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AN IMPROVED RADIATION INTEGRATOR FOR BIOLOGICAL USE

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(With Three Text-figures)

I. INTRODUCTION

The variation in the sun's radiation is the principal cause of variations in temperature in the field, with many familiar consequences; but the measurement of a single temperature gives a poor indication of what other temperatures in the neighbourhood are likely to be. For example, the temperature of the body of an insect exposed to full sunshine may be much higher than the air; this is known in both alpine (Krüger, 1931) and in tropical conditions (Buxton, 1924; Gunn, 1942). The importance of measuring the intensity of the sun's radiation directly has been cogently urged by Buxton (1926, 1927). Unfortunately, a convenient instrument for doing so in the field does not exist. It is not enough to measure light intensity, for the readings given by a photometer depend on the weight given to the various wave bands by the particular type of instrument used. No photometer gives due weight to the short infra-red between 1 and 3 μ. A considerable proportion of the heat from the sun, however, comes in this wave band. Moreover, the proportion of the total radiation in this region which reaches the earth's surface varies considerably according to solar altitude and atmospheric conditions. Consequently, if you want to know the heating effect of the sun, you have to convert all the incident radiation into heat and measure that.

Most pyrheliometers are delicate and expensive electrical instruments requiring skilled use. They do not lend themselves readily, therefore, to use in the field or in remote localities—the use of the Kalitin pyronometer by Strelnikov (1936) in the Terek river region is exceptional—with the result that no large general body of knowledge exists about the distribution of intensities of radiation over the earth's surface through the seasons of the year and through the daily cycle. The acquisition of such knowledge depends on the availability of an inexpensive, robust and dependable instrument for making measurements.

The type of instrument here described has developed from W. E. Wilson's 'Radio Integrator' (Griffiths, 1923). The principle of it is that radiation falls on a black body, so that it is all converted into heat, the heat is transferred to a volatile liquid and transformed into latent heat of evaporation, the vapour is condensed and its quantity is measured. If these processes can be carried out at 100% efficiency, without the leakage of heat, an exact measure of radiation can be obtained, the total distillate indicating the total amount of radiation.

II. PREVIOUS MODELS

The original Wilson 'Radio Integrator' is all glass, with some black material distributed through the volatile liquid, believed to be alcohol* (Fig. 1). Kennedy (1939) obtained distillates of over 60 c.c./day with this instrument in the Anglo-Egyptian Sudan, but we have been able to get rates of only fractions of 1 c.c./hr. under laboratory conditions. The bulb receiving the radiation is fully exposed to the air, so that in a given intensity of radiation its temperature would be much influenced by the speed and temperature of the wind. Consequently it could never give an uncomplicated measure of radiation.

For this reason, Buxton (1926, 1927) designed an improved model in which the radiation receiver is enclosed in an evacuated glass jacket (Fig. 2 *a*). Buxton obtained some valuable results with this in Samoa, but found it difficult to standardize the construction of the apparatus, and various instruments of the same design gave mutually inconsistent readings. The efficiency of this instrument is considerably lower than the estimated 38%, for there are errors in allowing for the exposed black area and in the latent heat of unit volume of alcohol. A figure of 4% seems to be somewhat nearer the truth. Clearly, proportionately slight variations in the 96% of heat loss will produce relatively large variations in the distillate, so that the instrument cannot be very accurate.

Buxton considered that the difference between his instruments might be due to variation in the length and diameter of the route followed by the alcohol vapour. He designed a model† (Fig. 2 *b*) in which this could be standardized and regretted that it was then technically impossible to use a black metal receiver instead of a glass one. His improved model has not been used in the field.

Consideration of the situation inside the radiation

* We are indebted to the Director of the Meteorological Office for the loan of this instrument.

