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THE DEVELOPMENT OF A FOIL HEAT FLUX METER

by

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FIRE RESEARCH STATION

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SUMMARY

An instrument has been developed for measuring heat flux in the range from 0 to 10 W/cm^2. It is of robust construction, suitable for outdoor use and designed so that it can be mounted flush with a surface to which the heat transfer is required to be measured.

The output of the instrument is proportional to the heat flux falling on it in the range from 0 to 5 W/cm^2 and at 8 W/cm^2 the deviation from direct proportionality is not more than 6 per cent. The sensitivity is sufficient to enable a change in heat flux of 0.1 W/cm^2 to be detected.

By using the heat flux meter with and without an infra-red transmission window on the front values of both the radiated and convected heat transfer can be obtained. The instrument is not very sensitive to draughts even without the transmission window, but with it the output is rendered completely unaffected by draught for all practical purposes.

KEY WORDS: Convection, Heat transfer, Infra-red, measurement, radiation, window, radiometer.

MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

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1. Introduction

The need has arisen for a heat flux meter that will measure the rate of heat transfer to a surface, both convective and radiative, in the range 0 to 10 W/cm^2 to an accuracy of at least 0.1 W/cm^2. The instrument required should be of robust construction and not greatly affected by low wind speed so that it could be used out of doors in reasonable weather conditions. It would also need to be capable of brief (say one or two seconds) immersion in flame without being permanently affected in any way and to be unharmed by smoky atmospheres.

There is also an occasional need for a higher range instrument, capable of measuring up to 25 W/cm^2 to an accuracy of at least 1 W/cm^2. Such a device, though planned, has not yet been constructed at the Joint Fire Research Organization.

When measuring a combined radiative and convective heat flux the target should be flat and mounted in the plane of the surface to which the heat transfer is taking place. This is clearly necessary in order to avoid disturbing the flow of hot gases over the surface near the target and to obtain a reliable measurement of convective heat transfer. An acceptance angle of 180 degrees would also enable a more accurate measurement to be made of heat flux from very wide sources such as flames playing over the surface. In addition it was hoped that, by providing some instruments with an infra-red transmission window, convective transfer could be eliminated so that by using a pair of heat flux meters, one with and one without a window, the convection and radiation heat transfer rates could be separately measured. Clearly, a requirement of the instrument with a window is to keep the widest possible acceptance angle. Also a window might render the heat flux meter practically insensitive to draughts, and this could be useful in special circumstances, e.g. when used as a radiometer out of doors.

The response time (taken as 95 per cent of final equilibrium reading) of a suitable instrument would not be critical so long as it did not exceed a value of the order of 10 seconds.

The effect of wind on the heat flux meter when used to measure radiation alone was investigated by directing a current of air from the "blowing" end of a domestic vacuum cleaner onto the front face at an angle of 45 degrees, the air velocity was measured with a vane anemometer before and after the experiments with the radiant panel running. The reduction in output when the blower was switched on was measured not only for the prototype heat flux meter but also for the Moll type thermopile* and a "field" radiometer[4] in which the sensing element is behind a mica window. Three values of wind velocity were employed and incident radiation intensities were maintained at around either 1 W/cm^2 or 2 W/cm^2. The results are all given in Table 1 as a percentage reduction of output due to wind.

Table 1

Effect of wind on heat flux meter

	Percentage reduction in output due to wind of velocity:- 1.3 m/s		2.4 m/s		7.2 m/s	
Moll Thermopile		8.1		20		40
Gardom Prototype	Radiation Intensity 2.1 W/cm^2	4.3	Radiation Intensity 1.7 W/cm^2	4.8	Radiation Intensity 1.9 W/cm^2	7.6
Field Radiometer		5.0		8.3		6.5
Moll Thermopile		6.2		18.3		40
Gardon Prototype	Radiation Intensity 1.2 W/cm^2	3.3	Radiation Intensity 1.1 W/cm^2	5.0	Radiation Intensity 0.9 W/cm^2	5.6
Field Radiometer		6.2		6.3		8.0

* This is essentially an accurate laboratory instrument and was never intended to be used in a draught; it was included here only for comparison purposes.

One of the heat flux meters was exposed to an intensity of 4.0 W/cm^2 for 40 minutes, with the cooling water running through, and the output recorded. There was no progressive alteration and the output remained between 1.33 and 1.38 millivolts, a variation of the same order as that of the incident radiation intensity.

The effect of turning off the flow of cooling water through the jacket was next investigated and it was found that with an incident intensity of about 4 W/cm^2 there was no progressive change in output on stopping the water flow even after 30 minutes. At the end of this time the temperature of the water jacket was probably about 80°C. On restarting the flow the output temporarily increased by about three per cent over a period of about five seconds and then returned to its former value over the next ten seconds. The same effect, of similar magnitude, was found at an intensity of 2.3 W/cm^2.

Another effect investigated was that of moving the receiver tube along the axis of the water jacket so that the constantan disc either projected in front or was recessed behind. It was found that a movement of some two millimetres either way could be tolerated without noticeably affecting the output, suggesting that shadowing the edge of the target is unimportant for the angular size of source employed (semi-angle about 37°).

Finally it was decided to find out if the effects of convective and radiative heat transfer to the instrument were reasonably additive. The radiant panel described earlier[3] was used to provide the radiation transfer while an electric firelighter was used to direct a current of hot air onto the heat flux meter as a source of convected heat. The output was measured with the convected and radiated heat on separately and also on together. Three levels of radiated heat (approx. 1, 2 and 4 W/cm^2) and two levels of convected heat (approx. 1 and 3 W/cm^2) were used and the sum of the individual instrument readings compared with the readings when both radiated and convected heat were on together. The results are given in Table 2 and show that in view of the difficulty of making this kind of experiment* the sum of the individual convection and radiation outputs is in good agreement with the output obtained when both heat sources were applied together, apart from one case where the value of I_c is in doubt.

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*For example, it is hard to avoid some cooling of the radiant panel when both it and the firelighter are on together.

Table 2

Effect of radiative and convective heating on Gardon radiometer G/1

All values in W/cm^2

Panel only I_R	Firelighter only I_c	$I_R + I_c$	Panel and Firelighter I_{RC}	Panel only I_R	Firelighter only I_c	$I_R + I_C$	Panel and Firelighter I_{RC}
1.13	1.10	2.23	2.02	1.10	2.96	4.06	3.97
2.24	0.79*	3.03	2.65	2.08	3.15	5.23	5.04
4.16	1.01	5.17	5.29	4.25	3.15	7.40	6.93

*Heat flow from firelighter unsteady

4. Production of further heat flux meters

Since the performance of the prototype was quite satisfactory a batch of twelve was made and individually numbered G/1 to G/12. Also a small brass collar with clamping screw was soldered to the water jacket of each heat flux meter to enable it to be mounted easily onto a vertical 9 mm diameter rod. The collar is not shown on Figs 1 or 2. Care was taken to see that it did not project beyond the circumference of the water jacket so that the whole instrument could be pushed into a tube of internal diameter about 50 mm (2 in) if required. The twelve water jackets were each drilled with three blind holes tapped for 8 B.A. screws (see Fig 1) to enable a window and frame to be fitted if required.

