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NOTES ON CHARRING RATES IN WOOD

by

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ABSTRACT

Char depths in wood, produced by irradiating the surface of the specimen with intense beams of thermal radiation have been reviewed and the results correlated with data from different laboratories.

Charring rates over a wide range of irradiance levels were found to be directly proportional to the incident flux.

Standard furnace tests for the endurance of timber beams and laminated columns indicates that resulting charring rates were produced by an equivalent square wave heat pulse.

The equivalent heat input into the char layer of irradiated wood required to produce the observed charring rates is approximately 1/3 the heat of combustion of the wood.

KEY WORDS: Combustion, charring, rate, wood.

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INTRODUCTION

Layers of char on a partially burned piece of timber are a permanent and often the only record of the intensity and duration of a fire. Char layers attract attention because of their distinct patterns of waves both parallel and at right angles to the grain of the wood. With good lighting these little squares often resemble black mosaics.

On close examination, there is a sharp boundary between the fragile, low density char and the unburned wood underneath. This fiducial line provides a useful and unambiguous reference for the measurement of depth of char. Furthermore, field data can be made on the spot with simple tools.

In air burst nuclear situations, depths of char as a function of distance and orientation are one of the most prominent effects of thermal radiation emitted by the fire ball. Strength of timbers under fire conditions is related to depths of char as dimensions change during the fire exposure. In a much more practical sense, the use of char depths as evidence of time since ignition is often employed by investigators interested in evidence for suspected arson.

The rate of burning of wood as a function of type of wood, its structural and thermal properties, fuel sizes, geometrical array, ambient conditions and other variables is fundamental to the whole problem of fire spread. Some of these factors can be interpreted in terms of charring rate, ie, how fast wood burns.

Depth of char in a piece of wood recovered after a fire is not easy to interpret unless the original thickness or the location of the unburned surface can be independently determined. Thus, large cat faces in coniferous trees which have survived a severe basal injury during the passage of a forest fire, are covered with char layers of varying thicknesses[1]. However, the distance from the original surface of the tree to the bottom of the char layer may be a metre or more. The thickness of the remaining char layer has little if any relationship to the intensity and duration of the fire, ie, whether the trunk burned out by itself, or whether fire in the surrounding brush provided the necessary heat to keep it burning.

For the same reason, the actual thickness of char layers is not considered in this paper; only the distance from the original surface to the plane of the unburned wood. Layers do not build up indefinitely in free burning fires, as contrasted with charcoal formed with burning under restricted ventilation.

WOOD BLOCK RADIOMETERS AND THEIR CALIBRATION

If the difference in thickness of a wood block before and after a fire exposure is measured, some parameters during exposure can be determined. The simplicity of blocks placed in strategic locations in and around fuel arrays in an experimental fire has led to their use in large scale field tests, such as project Flambeau[2]. When fire effects are to be measured in isolated areas char depths in wood blocks are often the only practical method of instrumentation.

Since the amount of wood heated to the charring temperature is a function of both the total flux and of the irradiance, wood blocks respond both as radiometers and as calorimeters. Separating the effects of the total flux from the irradiance requires detailed calibrations.

A radiation source is required with sufficient intensity to bracket the upper and lower limits of the irradiance to be expected. Appropriate timing and shuttering devices must be provided so that the energy falling on the surface is in the form of a square or rectangular pulse. Ideally, a source should have the same spectral characteristics, or nearly the same temperature as the unknown source, so that no corrections are required for the absorptivity of the wood as a function of wave length. The area of exposure, or the area of uniform irradiance should be large enough to cover the entire specimen.

While the focal plane of an image furnace can be directed at any angle, it is most conveniently operated in a horizontal position, with the specimen held vertically. Gas fired furnace panels are used in the same manner. These gas furnaces with large burners, if directed upwards would heat the specimen by convective as well as by radiative heat.

In the vertical position, hot gases generated in the wood rise from the irradiated surface, while cool air flows upward from the bottom. This position is not comparable to a horizontal one where the specimen would be heated from below.