† We are indebted to Prof. P. A. Buxton, F.R.S., for the loan of both of his patterns of instrument.

receiver and the alcohol condenser indicates that it is important for this space to be evacuated as highly as possible. If air is present, when the receiver is heated some alcohol will evaporate and the pressure will rise throughout the system; but, broadly speaking, the alcohol vapour will at first simply drive air out of the receiver and the rise of pressure in the condenser will be mainly due to the compression of air in it and not to the arrival of alcohol vapour. Alcohol will arrive slowly, after diffusion through the air. In the receiver the rise of alcohol vapour pressure will restrict further evaporation, insufficient heat will be transformed into latent heat and the temperature of the receiver will rise unduly. This, in turn, will lead to heat losses by conduction through the glass and by re-radiation. If, however, all air is removed, a rise of vapour pressure in the receiver will tend to lead to a practically instantaneous rise in alcohol pressure in the condenser, immediately offset by condensation, so that heat reaching the receiver can be rapidly removed and a considerable temperature rise avoided.

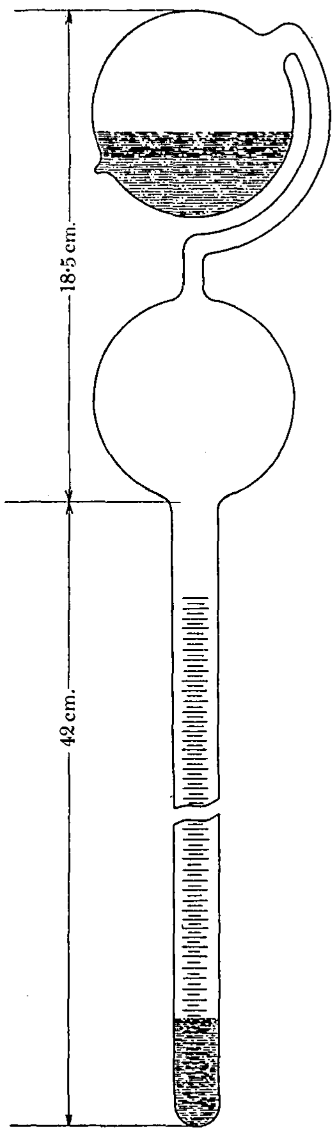

Fig. 1.

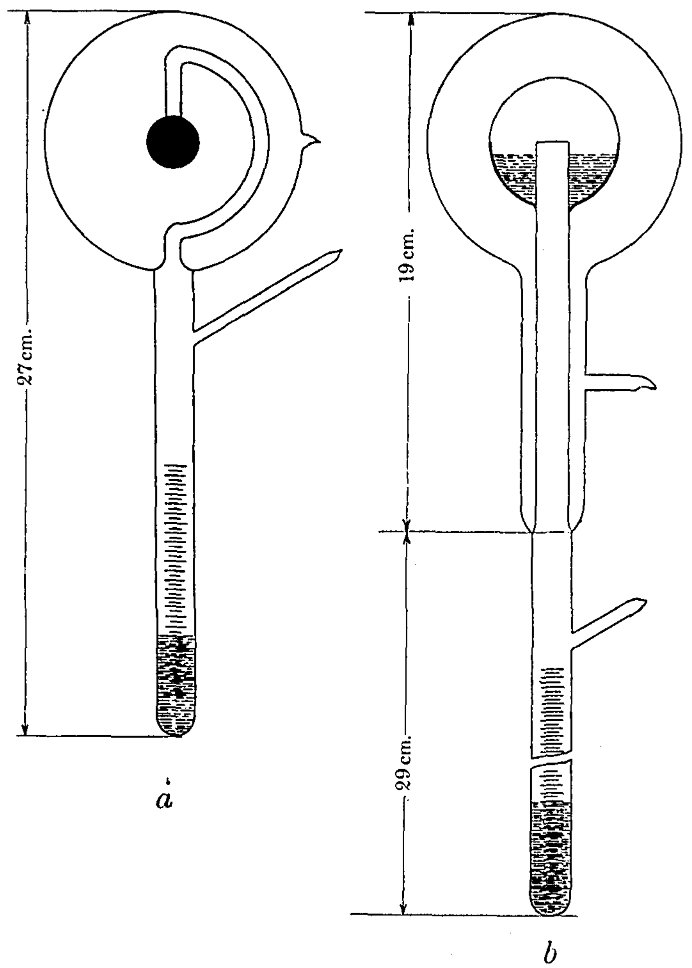

Fig. 2.