All twelve heat flux meters were calibrated against the Moll type thermopile using radiation over an intensity range of 0 to 4.5 W/cm^2.

The calibrations showed that the extreme range of sensitivity was about 35 per cent but all heat flux meters were approximately linear in response over this range of intensity.

The most sensitive, G/4, and the least sensitive, G/5, were then recalibrated with their receiver tubes and water jackets interchanged and it was found that the calibrations were unchanged, i.e. the calibration appears to be purely a function of the receiver tube construction and quite independent of the water jacket.

5. Use of infra-red transmission window

Two of the heat flux meters, G/1 and G/2, were fitted with a circular frame designed to hold a calcium fluoride disc in front of the constantan receiving element. A diagram of the frame and disc is shown in Fig. 5. The disc was 25 mm diameter and 2 mm thick with 20 mm diameter exposed to form a circular window for transmitting as much thermal radiation as possible while shielding the receiving element from draughts and convective heat transfer. An asbestos paper gasket was inserted between the disc and the frame to prevent damage due to differential thermal expansion.

Calcium fluoride was selected as a suitable material for a window as it has a high transmission coefficient for infra-red radiation over a wide range of wavelengths (see Fig. 6), withstands a reasonable rise of temperature and is considerably less expensive than other materials with comparable properties (notably Irtran 2). It is, however, easily scratched and requires careful handling.

Some experiments were carried out to investigate the acceptance angle to radiation of the heat flux meter by mounting it facing a radiation source. The front face was held vertical in a mounting that permitted rotation about a vertical axis through the constantan receiving disc. The radiation source was held in one position and consisted of a 100 watt quartz-iodine lamp placed at the near focus of an ellipsoidal mirror. The heat flux meter was located near but not at the further focus so that it received a concentrated radiation over a sufficient area of its front face. The mirror subtended an angle of ± 18 degrees at the receiving element. This was larger than is desirable for a measurement of this kind but was the minimum giving a high enough intensity for accurate measurement of the heat flux meter output.

By measuring this output for various angles between the plane of the constantan disc and the line joining it to the axis of the radiation source, the extent to which the instrument obeyed Lambert's cosine law could be determined. This experiment was carried out for the following situations:-

(a) Constantan disc set flush with front of water jacket
(b) Constantan disc recessed about 2 mm behind front of water jacket
(c) as (b) but with window frame fitted
(d) as (c) but with calcium fluoride window in position

The results are plotted in Fig. 7 in the form of the heat flux meter output against the cosine of the angular deviation from the normal. With the receiving disc set flush it is seen that the cosine law of absorption is well obeyed up to angles of at least 70 degrees off normal. With no window frame the effect of the constantan disc being recessed about 2 mm shows itself in a falling off in the response at angles of incidence exceeding about 55 degrees. When the window frame is fitted without the window itself the fall-off in response also commences at about 55 degrees but its magnitude is approximately doubled. With the window also in position the response-angle of incidence curve was more or less unchanged. Any deviation from the cosine law can therefore be attributed to the "shading" effect of the water jacket and window frame.

It was found that the effect of wind at ambient temperature on the output of the heat flux meter with window fitted was negligible. This was so for wind speeds up to 6 metres/second at radiation levels of 1, 2 and 4 W/cm^2.

The efficiency of the window in cutting off convective heat transfer i.e. a hot wind, was determined by using a hot air blast obtained from an electric firelighter on two of the heat flux meters, one with and one without the window. This test was performed at three different levels of thermal radiation falling on the instrument and also in the absence of such radiation. The hot air from the firelighter impinged on the heat flux meters with a velocity of about 1 metre/second.

The results are summarized in Table 3 below.

Table 3

Effect of window on convective heat transfer to disc

		Heat flux W/cm^2			
Intensity of radiation from panel (No wind)		0	0.85	2.13	4.09
With hot wind c. 1m/s	No window	1.67	1.67	3.03	4.95
	With window	0.13	0.91	2.19	4.19
Convected heat from firelighter (by difference)		1.67	0.82	0.90	0.86
Convected heat "penetrating" window*		0.13	0.06	0.06	0.10

*i.e. extra heat flux reaching target when a hot wind was directed on to the window.

Table 3 shows that about 8 per cent of the convected heat gets past the window, somewhat more with 4 W/cm^2 background of thermal radiation.

It was found, by moving the receiving tube along the cylindrical hole in the water jacket, that the heat flux reaching the target was roughly inversely proportional to its distance behind the window. This shows that this effect is mainly due to conduction of heat across the air space between target and window rather than to heat reradiated from the window. Thus, if for any purpose it was especially important to reduce to a very low level the effect of convection transfer from a hot gas, this could be achieved by moving the target back a few millimetres, provided that the angular size of the radiant source was not large enought to give too much shadowing.

The efficiency of the calcium fluoride window in transmitting radiation was tested by calibrating instruments G/1 and G/2 both with and without windows at intensities from 0 to 4.5 W/cm^2. All four calibrations were of linear form and the reduction of output with window present showed that the 2 mm thickness of calcium fluoride transmitted 91 per cent of the incident radiation. Comparison of this value with the transmission/wave-length curve for calcium fluoride (3 mm thick) and the black body intensity/wave-length relation given in Fig. 6 shows that the measured value of 91 per cent is reasonable.

6. Discussion

Gardon derived the following expression for the sensitivity of this type of instrument, assuming the receiving disc to be fully absorbent

$$V = 1.1 \times 10^{-3} \, ID^2/x$$

where V is the output (mV)

I is the intensity of radiation on receiving disc (W/cm^2)

D is the diameter of the disc (mm)

and x is the thickness of the disc (mm)

This expression was used to obtain the appropriate foil thickness for the present instrument and Fig. 3 shows that the sensitivity actually obtained is some 35 per cent below the theoretical value probably because of the presence of the solder bead. Thus the above expression can be used for design purposes but does not obviate the need for a direct calibration.

Up to an intensity of about 5 W/cm^2 the output of the prototype heat flux meter (Fig. 3) is accurately proportional to the incident radiation intensity, but above this level it appears to fall off slightly. By applying a relation developed by Malone[5] it can be shown that this apparent fall in sensitivity at high intensities is not due to the effect of convection transfer from the receiving element. It is most likely due to an over-estimation of radiant flux by the standard thermopile, caused by placing it where it may receive air heated by mixing with the hot combustion products from the radiant panel.