COMPARISONS OF LABORATORY CALIBRATIONS

Calibrations of wood blocks to be used as radiometers have been conducted at two laboratories, the Fire Research Station in Boreham Wood and the Naval Radiological Defense Laboratory in San Francisco. Each laboratory obtained data relating the irradiance H, the exposure time t, and the depth of char d. At FRS, Griffiths and Heselden[3] and Heselden and Griffiths[4], long pulses of low irradiances, (0.5 to 6.0 W cm^{-2}) were used. At NRDL, Butler and Martin[5], short pulses of high irradiances (30 to 330 W cm^{-2}) were used. Square or rectangular pulses were employed at both laboratories which are described by a constant irradiance falling on the surface of a specimen for a given interval of time. Shutter opening and closing times are always very short in comparison to exposure times.

The source of thermal radiation at FRS was a gas fired furnace operated at a temperature of 870°C which has a maximum spectral emission at 2.5 microns. At NRDL, the source was the plasma of a carbon arc whose maximum spectral emittance at 0.5 microns corresponds to a radiating temperature of approximately 5000°K.

The area of uniform irradiance determined by spot distribution measurements at FRS accommodates a specimen 10 cm square. At NRDL, the area was limited by the optics of the furnace to a circle 0.95 cm in diameter.

Baltic redwood conditioned at 10% moisture content was used at FRS; at NRDL, Guatemala cedar was selected with a moisture content of 8½%. In both laboratories, the grain of the wood was positioned normal to the incident rays.

Depth of char at FRS was measured by slicing the specimen in the middle and laying a straight edge along the dark line of demarcation between the char and the unburned light coloured wood. This line is not always straight because of slight inhomogeneities in the wood, but the method gave consistent results.

At NRDL, the thickness of the wood block was measured before and after exposure with a machinist's micrometer. The char layer was removed after exposure by brushing vigorously with a soft wire brush. The same pressure on the micrometer plunger was applied by the click spring setting. The brushing method often revealed little ridges at the base of the char; hence the micrometer measured the average thickness of the highest ridges. This may bias the results giving a char depth too small.

The results of these two sets of experiments at two laboratories are shown in Figure 1, those at FRS denoted with the symbol (O) those at NRDL (X).

The straight line portion of this graph represents the data from an irradiance (H) of 2 $W cm^{-2}$ to 330 $W cm^{-2}$. Over this range, the charring rate R in $cm\ s^{-1}$ is

$$R = 3.67 \times 10^{-4} H \qquad (1)$$

CHAR DEPTHS BY WEIGHT CHANGES IN CONTROLLED ATMOSPHERES

A series of tests reported by Thomas, Heselden and Law[6] at FRS were conducted to evaluate the effects of different atmospheres on weight loss in wood exposed to intense thermal radiation. Wood specimens were exposed behind a mica window in nitrogen, forced air convection and in free air. The results clearly showed that there is little change in the rate of weight loss under these three conditions. Since no marked difference could be seen between nitrogen and air, we conclude that the charring process is independent of the oxygen supply from the surrounding atmosphere. The heat required for the pyrolysis of the wood forming the char layer depends only on the composition of the wood and the small volumes of air in the pores.

If the density of the char is neglected, and that of the wood is assumed to be 0.5 $g\ cm^{-3}$, the results of this work can be expressed in terms of the charring rate.

At an irradiance level of 1.68 $W cm^{-2}$, the charring rate in these experiments was 6.2×10^{-4} $cm\ s^{-1}$. This point is plotted in Figure 1 with the symbol (⊡).

Calculating the depth of char from rates of weight loss has many advantages since the data is continuous. The effects of the changes in the thickness of the char can be measured over the entire exposure period.

CHAR DEPTHS BY WEIGHT LOSS IN AMBIENT ATMOSPHERE

An extensive study was conducted by Thomas, Simms, and Law[7] to evaluate the effect of density and permeability of several types of wood on the burning rate as measured by weight changes during exposure. Irradiances were varied by changing the distance of the specimen from the face of a gas fired furnace.

This work showed that the rate of weight loss, or the charring rate increases with the density, the permeability of the wood and the irradiance. The rate also varies with time depending on the thickness of the char layer.

