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AWRE REPORT No. T 1/75

OPERATION HURRICANE

Measurement of the
Total Integrated Heat Output

R J Wilson

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AWRE,
Aldermaston, Berks.

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May 1975

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Procurement Executive - Ministry of Defence

AWRE, Aldermaston

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OPERATION HURRICANE

Measurement of the Total Integrated Heat Output

R J Wilson

Recommended for issue by

P T G Flynn, Superintendent

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[redacted]

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FOREWORD (1975)

Operation Hurricane took place in the Monte Bello Islands, Western Australia in 1952. This report is now being issued because the information that it contains relates to some current interests. No attempt has been made to re-write the report, which contains the original descriptions and observations.

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SUMMARY

The time integral of the energy flux received at a number of sites is measured by the temperature rise of a blackened copper disc. The temperature rise is measured by means of a compensated copper resistance thermometer in a bridge circuit, and it is recorded by a camera taking repetitive pictures of a moving coil meter at the rate of one per second.

The apparatus is independent of external starting signals, and it requires an external supply of 12 V only.

An estimate of the total radiant thermal energy release is made, and an attempt is made to calculate the effects of scattering of light.

Additional instruments using thermocouples and clinical thermometers to measure the rise in temperature of the disc are described, and the results obtained are given.

1. PURPOSE OF MEASUREMENT

The total energy incident on a surface is a quantity of direct interest when defensive measures are considered. The damage done by thermal radiation is considerable [1] and the damage produced is largely dependent on the total quantity received [2] when the rate of supply of energy is high, except for a few cases where specific photochemical reactions are concerned [3], or where absorption of radiation is markedly dependent on wavelength.

The total heat is of less interest from a theoretical point of view owing to the effects of the hull of the ship and the water column, but it has some interest in that it provides an indirect check on temperature-time and area-time curves, and it may be of use in an analysis of the distribution of the energy release among its various forms.

The measurement also provides a check on measured intensity-time curves.

2. APPARATUS

2.1 The resistance thermometer units

The sensitive elements each consist of two copper discs, 6 in. in diameter, blackened on one side with flat windings of fine copper wire stuck to the other side with a minimum of shellac to act as resistance thermometers.

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The thickness of the discs is chosen so as to give a temperature rise of 5 to 10°C with the expected total heat; this is the only factor which is varied. In all other respects the calorimeters are as nearly identical as the manufacturing processes allow.

The discs were blackened by the metal process [4-6]. The metal used was aluminium, and the process was carried out in a 10 in. glass bell jar in an atmosphere of hydrogen at a pressure of 3 mm Hg. The discs were supported $12\frac{1}{2}$ cm from the tungsten evaporating filament, and the evaporation was continued for about 60 s, giving a good black deposit; longer treatment produces a greying of the black.

The resistance thermometers are of 44 swg enamelled copper wire, and are made by winding 400 turns in a flat coil on a jig consisting of two $\frac{1}{8}$ in. diameter steel rods with removable spacers at the ends. The turns are wound 100 to the inch, and the rods are held 4 in. apart, then the copper disc is covered with a very thin layer of shellac, the spacers are removed and the coil is pressed down on the disc with a methacrylate plate. The plate and disc are pressed under a weight and left to dry. It was found necessary to use Lewcos insulated wire, as ordinary enamel wire showed a tendency to crack under this treatment. With this precuation it was found possible to achieve thermal contact between the disc and the winding without a corresponding electrical contact. The resistance of each winding was about 250 Ω.

The support consists of two 6 in. aluminium discs held $\frac{1}{4}$ in. apart by three bolts around the edge. These three bolts are used to fix the elements at the centre of a shield can 16 in. long by 8 in. diameter by means of $\frac{1}{8}$ × 1/16 in. rubber strips. Two strips of $\frac{1}{4}$ in. square rubber are threaded between the discs and fixed to the can, and two pads of foam rubber to support the copper discs are wired to the aluminium discs.

The blackened discs are held on to the support by tying each pair together with PVC string around the outside of the mount.

2.2 The bridge circuit

The two resistance thermometer windings constitute two arms of a Wheatstone bridge, the other two arms being two 33 Ω resistors. A third arm consists of two 560 Ω resistors in series with a 500 Ω potentiometer, the moving contact being connected to the join of the 33 Ω resistors to give balance control.

The meter circuit consists of two moving coil meters in parallel with series resistors added to make the sensitivity of one meter five times that of the other. The combined resistance of the meter circuit was about 600 Ω and the sensitivities of the meters were 90 and 450 mV for full-scale deflection respectively.

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2.3 The recording camera

The camera used is a standard Shackman Auto Camera, and the repetitive pulses to operate it are derived from a pair of contacts on a relay which is energised from a 45 V battery via a resistance, with a large condenser (1000 mF) across its coil. Another pair of contacts on the relay remove the 45 V supply when the coil is energised, giving the required repetitive action.

The cameras are not entirely suitable for repetitive operation at intervals of $\frac{3}{4}$ s, and some trouble with jamming was experienced. In some cases the interval between frames was increased to $1\frac{1}{2}$ s to overcome this.

The meters were illuminated by two 12 V, 6 W lamps placed beside them, and an exposure of 1/100 s at f/2.8 was found to be suitable with HP3 film. It is noticeable that the first frame of the film is relatively under-exposed due to the time taken by the lamp filaments to heat up. This effect can be reduced by using higher resistance lamps, but none was available at the time of the trial.

2.4 Starting circuits

The bridge is permanently connected to the 12 V battery, as is the filament of the light-trigger valve, giving a steady drain of about 360 mA, and the light-trigger valve anodes are permanently connected to the 45 V battery, giving a drain of 30 μA.

The voltage supplies to the rest of the unit are controlled by a relay, with four heavy-duty "make" contacts, which holds itself "in" on receiving a shorting contact from a manual switch, the light-trigger relay, or the RCS line. After about 30 s the circuit through the relay coil is broken by a thermal delay switch, and the apparatus remains quiescent until it receives another starting pulse.

