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THERMOMETER SCREENS

[*Proc. R.S.E.*, Vol. XL, 1921]

[This paper was finished a few days before Dr Aitken's death in 1919, and was communicated on January 16, 1920 to the Royal Society of Edinburgh by Dr C. G. Knott, F.R.S.]

IT is now thirty-two years since I last brought this subject before the Royal Society of Edinburgh. Since then nothing has been done to remedy the imperfections which were then shown to characterise the thermometer screens used throughout the country. In some respects these imperfections may seem to be of small importance. Yet in these days when accuracy of measurement is being more and more insisted on, and particularly now when reconstruction is everywhere in vogue, it does seem desirable that apparatus largely used by thousands of observers should be as perfect as it is possible to make it.

In my previous papers* it was shown that in sunshine the Stevenson screen always gave too high readings. The trouble taken to get Kew corrections for thermometers whose errors in that respect rarely exceed 0°·2 or 0°·3, and the application of the corrections to readings obtained under conditions in which they may be easily 2° or 3° in error, do not commend themselves as worthy examples of scientific method—it is very like a case of straining out a gnat and swallowing a camel.

Having changed to other surroundings since the former series of observations were carried out, I determined to repeat the work in the altered conditions; but it was not till after the middle of August of this year (1919) that I was able to instal all the necessary instruments and make comparisons. Soon after I came to Ardenlea, the Stevenson screen had been fitted up on a lawn-tennis green more or less surrounded by trees, but subject nevertheless to a fairly free circulation of wind. On this green the new tests and comparisons were made.

Taking the temperature of the air seems to be, at first sight, a very simple matter. It is, however, very far from being simple; and, as a matter of fact, no one has ever attempted to define what we are to measure.

The fine-bulb† thermometer used in previous tests showed that, when there

* *Proc. Roy. Soc. Edin.*, Vol. XII, 1882–84; Vol. XIII, 1884–86; Vol. XIV, 1886–87. See also No. 34 above, page 537.

† The bulb is cylindrical, with a length of 25 mm. and a diameter of a little over 1 mm. It is provided with a sheath of pure silver which fits it closely. The readings of this instru-

is any radiation, the air passing the thermometer bulb is very variable as regards temperature, rising and falling quickly, changes of 1° F. being frequently observed to occur in the thermometer during five seconds. A thermometer with an ordinary-sized bulb similarly placed responds very slowly to these fluctuations of temperature in the air. Even the fine-bulb thermometer does not, in fact, show the extreme variations of temperature in the air. Sensitive though it is, it has what might be called a "thermal inertia"* of appreciable amount. If the thermometer were smaller and of less thermal inertia, its up-and-down movements would be greater. Probably an electric resistance thermometer with a very fine short wire would respond more quickly to the variations of air temperature. Every thermometer will have its own thermal inertia determining how quickly it will respond to, and how far it will follow after, a temperature change in the air. With solar radiation heating all kinds of matter at the earth's surface, the air is full of heated currents rising and spreading more or less irregularly. What are we then to understand by the temperature of the air at a given time and place, and how are we to measure it? It is obviously impossible to measure the temperature of the hottest whiff of air; for a registering thermometer of no thermal inertia is unthinkable. Every thermometer must give its own averaging of the varying temperatures to which it responds more or less sluggishly according to its own thermal inertia.

For example, let the fine-bulb thermometer and an ordinary thermometer with a bulb of 5 or 6 mm. diameter be exposed under a sunshade and let their indications be observed for a few minutes. While the fine-bulb readings are subject to continual ups and downs, the other responds much more slowly, neither going so high nor falling so low. If the temperature is rising on the whole through a series of variations, the average of the fine-bulb readings will be above the average of the other; and if the temperature is falling as a whole, the fine-bulb thermometer will give the lower average. (See paper on "Thermometer Screens," Part IV, *Proc. Roy. Soc. Edin.*, Vol. XIV, 1886–87, for detailed experiments.)

Thus there is nothing really determinate until we fix on a definite size of bulb for the thermometer, and make the thermal inertia of the screen as small as possible. If the thermal inertia of thermometer and screen is very small, the thermometer will give nearly the average temperature of a small amount of air. If the thermal inertia is very large, the thermometer will give roughly the

ment when simply placed under a sunshade were found to agree very closely with those given by shaded thermometers in a steady draught of air. It may be regarded as giving very nearly the true temperature of the air. See *Proc. R.S.E.*, Vol. XII, p. 688, 1882–84.

