# Fire Research Note

# No. 648

## THE USE OF WOODEN BLOCKS AS SIMPLE RADIOMETERS

by

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F.R. Note No.648.
(For Flambeau Symposium, February 1967)

MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
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## 1. INTRODUCTION

A simple form of meter is required to measure the heat flux conditions in and around experimental mass fires. The instrument should be robust and easy to use in the field, and also inexpensive because a large number will be needed. High accuracy is not very important. This paper describes how a block of wood may be used for this purpose by measuring the extent of thermal damage to an exposed block or by measuring its surface temperature. An inherent advantage of a standardized wood block is that it is a material whose ignition and thermal damage are of direct importance in practice because in real situations fires spread by ignition of wood. The investigation is not complete, but sufficient work has been carried out to enable the effectiveness of the methods to be assessed.

The blocks would be placed in the spaces between piles of fuel arranged in a rectangular array, and the heat transfer to the blocks should be largely radiative, but convective heat transfer could occur from flames deflected by wind. The calibration experiments were, however, carried out with radiation since facilities for the production of known intensities of radiation were available.

Above a certain intensity of radiation, the surface of an irradiated block of wood suffers thermal damage, at first darkening in colour and eventually, at a high enough intensity, charring, the base of the charred layer moving into the block with a well-defined boundary. A measure of the thermal damage may be obtained either from the depth of the charred layer, or, when no charring occurs, by measuring the change in optical reflectivity of the surface due to its darkening. The extent of the thermal damage depends principally on the intensity of radiation and the time of exposure and the effects of these factors have been investigated in greatest detail. However, a few additional experiments have been conducted with different types of wood, different moisture contents and blocks of different thicknesses. The effect of wind has not yet been explored.

Below a certain intensity of irradiation no thermal damage occurs, but the intensity may be measured by its relation to the surface temperature of the wood block. This may be estimated by means of a series of small pieces of temperature-sensitive papers stuck onto the surface of the block.

The calibration experiments covered the range of intensities from 0.2 to 3.5 W $cm^{-2}$.

## 2. EXPERIMENTAL PROCEDURE

The blocks used for most of the experiments were of Baltic Redwood (Pinus sylvestris) 10 cm square and 5 or 2.5 cm thick, with fairly uniform, knot-free surfaces. Except for a few experiments where moisture content was varied, the blocks were conditioned to 10 per cent moisture content.

The blocks were exposed in a vertical position to the radiation from a vertical 30 cm square gas-fired radiant panel[1], the intensity of radiation being measured with a thermopile[2].

### 2.1. High Intensities

The blocks of wood were exposed to intensities of radiation in the range 0.5 to 3 W $cm^{-2}$ for times of 5 to 40 minutes. Thermal damage occurred to the surface of the wood and measurements were made of the change of reflectivity or the depth of charring according to the extent of the damage. Some additional experiments were conducted with oven dried blocks and blocks of approximately 20 per cent moisture content; also with blocks of chipboard and balsa wood, in the range of intensities where there was a change of reflectivity.

Before irradiation, the reflectivity of each block was measured using a photoelectric reflectometer (see Appendix) and the thickness of the block was noted. After irradiation, if the block had darkened in colour, another reading of reflectivity was made at about the middle of the face; if it had begun to char, it was cut in half and the thickness of uncharred wood at the centre of the block noted so that the depth of charring could be found. This value included any decrease in thickness due to decomposition of the outer surface of the charred layer (Plate 1).

### 2.2. Low Intensities

For intensities below 0.5 W $cm^{-2}$, where there was no measurable thermal damage, a different method had to be employed and experiments were carried out to relate the surface temperature of a block to intensity. This temperature was determined using small pieces of temperature sensitive papers* which changed irreversibly from white to black at particular temperatures, glued to the surface of the block. First a series of papers was selected, then blocks with samples of the series mounted were exposed to various intensities of radiation.

The series of papers was selected as follows. A 2.5 cm thick block was exposed to intensities of irradiation of 0.21, 0.31 and 0.42 W $cm^{-2}$ and the temperature rise of the surface was measured by means of a chromel-alumel thermocouple embedded in the surface. A series of temperature-time curves were obtained, showing that a steady temperature was reached after 20 to 30 minutes exposure, the final equilibrium temperature being nearly proportional to the incident intensity. Using this data, five temperatures for papers were chosen so that intensities in the ranges 0.15 to 0.21, 0.21 to 0.31, 0.31 to 0.42 and 0.42 to 0.63 W $cm^{-2}$ could be distinguished.

The chosen series of papers was then tested. Small specimens were mounted on a number of blocks and these were then exposed to intensities of radiation from 0.17 to 0.63 W $cm^{-2}$ in steps of 0.02 W $cm^{-2}$. As far as possible the time at which each colour change occurred was noted, but in all cases the papers which had changed colour after 30 minutes were noted.

## 3. RESULTS AND DISCUSSION

When the blocks were exposed to high heat fluxes, i.e. above about 1.25 W $cm^{-2}$, for ten minutes or longer the front surface became completely blackened and began to char. From about 0.4 W $cm^{-2}$ to 1.25 W $cm^{-2}$ there was a gradual darkening of the surface, (see Plate 2) and below about 0.4 W $cm^{-2}$, there was no appreciable darkening. The results will be treated in these three sections, according to the type of measurement used. No attempt to carry out a theoretical analysis of the results has been made.

### 3.1. Depth of Charring

The depth of char is shown in Figure 1 for various radiation dosages. For a given intensity, depth of char was found to be nearly proportional

*Thermopaper - manufactured by the Paper Thermometer Company, Massachusetts. Manufacturers claim the accuracy is within ± 1 per cent of calibrated values and colour change occurs within a fraction of a second at indicating temperature.