However, it would be sufficient for many purposes to take the sensitivity as constant up to 8 W/cm^2 so that the instrument calibration could be expressed by a single value, the slope of the line drawn in Fig. 3, i.e., the sensitivity. This would be very convenient when data collected by a data-logging system were being processed by computer to yield intensity values. The error incurred would not be more than about 6 per cent at 8 W/cm^2 and would be very much less than this over most of the range.

Individual calibration is always necessary in view of the range of sensitivity obtained within a batch, probably due to small differences in the quantity and disposition of solder used to fix the constantan disc to the copper wire and tube.

At 8 W/cm^2 the temperature rise at the centre of the target is in the region of 45 deg C so that even at 25 W/cm^2, an intensity higher than any yet encountered in building fires, the temperature of the target centre would still be much too low for the hard-soldered thermocouple junction to be loosened, provided the water jacket was not allowed to run dry. Although the rim of the constantan disc is only soft -soldered to the end of a copper tube, this is cooled by its contact with the water jacket.

It is necessary when using the heat flux meter at these higher intensities to ensure that only the front part of the water jacket is exposed otherwise the soft soldered terminals, leads and rubber tubing used at the rear of the instrument may be damaged. This is particularly important when measuring heat flux in locations likely to be enveloped in flame from time to time. In these circumstances it would probably be necessary to mount the instrument with its front face flush with a surface panel which will protect the rear.

Calibration of the heat flux meter at high intensities must await the installation of a high intensity source at the Fire Research Station, and this is in hand.

The effect of wind on the heat flux meter is satisfactorily small, being considerably less than that with the Moll thermopile and in some cases below that with the field radiometer with a window.

It is also apparent that the regularity and rate of flow of the cooling water can be varied considerably without greatly affecting the output, and also the setting of the constantan disc flush with the front face of the water jacket need not be done within an accuracy greater than $\pm$ 2 mm unless a substantial part of the incident radiation is received at a very wide angle.

The response time of the prototype is below $2\frac{1}{2}$ seconds for 95 per cent of final equilibrium and in six seconds equilibrium has virtually been attained, this performance is quite adequate for the uses envisaged for this instrument. It is seen that the response is much quicker than that of the field radiometer[3].

In Gardon's original paper[1] an experimental expression is taken to represent the rise in radiometer output with time of exposure

i.e. $T = T^{*} \; (1 - e^{-t/\tau})$

where T = output after time t

T^{*} = final steady output

and τ = a time constant

The value of τ was given by Gardon as $0.0093 \, D^2$. For the radiometer described in this note D is 9.5 mm, giving a time constant of 0.84 seconds in good agreement with the value obtained by experiment (Fig. 4), of 0.75 seconds.

7. Conclusions

1. A robust heat flux meter, simple to construct and operate has been developed for the intensity range 0 - 10 W/cm^2. Although possibly suitable for measuring higher intensities, its performance at intensities above about 6 W/cm^2 will need further exploration with a high intensity radiant source now under construction.

2. In its normal form, without a window, both radiation and convection heat fluxes can be measured. It is not sensitive to wind, or to changes in the cooling water flow, and it obeys Lambert's Cosine Law of absorption.

   It is less sensitive than the field radiometer, but nevertheless readings can be made with adequate accuracy using data-logging equipment, as was originally intended.

3. A higher range version can now be designed and made up with some confidence, although it cannot be calibrated properly until the new high intensity radiant source is in operation.

4. In a form with a fluorite window, the instrument can be made almost completely insensitive to convection transfer, either with cool or hot gases. The acceptance angle is still large. This instrument can be used with a normal version, to obtain convection transfer separately.