* [Dr Aitken introduced the word "inertia" to mean the slowness of response of any body to a heating or cooling process. It depends on many factors, such as thermal capacity, absorption, radiation, conductivity, etc. I have taken the liberty of prefixing the word "thermal" in all cases, so as to prevent confusion.—C. G. K.]

average temperature of a greater amount of air than in the former case. Large bulbs and certain forms of screen occasion a further source of error on account of radiation effects.

With these considerations as a guide, two exactly similar Fahrenheit thermometers with bulbs 10 mm. in diameter were used. The scales were wide and easily read, and the Kew corrections were very small, never more than 0°·1 at any part of the scale. They were placed under two sunshades of my own design, of which one variety is shown in the accompanying figure (p. 584).

This screen consists essentially of two horizontal boards one above the other, with an air space between, as indicated in the sketch. The thermometer bulb lies a short distance below the lower board, and the stem passes upwards through holes pierced in the boards. This form of screen is more efficient than the Stevenson arrangement. A thermometer protected by it always reads lower than the thermometer in the Stevenson screen when there is any radiation, although the latter may read as low as the former at the beginning of the rise in the presence of sunshine. This is owing to the great thermal inertia of the Stevenson screen. Further, the errors in the readings of the Stevenson screen thermometer go on increasing with the duration of the radiation. There is no such effect in the case of the other form of screen, and all maximum readings taken under it are lower than those taken in the Stevenson screen.

There are several reasons for the temperatures within the Stevenson screen being recorded too high. First, the air comes into the screened region over louvres heated by radiation. Second, the open bottom of the screen allows radiant heat from the soil to enter. Third, the thermometer readings are also raised by the heating of the inside of the roof during continuous radiation. This may be easily remedied by fitting to the screen another cover, with an air space between.

We return to the experiments with the two thermometers. These were placed with their bulbs about 4 cm. below the underside of the screen. The readings were always the same even under the condition of strong sunshine.

The bulb of one of the thermometers was now coated with aluminium paint, which is known to have small absorption powers for heat, and placed under the sunshade alongside the other thermometer. The readings of the two remained practically the same. Gold paint was then tried, with the result that the reading of the thermometer with the gilded bulb fell to nearly one degree below the other, showing therefore considerably less absorption of radiant heat. Compared with the silver-sheathed fine-bulb thermometer, the gilded-bulb instrument read about 0°·5 higher. The next protection tried was gold leaf. The bulb and part of the stem were dipped into a thin solution of spirit varnish, taken out, shaken to get rid of the last drop, and then turned bulb up so as to have as thin a layer of varnish as possible.

A piece of gold leaf previously prepared was placed on the bulb, and was at once drawn round it by the capillarity of the varnish. A blast of air immediately applied caused the creases to fold closer to the glass. After drying for two or three days, the gilded bulb was rubbed with a fine brush and the superfluous leaf removed. This gold-gilt thermometer when tested against the silver-sheathed fine-bulb instrument gave the same reading when the air temperature was fairly steady. It was not, of course, so sensitive to rapid changes.

In the following tests the gold-gilt thermometer was used as a standard, since its thermal inertia was about the same as that of the other thermometers in use. The silver-sheathed thermometer was, however, always placed alongside as a check on the gold-gilt one.

The thermal inertia of the Stevenson screen is very marked. It lags behind both in a rising and in a falling temperature, the enclosed thermometer reading lower in the former case and higher in the latter than a freely exposed shaded thermometer.

There is also increased thermal inertia in the maximum and minimum thermometers, which are usually constructed with heavy metal frames. These are nearly in contact with the bulbs, thereby checking the free circulation of the air. This adds needlessly to the thermal inertia, as direct testing clearly proves. Maximum and minimum thermometers should have the frames cut away all round the bulb to give free access of air.

All screens must have more or less thermal inertia, but we should endeavour to keep this factor as low as possible and effect a reasonable compromise. The thing to be avoided is too great thermal inertia, especially when combined, as in the case of the Stevenson screen, with the "bottling up" of heat consequent on the long-continued action of radiation.