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to the time of exposure and therefore the results obtained are plotted in Figure 2 as a rate of charring against intensity of irradiation. This figure also contains some data obtained by Margaret Law[3] for Oak, Columbian Pine and Parana Pine. The rates of charring are similar to that of Baltic Redwood except at the highest intensities. The rate of charring rises fairly steadily with intensity up to about 3.5 W $cm^{-2}$, but above this intensity it seems to increase rather more rapidly for Oak and Columbian Pine. A few results obtained for Baltic Redwood at these high intensities also show this trend. The reason for this upward trend at high intensities is almost certainly due to an acceleration in the rate of an exothermic reaction in the wood. Considering the region of the graph up to about 3.5 W $cm^{-2}$, within the limits of experimental error, all the results fall close to one curve. If the depth of charring of one wood, Baltic Redwood, is measured and the time of exposure is known, the intensity of irradiation may be found to within an accuracy of the order of 0.2 W $cm^{-2}$.

After exposure to a varying flux the depth of char is neither a function solely of the maximum intensity nor of the total radiation dose.

When exposed to a high enough intensity to cause charring, the blocks cracked on the surface due to a reduction in volume as carbonization occurred, the degree of cracking depending both on intensity of radiation and time of exposure. Five main types of cracking could be distinguished according to width and number of cracks, see Plate 1 and Table 1.

Table 1. Classification of Surface Cracking

| Type of charring | Description of cracking on a 5 x 5 cm block | Approx. width of largest cracks (mm) |
|---|---|---|
| 1 | Surface blackened, but not cracked. | 0 |
| 2 | Fine cracking has occurred on part of the surface. | 1 - 2 |
| 3 | Small cracks running in both directions across the block cutting it into charred areas $\simeq$ 1 $cm^2$ | 2 - 3 |
| 4 | Fairly wide cracks running across the grain of the wood (about 4 to 6 cracks) smaller cracks running along the grain. | 3 - 4 |
| 5 | Wide cracks running across the grain (about 2 to 4 cracks) occasional smaller cracks running with the grain. | 4 - 5 |

The variation of degree of cracking with intensity for different times is shown in Figure 3. This graph could be used to give a rough estimate of the intensity of radiation received by a block, provided time of exposure is known.

3.2. Reflectivity

Because there was some variation in initial reflectivity (66 to 74 per cent) the reflectivity ratio, the ratio of final to initial reflectivity, has been taken as a measure of the amount of darkening. The variation of reflectivity ratio with intensity for different times is shown in Figure 4. No difference in reflectivity ratio was found between 5 cm and 2.5 cm thick blocks for like exposure and intensities, so results for both thicknesses have been pooled. The data may be represented approximately by a single curve if reflectivity ratio is plotted against $It^{\frac{1}{3}}$ where $I$ is the intensity and $t$ is the time of exposure. (Figure 5). There is some systematic difference between results from blocks of two different batches of wood, but this is, on the whole, within the limits of accuracy of the experiments. Figure 5 could be used to find intensities from 0.4 to 1.25 W $cm^{-2}$ by measuring the reflectivity ratio, and, since time appears as a one third power, only an approximate measure of exposure time is necessary. The accuracy would be better than $\pm$ 0.1 W $cm^{-2}$, for an exposure time of 20 minutes.

There are not yet enough results to enable nay definite conclusions to be drawn about the effect of moisture content. All the experiments done with dry blocks gave slightly lower reflectivity ratios than those for 10 per cent moisture (Figure 5). This difference, however, is within the limits of experimental accuracy and may not be significant. The blocks of about 20 per cent moisture did not show any tendency to darken less than those of 10 per cent moisture, but the results show much scatter, possibly because of some discoloration of the blocks during conditioning. Moisture content does not, therefore, seem to have any large effect on reflectivity, but a more thorough investigation would be needed before its exact effect could be determined.

Experiments with Balsa wood and chipboard showed that these materials are less useful than Baltic Redwood because there reflectivity changes occurred over a smaller range of intensities which lay within the range covered by the Baltic Redwood.

In practice it would clearly be necessary to keep the surface of the blocks clean by suitable distribution and collection precedures.

### 3.3. Surface temperature

The results for an exposure time of 30 minutes are shown in Figure 6 and summarized in Table 2, and show that the change in colour of these paper specimens could, under ideal conditions, be used to estimate radiation intensity with an accuracy of the order of $\pm$ 0.06 W $cm^{-2}$. This accuracy is determined partly by the number of papers which it is convenient to employ, but in view of the dependence of final temperature attained by the surface on ambient temperature and on the intensity of irradiation of the sun* there is little point in striving for too high an accuracy or setting the lower limit too low. For exposure times of much less than 30 minutes, intensity will be underestimated from Table 2 because the block will not be able to respond quickly enough. However, by obtaining a set of results for the same series of papers for shorter exposure times, intensities could be estimated for these times.

Table 2. Intensity Ranges Predicted from Colour Changes of Heat-sensitive Papers

| Temperature indicated by papers °C | Intensity range W $cm^{-2}$ |
|---|---|
| $< 77$ | $< 0.17$ |
| 77 - 110 | 0.17 - 0.21 |
| 110 - 138 | 0.23 - 0.31 |
| 138 - 171 | 0.34 - 0.42 |
| 171 - 199 | 0.44 - 0.54 |
| $> 199$ | $> 0.57$ |

Although a thinner block could be used, or a material of different thermal properties (e.g. an incombustible material) a thick wooden block is required for the highest intensities and in the field it would be of great advantage to use only one kind of measuring device for all intensities.

*The intensity of radiation received by a horizontal surface from the sun at an angle of elevation of 82° is given as 0.125 W $cm^{-2}$[5]. Of this, about 0.1 W $cm^{-2}$ would be absorbed by a wood surface. However, the block could be exposed to the sun for longer than to the fire.