During the period of steady state weight loss, ie, from 10% to 30%, charring rates were measured for each of 8 different species of wood, whose densities ranged from 0.34 $g\ cm^{-3}$ to 0.65 $g\ cm^{-3}$ and whose permeabilities varied from 10^{-3} $cm^3/s\ cm^2\ atm/cm$ to 2×10^2 $cm^3/s\ cm^2\ atm/cm$. The resulting charring rates are shown by a vertical bar in Figure 1. The central symbol (◇) on each of these bars is the value for Douglas fir.

SAUR CORRELATION SCHEME

Saur[8] showed that the depth of char in wood exposed to thermal radiation may be correlated over wide ranges by plotting the product of the irradiance and the square root of the exposure time against the product of the irradiance and the depth of char. The abbreviated form used here is derived from a Fourier correlation analysis which includes the thermal properties of the wood, as well as its temperature.

This method has been employed to compare the results of the work reviewed above as shown in Figure 2. It is immediately apparent that the data from the two laboratories, FRS and NRDL do indeed correlate.

It will also be seen that char depths calculated from weight loss measurements fall on the same line. The three points indicated by the symbol ◇ are for Douglas fir in ambient atmosphere. The three points indicated by the symbol ⊡ are data for exposures in a controlled atmosphere.

A straight line drawn through the data points in Figure 2, may be approximated by the expression

$$H \times t = 53 \times Hd \qquad \text{............ (2)}$$

or

$$\frac{H \times t}{d} = 2.8 \times 10^3$$

Since H x t, the total amount of thermal energy deposited during exposure is often called the "dose", we can write:

$$\frac{\text{Dose}}{\text{Depth of Char}} = \text{Constant}$$

ENERGY CONSIDERATIONS

If a char layer is formed on one side of a piece of wood by radiation, the temperature of this layer very quickly rises to some value above the ignition point and the wood burns. As the wood combusts, it supplies its own heat of combustion in addition to that already present from the thermal source. Since the gases burn at an indeterminate distance from the actual surface of the char, their contribution to the radiation flux is not known. Hence, the heat of combustion of the wood under these conditions is not necessarily supplied to the surface of the char layer.

In the work reported here, the wood never burns by itself, because the heat fed back into the surface from the flames is never sufficient to sustain the charring rate. If this were not the case, a square wave exposure time would have no meaning. The charring always ceases immediately after the shutter is closed, without the application of water to the hot char layer.

The linear relationship between charring rates and irradiance, implies that the rate of heat supplied by the combustion of the wood is a constant.

The rate of combustion of the wood, $\dot{K}$ cal $g^{-1}s^{-1}$, as the char layer moves into the unburned wood, can be expressed in W cm^{-2} by making certain assumptions about the wood and the char. The density of the char is assumed to be negligible.

The rate of combustion as described above is

$$\dot{K} = 4.18 \; K \rho R \qquad \ldots\ldots\ldots\ldots (3)$$

where $K = 4500$ cal g^{-1}

$\rho = 0.5$ g cm^{-3} for the unburned wood.

Substituting the values above, together with the charring rate from (1), we have

$$\dot{K} = 3.45 \; H \qquad \ldots\ldots\ldots\ldots (4)$$

Three points are shown on both Figure 1 and Figure 2, which do not lie on the straight line. These are values measured at irradiances below 2 W cm^{-2}, where convective losses are sufficient to significantly alter the charring rate.

The value of the constant shown in Equation 4 suggests that less than a third of the total heat required to sustain the observed charring rates is supplied by the source of thermal radiation.

CHAR DEPTHS IN WOOD TESTED IN STANDARD FURNACES

Tests conducted by Lawson, Webster and Ashton[9] to measure the time to collapse of timber beams and floors were designed to evaluate the fire endurance of wood structural members in real fires. The beams were cut from Douglas fir in three sizes, nominally 22.9 cm by 5.1 cm; 17.8 cm by 3.8 cm and 15.1 by 5.1 cm. All beams were cut to the same length, 4.75 m., and were fastened with nails to short pieces of 1.9 cm tongue and groove flooring, thus forming a floor section. Each section was supported in a floor testing furnace, whose temperature was programmed to follow the B.S.476 time-temperature curve.