8. Acknowledgements

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9. References

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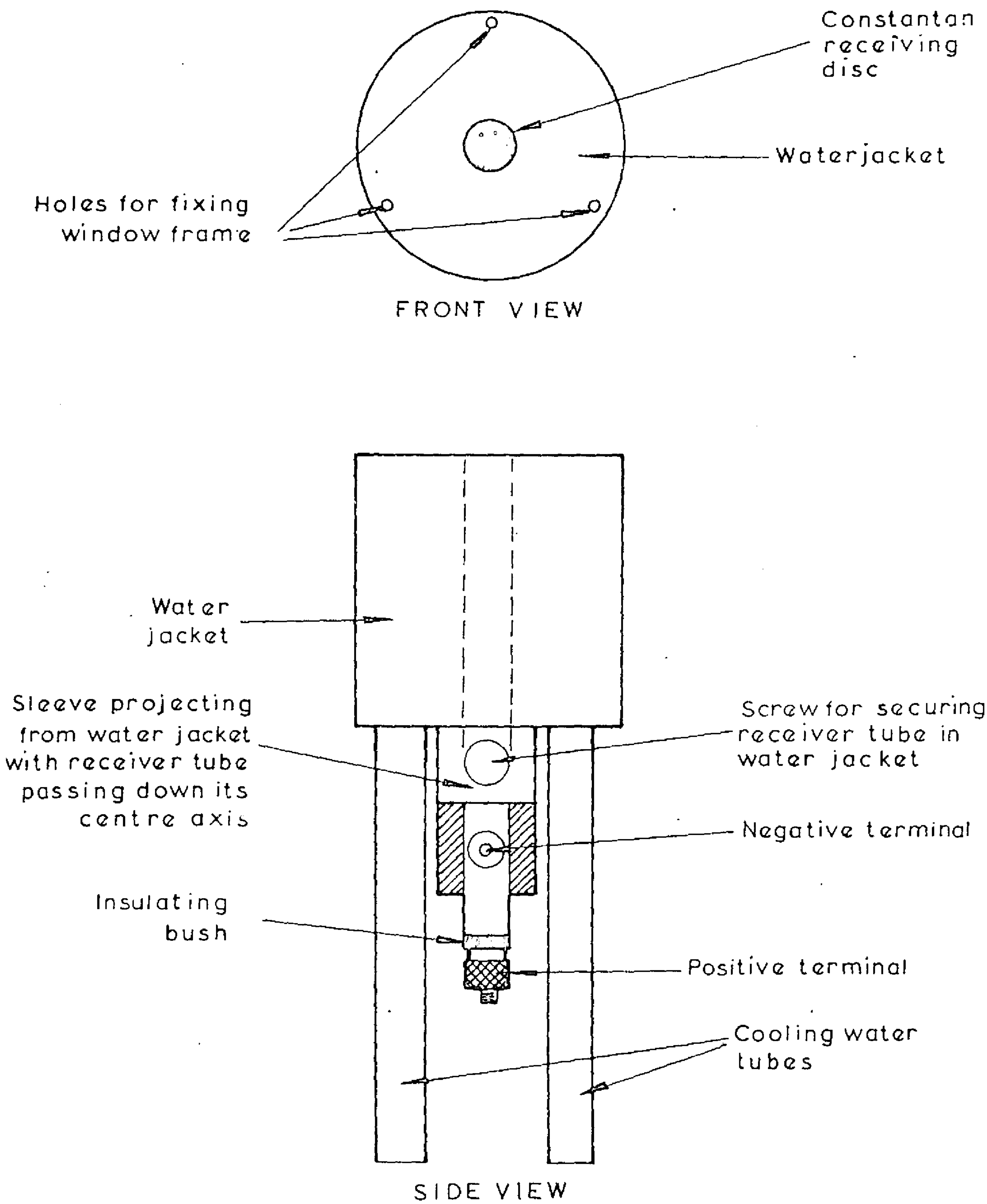
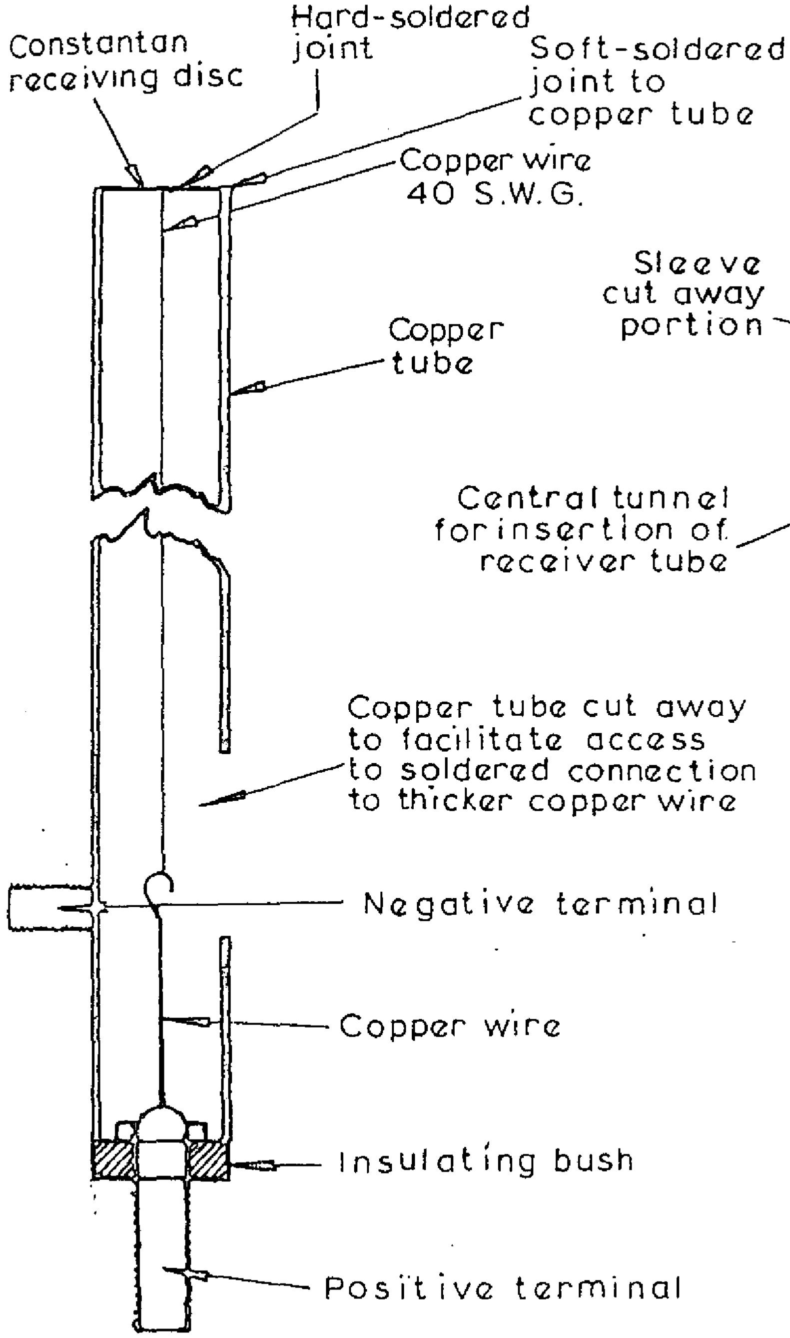
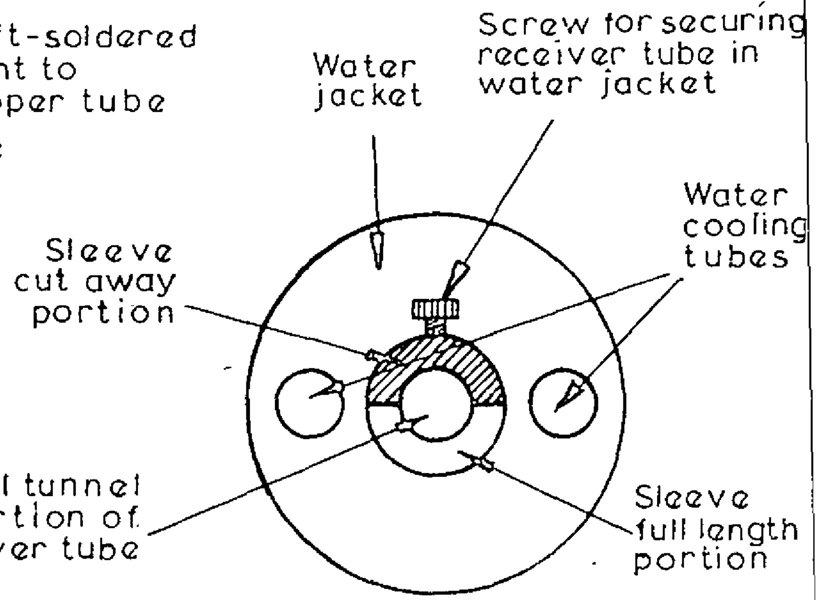