III. AN IMPROVED RADIATION INTEGRATOR

Our instruments incorporate the evacuated jacket of Buxton's first instrument and the shortened diffusion route of his improved model. The receiver is a hollow copper sphere blackened on the outer surface, so that radiation falling on the top is converted into heat and rapidly conducted to the liquid below. The air is removed from the condenser. In some of the instruments a short piece of copper tubing has been inserted at the top of the condenser column (Fig. 3 *a*) to allow rapid escape of latent heat of condensation. Both alcohol and water have been used as the volatile liquid to give instruments of different sensitivity.

IV. CONSTRUCTION OF THE APPARATUS

The incorporation of copper in a glass apparatus which has to be vacuum-tight requires highly skilled construction. The principal difficulties which have to be overcome arise from the necessity of avoiding damage to one joint—glass to glass, glass to copper, or copper to copper—when making another. The details are here given in the order in which they were carried out.

The copper sphere, which weighed 20 g. and was 5·08 cm. in diameter, was supplied as two hemispheres, mated and ready for soldering together.* The lower half was drilled axially to receive a shouldered sleeve, which was then fixed with hard solder (Fig. 3 *b*). The copper tube, to which a piece of glass tubing had already been fixed, was then hard soldered to the top of the sleeve in such a way that no copper tube showed outside the sphere. The upper hemisphere was then soldered into position and the assembly tested for air-tightness.

A cup-shaped piece of glass was fused on to a piece of the same kind of tube ready to receive the glass envelope. This tube was then fused at one end to the glass tube projecting from the copper sphere and, at the other end, either to the condenser tubing or to a double-ended copper-glass seal. At this stage the copper sphere was heavily coated with lamp black from a coal-gas and benzene flame, such as is used for smoking kymograph papers. It is important, if high absorption is required over the entire spectral range from 0·4 to 3·0 μ, not to paint on the blackening material and not to use anything but lamp black deposited from a flame. The copper sphere was then inserted into the outer envelope—a 600 c.c. Chance's Hysil CO_2 titration flask with the rim cut off and the flat bottom blown out in an attempt to complete the spherical shape.† The flask was fused on to the cup prepared for it, and the whole apparatus oven heated at 400° C. for 30 min. to release adsorbed gases, while a high-vacuum pump evacuated the envelope through a side tube attached below the level of the receiver. The envelope was sealed off when a steady vacuum of 10^{-5} mm. Hg had been reached. The condenser (Chance's Veridia Hysil of very uniform bore) was next fused into position.