2.5 The light trigger

The light trigger, which starts the apparatus if a sudden flash or light occurs in its field of view, consists of a cathode-coupled multi-vibrator (12 AU7) biased back to a quiescent condition, which is triggered by a selenium photo-voltaic cell and closes a high-sensitivity Carpenter relay. The multi-vibrator has a direct input connection with a 4700 Ω grid resistor, and one ac coupling, so that it partly differentiates the input and does not respond to slow changes in background light.

It was found necessary to select valves to give a suitable sensitivity.

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2.6 Thermocouple instruments

These consist simply of a pair of blackened discs mounted separately in two shield cans, one normal to the axis of its can and the other making an angle of 60°. Copper-constantan thermocouples are soldered on to the back of the discs using the least possible amount of solder.

The output from the two thermocouples connected in opposition is measured with a Cambridge Scalamp galvanometer of resistance 50 Ω and sensitivity 23 division μA^{-1}. A resistance of about 250 Ω is included in the circuit, giving a sensitivity of about 13 μV division^{-1}; the deflections of the meter were recorded visually.

2.7 Clinical thermometer instruments

These are similar to the thermocouple instruments except that clinical thermometers are used to measure the temperature rise instead of thermocouples.

A thermometer case is brazed on to the back of the disc and then partly filled with mercury. The thermometer is mounted in the case with rubber sleeving to protect it from the shock of the blast-wave.

Both these instruments have the disadvantage that the measuring devices increase the thermal capacity of the disc at the point of contact, and thus reduce the sensitivity since the discs are, in general, too thin to allow any considerable lateral conduction of heat.

In addition, the range of recording is very limited, especially for the clinical thermometers, where the ambient temperature plays an important part.

3. CALIBRATION

It was originally hoped that the apparatus would provide an absolute method of measuring radiant energies, but time did not permit sufficient investigation of one or two uncertain points, particularly the absorption of the metal black, and the effect of the loops of wire at the end of each turn of the resistance thermometers.

It was decided that the units should be individually calibrated, using a thermopile as a reference detector.

The actual calibrations reveal that it is possible to derive corrections which can be applied to all calorimeters to allow for these, and other effects, and it is believed that the sensitivities of any future calorimeters built in a similar manner could be predicted within 5%. By applying individual corrections, or by improving the manufacturing techniques, it is thought that the instrument can be made accurate within 1%, although this accuracy was not achieved in the present case for other reasons.

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3.1 The thermopile

The thermopile used was of the Moll type, and it was always used with a mica window to protect the sensitive elements from air disturbances. The output from it was measured with a Cambridge Scalamp galvonometer of 57.3 Ω resistance, with a sensitivity of 23 divisions μA^{-1}; a series resistance of 164 Ω was included in the circuit, giving a sensitivity of 9.65 μV division^{-1}.

Its sensitivity (see table 1) was stated to be 0.044 cal cm^{-2} mV^{-1}, but no information was available regarding the variation of sensitivity with wave length and, in particular, the effect of the mica window [7].

After the trial, it was re-calibrated by the National Physical Laboratory (NPL) [8] for sources at temperatures of 1000°C and 2850K, but unfortunately they were unable to calibrate it for a source of higher temperature, so that some means of estimation must be used to find the corrections to be applied when using the sun as a calibration source, since these may be significant.

For this purpose it will be assumed that the thermopile has a rectangular response versus wavelength curve, but the NPL measurements do not give sufficient information to find the wavelength limits.

The observations of the flux received from the sun near the zenith during calibration would provide an indirect method if the atmospheric attenuation were known, since the output of the thermopile was reasonably constant at 0.561 mV (with a standard deviation of 0.053 mV for 7 degrees of freedom) under these conditions.

Astronomical measurements are useful in making an estimate of atmospheric attenuation since the astronomical requirements ensure that attenuation due to industrial smoke, etc, is absent, as it was at Monte Bello.

Observations at Mount Wilson [9,10] suggest a value of about 77%, while measurements by Müller, Abney, Dimitrof and others [11] suggest a somewhat higher value of 81%. A series of observations by Beck et al. [12] at Khartoum gives a mean value of 82%. Reducing this to sea level, assuming an absorption index of 0.1 km^{-1}, gives a value of 78%. Measurements taken at Emu under similar conditions give a value of 80%.

For the purpose of this report, a value of 79% will be assumed. Any error in this figure is not reflected directly in the results, and its effect depends greatly on the temperature of the source, as shown in table 2. It is seen that a 5% variation in assumed atmospheric transmission produces a variation of only 1.7% at 4000K and 0.5% at 3000K in the best case, and 3% at 4000K and 0.9% at 3000K in the worst case. For temperatures above 6000K any error is greatly accentuated.

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Some allowances must be made for the energy at wavelengths which are totally absorbed before reaching the ground, since the transmission figures given above are based on a simple exponential attenuation law with the constants derived from measurements at ground level. There are two regions of importance; one is for wavelengths shorter than 0.35 microns, where it is assumed that all the energy is absorbed by the air and in relatively localised ozone layers, giving a loss of 6.9% of the energy for a black-body source at 5750K. The other region of interest is the water-vapour absorption bands in the near infra-red [13-15]. The amount of the sun's energy removed in this way is estimated to be 6% of the total energy for a black-body radiator at 5750K.

Combining these figures with the solar constant [10,16,17] (0.0324 cal cm^{-2} s^{-1}) gives the "absorbed energy" sensitivity of the thermopile as 0.0382 cal cm^{-2} mV^{-1}, with the cut-off wavelengths at 8.5 and 0.39 microns. Using these figures, a correction for the temperature of the (black-body) source is calculated, as shown in table 3. The sensitivity to sunlight does not lie on the black-body locus owing to the total extinction discussed above, and the corresponding corrections must be made.

3.2 Calibrations

The calibrations were carried out by exposing the sensitive elements to a suitable light source, and then observing the rate of rise of the meter reading. The flux produced at the calorimeter disc was measured with the thermopile, thus giving the sensitivities in calories per square centimetre per division. Both the sun and a high temperature (3200K) tungsten lamp were used as sources.