## 4. CONCLUSIONS

(i) Wooden blocks may be used as simple radiometers over an intensity range from about 0.2 to 3.5 W $cm^{-2}$ provided the time of exposure is known.

(ii) For the intensity range from 1.25 W $cm^{-2}$ up to about 3.5 W $cm^{-2}$ the intensity of radiation received by a block of Baltic Redwood may be found to within about $\pm$ 0.2 W $cm^{-2}$ by measuring the depth of wood which has charred, provided the time of exposure is known. These higher intensities may also be estimated by noting the type of cracking on the surface of the block, again if the exposure time is known.

(iii) Intensities from 0.4 to 1.25 W $cm^{-2}$ may be found to within $\pm$ 0.1 W $cm^{-2}$ by measuring the reflectivity of the surface of the block before and after irradiation and noting the time of exposure. Time of exposure need not be known very accurately as reflectivity ratio depends on a weak power ($\frac{1}{3}$) of time.

(iv) For intensities lower than about 0.6 W $cm^{-2}$, intensity of radiation may be estimated by means of a series of pieces of temperature sensitive papers, stuck to the surface of a block. Under ideal conditions, with five papers, estimates of intensity in the range 0.2 to 0.6 W $cm^{-2}$ can be made to within $\pm$ 0.06 W $cm^{-2}$, but in the field the accuracy would probably be lower, particularly with exposure times of less than 30 minutes.

## 5. ACKNOWLEDGEMENTS

The paper is Crown Copyright, reproduced by permission of the Controller, H.M. Stationery Office. It is contributed by permission of the Director of the Joint Fire Research Organization.

The authors are indebted to Mr. A. M. Western for suggesting that wood blocks could be used for this purpose.

## 6. REFERENCES

(1) SIMMS, D. L. and COILEY, J. E. Radiation characteristics of a gas-fired panel. Brit. J. Appl. Phys 14, 292-294, 1963.

(2) SIMMS, D. L., PICKARD, R. W. and HINKLEY, P. L. Modified moll thermopiles for measuring thermal radiation of high intensity. Journal of Scientific Instruments, 39, 204-207, May 1962.

(3) LAW, MARGARET. Private communication.

(4) Paint Research Station. Private communication.

(5) Smithsonian Institute.

(6) The Chemical Rubber Company. Handbook of Chemistry and Physics Forty-fifth Edition, 1964 - 1965.