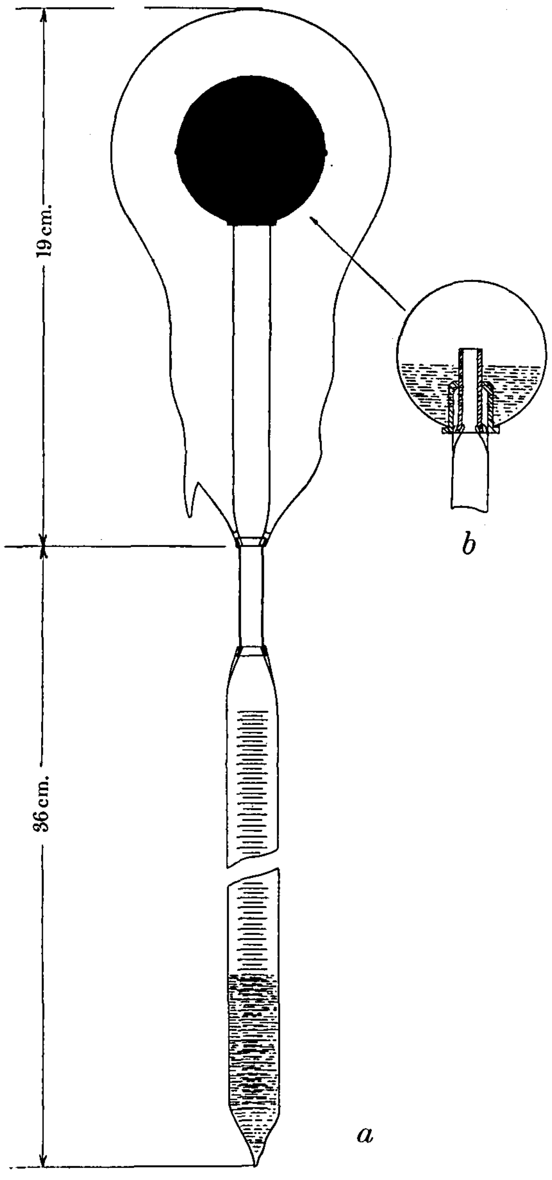

Fig. 3.

The final operation is to put in the alcohol and seal up the condenser. This was also done by high-vacuum technique, the whole of the sealed system, including the alcohol, being cleared of air before the alcohol was distilled from a reservoir into the condenser. The condenser was then sealed off in the blowpipe, enough alcohol having been left in the apparatus to come up to the first undistorted gradua-

* We are indebted to Mr John Levick, of Levick and Sons Ltd., Aston, Birmingham, for the gift of a number of these spun spheres of different weights and sizes.

† Chance's Hysil was chosen because of its remarkably good transmission up to nearly the limit of the solar spectrum at the earth's surface. For a specimen 2·5 mm. thick the percentage transmission is 90 between 0·5 and 2·0 μ, 80 at 2·5 μ and 20 at 2·7 μ.

tion on the condenser when the receiver was holding as much as it could in the operating position. The same filling procedure was followed when the alcohol was replaced by water, with the exception that with water-filled radiometers, 0·09 g. of soap dried at 100° C. was put into each receiver before starting the evacuation.

The inclusion of the neck of the flask in the apparatus is undesirable, but it appears to be necessary in order to avoid overheating the radiation receiver during manufacture and so oxidizing the copper and causing scaling.

V. LABORATORY TESTS

(*a*) *Source and intensity of radiation*

Since sunshine is too rare and weak in Birmingham in winter to provide reasonable test conditions, an artificial source of radiation has been used in all laboratory tests. The source consisted of a 1000 W., 230 V. tungsten filament lamp with a white enamel hemispherical reflector. A 5 cm. water filter was used to cut off all radiation of wave-length longer than 3 μ. The water filter was kept at a temperature below 30° C. by using a continuous flow of tap water at room temperature, so that it did not act as a serious source of secondary radiation. The peak intensity from such a lamp and filter combination is about 0·9 μ. The radiation distribution is, therefore, somewhat different from that of solar radiation at the earth's surface.

Absolute values of radiation intensity at different points in the radiation field were determined by means of an Ångström pyrheliometer* (Ångström, 1894; Hogben & Kirk, 1944). Measurements with the pyrheliometer in the same position, on different days, showed that the radiation intensity varied about a mean value by $\pm 7\%$. By using the mean of a series of values it was possible to show that, for approximate purposes, the filament of the lamp could be considered as a point source and that the radiation intensity varied inversely as the square of the distance. This relationship has been made use of in calculating all intermediate values of radiation intensity when required. The range of intensity available for testing purposes was 0·1–0·7 g.cal./cm.^{2}/min.

