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DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH AND FIRE OFFICES' COMMITTEE
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THE FIRE ENDURANCE OF LOADED TIMBER BEAMS

by

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SUMMARY

Previous work on the fire endurance of timber beams [1] led to an equation giving the most probable fire endurance in terms of the dimensions and loading conditions. A further analysis of the results is described in this paper, and a simpler equation - a formula - is derived for the most probable fire endurance. A formula for the minimum likely fire endurance is also deduced.

I Introduction

The fire endurance tests which are analysed in this paper were carried out on beams of douglas fir. The beams were of five nominal cross-sections, varying in breadth between $1\frac{1}{2}$ in. and 2 in., and in depth between 4 in. and 9 in. They were subjected to various loads.

II The probable fire endurance

In the original paper [1], the equation connecting the fire endurance with the dimensions and loading conditions was

$$\sqrt{r} = \frac{1}{2} \left(1 - \frac{t}{20b}\right) \left(1 - \frac{t}{40d}\right)^2 \qquad (1)$$

where r is the ratio $\dfrac{\text{applied load}}{\text{breaking load}}$,

b is the initial breadth of the beam (in.),

d the initial depth of the beam (in.),

and   t the fire endurance (minutes).

From the test results of the previous work, and using the same notation, values of (t/b) are plotted against a function of r in Fig. 1. As can be seen, the points corresponding to the various tests lie approximately on a straight line ((a) Fig. 1). The equation of this line is found to be empirically.

$$t = b\left[23.8 - 52.8 \left(\frac{r}{d}\right)^{\frac{1}{3}}\right] \qquad (2)$$

This formula has the advantage over equation (1); that, given r, d and b, it is much simpler to find the fire endurance t.

III Extrapolation for less heavily loaded beams

It will be seen from Fig. 1 that no experimental results were obtained for values of $\left(\frac{r}{\sqrt{d}}\right)^{\frac{1}{3}}$ less than 0.18; this corresponds to maximum fibre stress of 200 lb/sq.in. In extrapolating to predict the performance of beams with lower load, that is with fibre stresses lower than 200 lb/sq.in., account is taken of the fact that an unloaded beam would collapse before being completely charred away, due to the superincumbent load of the charcoal. This inherent stressing may be allowed for in predicting the fire performance of lightly loaded beam sections. This calculation has been made for beams of five different cross-sections, 9 in. x 2in., 7 in. x $1\frac{1}{2}$ in., 6 in. x 2 in., 5 in. x $1\frac{1}{2}$ in., and 4 in. x 2 in., shown respectively in Fig. 1 as the points A, B, C, D and E. The calculation has been made for the value t/b = 20, as the beam would be completely charred away, using a rate of charring 1/40 in./min [1]. It appears therefore that more lightly loaded beams would be represented by points lying above the extrapolated straight line, the precise amount depending on the depth of the beam.

IV The minimum likely fire endurance

As can be seen from Fig. 1, there is some spread about the line corresponding to equation (2). It is often important to know the minimum likely fire endurance of a beam. As in none of the tests plotted in Fig. 1 the fire endurance was less than is represented by the straight line (b) in that figure, this straight line can probably be taken to represent the minimum likely fire endurance. The formula corresponding to this is

$$t = b \left[23.8 - 62.5 \left(\frac{r}{\sqrt{d}}\right)^{\frac{1}{3}} \right] \tag{3}$$

The validity of this is born out by an examination of the results of further tests [1], which were carried out on eleven beams of douglas fir of the same cross-section and equally loaded. The minimum fire endurance was 12 minutes, and this is to be compared with 11.3 minutes allowed by equation (3).

V Conclusions

From tests done previously, it seems that the probable fire endurance of loaded douglas fir beams is

$$b \left[23.8 - 52.8 \left(r/\sqrt{d}\right)^{\frac{1}{3}} \right], \text{ in minutes.}$$

For beams 9 in. deep less heavily loaded than the tested beams, the fire endurance is probably given by the same expression.

The minimum likely fire endurance is

$$b \left[23.8 - 62.5 \left(r/\sqrt{d}\right)^{\frac{1}{3}} \right], \text{ in minutes.}$$