The results are given in table 4. The discrepancy between the sensitivities for sunlight and the tungsten lamp are attributed to the failure of the metal black to absorb violet and ultra-violet light, in view of the observed colour of an obliquely reflected image of the sun in the discs and a correction for the temperature of the source is calculated on this basis (table 5).

3.3 Linearity of the bridge circuit

The linearity of the bridge circuit was checked by introducing resistances of 10, 5 and $3^{1/3}$ Ω into a thermometer arm (figures 1 and 2).

It is seen that the non-linearity is of the order of 3% for full-scale deflection. Since the deflections used during calibrations and measurements did not greatly exceed 30 divisions, no corrections for non-linearity will be made.

3.4 Cooling corrections

It was proposed to apply a cooling correction based on Newton's law of cooling, but when cooling curves were taken it was discovered

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that the law did not apply, the rates of cooling decreasing much less rapidly than the temperature (see figure 4). It is thought that this is due to the presence of the foam rubber which absorbs heat from the disc during the heating period and returns it slowly during cooling.

Since the rate of cooling is not a unique and single valued function of temperature, no cooling correction can be applied.

Fortunately the energy measured was rather less than anticipated and the temperature rise of the discs was only 1 - 2°C, so that the effect of cooling losses was small, as the agreement between values for the same site but different thickness discs show.

3.5 Use as an absolute instrument

Since the temperature rise of a blackened disc in a uniform radiation field is inversely proportional to its thickness, the sensitivities of the calorimeters, expressed in calories per square centimetre per division, should be directly proportional to the thickness of the discs.

Figure 3 shows that this is true within 5% if 0.003 in. is added to the thickness of the discs to allow for the thermal capacity of the wire, shellac and foam rubber. It also shows that the metal black of all the discs may be supposed to fail to absorb light of wavelengths shorter than 0.46 microns with the same accuracy.

Hence, the sensitivity of a calorimeter with discs of thickness t (0.001 in.) may be found from the formula

$$S_t = 0.00047(t + 3)f(T),$$

where $f(T) = (1 - R_{0.46}/R_{00})^{-1}$ = source temperature correction.

This takes no account of cooling corrections, since no simple form of correction is possible.

3.6 Thermocouple instruments

These were calibrated in a similar manner to the resistance elements. One of the resistance units was used to measure the intensity, and the results are given in tables 8, 9 and 10.

4. RESULTS

4.1 Resistance calorimeters

The results obtained are set out in table 9. The records from units M2 and S2 were rendered illegible by radioactive fogging of the film while those from units M3 and S3 were partially fogged, so that the final steady reading of the meter had to be used in place of the initial value. Experience shows that this may be as much as 1 division too high, so that the results obtained from these units represent a lower limit.

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Using the basic sensitivities given in table 5, and applying no correction for the temperature of the source, gives the total heats shown in table 10.

For a considerable period the effective temperature of the ball of fire is about 4000K [18], and as the area is very large at this time a large part of the total energy is emitted at this temperature. A correction based on a source temperature of 4000K is applied (table 6), which gives the results listed in table 11.

The agreement between the two values obtained for each site indicates that losses by cooling have no significant effect on the results.

4.2 Atmospheric attenuation and radiant thermal energy release

By plotting the logarithm of $4\pi r^2 h$ at different ranges against the range, a mean value of the attenuation coefficient is obtained and hence an estimate is obtained of the energy released as thermal radiation (see figure 5).

The uncertainty as to the results at N4 gives some difficulty in this case; if the values at N4 are ignored, the remaining two sites give an absorption index of 0.085, corresponding to a visibility of 30 miles [19]. On the other hand the best straight line through the three points on the basis of the methods of least squares gives an index of 0.065, corresponding to a visibility of 38 miles. It is assumed that the true value lies between these two limits, and the value of 0.075 is taken, corresponding to a visibility of 33 miles. This gives a radiant energy release, corrected for absorption, of 0.36×10^{12} cal.

It must be realized that this estimate is liable to much larger errors than the individual total heat measurements for each site since the sites are too close to give a reliable figure for air absorption, due to the destruction of the records at site TT9 (R = 3 km). The error in radiant energy release corresponding to the limits for air absorption given above is $\pm 0.03 \times 10^{12}$ cal.

4.3 Scattering and field of view

A further factor which must be taken into account is the diffuse light which falls on the elements after being scattered. The amount of energy which reaches the discs in this way depends on the field of view of the instrument and this energy reduces the apparent attenuation coefficient. An estimate of the effect is made using the semi-empirical formula developed by Curcio and Stewart [20]. This gives an attenuation coefficient of 0.156 km^{-1} for direct illumination, and 0.48×10^{12} cal for the radiant energy release.

4.4 Other corrections

There are a number of other corrections whose effects are not so far included in the analysis and which must be examined. They are:-

(a) Diffuse reflection of light from the sea on to the elements.

(b) The shape of the ball of fire.

(c) The assumption of a simple exponential law of attenuation.

In this particular case, it is known that (a) can be neglected; measurements taken with the thermopile for the sun show that for small glancing angles the light reflected from the sea is less than about 2% of the direct light.

The method employed to estimate the radiant energy release, ie, multiplying the measured total heat by $4\pi r^2$, is only known to be valid if the ball of fire is either a hemisphere in contact with the ground, or a sphere in free air. This is not true here; the ratio of vertical height to horizontal radius is near 1.3 at all times, and the photographic records show that the ball is very much broken up by darker areas. The significance of these dark areas is not clear, since the appearance is markedly dependent on the photographic processing conditions. The records examined were taken without a colour filter, so that the emulsion was predominantly blue-sensitive; in this case relatively small differences in surface temperature would be expected to produce large changes in the density of the photographed image, although they would have only a negligible effect on the total energy radiated.

Even if the dark areas are non-radiating, no correction is necessary provided that they are uniformly distributed over the surface, since this would be equivalent to a reduction in size, and the dimensions of the ball do not appear in the expression for total energy release to a first order of approximation.

If the radiating surface is assumed to be that of a prolate hemisphere of eccentricity e (= horizontal radius/height), it can be shown that

$$E_o = 2\pi(e + \sin^{-1}\sqrt{1 - e^2}/\sqrt{1 - e^2})d^2.B_d,$$

where E_o = total energy radiated,
B_d = energy flux measured at range d along a horizontal line.