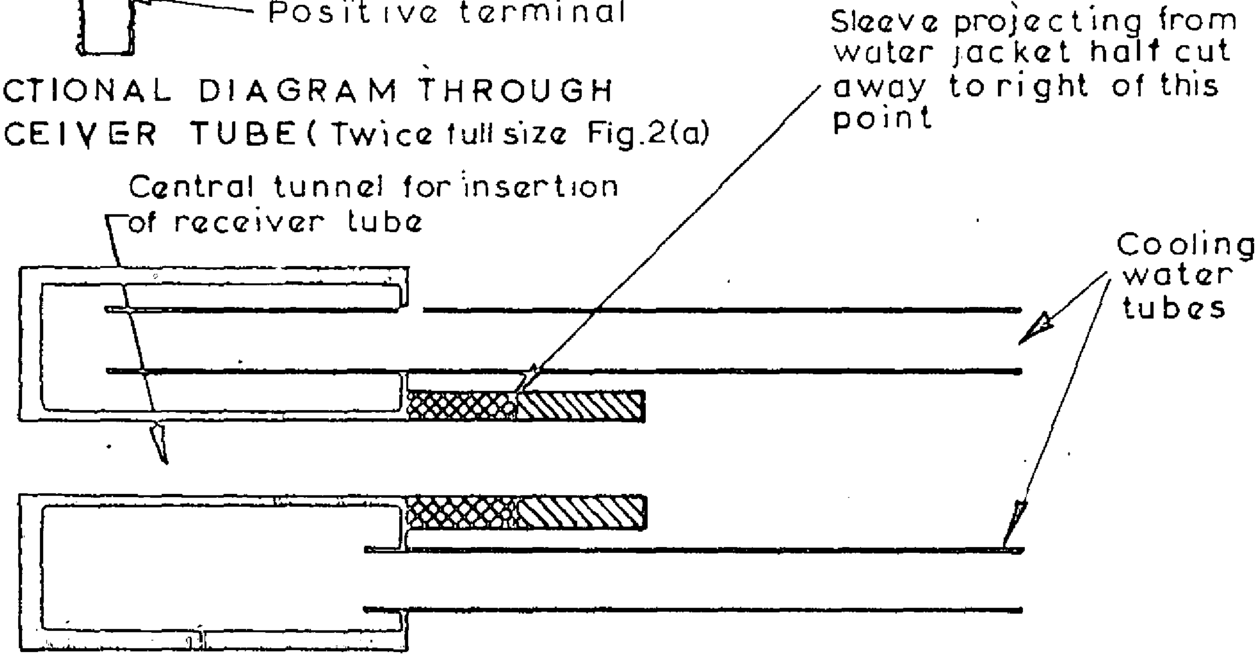
FIG.1. DIAGRAM OF PROTOTYPE HEAT FLUX METER MOUNTED IN WATER JACKET



SECTIONAL DIAGRAM THROUGH RECEIVER TUBE (Twice full size Fig.2(a)



REAR VIEW OF ASSEMBLY (Full scale) Fig.2 (c)



SECTIONAL DIAGRAM THROUGH WATER JACKET (Full scale) Fig.2 (b)