Following collapse, the wood and char was cooled with water and char depths measured. These varied from 0.63 cm to 1.9 cm, depending on the time of exposure and beam dimensions. The results showed that the charring rate was very nearly linear at 11×10^{-4} cm s^{-1} for exposures ranging from 5 to 30 minutes. Furnace temperatures during this period varied from 630°C to 840°C.

From Figure 1, it can be seen that the rate observed in these standard tests is equivalent to a square wave irradiance pulse of approximately 3 W cm^{-2}. This is barely sufficient to induce ignition, but if continued for long periods of time, ie several minutes, will produce charring.

In another series of tests, charring rates in laminated columns exposed in a column testing furnace were measured by Rogowski[10]. The purpose of these tests was to determine the fire resistance of wood columns as a function of wood species, type of glue, shape of the cross section and magnitude of the load.

Four species of wood; Douglas fir, European redwood, Western hemlock and Western red cedar were cut and glued to form four column cross sections, measuring 150 mm, 230 mm, 300 mm and 380 mm on each side. All columns were the same length, 3.1 m. Four glues were used, phenolic, resorcinol, casein and urea. During the tests, three design loads were employed; 100%, 50% and 25%.

At failure, the furnace was opened, the column cooled with water, and the depth of char measured in a mid section piece by drawing an outline of the char line and comparing this to the equivalent uncharred cross section. Two charring rates were calculated, one parallel and the other perpendicular to the plane of lamination.

Mean rates of charring parallel to the direction of lamination were 10.8×10^{-4} cm s^{-1}. The perpendicular rate was 12.8×10^{-4} cm s^{-1}.

Referring to Figure 1, these two rates correspond to an equivalent square wave pulse of 2.9 W cm^{-2} and 3.4 W cm^{-1} respectively. It will be noted that these values bracket charring rates found in similar tests on timber beams and floors.

DISCUSSION

Char depths in wood irradiated by intense beams of thermal radiation can be correlated over a wide range of experimental conditions. This suggests that the technique may have other applications, such as in monitoring the total heat flux in standard testing furnaces.

Considerable efforts were made to eliminate variations normally anticipated in a biological material like wood, but the results indicate that many of these precautions were unnecessary. Intensity and hence the temperature of the source does not appear to be critical. Very large differences in the irradiance do not influence the rate constant. The method of measuring the depth of char likewise does not appear to be critical, since the boundary line between char and unburned wood is so clearly marked both by colour and apparent hardness differences.

The essential requirement seems to be that the surface of the wood shall be irradiated with a square wave pulse of thermal energy, uniform over the exposure period. Thus, the rate at which energy is deposited into the surface of the wood must be a constant, regardless of the amount and form of the residual char adhering to the wood. It appears that the first thin layer of wood soon chars, becomes black and porous and depending on the irradiance, flakes, burns and spalls away leaving an indeterminate amount of char clinging to the wood.

At high irradiances, gas pressures within the first few layers of wood cells blow off the char continuously, thus exposing a new surface which is probably black, but very thin.

Transient flaming above an irradiance of about 30 W cm^{-2} is almost always observed, while below 6 W cm^{-2} flames are rarely observed unless sufficient time has elapsed to heat the wood to ignition temperatures. The work reported here does not include cases where flaming was observed at the low irradiances. Since both high and low irradiances can be correlated, there does not appear to be any significance to the existence or absence of flame.

The "rule of thumb" rate of charring, usually spoken of as 1/40 inch per minute (11×10^{-4} cm s^{-1}) as observed in timber beams and laminated columns in standard furnace testing has been explained qualitatively (7). As the char builds up, the rate of heat flow from the furnace to the base of the char layer decreases. This decrease however, is compensated for by the heat of combustion of the wood, so that the actual rate of charring remains constant throughout the test, even though the "temperature" of the furnace continues to rise.

Assuming that the rates of charring produced by thermal radiation are applicable under furnace testing conditions, the total heat flux from the gas flames and the walls of the furnace can be estimated from measured charring rates. Since the furnace tests actually produce a constant charring rate, we conclude that the B.S. 476 time-temperature curve is equivalent to a square wave pulse of thermal energy of about 3 W. cm^{-2}.