As clearly established by prolonged observations, the simple double-board sunshade with the thermometer bulb freely exposed under it, as shown in fig. 1, is more efficient than the Stevenson screen, besides being very much simpler in construction. It may, however, be greatly improved. Thus radiation from below can be intercepted by a small horizontal screen *a* placed under the bulb, as shown in fig. 2; and secondary radiation from the lower surface of the shade proper can be intercepted by a small screen, similar to *a*, and placed above the bulb. Finally, the radiation from more distant objects or from the sky on the sides of the apparatus can be intercepted by means of a small annular piece with wide central hole surrounding the bulb, as shown in fig. 3. It should be grooved on the outside vertical rim so as to prevent the air heated on it from entering the bulb enclosure. Another obvious improvement would be to make each of the small disks *a* of two thin parallel disks with air space between, in place of one thickish disk of wood.

With all these precautions there still remains some secondary radiation which, falling on the bulb, causes the thermometer to read too high by an amount depending on the size of the bulb and the nature and thickness of the glass. No amount of air circulation can check this heating effect. For example, if we take two similar thermometers and protect one with a silver sheath, and then sling them in the usual manner so as to cause them to move rapidly through the air, we find that the unprotected thermometer may read as much as a degree higher than the other. This is due to radiation entering the unprotected bulb. The best protection is, of course, to gild the bulb. This plan, though satisfactory for experimental purposes, must, I fear, be dismissed as unpractical under ordinary working conditions, since it would be impossible to keep all the bulbs constantly bright.

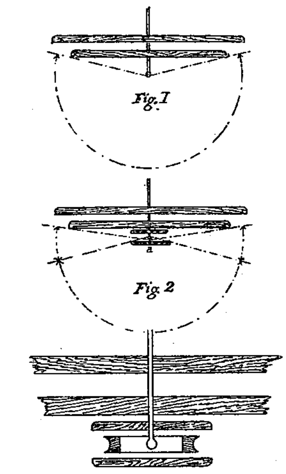

Fig. 3.

In addition to the ordinary measurements of temperature by means of shaded or protected thermometers, it is important to record measurement of radiation of direct sunshine. This is usually done by means of a black-bulb thermometer; but there are advantages in the use of an instrument first described in my early papers on Thermometer Screens already referred to, and used in connection with my researches on Dew. (See "Thermometer Screens," *Proc. R.S.E.*, Vol. XII, 1883–84; also paper "On Dew," *Trans. R.S.E.*, Vol. XXXIII, 1885–86.) This instrument is called the radiation box, R.B. and its indications are compared with the readings of the black-bulb thermometer, B.B.

One of the radiation boxes with its enclosed maximum and minimum thermometers is placed horizontally on a light wood frame with its surface at the same height as the thermometers in the screen. During the day the maximum radiation temperature is recorded, and the minimum during the night. During summer its average maximum is higher than the black bulb *in vacuo*; but in winter it is lower owing to the low sun, so that the rays fall very obliquely on the surface of the radiation box. For no particular height of the sun, however, do these two types of instrument agree in their maximum readings, since the radiation box is greatly affected by the wind. The temperature of the radiation box is also raised by long-wave radiations from sky, cloud, and surrounding objects. As already pointed out in previous communications, the indications of the radiation box are more in accordance with climate than are the readings of the black bulb.

The accompanying table (p. 586) contains observations from August 17, 1919, to October 31 of the same year*. A brief discussion of these will illustrate the points now being emphasised.

[* In the original notebook from which these observations are taken, the daily observations continue till November 8, six days before Dr Aitken's death.]

To all temperature readings the Kew corrections of the thermometers have been applied. The observations here recorded were all made at 9.30 a.m. The first item entered for each day is the direction and strength of wind. Then follow the temperature readings of the thermometers in (1) the Stevenson screen; (2) the screen C as shown in fig. 2, without the annular piece shown in fig. 3; (3) the difference between these; (4) the temperature registered by the thermometer in screen D, which was provided with a vertical draft tube. Then follow the readings of the radiation box, R.B., and the black bulb *in vacuo*, B.B.; and finally a general description of the weather for the day.

An inspection of the table will establish clearly the following points:—

1. The thermometer in the Stevenson screen reads always higher than the others.
2. The error of the Stevenson screen thermometer is greatest when the R.B. and B.B. readings are high and there is an absence of wind.
3. The error is small when the weather is dull and the R.B. and B.B. readings are slightly above the temperature of the air.