FIG.2 DETAILS OF RECEIVER AND WATER JACKET

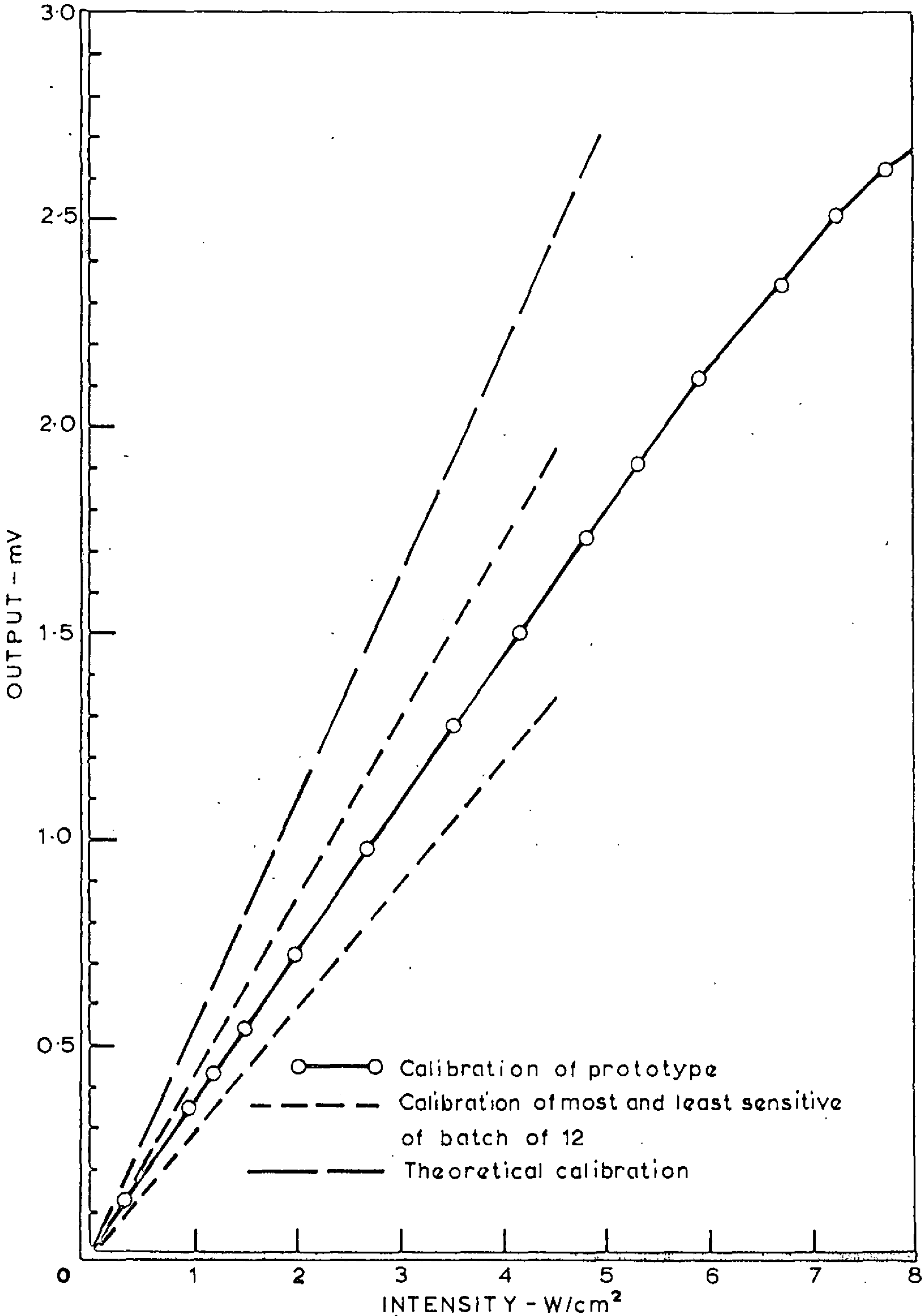


FIG.3. HEAT FLUX METER CALIBRATIONS

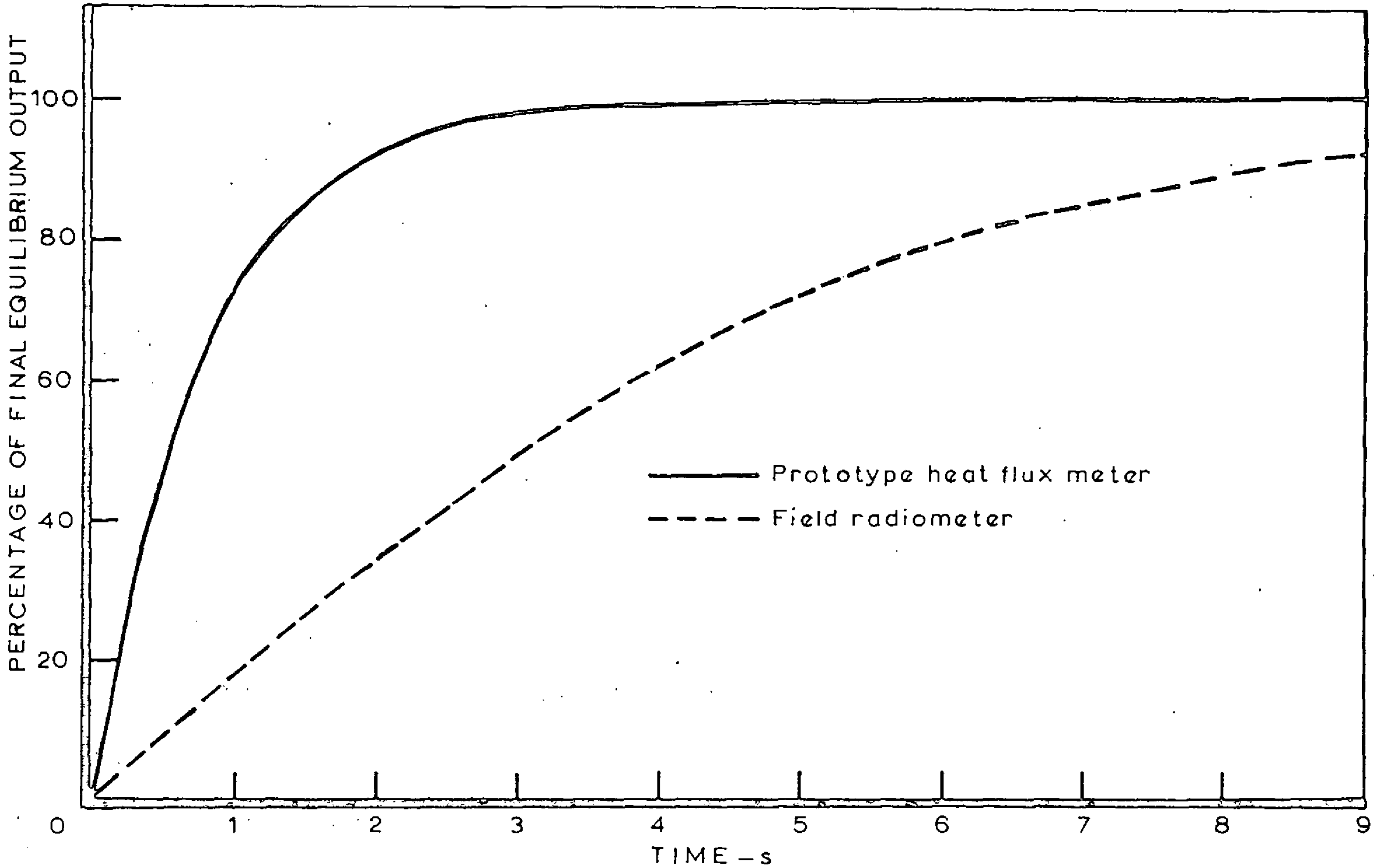


FIG.4. RADIOMETER SPEED OF RESPONSE

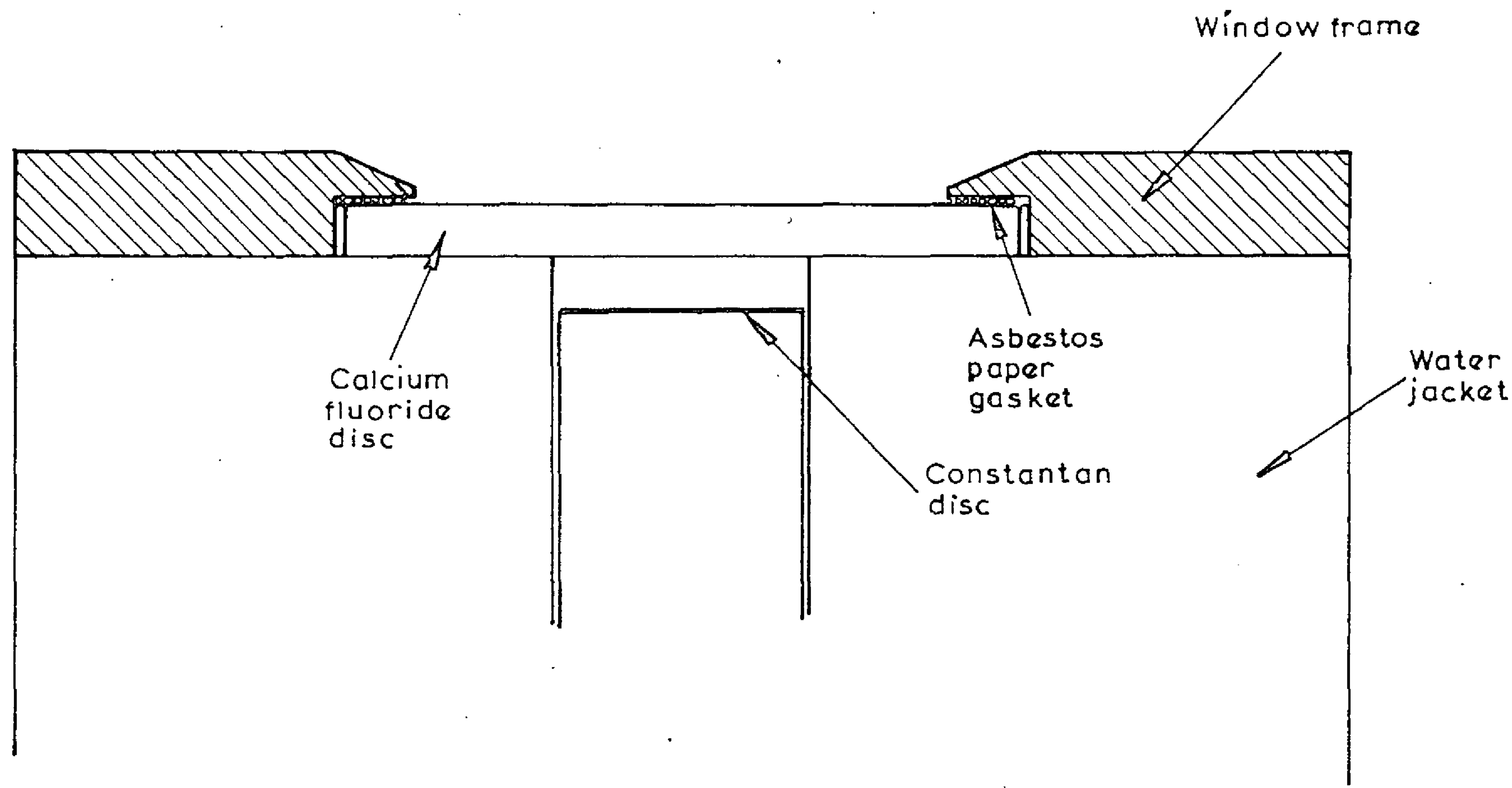


FIG. 5. WINDOW FRAME ASSEMBLY(Four times actual size)