The temperature of the furnace describes the actual temperature of one or more thermocouples located three inches from the test specimen. During the initial warm-up period, the thermocouple is measuring the temperature of the gas flames only, but at some later time, flames from the wood itself also contribute to the thermocouple temperature. When this occurs, the amount of gas is reduced, so that the temperature will remain on the standard curve. It is reasonable to suppose that under such conditions, part of the standard time-temperature curve is reproduced without the addition of any gas through the burners.

Since the charring rate at high and at low irradiances can be correlated, the effect of the actual char thickness appears to be of secondary importance. Thus, the surface of the wood may be thought of as a liquid surface irradiated by an appropriate thermal source. As the liquid evaporates, there is no change in the optical properties of the actual surface, so that the absorbed flux is a constant. We further postulate that the volatiles emitted from the wood through the char layer may be compared to the vapours rising above the surface of the liquid. The thin gaseous layer immediately above the liquid surface may be likened to the char layer, it does not appreciably absorb nor reflect the incident flux, and neither does it impede the evaporation rate.

On the basis of this argument, the wood behaves in a manner analagous to a liquid, with a total heat required for "evaporation" of

$$\frac{4500}{3.45} \approx 1300 \text{ cal g}^{-1}$$

Some of this heat is required to raise the temperature of the unburned wood to the ignition point, some to make good the convective and reradiative losses from the front surface of the char layer.

CONCLUSIONS

1. Depth of char produced in wood by intense beams of thermal radiation have shown that the rate of charring is a linear function of the irradiance, with little dependence on species of wood, type of thermal source, or method of measuring char depths.

2. For square wave pulses of irradiance from about 2 W cm^{-1} to 330 W cm^{-1}, the rate of charring in cm s^{-1} is equal to 3.67×10^{-4} times the irradiance in W cm^{-2}.

3. Constant charring rattes measured in furnace testing of the fire endurance of beams and laminated columns suggests that the B.S. 476 standard curve produces an equivalent square wave pulse at the surface of the test piece of 3 W cm^{-2}.

4. The equivalent heat input to sustain the charring rates reported here is approximately 1300 cal g^{-1} of wood.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the invitation of the Director of the Fire Research Station to join the staff and to use their facilities for a few months. While most of the reports listed in the bibliography are readily available, it is not always possible to interpret a report without conversations with the author, especially in those areas where problems still exist. These brief notes could not have been put together without frequent discussions with other members of the Station.

REFERENCES

1. DAVIS, KENNETH P. Forest fire control and use. McGraw-Hill, New York, 1959.

2. COUNTRYMAN, CLIVE. Project Flambeau, Final report, OCD-PS-65-62. Pacific Southwest Forest and Range Experimental Station, Riverside, California, 1969.

3. GRIFFITHS, LYNDA G. and HESELDEN, A. J. M. Fire Research Note No. 648. Fire Research Station, Boreham Wood, Herts, 1967.

4. HESELDEN, A. J. M. and GRIFFITHS, LYNDA G. Fire Research Note No. 747. Fire Research Station, Boreham Wood, Herts, 1969.

5. BUTLER, C. P. and MARTIN, S. B. Char Depth Measurements at Operation Teapot USNRDL-TR-144. U.S. Naval Radiological Defense Laboratory, San Francisco, California, 1956.