(*b*) *Preliminary tests*

Experiments with Buxton's improved instrument encouraged the belief that evacuation of the condenser was an important factor in the performance of the Integrator. Distillates obtained when the condenser of his improved instrument was roughly evacuated were twice as great as when there was air in the condenser at atmospheric pressure. The first instrument to be constructed, therefore, was evacuated to 10^{-5} mm. Hg, and although the copper receiver was unblackened, distillates of 2·5 c.c./hr. were obtained at a radiation intensity of 0·7 g.cal./cm.^{2}/min. Quite obviously the efficiency of the instrument also depends on the rate at which latent heat of condensation can be transferred from the condenser to the surrounding air. Using thermocouples dipping into mercury contained in plasticene cups attached to the outside of the condenser tube it was possible to determine the rise in temperature of various parts of the condenser when vigorous distillation was taking place. At a distillation rate of 5 c.c./hr. the temperature of the upper section of the condenser tube was 11° C. above that of the surrounding air. Two possibilities presented themselves for preventing this large rise in temperature. The first was to increase the area of glass on which the condensation could take place by the inclusion of a glass globe at the top of the condenser column. The second was to increase the rate of transfer of heat from the condenser to the air by including in the condenser column a section of material of high thermal conductivity. Consideration of the mathematics of the thermal conductivities of copper and glass suggested that, to be as effective as a short piece of copper tube let into the condenser column, the glass globe would have to be so large as to make the whole apparatus unwieldy. The second alternative was adopted, therefore, when constructing some of the final instruments.

(*c*) *Calibration of the improved models of the radiation integrator*

Table 1 gives a list of the instruments finally made, with an indication of their special characteristics.

Table 1

Instrument no.	Volatile liquid	Form of condenser
1	Water	Copper-glass. Condenser contains air at atmospheric pressure
2	Water	Copper-glass. Condenser evacuated
3	Water	Copper-glass. Condenser evacuated
4	Water	All glass. Condenser evacuated
5	Water	All glass. Condenser evacuated
6	Alcohol	Copper-glass. Condenser evacuated
7	Alcohol	Copper-glass. Condenser evacuated
8	Alcohol	Copper-glass. Condenser evacuated
9	Alcohol	All glass. Condenser evacuated
10	Alcohol	All glass. Condenser evacuated

These instruments have been tested under artificial radiation conditions and the results are tabulated in Table 2. The values of distillate in c.c./hr. were obtained by plotting condenser reading against time and determining the slope of the resulting straight line when a steady rate of distillation had been reached (generally after about 30 min.). At first some diffi-

* We are indebted to Mr R. H. Knight, M.Sc., for the construction of this apparatus.

culty was met in using the instruments containing water due to the formation of droplets which refused to run smoothly down the side of the condenser column. The inclusion of the small amount of soap, already referred to, in the water in the condenser overcame this difficulty. The soap films which tend to form when the liquid is disturbed can easily be removed by gentle warming of the condenser and a sharp meniscus is obtained.

The instruments were tested close to the two extremes of radiation intensity available to us. Considerable differences occur when individual instruments are tested on different occasions, and between different instruments when tested together. Some possible causes of these differences could easily have been removed had the instruments not been urgently required for field work. For example, the glass envelopes were not spherical and of a uniform thickness, so that lens effects and reflexions could occur; there were in some cases spots of dirt on the inside of the glass; it is not certain that the copper receivers were all equally, evenly or adequately blackened. Moreover, there was a variation in the intensity of radiation, as shown by the pyrheliometer at one point at different times, presumably due to variations in mains voltage, and the intensity measurement could not be carried out at the same time and point in space as the radiometer test. It is clear, however, that since the instruments fall approximately in the same order in different tests it is possible to average the results for a number of tests and to work out a mean efficiency for each of the instruments.

The calculated mean efficiencies are given in Table 3. When a steady rate of distillation is reached, we may neglect the thermal capacity of the receiver and condenser systems. Then, if we assume perfect black-body absorption, the radiation received by a sphere from a point source at a distance d from the centre of the sphere is proportional to the solid angle subtended by the sphere at the source, i.e.

$$\text{the radiation received} \propto 2\pi\,(1-\sqrt{[1-a^2/d^2]}),$$

where a is the radius of the sphere. The tungsten filament was in the form of a circle, so that each point on it could be considered as a point source at the same distance from the centre of the sphere.