In this case, $E_o = 3.6\pi d^2 B_d$ which gives an energy release of 0.43×10^{12} cal.

The effect of the water column further reduces this figure since it reduces the projected area of the ball by greater amounts for increasing altitudes. The magnitude of the correction involved cannot be calculated, since this would require a knowledge of the projected area of the ball as a function of both altitude and time, and this information is not available.

There are two factors which can produce deviations from a simple exponential law of attenuation for the total energy. The first factor is the variation of attenuation index with wavelength. The nature of this variation is not simple, since it involves the variation of both absorption and scattering with wavelength, but an approximate solution can be arrived at by assuming that the energy in particular wavelength regions is completely removed. In this case it is assumed that energy of wavelength shorter than 0.35 micron, and in the water-vapour bands in the near infra-red (section 3.1), is totally removed.

If the event is assumed to be a full radiator at a fixed temperature during its main radiating period, the fraction of the energy lost due to this total extinction can be calculated.

For a temperature of 4000K, this gives the radiant thermal energy release as 0.49×10^{12} cal. The figures for 3000 and 5000K are 0.495×10^{12} and 0.51×10^{12} cal respectively.

The other factor which may cause deviations from exponential attenuations is light which enters the instrument from the direction of the source after being multiply scattered. No analysis of the distribution of this light has been made at this stage, although a similar problem has been studied by Deimendjian and Sekera [21]. They find for sunlight that the multiply scattered light is only of the order of 10^{-4} times the direct illumination for small acceptance angles, but it is to be expected that the intensity of such light would be considerably greater when the radiating source is in the scattering medium.

4.5 Thermocouple calorimeters

The results obtained with the thermocouple units are given in tables 9 and 14. The units were not calibrated with the tungsten lamp, but a correction for the temperature is made by assuming that the cut-off wavelength is the same as the mean wavelength referred to in 3.5.

This gives 0.0109 cal cm^{-2} for unit T1, and 0.0101 cal cm^{-2} for unit T2, which agrees well with the values obtained from the resistance calorimeters also at H1, since the accuracy can hardly be better than 15% owing to the small deflections observed.

4.6 Clinical thermometer calorimeters

These were set out at each site with the resistance thermometer calorimeters, but with one exception all the thermometers registered 96.2°F. This was due to the fact that the total heat was not greater than about 20% of the predicted value, and the temperature rises therefore smaller than the normal daily change in temperature. The one exception was at site H3, where a thermometer registered 120°F; this is much too large to be attributed to the explosion and is probably due to the wind disturbing the shield-can and exposing the disc to the sun.

It is considered that these units might serve a useful purpose in recording total heats at short ranges if the energy release could be accurately predicted and the thermometer mounted to withstand the shock of the blast wave.

5. DISCUSSION OF RESULTS

It is considered that the significant information to be derived from the results is the total heat at any given range.

The radiant thermal energy release can only be of academic interest since a large proportion of the energy which would have been, or was, released in this form is cut off by the water-spout, so that the "corrections" which would have to be applied are greater than the measured energy.

This raises the general problem of energy which changes its form during the event; if the quantity lost from any given form can be calculated, and it is added to the measured energy, there is a possibility that it will be included in the measured quantity for some other form, and thus appear twice in any analysis of the total energy release. A further example of this problem is the ultra-violet energy lost by total extinction referred to in section 4.4, which might contribute to the measured blast energy or to some other form.

The radiant thermal energy flux incident on a surface at any point is a function of its angular field of view owing to the scattering, and the semi-empirical function of Curcio and Stewart is applied to the measured results to give the total heat as a function of range and angle of acceptance. The accuracy of these results must depend on the applicability of Curcio and Stewart's analysis to this particular case, and the possibility of error increases as the results are extrapolated further from the region and conditions of the measurements.

6. CONCLUSION

It is concluded that the total integrated heat received by instruments with a field of view of approximately $\frac{3}{4}$ radian at sites H1, N4 and H3 were as indicated below.

Site	H1	N4	H3
Range, km	10.73	6.91	6.49
Total heat, cal cm^{-2}	0.0113	0.0293	0.0389

Assuming a hemispherical shape for the first ball and simple exponential air attenuation, these figures lead to a radiant thermal energy release of 0.36×10^{12} cal and an attenuation coefficient of $0.075\ km^{-1}$.

An attempt has been made to take account of scattering of light, and the angle of view of the instruments, which leads to the expression for the total heat

$$H = E_o/4\pi d^2 \exp(-p)\,[\exp(-kd)\cosh p + \sinh p],$$

where $E_o = 0.48 \times 10^{12}$ cal, $k = 0.156$ km^{-1} and p is the angular semi-diameter of the field (radians).

This expression gives the same values of H as the above figures for $p = \frac{3}{8}$ radian at the long ranges.

For short ranges, between 1 and 3 km, where the scattered light is not a major factor, the best estimate of H can be obtained from

$$H = 43/4\pi d^2 \exp(-0.10d) \text{ cal cm}^{-2},$$

where d is in kilometres.

A further attempt has been made to take account of the shape of the fire-ball and the total extinction of some wavelengths, and it is estimated that the radiant thermal energy release was 0.49×10^{12} cal.

7. ACKNOWLEDGMENTS

Acknowledgment is due to the efforts of the following people, who contributed to the final results:-

Dr J A Carruthers, ADTE
Mr G E Miller, AWRE
Mr C Collins, AWRE
Mr J Evans, AWRE
Mr Sherman, AWRE
A/B Moule, RN

Special recognition is due to the part played by Dr Carruthers, who guided and assisted the work in all its stages. Messrs Miller and Collins assisted in the building of the equipment, Mr Evans carried out the blackening of the discs and Mr Sherman was responsible for winding the resistance thermometers. A/B Moule assisted in assembling the sensitive elements and installing the equipment at the sites.