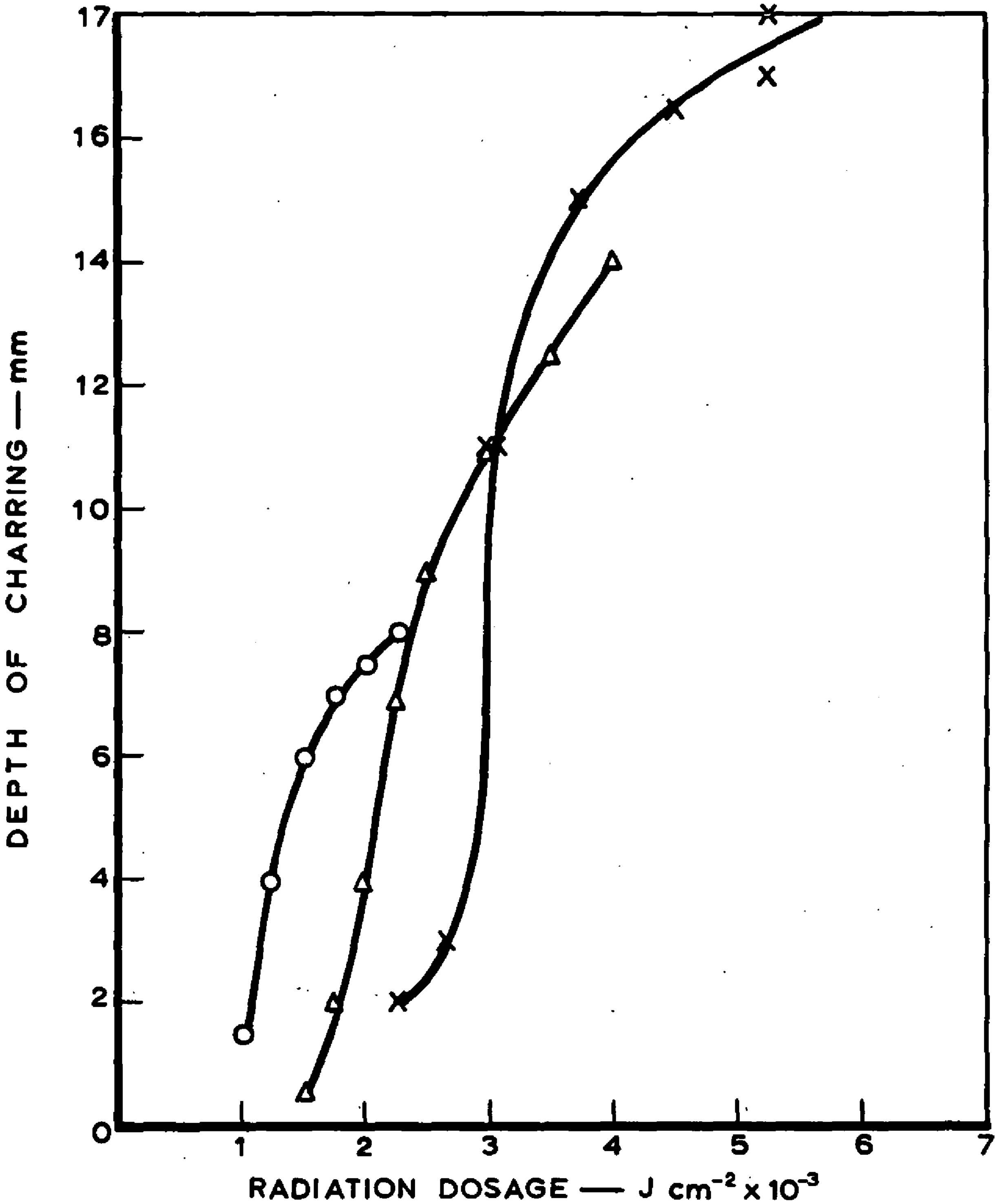
## APPENDIX

### The Reflectometer

The reflectometer used was a commercially available instrument of the type originally developed by the Paint Research Station[4], and consisted of a small head containing a lamp and photocell connected by a flexible lead to a millivoltmeter with a hundred-division scale. The head was placed on the surface of which the reflectivity was required. The surface was illuminated by a beam of light through a circular hole in the centre of a circular barrier-layer photocell and the diffuse reflected light was received by the annular photocell. The sensitivity could be altered by means of a variable resistance.

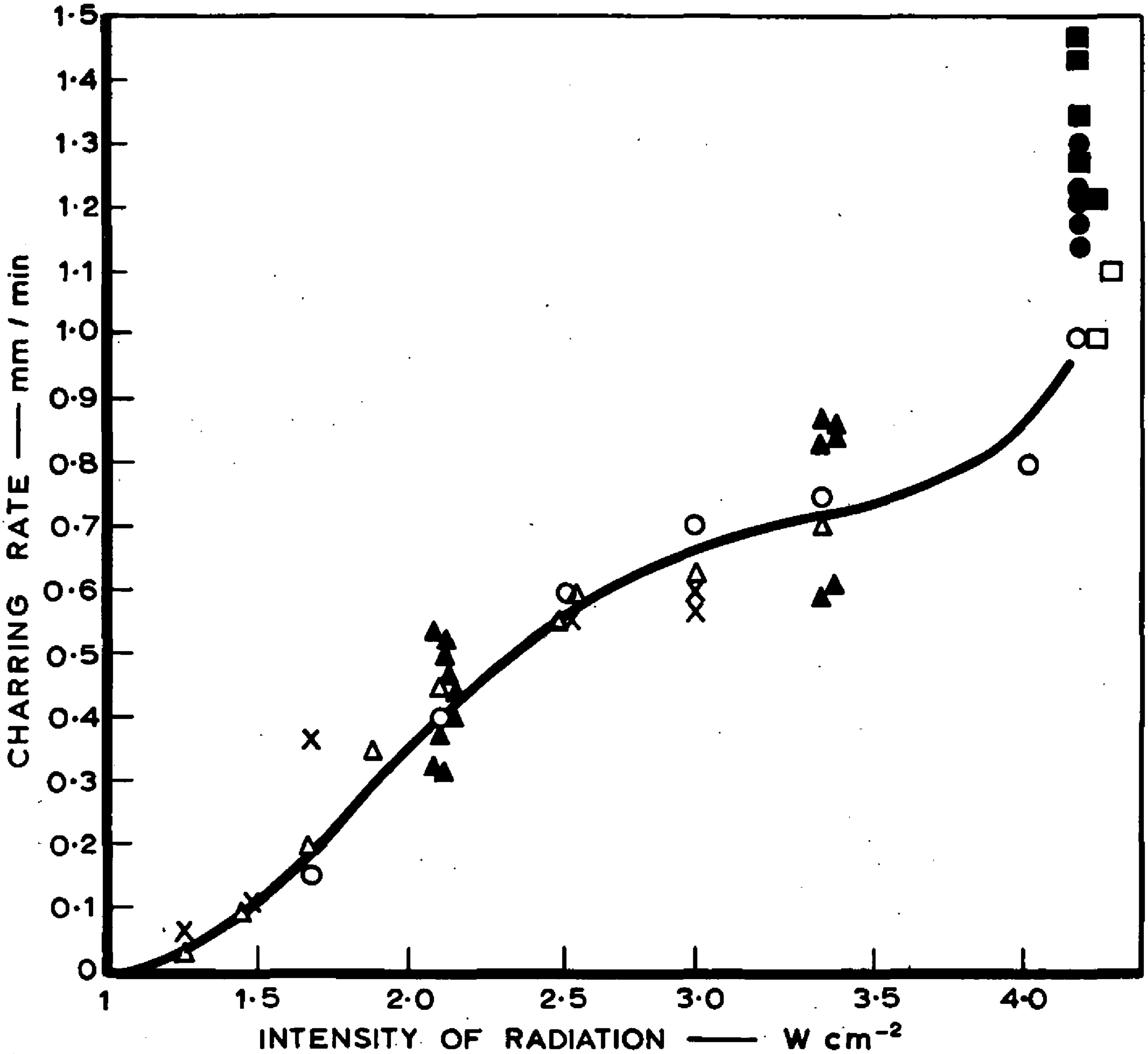
The reflectometer was calibrated absolutely as follows.

A piece of aluminium sheet smoked with magnesium oxide to a depth of about two millimetres and having a reflectivity of 98 per cent[6] formed a standard surface of high reflectivity. This was used to determine the reflectivity of a piece of matt white card, assuming that the reading of the meter was approximately proportional to reflectivity. The white card then formed a secondary standard surface which was used to set the sensitivity of the instrument each time it was used. The linearity of the instrument was then explored by means of specimens of known reflectivity. Circular specimens were accurately constructed with one or three quadrants of matt black surface of known reflectivity and the rest of white card. The average reflectivity of each of these specimens was calculated and compared with the reflectometer reading, with the head placed exactly at the centre of the circle. (In case the sensitivity of the head varied with angle, a number of readings were taken with the heat rotated between readings). The readings of the instrument were found to be accurately proportional to surface reflectivity.