These features are brought out very strikingly in the week beginning September 20. The fine, sunny, comparatively calm weather of the 21st and 23rd days are associated with large errors in the Stevenson screen thermometer; while the errors are very small on the contiguous days of cloudy and stormy weather. The long stretch of fine weather beginning October 6 and ending October 16 is characterised by large errors of the Stevenson screen thermometer and high readings of the radiation box.

[The average results may be brought out very simply by forming the data into three groups: (1) those in which the error of the Stevenson screen thermometer is 1·5 and upwards; (2) those in which the error lies between 1·0 and 1·5; (3) those in which the error is less than 1. Tabulate alongside each of these numbers the corresponding excess of the R.B. reading over the air temperature. Adding and taking the average values for each group, we find as follows:—

	Average Error	Average Excess	No. of Cases
Group (1) ..	2·8	47	33
Group (2) .	1·1	36	7
Group (3) .	0·4	22	30

Comparing groups (1) and (3), we see that with an average increase of 25° in the excess of the R.B. temperature above the air temperature, the average error of the Stevenson screen thermometer is increased sevenfold. From the middle of August to the end of October nearly 50 per cent. of the morning readings

TABLE COMPARING THE ACTION OF THE STEVENSON SCREEN WITH THAT OF AITKEN'S SCREEN C, ETC.

Date	Wind	Stevenson	C	Difference	R.B.	B.B.	Weather
Aug. 17	S.W. ·5	73·7	72·0	1·7	130·1	123·5	Fine, sunny, strong S.W.
„ 18	S.S.W. 1·	66·8	65·4	1·4	117·0	119·0	Cloud and sun, strong S.W.
„ 19	S.W. 1·	67·7	66·0	1·7	130·6	124·8	Cloudy to fine, S.W. 2
„ 20	Calm	65·8	64·0	1·8	120·5	117·0	Variable, showery, W.S.W. 1·
„ 21	S.W. ·1	61·9	59·6	2·3	121·5	118·0	Cloudy to fine, S.W. 2·
„ 22	S.W. ·5	65·8	63·9	1·9	127·2	117·6	„ „ S.W. 3·
„ 23	S.W. ·2	64·8	63·0	1·8	124·0	117·4	„ „ W.S.W. ·5
„ 24	Calm	66·7	62·4	4·3	138·7	121·0	„ „ calm
„ 25	E ·1	54·3	54·0	0·3	67·0	69·0	Light drizzle all day, E.N.E. ·2
„ 26	Calm	60·0	59·4	0·6	84·5	86·8	Variable, S.W. ·2
„ 27	N.N.W. ·5	59·6	58·4	1·2	103·0	110·0	„ little sun, W.S.W. 1·
„ 28	Calm	54·7	53·3	1·4	89·2	80·0	Cloudy, calm
„ 29	W.S.W. ·5	62·9	60·5	2·4	123·0	117·0	Cloudy to fine, W.N.W. 1·
„ 30	S.W. 1·	60·2	58·3	1·9	113·0	113·0	„ „ W. ·5
„ 31	N. ·5	62·9	60·1	2·8	131·8	122·0	„ „ W. 1·
Sept. 5	S. ·5	72·0	70·0	2·0	119·5	118·2	Fine but stormy, S.
„ 6	S.W. ·5	64·8	63·3	1·5	102·0	114·0	Cloudy, S.W. 1·
„ 7	W.S.W. 1·	66·7	65·0	1·7	121·2	120·0	Fine, S.W. 1·
„ 8	S.W. ·5	60·7	...	...	83·2	81·6	Dull all day, S. ·5
„ 9	S.W. ·5	63·9	63·3	0·6	82·4	78·2	Dull, S.W. ·5
„ 10	S.S.W. 1·	69·8	69·1	0·7	111·2	117·4	Fine, S.W. 1·
„ 11	Calm	65·9	65·1	0·8	90·0	85·3	Dull
„ 12	E ·2	50·6	50·9	−0·3	57·0	59·5	Very dull, drizzling. Dull till eve, E. ·2
„ 13	Calm	56·4	56·4	0·0	95·2	103·0	Changeable
„ 14	„	64·8	61·1	3·7	115·2	102·3	Fine, calm, cloudless
„ 15	„	67·8	64·5	3·3	117·0	106·2	Cloudless, S.W. ·2
„ 16	S.S.W. ·2	64·9	63·6	1·3	106·4	102·5	Fine but cloudy
„ 17	S.W. 1·	63·1	62·8	0·3	95·0	92·0	Dull, S.W. 1·
„ 18	S.S.W. 2·	62·6	61·2	1·4	102·6	105·0	Showers and stormy
„ 19	N. 1·	52·9	...	...	104·0	104·0	Cloudy to fine, S.W.
„ 20	W.S.W. ·5	55·7	55·0	0·7	109·1	105·5	Cloudy to fine
„ 21	W. ·2	59·9	56·3	3·6	111·3	107·2	Fine, sunny, W. ·2
„ 22	S. 1·	55·6	55·4	0·2	92·2	60·0	Raining, stormy
„ 23	W.S.W. ·2	58·6	55·6	3·0	113·6	106·3	Fine, sunny, W. ·2
„ 24	S.W. 2·	58·3	58·0	0·3	78·9	86·2	Showery, stormy, S.W.
„ 25	W.S.W. 3·	59·6	59·2	0·4	68·2	79·2	Drizzling, dull, S.S.W. ·4
„ 26	S.W. 1·	54·5	54·7	−0·2	94·2	101·	Cloudy, stormy
„ 27	W. ·2	58·5	56·0	2·5	103·5	105·0	Fine, W. ·2
„ 28	Calm	55·5	54·0	1·5	105·7	101·0	Fine a.m., dull p.m.
„ 29	S.W. 1·	52·6	52·7	−0·1	69·5	63·0	Dull, drizzling all day
„ 30	S.S.W. 1·	58·9	58·2	0·7	86·6	87·6	Dull day
Oct. 1	Calm	53·5	53·0	0·5	74·5	71·0	Dull, drizzling, S.W. ·2
„ 2	S.W. ·5	60·5	58·7	1·8	108·4	103·0	Fine, S.W. 1·
„ 3	S.W. ·5	58·2	58·0	0·2	67·0	75·0	Dull all day, S.W. ·2
„ 4	S.S.W. 1·	64·8	64·0	0·8	99·5	104·0	Hazed sky, calm