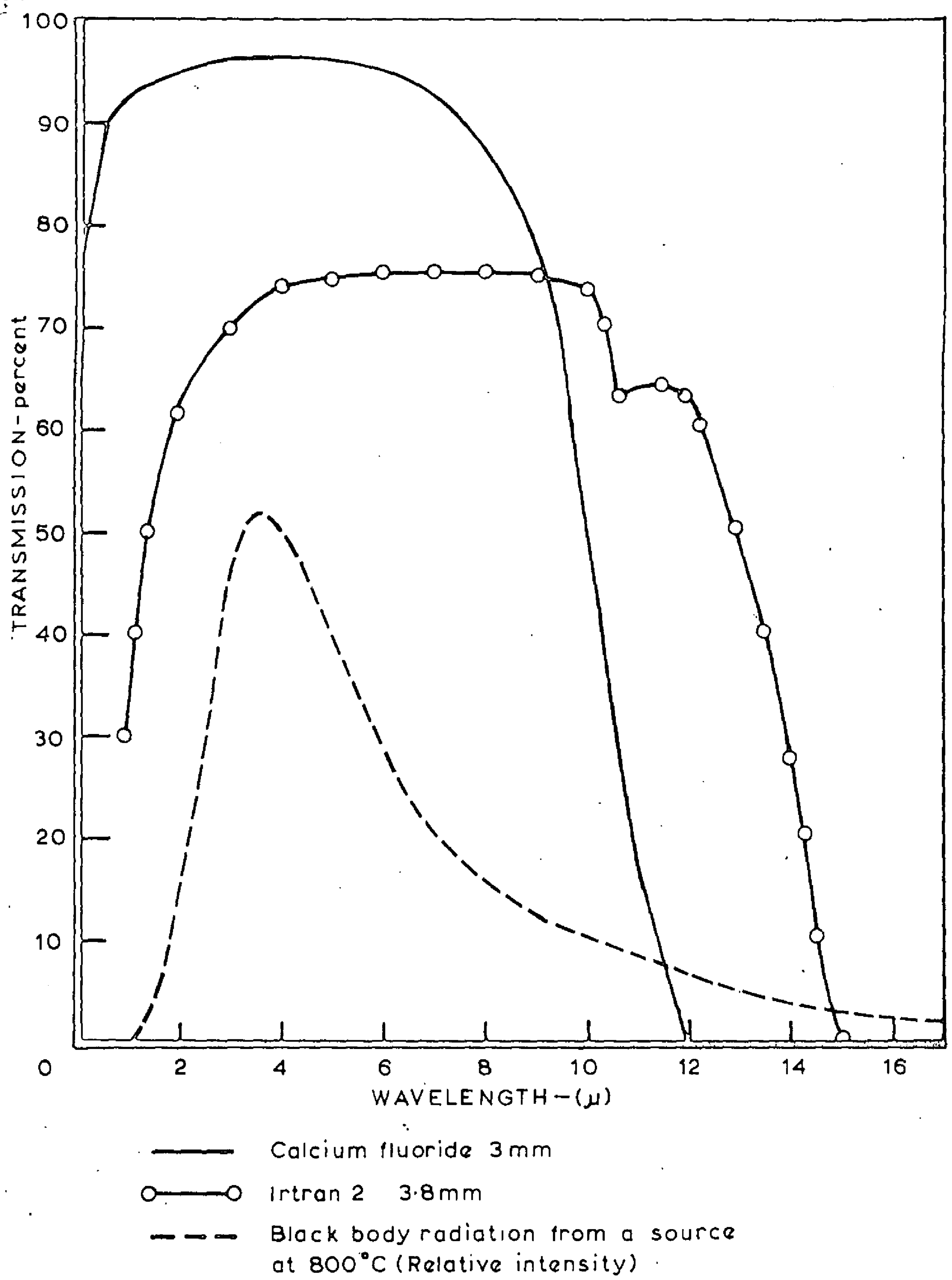


FIG. 6. TRANSMISSION CURVES FOR INFRA-RED GLASSES

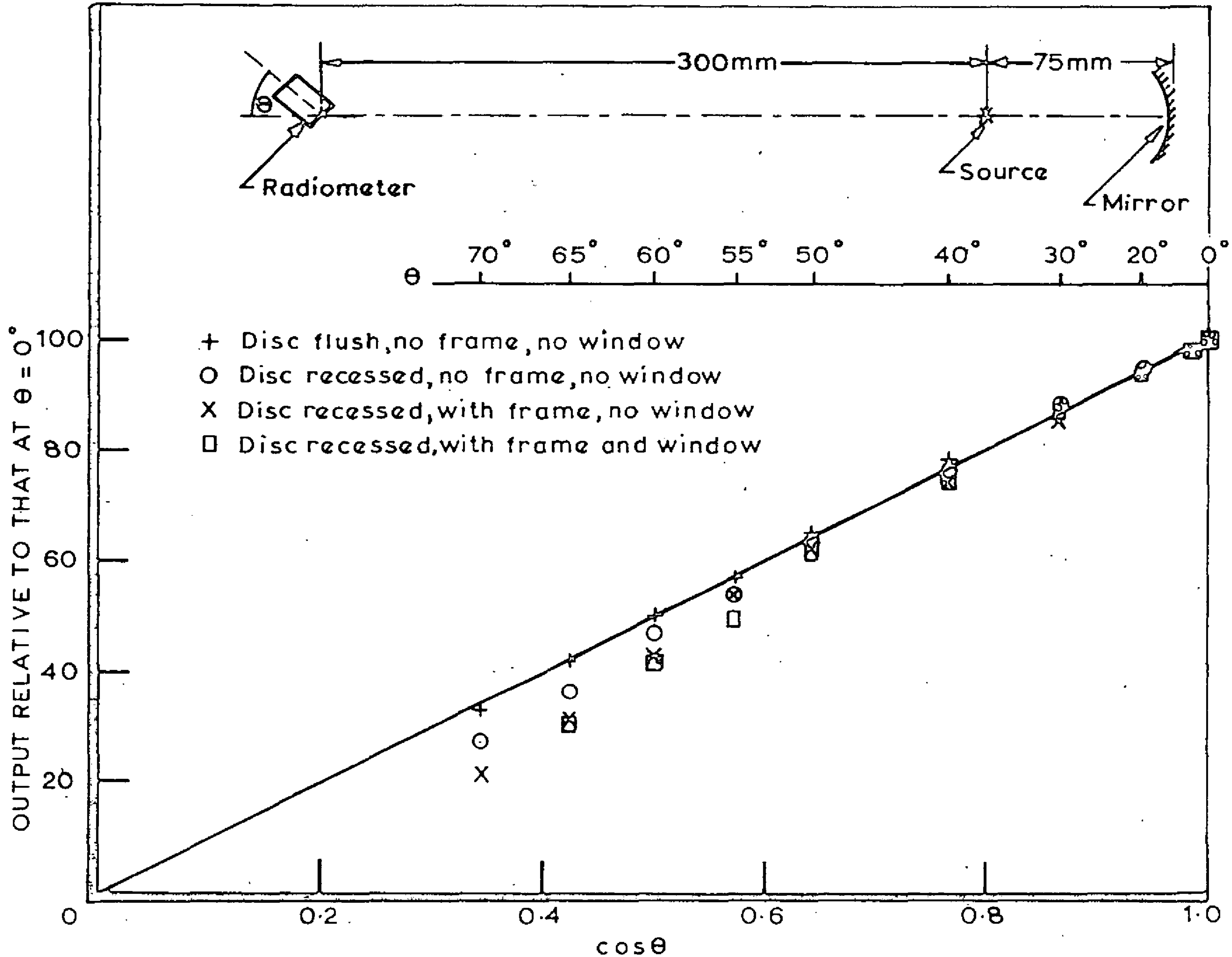
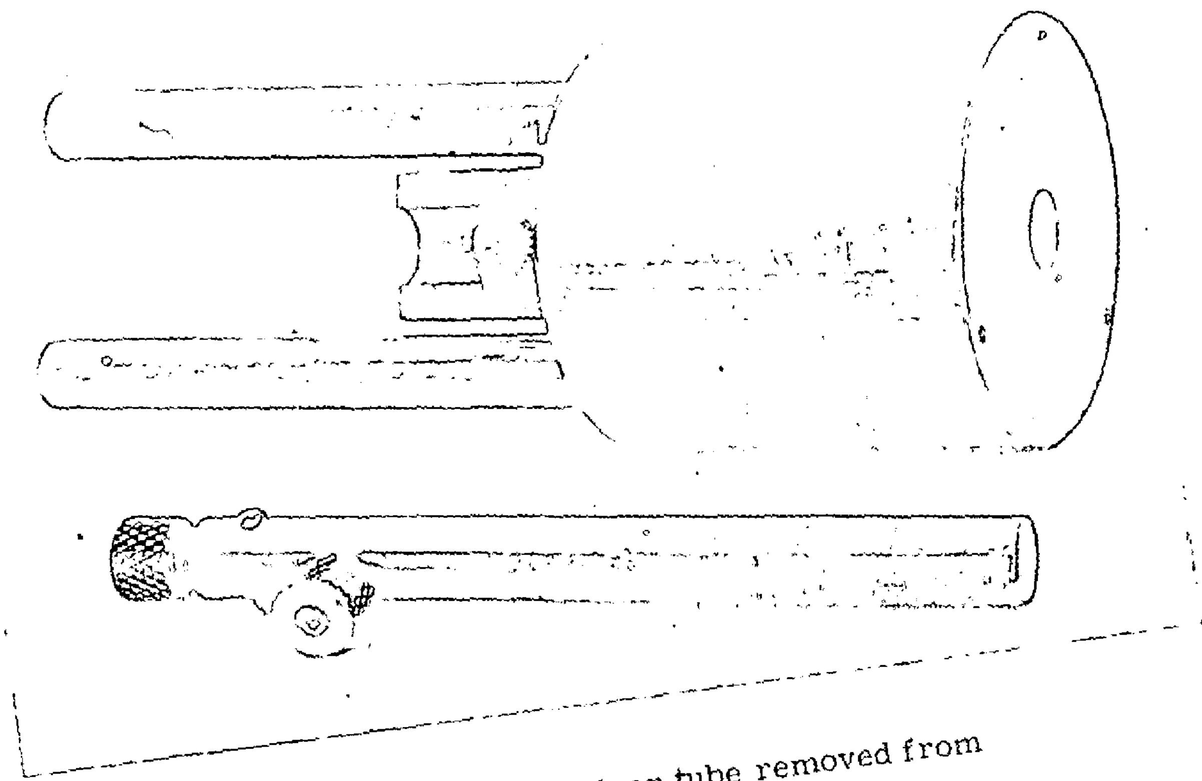