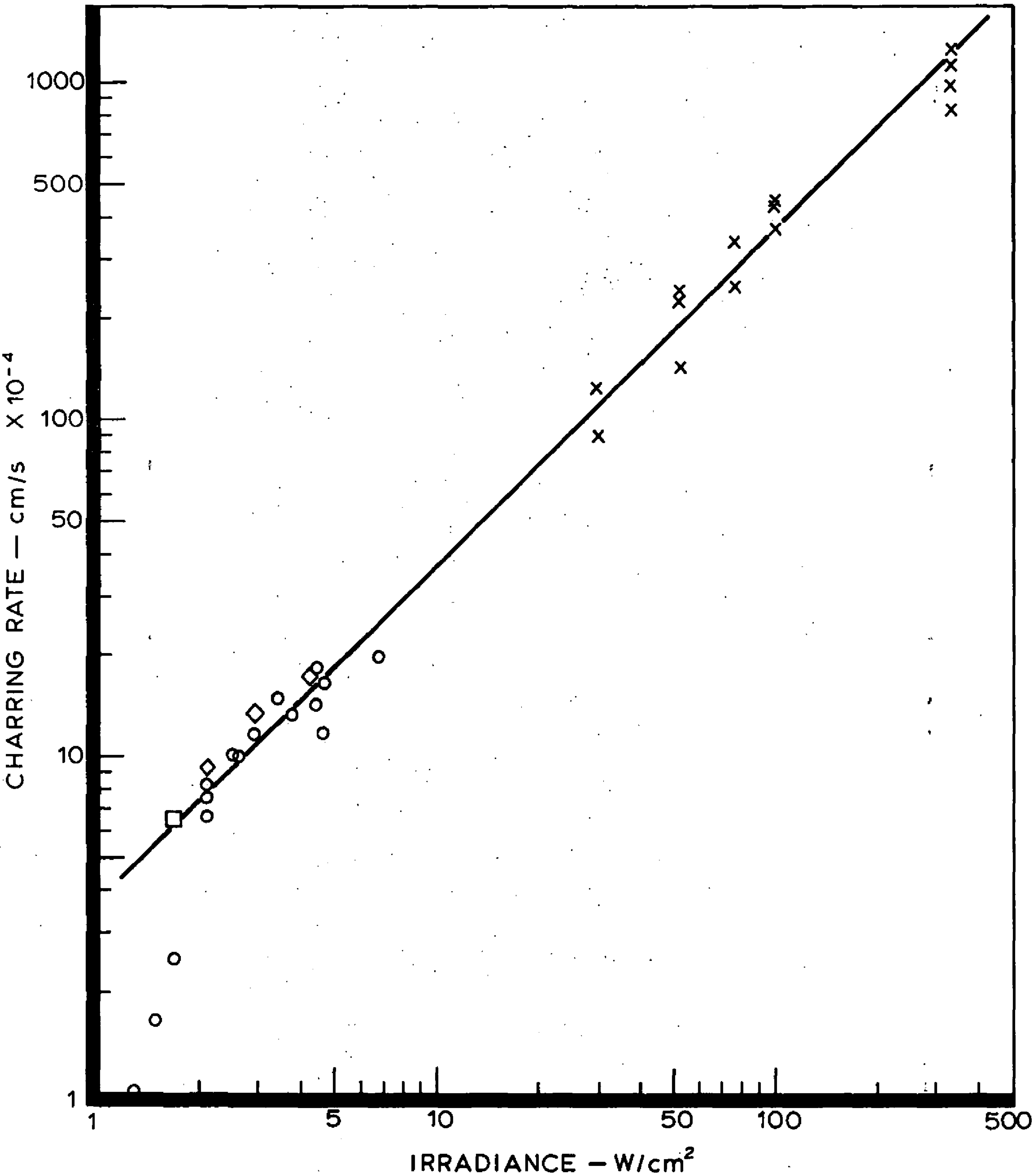
6. THOMAS, P. H., HESELDEN, A. J. M. and LAW, MARGARET. Fully developed compartment fires - two kinds of behaviour. Fire Research Technical Paper No. 18. Ministry of Technology and Fire Offices Committee Joint Fire Research Organization, HMS Office, 1967.

7. THOMAS, P. H., SIMMS, D. L. and LAW, MARGARET. The rate of burning of wood. Fire Research Note No. 657. Fire Research Station, Boreham Wood, Herts, 1967.

8. SAUR, F. M. The charring of wood during exposure to thermal radiation. California Forest and Range Experiment Station, Berkeley, California, 1956.

9. LAWSON, D. I., WEBSTER, C. T. and ASHTON, L. A. Fire endurance of timber beams and floors. National Building Studies Bulletin No. 13. Department of Scientific and Industrial Research and Fire Offices' Committee, Fire Research Station, Boreham Wood, Herts, 1951.

10. ROGOWSKI, BARBARA F. W. Charring of timber in fire tests. Fire and structural use of timber in buildings. Symposium No. 3. Proceedings of the Symposium held at the Fire Research Station, Boreham Wood, Herts, October 25th, 1967.