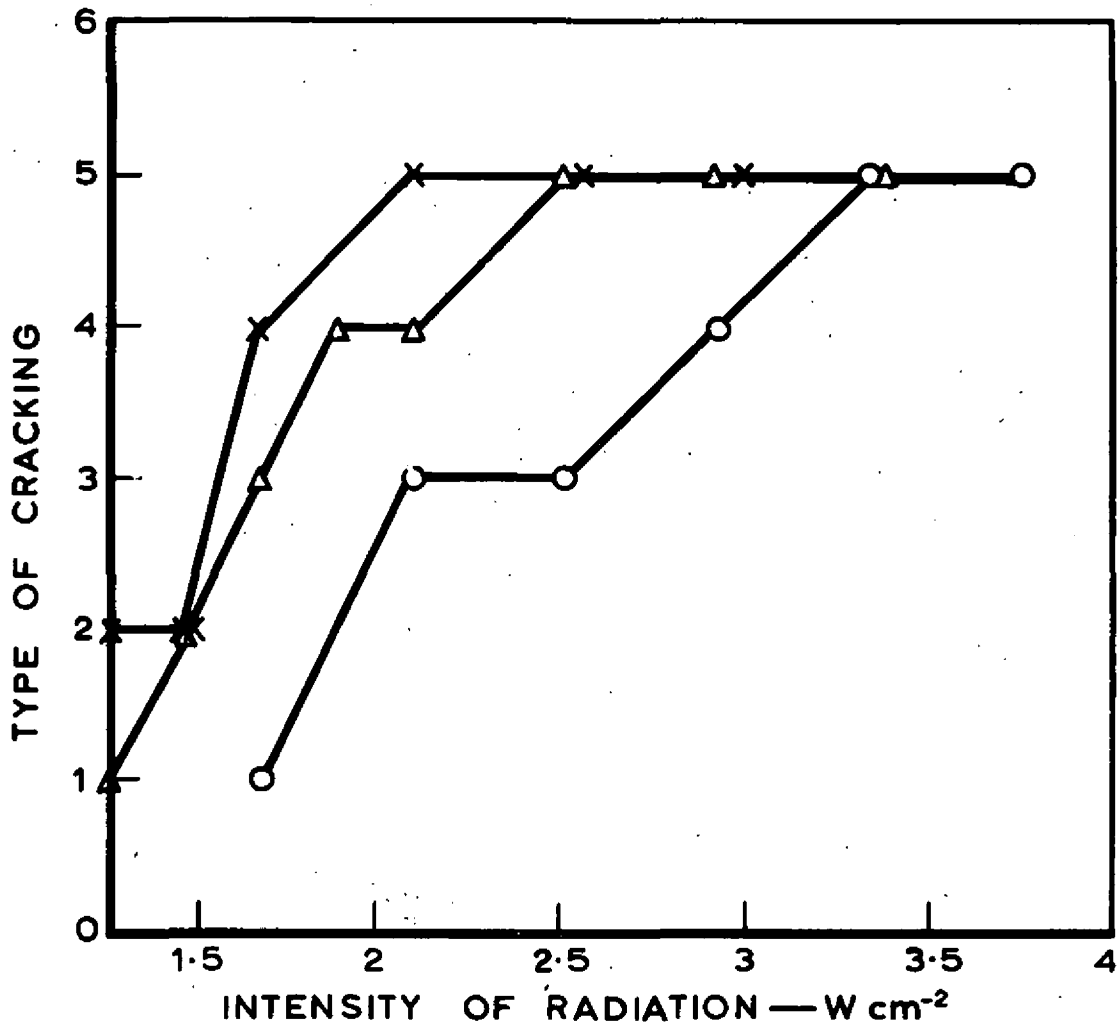

| Exposure time min | Symbol |
|---|---|
| 10 | O |
| 20 | Δ |
| 30 | X |

FIG. 1. DEPTH OF CHARRING AND RADIATION DOSAGE



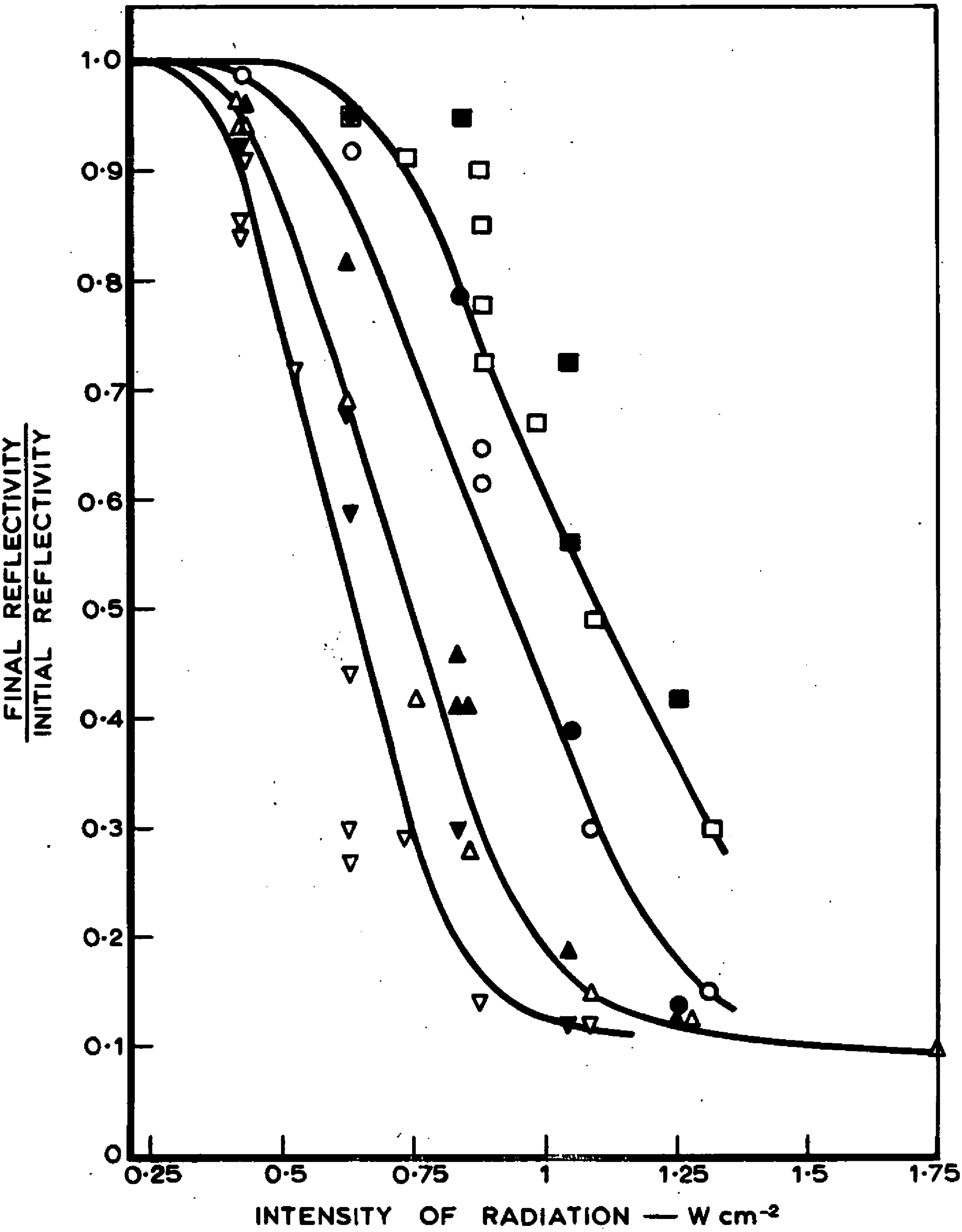

| Wood species | Exposure time min | Symbol |
|---|---|---|
| Baltic Redwood | 5 | □ |
| | 10 | ○ |
| | 20 | △ |
| | 30 | X |
| Oak | <10 | ● |
| Columbian pine | | ■ |