Date		Wind	Stevenson	C	Difference	R.B.	B.B.	Weather
Oct.	5	S.W. ·2	61·7	60·7	1·0	76·2	74·4	Dull day
"	6	S.W. 1·	68·1	66·2	1·9	102·0	104·0	Fine, E. ·5
"	7	Calm	60·0	56·5	3·5	83·0	85·5	Fine, calm
"	8	S.W. ·5	66·4	64·4	2·0	99·0	106·0	Cloudy to fine, W. ·5
"	9	W. ·2	57·6	53·0	4·6	100·0	96·0	Fine, calm
"	10	S.S.W. ·5	56·1	54·0	2·1	85·0	80·0	Fine, E. ·2
"	11	W. ·2	54·9	51·2	3·7	102·1	95·2	Fine, calm
"	12	W. ·2	50·6	50·8	-0·2	72·7	89·4	Fine a.m., dull p.m., N.W. ·5
"	13	N. ·2	55·6	54·2	1·4	94·4	92·5	Most dull and calm
"	14	W. ·2	52·6	49·3	3·3	87·0	86·4	Fine a.m., cloudy p.m., N. ·2
"	15	W. ·2	52·1	49·0	3·1	80·0	90·0	Fine, N.W. ·1
"	16	W. ·2	52·6	50·2	2·4	91·0	89·4	Fine a.m., Dull p.m., W.N.W. ·5
"	17	S.W. 1·	58·6	57·8	0·8	83·0	86·5	Fine to cloudy, W. 1·
"	18	S.W. ·5	53·8	53·6	0·2	72·0	73·0	Dullish all day, S.W. ·5
"	19	Calm	58·6	57·6	1·0	74·4	82·0	Dullish, S.S.W. ·5
"	20	S.S.W. ·5	55·7	55·6	0·1	63·2	66·0	Cloudy a.m., rain p.m., S.S.W. ·5
"	21	S.S.W. ·2	59·3	58·5	0·8	70·3	70·3	Dull, calm, foggy
"	22	S.S.W. ·2	58·8	58·1	0·7	71·2	73·1	Dullish
"	23	Calm	55·6	55·5	0·1	59·6	64·0	Very dull, dark day
"	24	N.E. ·5	46·8	46·7	0·1	56·7	55·0	Dull day, N.N.E. ·5
"	25	Calm	52·7	48·2	4·5	76·2	86·4	Fine, calm, cloudless
"	26	W. ·5	52·4	50·0	2·4	75·6	89·3	Fine, N.W. ·5
"	27	N. 1·	45·9	45·1	0·8	54·2	64·0	Cloudy
"	28	N.W. ·5	49·7	47·1	2·6	76·0	77·2	Fine, N.W. ·5
"	29	N.E. ·5	50·4	47·9	2·5	62·3	73·0	Sunny to cloudy, N. 1·
"	30	N. ·5	46·5	46·3	0·2	51·5	52·2	Dull day, E.N.E 1·
"	31	Calm	49·9	49·1	0·8	77·3	81·6	Mostly cloudy, N.E. ·2