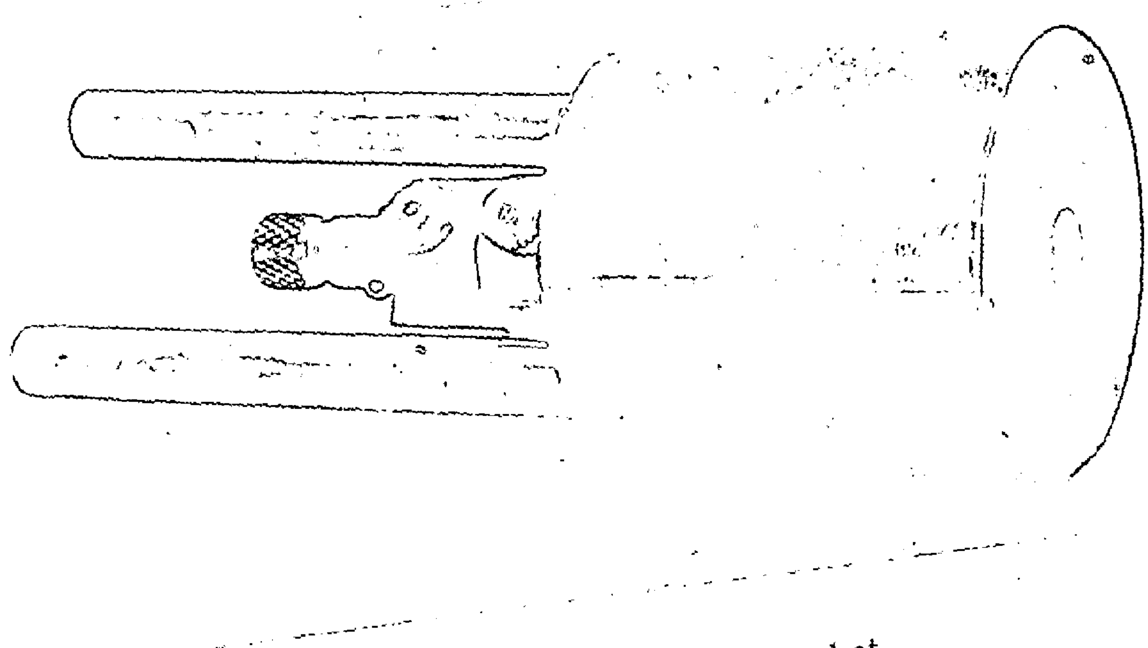


FIG. 7. ANGULAR RESPONSE OF HEAT FLUX METER



(a) Radiometer with receiver tube removed from water jacket



(b) Receiver tube replaced in water jacket

PLATE 1