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TABLE 1

Thermopile Sensitivities

Temperature of Source	1000°C	2850K
Sensitivity, cal cm^{-2} s^{-1} mV^{-1}	0.0410	0.0385
Sensitivity, cal cm^{-2} s^{-1} mV^{-1}	0.0307	0.0308

TABLE 2

Effect of Error in Assumed Value of Atmospheric Attenuation [22]

Atmospheric Attenuation, T%	Thermopile Loss $\frac{T - 67\%}{T}$,	Additional Calorimeter Loss, %	Total Loss, %	Correction to be Added to Calorimeter Readings, %		
				3000K	4000K	6000K
70	5	10	15	0.1	2.2	15
75	10	10	20	0.6	3.9	20
80	15	10	25	1.0	5.6	25
70	5	20	25	1.0	5.6	25
75	10	20	30	1.7	7.8	30
80	15	20	35	2.6	10.7	35

TABLE 3

Corrections to Thermopile for Temperature of Source

Temperature of Source, K	Corrected Sensitivity, cal cm^{-2} mV^{-1}
1000	0.0436
1273	0.0410
2000	0.0391
2850	0.0385
3000	0.0385
3200	0.0385
4000	0.0390
5000	0.0407
5750	0.0429
6000	0.0442
Sunlight	0.0379

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TABLE 4

Calorimeter Calibrations

Source: Tungsten Filament Lamp

Thermopile Sensitivity: 0.0385 cal cm^{-2} s^{-1} mV^{-1}

Unit No.	Discs	Thickness, 0.001 in.	Rate of Rise of Needle	Incident Flux	Sensitivity, cal cm^{-2} $division^{-1}$
M1	01, 02	14.6	2.92	0.0228	0.00781
S1	C5, C7	3.4	7.72	0.0228	0.00296
M2	J8, J10	10.0	3.80	0.0230	0.00605
S2	DJ1, DJ2	48.6	0.925	0.0230	0.0248
M3	J7, J9	9.9	3.88	0.0226	0.00582
S3	C4, C6	3.3	8.40	0.0230	0.00274
M4	E7, E8	5.4	6.07	0.0230	0.00379
S4	B9, B10	2.35	9.20	0.0230	0.00250

Source: Sunlight

Thermopile Sensitivity: 0.0399 cal cm^{-2} s^{-1} mV^{-1}

Unit No.	Discs	Thickness, 0.001 in.	Rate of Rise of Needle	Incident Flux	Sensitivity, cal cm^{-2} $division^{-1}$
M1	01, 02	14.6	2.39	0.0223	0.00933
S1	C5, C7	3.4	6.16	0.0227	0.00369
M2	J8, J10	10.0	3.07	0.0223	0.00726
S2	DJ1, DJ2	48.6	0.79	0.0223	0.0282
M3	J7, J9	9.9	3.09	0.0221	0.00715
S3	C4, C6	3.3	6.28	0.0223	0.00355
M4	E7, E8	5.4	5.54	0.0227	0.00410
S4	B9, B10	2.35	7.38	0.0221	0.00299

TABLE 5

Temperature of Source, K	2000	3000	4000	5000	6000
Correction (Add to Tungsten Lamp Sensitivities), %	0.0	0.7	3.9	10.7	17.4

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TABLE 6

Corrected Sensitivities for Source Temperature 4000°K

Unit No.	M1	S1	M2	S2	M3	S3	M4	S4
Sensitivity	811	308	625	2580	605	285	394	260×10^{-5}

TABLE 7

Rate of Cooling of Calorimeter

θ, divisions	50	40	30	25	20	15
$d\theta/dt$, division s^{-1}	0.520	0.426	0.244	0.182	0.106	0.057
$1/\theta.d\theta/dt$, s^{-1}	0.0104	0.0107	0.0081	0.0074	0.0053	0.0038

TABLE 8

Calibration of Thermocouple Calorimeters

Source: Sunlight. Resistance Calorimeter M4 Sensitivity = 0.0410

Sensitivity of Thermocouple Meter (L-302652 + 231 Ω) = 12.5 $\mu V\ mm^{-1}$

Mean Rate of Rise of Reading of Unit M4 = 5.33 division s^{-1}

Mean Rate of Rise of Reading of Unit T1 = 2.13 division s^{-1}

Mean Rate of Rise of Reading of Unit T2 = 10.37 division s^{-1}*

Sensitivity of Unit T1 = $\frac{5.33 \times 0.0410}{2.13 \times 12.5} = 0.000820$ cal cm^{-2} μV^{-1}

Sensitivity of Unit T2 = $\frac{5.33 \times 0.0410}{10.37 \times 12.5} \times 2 = 0.000337$ cal cm^{-2} μV^{-1}†

*Normal Disc only Exposed to Sunlight.
†Both Discs Exposed to Radiation.

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TABLE 9

Results of Trial

Site	Range, km	Unit	Unit	Unit	Unit
H1	10.73	M4 2.9 divs	S4 4.3 divs	T1 1.2 divs	T2 2.5 divs
N4	6.86	M3 4.9 divs	S3 10.2 divs		
H3	6.49	M1 4.9 divs	S1 12.4 divs		

TABLE 10

Total Heats without Source Temperature Correction

Site	Range, km	Unit	Unit
H1	10.73	M4 0.0110 cal cm^{-2}	S4 0.0108 cal cm^{-2}
N4	6.86	M3 0.0285 cal cm^{-2}	S3 0.0279 cal cm^{-2}
H3	6.49	M1 0.0382 cal cm^{-2}	S1 0.0367 cal cm^{-2}

TABLE 11

Total Heats Corrected for Source at 4000K

Site	Range, km	Unit	Unit
H1	10.73	M4 0.0114 cal cm^{-2}	S4 0.0112 cal cm^{-2}
N4	6.86	M3 0.0296 cal cm^{-2}	S3 0.0290 cal cm^{-2}
H3	6.49	M1 0.0397 cal cm^{-2}	S1 0.0381 cal cm^{-2}

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TABLE 12

Total Spherical Flux

Site	H1	N4	H3
Range, km r	10.73	6.86	6.49
Total Heat, cal cm^{-2} h	0.0113	0.0293	0.0389
Total Spherical Flux, $4\pi r^2 h$, $\times 10^{12}$ cal	0.163	0.196	0.230