| Parana pine | 5–30 | ▲ |

FIG. 2. VARIATION OF CHARRING RATE WITH INTENSITY



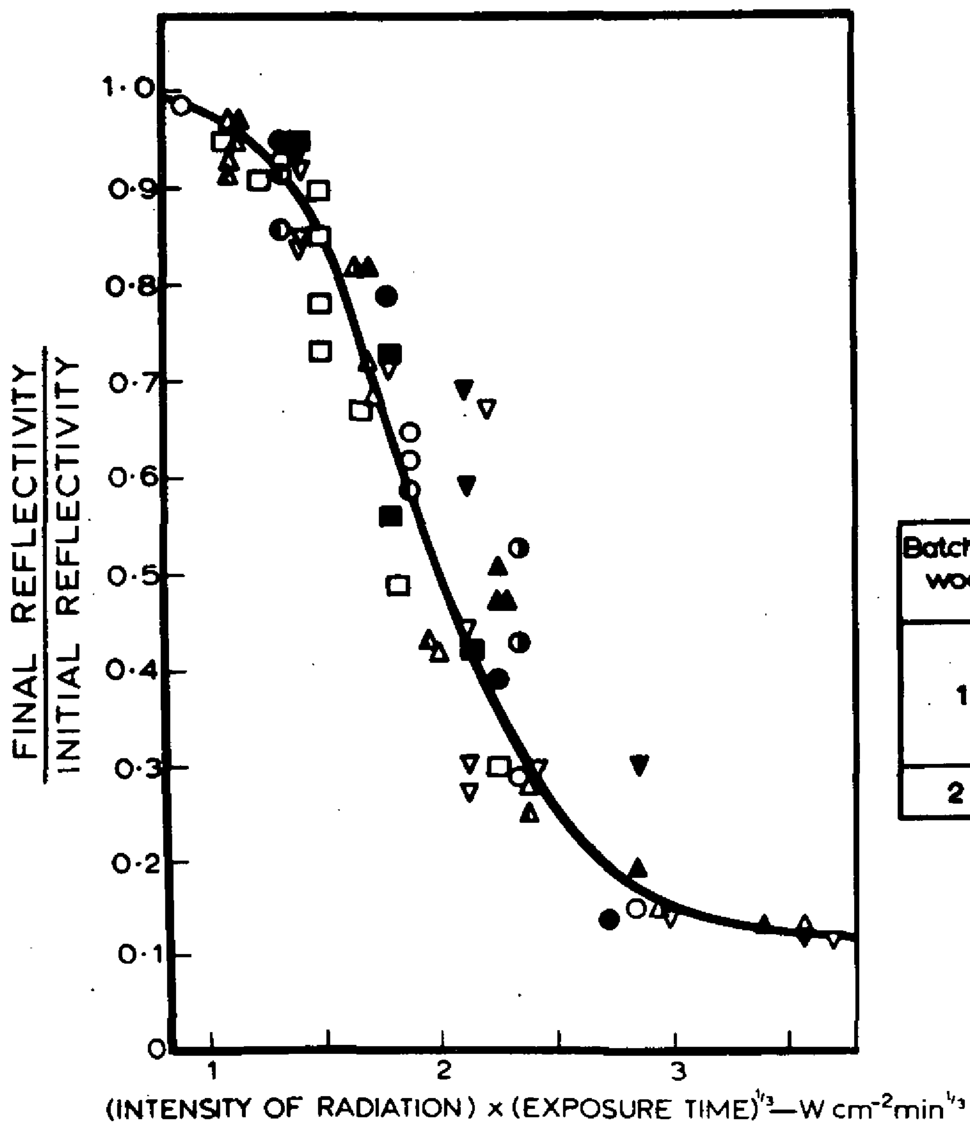

| Exposure time min | Symbol |
|---|---|
| 10 | O |
| 20 | Δ |
| 30 | X |

FIG. 3. TYPE OF CHARRING AGAINST INTENSITY




| Batch of wood | Exposure time – min | | | |
|---|---|---|---|---|
| | 5 | 10 | 20 | 40 |
| 1 | □ | ○ | △ | ▽ |
| 2 | ■ | ● | ▲ | ▼ |