If the intensity measured by the pyrheliometer at distance d from the filament is I g.cal./cm.^{2}/min.

the radiation received

$$= Id^2 \times 2\pi\,(1-\sqrt{[1-a^2/d^2]})\ \text{g.cal./min.}$$

The latent heat of pure ethyl alcohol at 40° C. (approx. temp. of copper sphere) = 218·7 cal./g. and the density of pure ethyl alcohol at 20° C. (approx. temp. of condenser) = 0·7876 g./c.c.; therefore the distillation in the condenser is given by

$$D_A = \frac{Id^2 \times 2\pi\,(1-\sqrt{[1-a^2/d^2]})}{218{\cdot}7 \times 0{\cdot}7876}\ \text{c.c./min.}$$

Similarly for water the distillate is given by

$$D_W = \frac{Id^2 \times 2\pi\,(1-\sqrt{[1-a^2/d^2]})}{573{\cdot}7 \times 0{\cdot}9982}\ \text{c.c./min.}$$

The value of a is 2·54 cm., and for a value of $I = 0{\cdot}7$ g.cal./cm.^{2}/min. $d = 27{\cdot}7$ cm., so that

$$D_A = 5{\cdot}031\ \text{c.c./hr.} \quad \text{and} \quad D_W = 1{\cdot}513\ \text{c.c./hr.}$$

The efficiency is obtained by dividing the observed distillate at a given radiation intensity by the appropriate calculated distillate.

Despite the uncertainties involved in calculations

Table 2. *Distillate in c.c./hr.*

Intensity of radiation g.cal./cm.^{2}/min.	Instrument no.									
	1	2	3	4	5	6	7	8	9	10
0·18	0·00	0·27	0·42	0·42	0·40	1·28	1·18	1·20	0·63	1·06
0·20	0·07	0·30	0·46	0·40	0·38	1·29	1·50	1·47	1·00	1·23
0·70	0·27	1·37	1·48	1·58	1·40	4·85	5·40	4·75	4·60	4·65
0·70	—	—	—	—	—	4·80	5·15	5·10	4·25	4·90
0·70	—	—	—	—	—	4·57	4·88	4·75	4·32	4·47

Table 3. *Ratio: observed distillate/calc. distillate.*

Intensity of radiation g.cal./cm.^{2}/min.	Instrument no.									
	1	2	3	4	5	6	7	8	9	10
0·18	—	0·694	1·079	1·079	1·028	0·989	0·912	0·928	0·487	0·819
0·20	0·162	0·695	1·066	0·927	0·881	0·899	1·046	1·025	0·697	0·856
0·70	0·178	0·905	0·978	1·044	0·925	0·942	1·022	0·970	0·873	0·928
Mean efficiency %	17·0	76·5	104·1	101·7	94·5	94·3	99·3	97·4	68·6	86·8

of this kind, it is probable that the overall efficiency of our instruments, with the exception of nos. 1, 2 and 9, exceeds 80 %, and that in some of the instruments it is close to the theoretical maximum.

(*d*) *Direct comparison with other types of radiation integrator*

We have carried out a number of tests designed to compare directly the efficiency of our own instruments with other types of radiation integrator. Table 4 is the record of a number of such tests on the original Wilson 'Radio Integrator' and Prof. Buxton's first model and also his improved model with the condenser either evacuated or containing air at atmospheric pressure.

improves the efficiency by about 10 %. For general purposes, however, the inclusion of this refinement may not be advisable because it considerably increases the difficulties of construction and also because the exposed copper-glass seals are liable to fracture.