TABLE 13

Total Heats due to Direct Illumination

Site	H1	N4	H3
Range, km	10.73	6.86	6.49
Flux, cal cm^{-2}	0.0079	0.0232	0.0335

TABLE 14

Thermocouple Calorimeter Results

Site: H1 Range: 10.73 km

	Unit T1	Unit T2
Discs	C9, C10	A1, A2
Total Circuit Resistance, Ω	295.3	271.3
Galvanometer Sensitivity, μV $division^{-1}$	12.8	13.6
Calorimeter Sensitivity, cal cm^{-2} μV^{-1}	0.000820	0.000337
Initial Reading, divisions	20.8	20.5
Final Reading, divisions	22.0	23.0
Deflection, divisions	1.2	2.5
Total Heat, cal cm^{-2}	0.0126	0.0116

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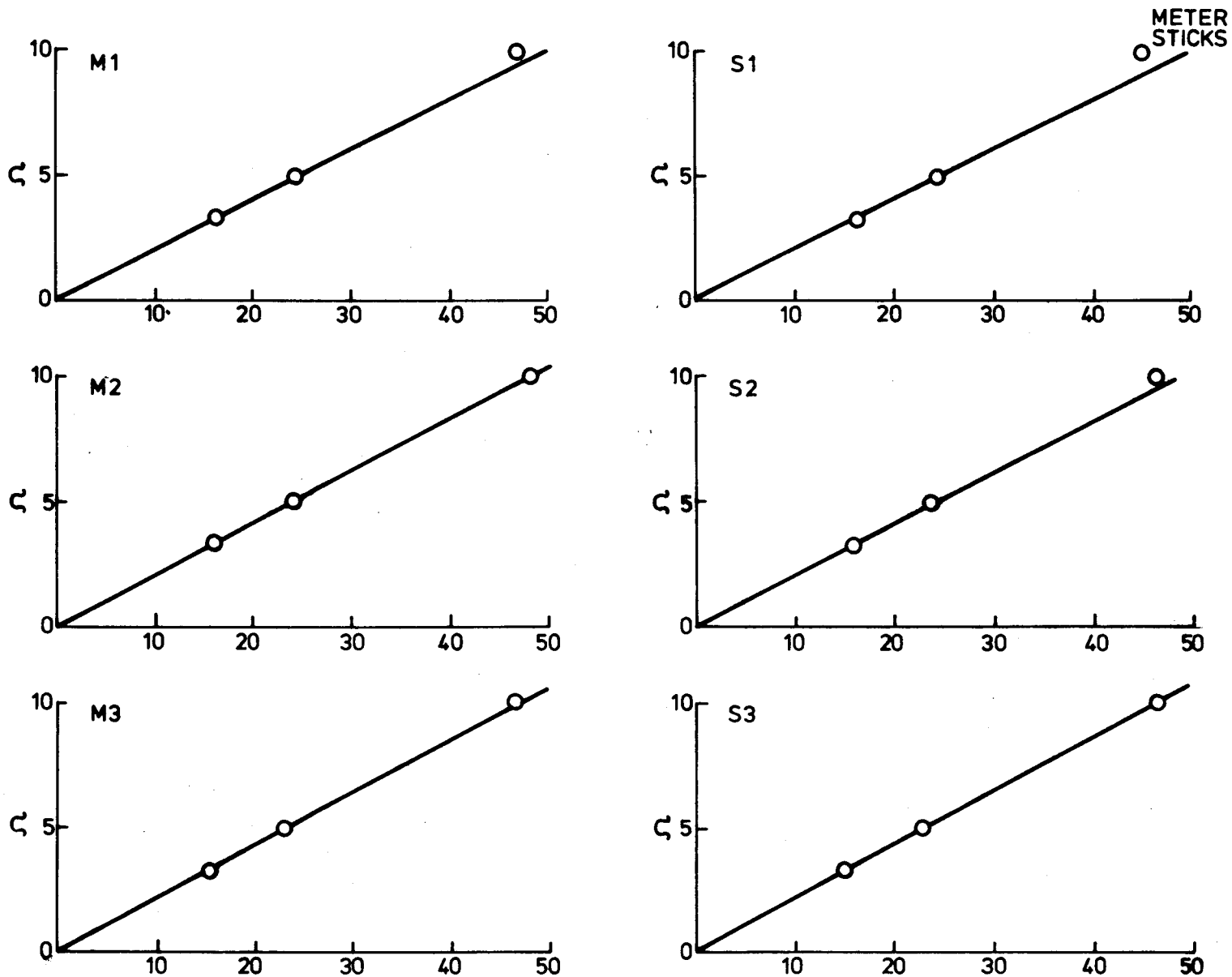