○ Reference 3 and 4 □ Reference 6

× Reference 5 ◇ Reference 7

FIG. 1. VARIATION OF CHARRING RATE WITH IRRADIANCE

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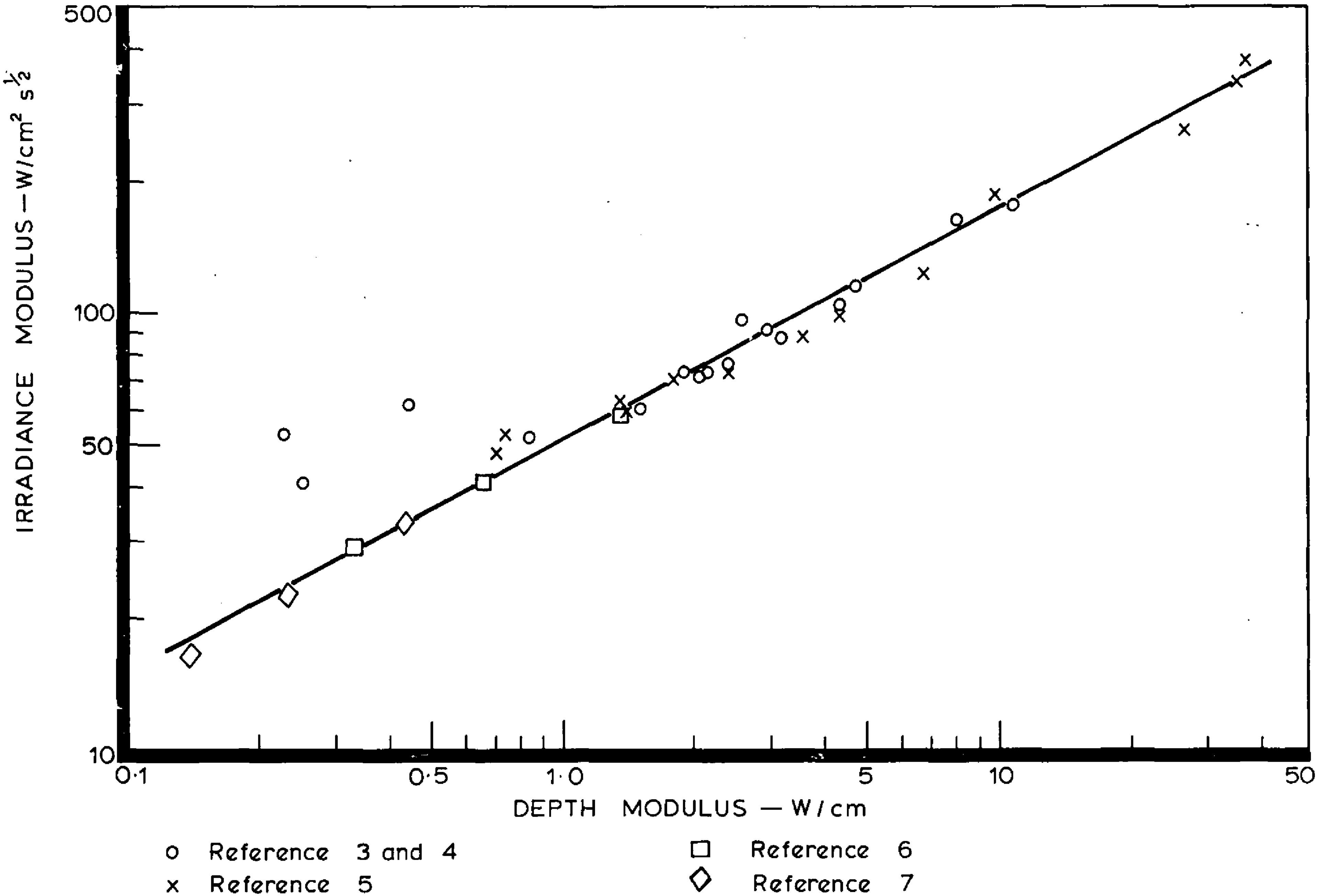

FIG. 2. CHAR DEPTH AND IRRADIANCE MODULI