While, as yet, none of our instruments have been exposed to tropical sunshine,* it is possible to estimate roughly the amount of distillate which would be obtained under such conditions. At an intensity of 1·5 g.cal./cm.^{2}/min. the alcohol instruments would distil about 10 c.c./hr. Changes in radiation intensity over half-hour periods can, therefore, be detected with ease if readings are taken every 5 min. The time necessary for the determination of intensities in the early hours of the morning and late afternoon will, of course, be somewhat longer, and since this is the time of the day when the intensity of solar radiation is changing most rapidly, the accuracy of the estimates will be correspondingly lower. It is obvious, however, that the systematic use of one of these alcohol instruments can yield valuable information about variations in intensity of solar radiation in localities where such measurements have hitherto been impossible.

Table 4

Radiation intensity g.cal./cm.^{2}/min.	Distillates in c.c./hr.				
	Wilson Integrator	Buxton no. 1	Buxton no. 2 (condenser evacuated)	Buxton no. 2 (condenser not evacuated)	Mean value for instruments nos. 5–10
0·7	0·14	0·017	0·12	0·02	4·70

VI. DISCUSSION

In an apparatus of the size and type under discussion it is still not possible to standardize completely all the factors which affect the final performance of the instrument. Such factors as the departure from sphericity of the glass envelope, the thickness and quality of the lamp-black deposit on the copper receiver, and, of particular importance in the case of the water instruments, the degree of chemical cleanliness of those parts of the apparatus in contact with the volatile liquid, will inevitably produce differences between instruments otherwise constructed with the greatest care. Bearing this in mind, the type of radiation integrator here described represents a considerable improvement on previous models. Under carefully controlled laboratory conditions neither the original Wilson instrument nor the Buxton instruments will satisfactorily measure low intensities of radiation unless exposed for long periods of time. Moreover, it is certain that in instruments with such a low overall efficiency, estimates of higher intensities of radiation are subject to considerable errors. This does not apply to anything like the same extent in instruments with efficiencies of the order of 80 % or more.

The chief differences between the improved Buxton model and our own are the use of a copper receiver instead of a glass one, and the evacuation of the condenser system. Of the two alterations in design the latter would seem, from experimental results, to be far the more important. The inclusion of a copper section in the condenser column further

The water instruments, on the other hand, would seem to be most satisfactory for determining the mean daily intensity of sunshine, and so elucidating the variations in this meteorological element at different periods of the year and at different places. Assuming a mean intensity of 0·6 g.cal./cm.^{2}/min. one of the water instruments would distil about 15 c.c. during 12 hr. of sunshine.

The radiation integrator, together with a metal shield, has been fitted into a kind of suit-case and its total weight is then 12 lb. It can easily be carried by hand, can rapidly be set up in the operating position, and requires little attention while in use.

The most serious disadvantage of this type of instrument is its high thermal capacity. This means that it is incapable of detecting rapid fluctuations in radiation intensity, such as is caused, for example, by the presence of clouds. For some kinds of biological work, therefore, where such rapid fluctuations in intensity may be of importance, there does not seem to be any alternative to the use of a more delicate electrical pyrheliometer. The design of such an

* It is hoped to publish shortly some results of the field use of the new type of radiation integrator.

instrument, robust enough to withstand transport and requiring the minimum of accessory apparatus, must be elaborated in the future if every aspect of solar and terrestrial radiation of importance to the biologist is to be evaluated.

VII. SUMMARY

1. A new radiation integrator is described similar to one previously described by Buxton.
2. Methods of construction are given in detail to facilitate the standardization of future instruments.
3. Instruments of different sensitivities have been constructed by the use of either alcohol or water as the volatile liquid. The alcohol instruments can be used for determining changes in intensity over short periods of time; the water instruments are of most value for determining the mean daily intensity of sunshine.
4. The instruments have been calibrated against absolute measurements with a pyrheliometer. Compared with previous instruments of the same type a very much improved efficiency has been obtained.
5. The value of this type of instrument for work in the field is discussed; its limitations are briefly indicated.

Two of us (R. L. K. and J. A. H. W.) are indebted to the Rockefeller Foundation for a grant which we received during the course of this work.

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