FIGURE 1. LINEARITY OF BRIDGES

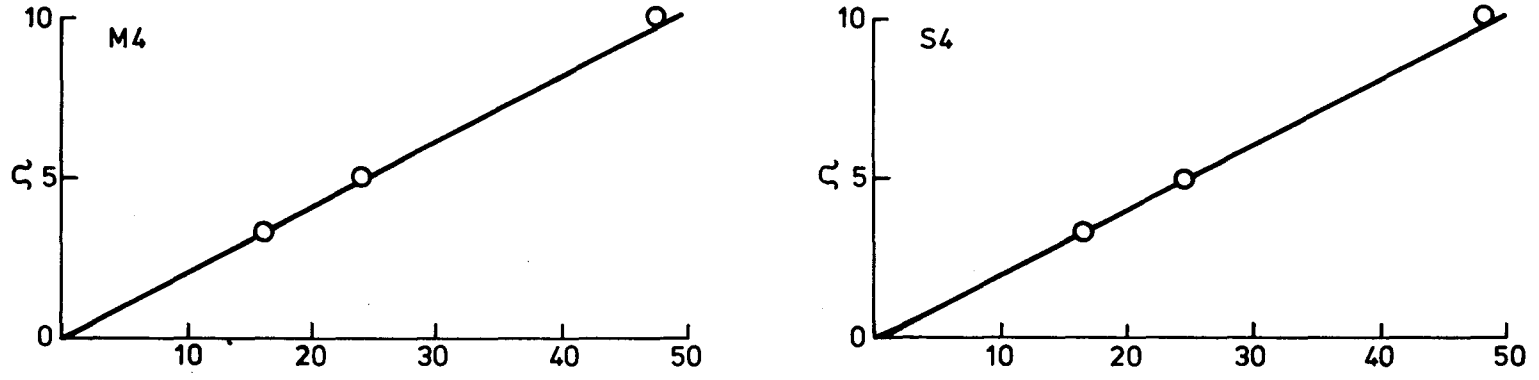

FIGURE 2. LINEARITY OF BRIDGES

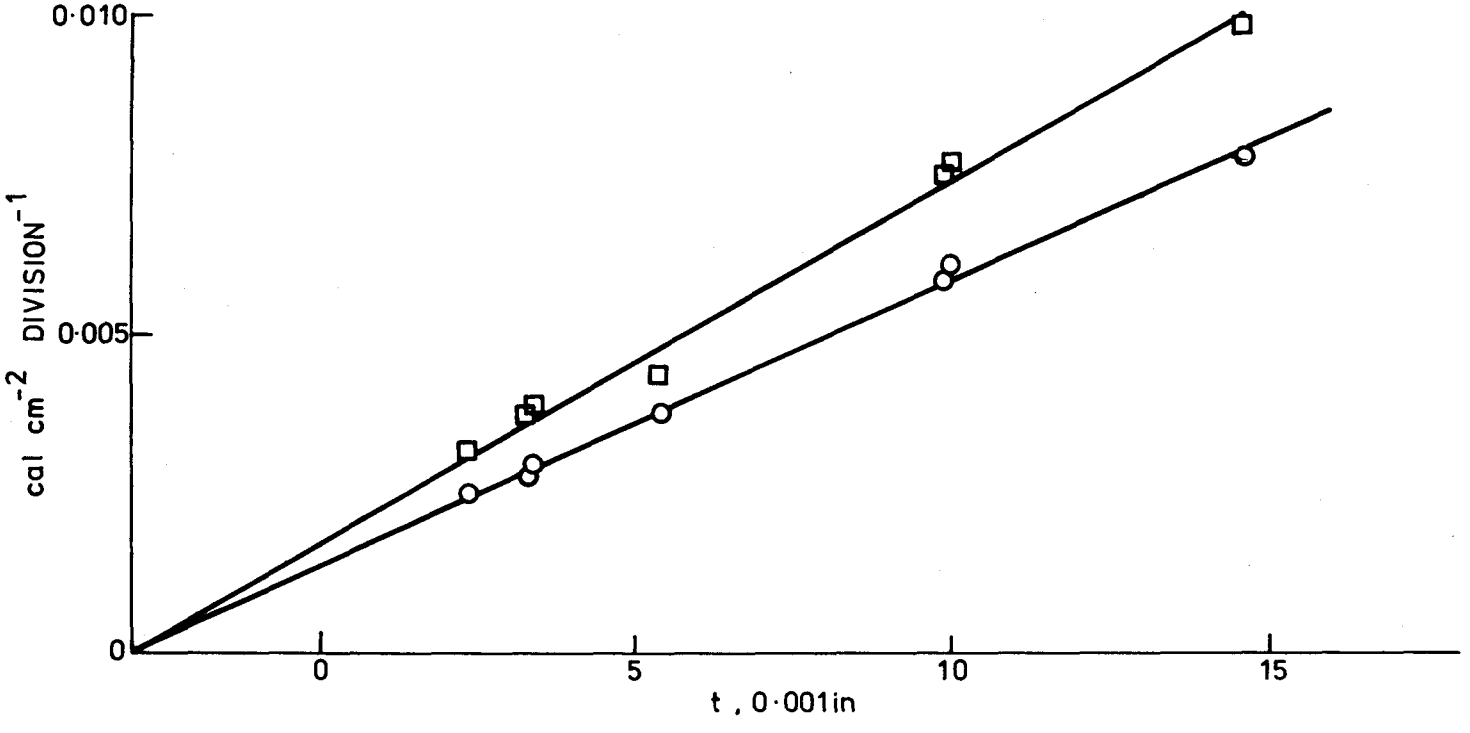

FIGURE 3. SENSITIVITIES OF CALORIMETERS

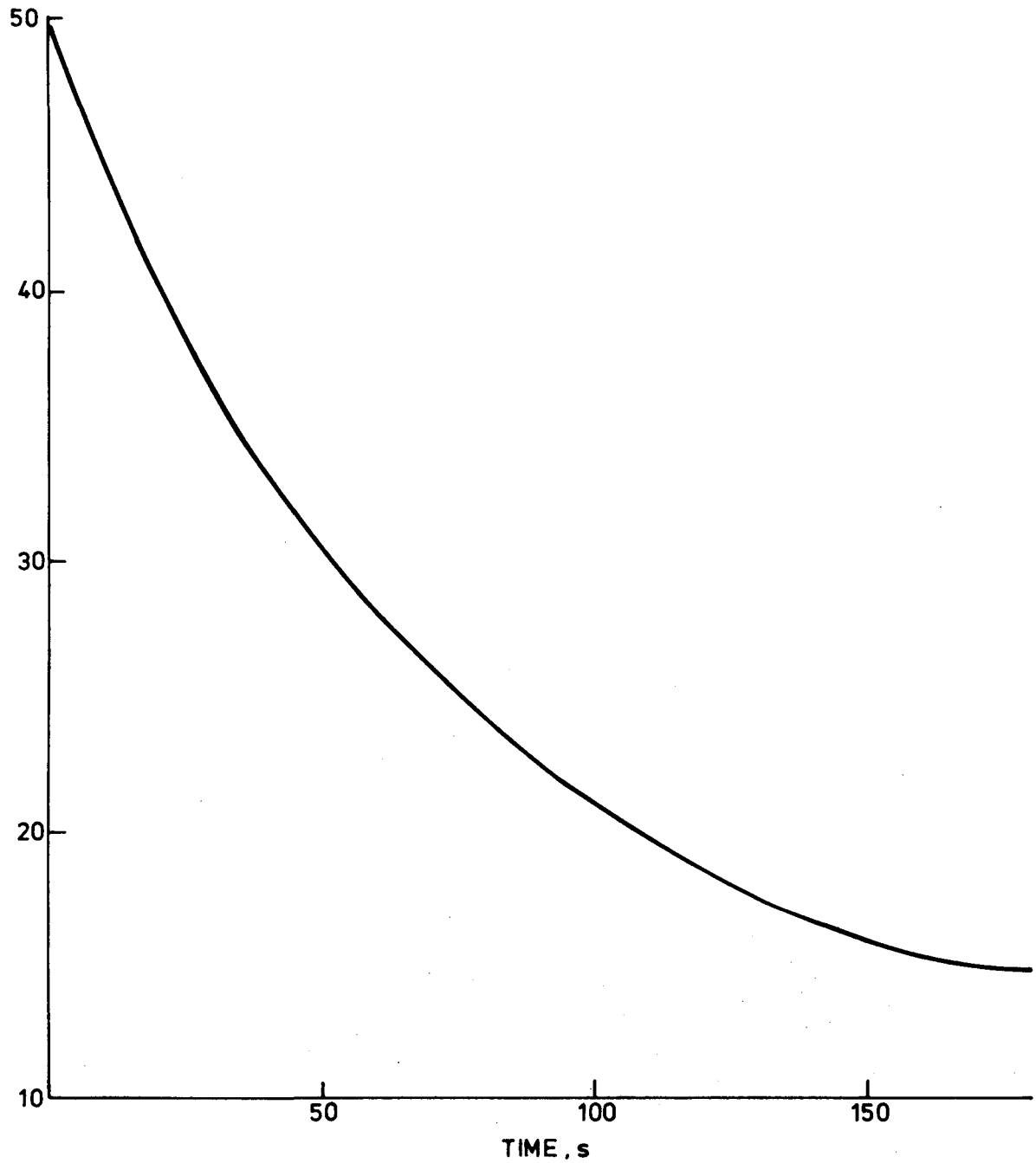