of the thermometer in the Stevenson screen were in error by more than 1°·5 the average being 2°·8.—C. G. K.]

In addition to the regular morning and evening readings, many others taken at different hours during the rise of temperature tell the same tale as to the lag in the records of the Stevenson screen thermometer.

A comparison of the figures given here with the results given in previous papers shows that the conditions at Ardenlea were much more trying for the Stevenson screen than those at Darroch, where the early observations were made. The situation at Darroch had a much freer exposure; but there are sure to be some situations with a worse exposure than the Ardenlea tennis lawn. It is only on the top of a hill or on a wide perfectly open space that the temperature within the Stevenson screen can be kept down near to the true air temperature. Even at the Ben Nevis Observatory the tests showed that the Stevenson screen was influenced by radiation.

There are still two points to be settled with regard to the C screen, namely, the size of the upper screen and the size of the bulb of the thermometer. Both must be standardised if different screens are to give comparable and concordant readings. The screen used in the present investigation was small, the upper protecting screen being a circular disk 19 inches (48 cm.) in diameter, and the lower 14 inches (36 cm.). The two under screens *a* and *b* were 4·6 inches (11·6 cm.) in diameter. With so small a screen the sun's rays at early morning and late evening will fall on the bulbs and tend to heat them. This does not, however, happen near the hour of maximum temperature for the day; and up to November it had no influence on the maximum recorded during the heat of the day.

To test the point here raised a larger rectangular screen was set up. The top part measured 30 by 21 inches (76 by 53 cm.) and the under part 24 by 15 inches (61 by 38 cm.). The screen was placed with its length E. and W. to shut out the morning and evening rays. The small under screens were the same as in the other case. So far as observations have been made there is no evidence of any difference in the behaviour of the large and small screens*.

Before concluding I would like to refer again to night temperatures taken on grass. The present haphazard method is of little value if the measurements made at different stations are to be taken as true indications of the intensity of the night radiation at these stations. The variables are far too numerous. Thus a thermometer placed on a small grass surface surrounded by bare ground reads higher than one placed on a large grass surface, owing to the drifting in of the warmer air over the bare ground. A thermometer placed on thin turf reads higher than one placed on thick, mossy turf, because it receives more heat from underneath. When placed on turf protected from wind, the thermometer reads lower than one more freely exposed to air currents, which mix the higher warmer air with the colder air at the grass level. Since it is impossible to have the same conditions at all stations, some less objectionable method is desirable.

I have previously advocated the use of the radiation box placed at the height of the screen thermometers. It is not affected by variations in the amount of heat received from beneath, as with the grass thermometers. It minimises the effect of the variations due to the extent of surface under grass and the variations due to wind. At night the R.B. always reads much lower than the grass thermometer. It must however be standardised. All radiation boxes must be of equal size. The ones I use are 36 cm. to the side, since tin plates can be easily got of that size. Any other convenient size might, however, be adopted. Again, the weight and kind of metal used for the top surface and for the tubes holding the thermometers must also be standardised, so that the thermal inertia may be a definite quantity; and similar precautions must be taken as regards the depth of the box, the amount and nature of the non-conducting packing, the size and shape of the thermometers, and the like. These precautions were taken in the construction of a number of boxes used, and all gave the same radiation temperatures.

[* Further work as planned was interrupted by Dr Aitken's death.]