FIG. 4. VARIATION OF REFLECTIVITY RATIO WITH INTENSITY OF RADIATION




| Batch of wood | Moisture content per cent | Exposure time min | | | |
|---|---|---|---|---|---|
| | | 5 | 10 | 20 | 40 |
| 1 | 0 | – | ◐ | △ | – |
| | 10 | □ | ○ | △ | ▽ |
| | 20 | – | ◑ | △ | – |
| 2 | 10 | ■ | ● | ▲ | ▼ |

FIG. 5. CORRELATION OF REFLECTIVITY DATA

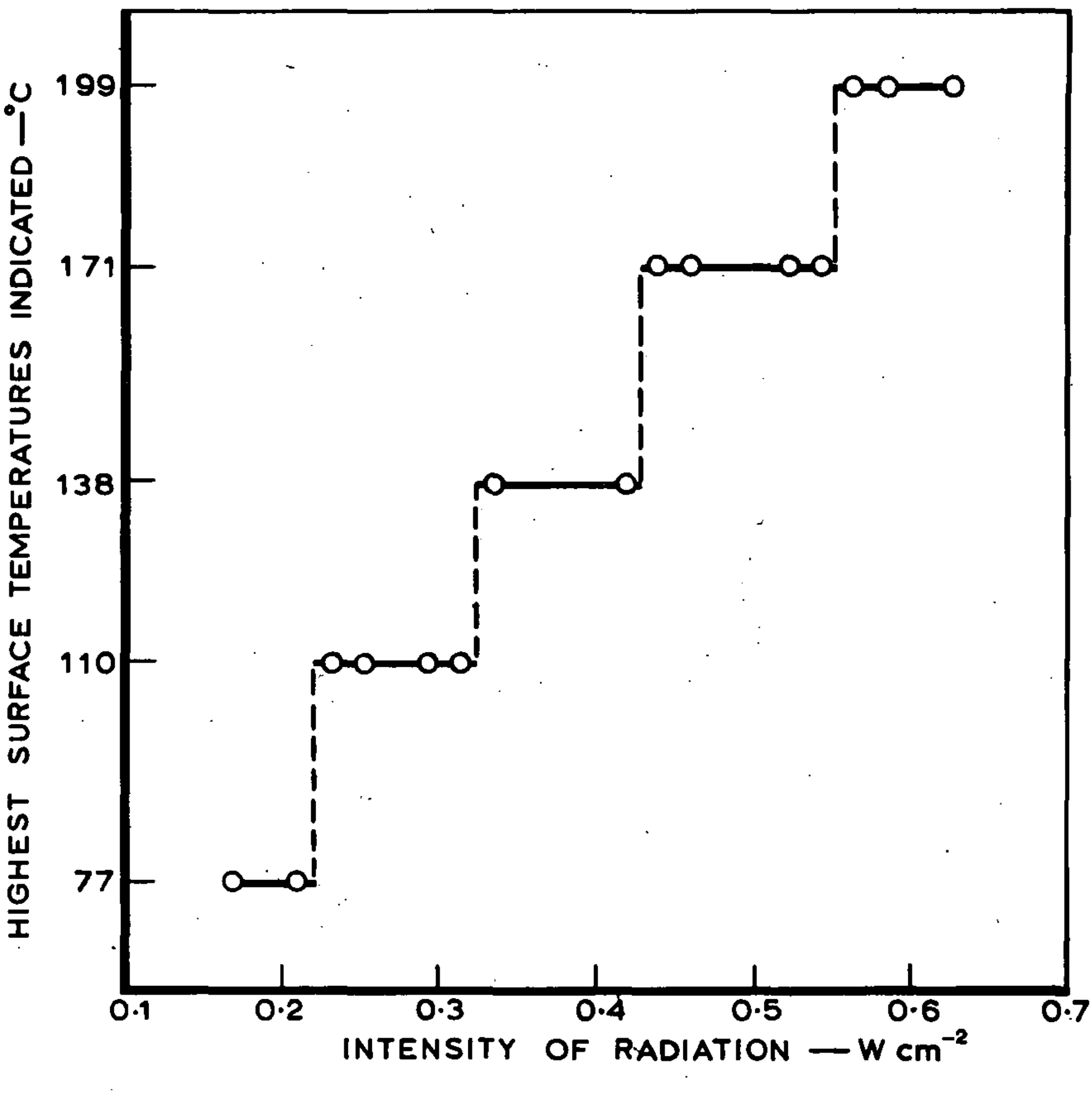



FIG. 6. TEMPERATURE INDICATED BY SENSITIVE PAPERS AFTER 30 MINUTES EXPOSURE

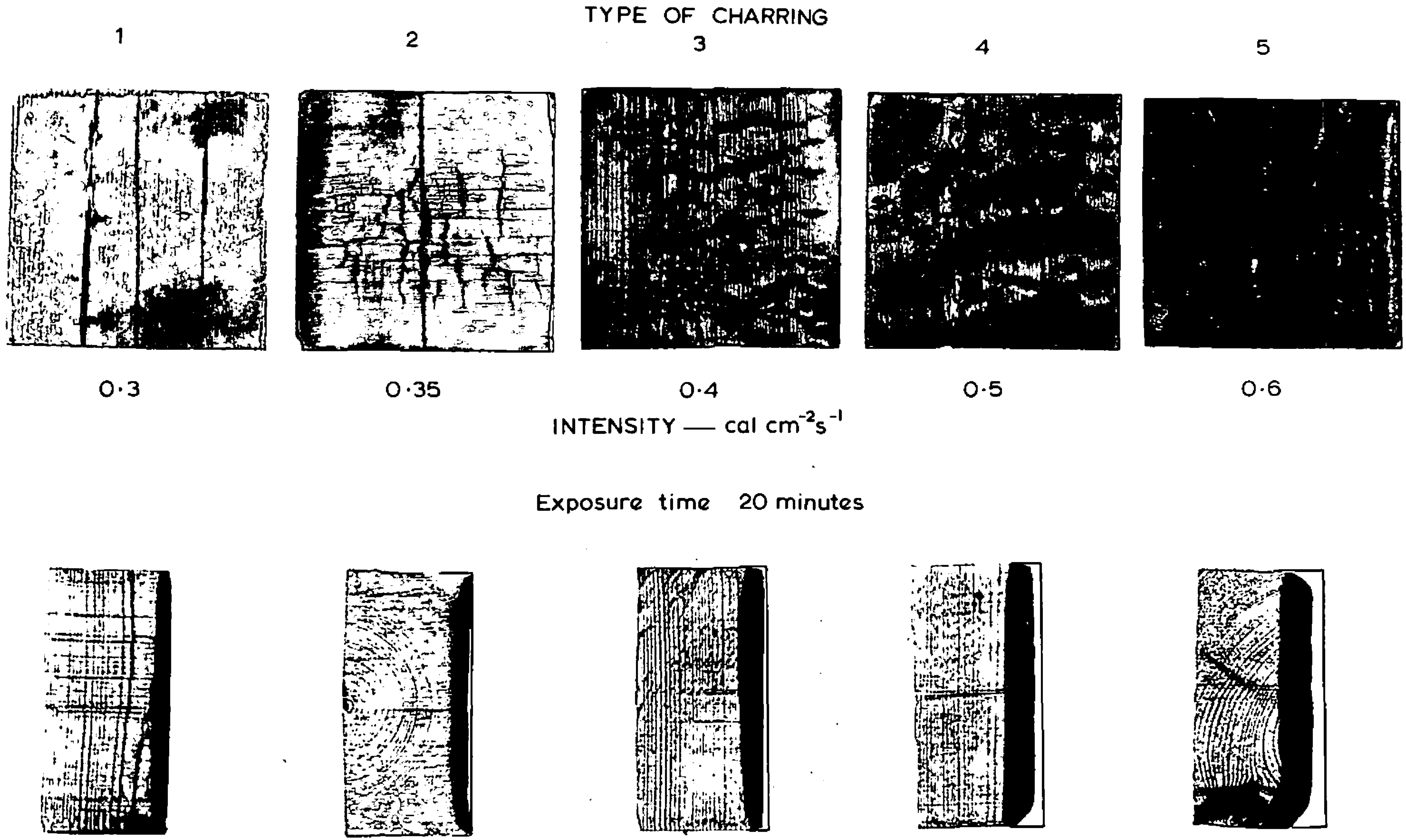



PLATE. 1. CHAR LAYER FORMED BY EXPOSING WOOD BLOCKS TO THERMAL RADIATION

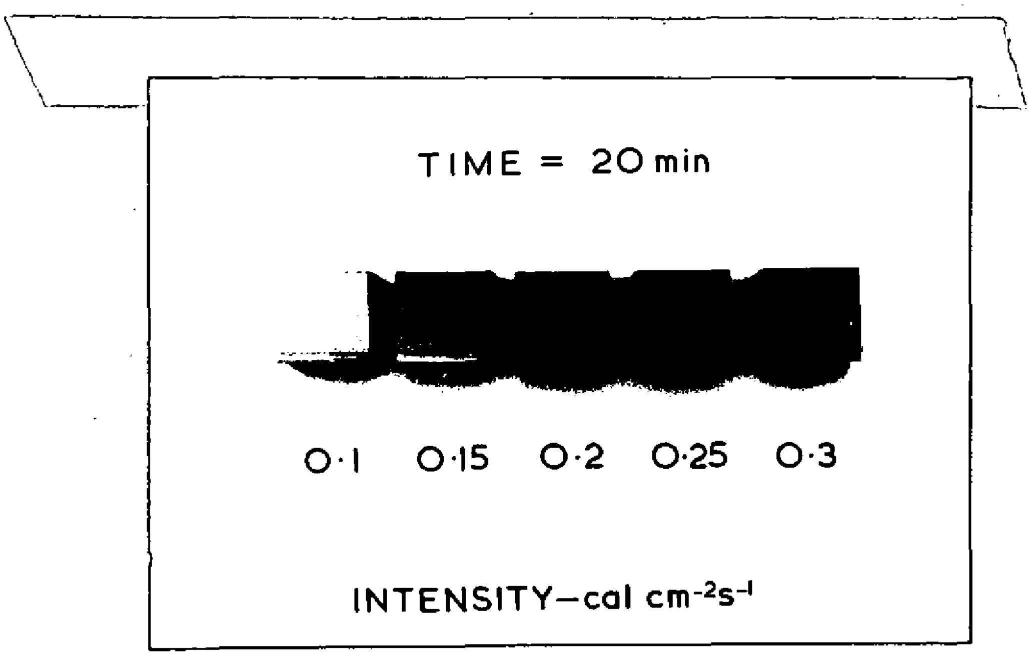



PLATE. 2. DARKENING OF SURFACE OF BLOCKS