FIGURE 4. COOLING CURVE FOR UNIT M2

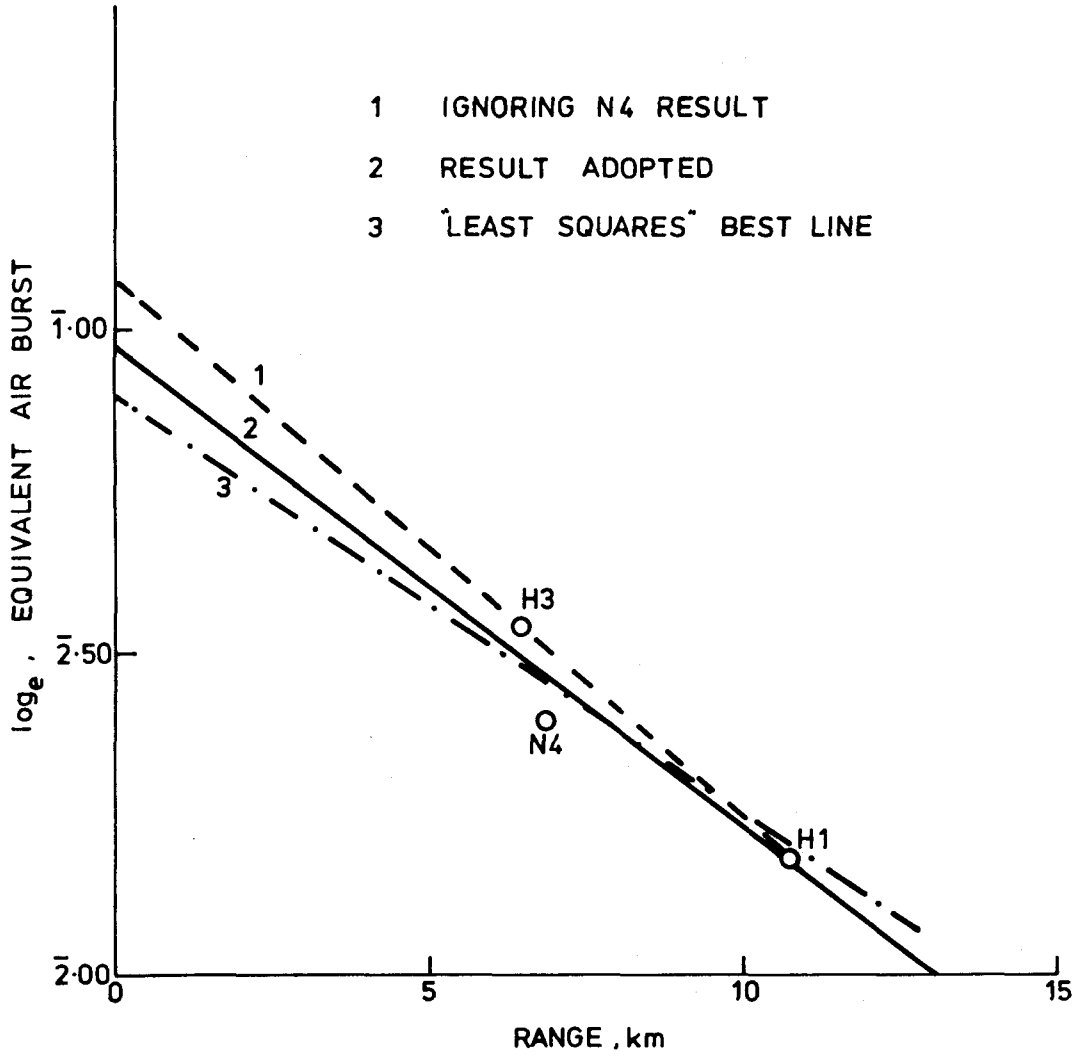

FIGURE 5. ATMOSPHERIC ABSORPTION AND EQUIVALENT AIR BURST

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