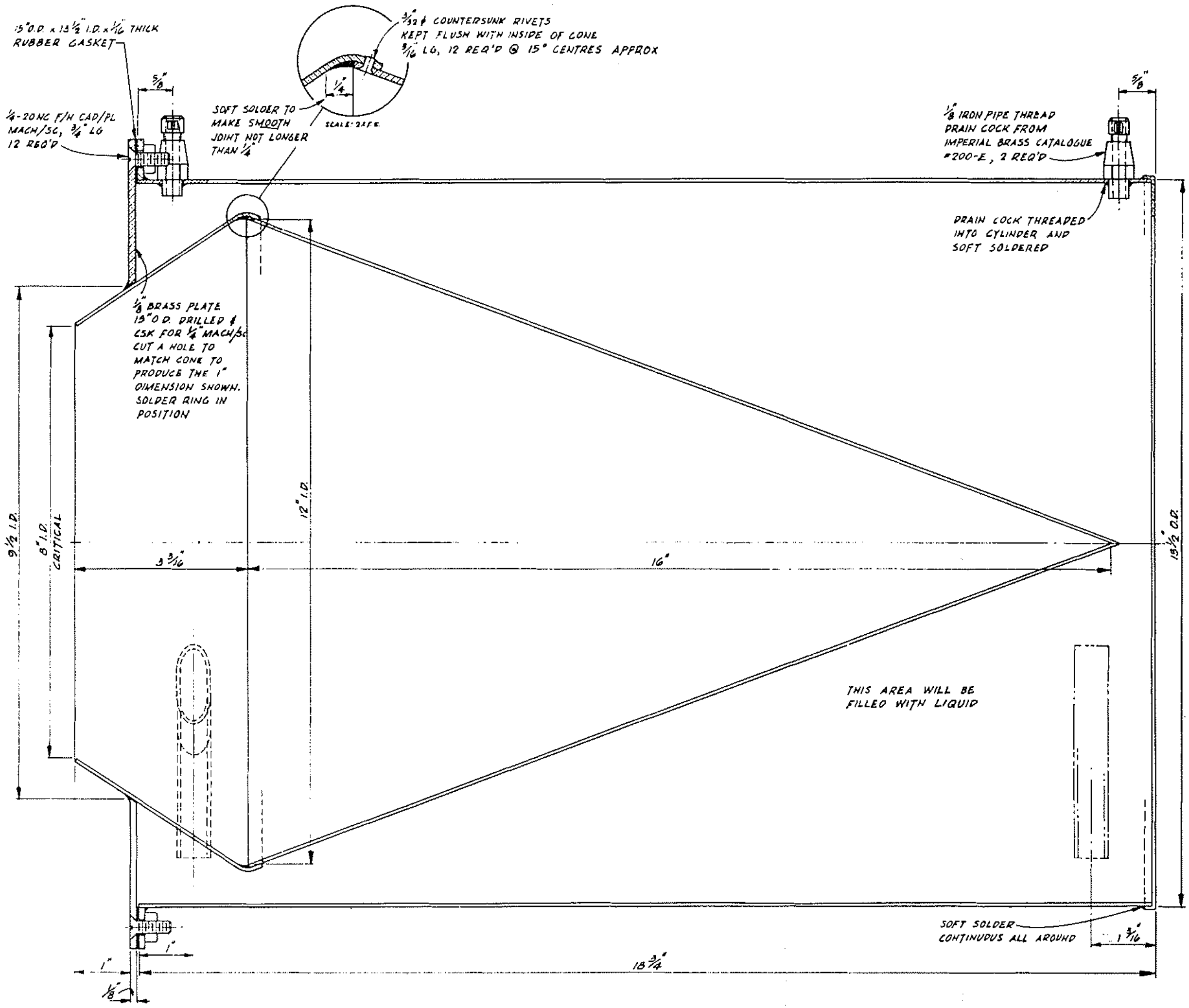

FIGURE 6

CONICAL CAVITY AND ENCASING CYLINDRICAL CAN

DISCUSSION

Recorder: V. R. Turner

Dr. J. Maybank: Have you calibrated the CSIRO polythene shielded radiometer, and were you able to test the transparency of the shield? Did it have any noticeable effect on the response?

D. W. Boyd: We did calibrate one CSIRO net radiometer with the polythene shields in place as used in the field. No attempt was made to calibrate the instrument without the shields or to test the transparency of the shields in any other way.

J. R. Latimer: The final equation in the paper for the calculation of the flux of radiation from the cavity is only valid for a small area at the centre of the thermopile. This expression must be integrated over the entire sensitive surface.

D. W. Boyd: Mr. Latimer is quite right. The calculations yield the radiation flux density at the centre of the upper surface of the radiometer. What is really wanted is the average over a small rectangular surface. I wrote down the required integrals but did not get much further.

Mr. Latimer informs me that the particular case of a circular area was first integrated by J. H. Lambert (1). The weighting factors applied to the radiation from the conical cavity for various sizes of circular radiometers would be;

Radius of Radiometer	Factor	Error
small	.2000	---
½ inch	.1995	¼ %.
1 inch	.1980	1 %
2 inches	.1922	4 %

These can be used to estimate the errors for the various rectangular radiometers:

Radiometer	Dimensions in Inches	Estimated Error
B and W	3½ × 4½	at least 5 %
CSIRO	1.4 × 1.4	less than 1 %
Schulze	½ × 1	less than ¼ %
Suomi	1 × 3	more than 1 %

Except for the B and W these errors are smaller than the probable error caused by inaccurate positioning of the radiometer, where a typical inaccuracy of 1/8 inch causes a 2 per cent error.

The standard deviation of 17 runs from their means in groups of 4 or 5 was 0.83 cal/cm^2-min. A calibration factor computed from 4 runs would have half this standard deviation which would be about 2 per cent for a calibration factor near 20 or about 10 per cent for a calibration factor near 4.

Both the accuracy (2 to 5 per cent) and the precision (2 to 10 per cent) depend, therefore, on the instrument being calibrated.

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