VI Reference

(1) LAWSON, D. I., WEBSTER, C. T. and ASHTON, L. A. The fire endurance of timber beams and floors. National Building Study No. 13. London, 1951. H. M. Stationery Office.
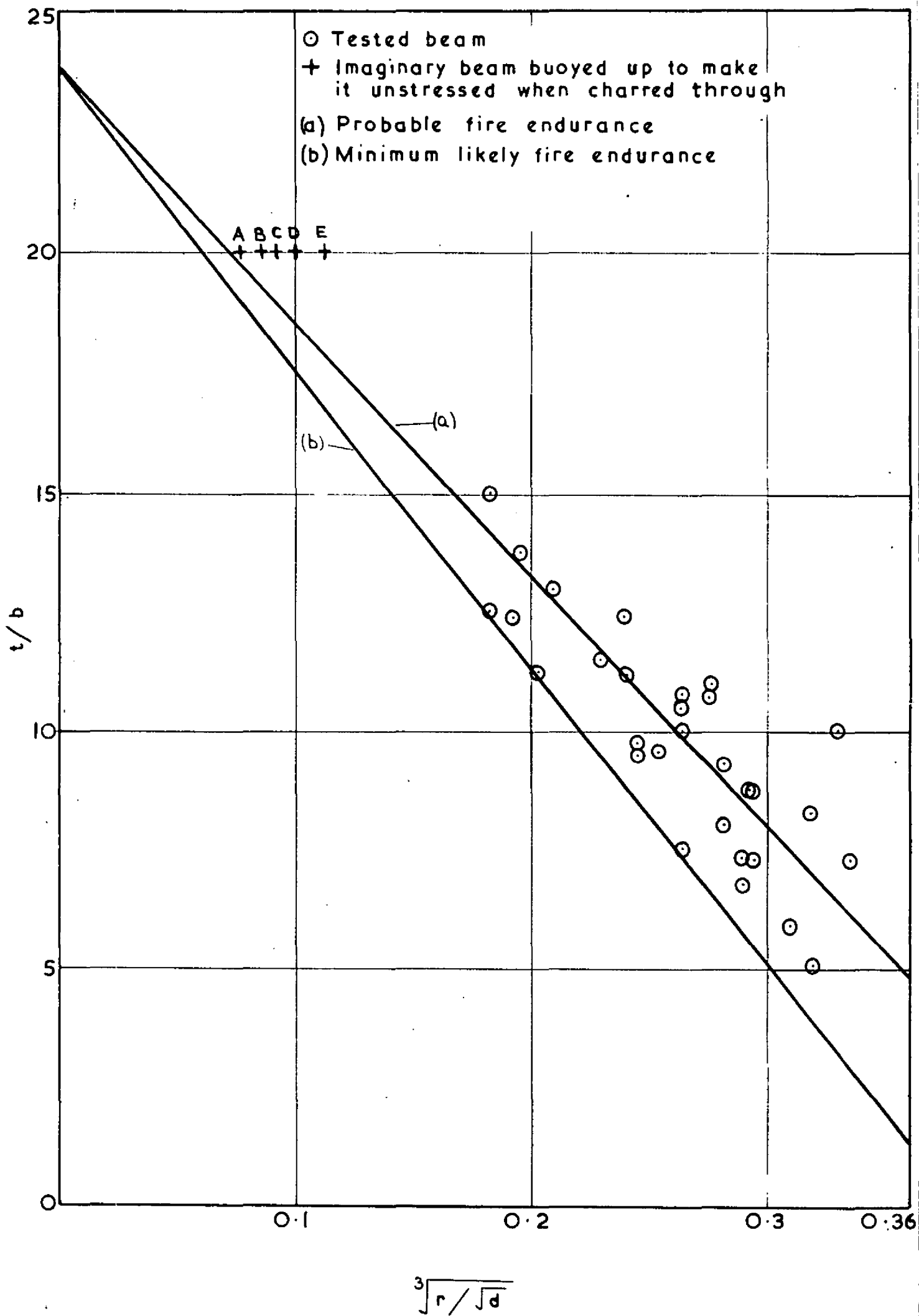
VHM

FIG.I. FIRE ENDURANCE OF LOADED TIMBER BEAMS

Preliminary tests with specimens packed at a mean density of 0·15 g/cm³, and an oil/fibre ratio of 0·5 by weight, indicated that there was an optimum rate of air flow of about 120 cm³/min for self-heating, but the maximum temperature reached was only 114·5°C; no discoloration of the interior of the specimen was observed.

In investigating the reason for the low maximum temperatures obtained in the pyrex tube, tests were carried out in the Mackey tester itself with the specimen of oiled jute contained first in a pyrex tube and then in a paper tube of the same diameter; with arrangements for circulating air at a constant rate through the tube containing the specimen. A maximum temperature of 119°C was observed in the top of the specimen in the paper tube and 107°C in the specimen in the pyrex tube under similar conditions in these tests. This indicated that heat dissipation to the walls of the pyrex tube was responsible for the low temperatures observed. The apparatus was therefore abandoned in favour of the modified form of the Mackey Tester described below.

(c) New apparatus for the study of spontaneous heating

The investigation was continued in the prototype of the apparatus shown in Figs. 1 and 2; Fig. 2 shows the principal dimensions. The prototype was made with "tin" cans and was found sufficiently useful to warrant construction of the permanent form which is described here. From the point of view of the investigation there was no significant difference between the two forms.

The apparatus, which is constructed of sheet brass and copper, consists of a water boiler fitted with an electric immersion heater and a water-cooled condenser. The specimen chamber is suspended inside, above the water level, by a short neck. The air supply is passed through a preheater, in the steam space, which consists of 16 ft. of 20 S.W.G. copper tubing, ⅜ in. O.D., wound in a spiral of nine turns and which is joined tangentially to the side of the specimen chamber at the bottom.

Paper tubes containing the specimens are fitted to the cork at the end of the short glass tube (about 1 cm diameter) which passes through the rubber bung in the neck of the specimen chamber. Either a thermocouple, as shown, or a long-stem thermometer, may be used to observe the temperature in the specimen. A closed tube is suspended in the steam space to take the reference junction of the thermocouple.

The apparatus can be readily modified, in order that the air supply to the interior of the specimen may depend on natural convection as in the Mackey tester, by using a gauze cylinder to contain the specimen and providing vents in the rubber bung.

The immersion heater is rated at 850 watts but is normally run at about 650 watts, with 3 litres of water in the boiler; if desired, liquids with other boiling points may be used.

(d) Effect of air flow on heating of oiled jute in new apparatus (prototype)

Tests were carried out on two batches of jute fibre cut from the stock, the second batch being cut six months after the first. The moisture content was 9·62 per cent for the first batch, Batch A, but was not determined for the second, Batch B. The linseed oil free from white spirit was used.

The paper cylinders used for containing the oiled fibre were treated with dilute shellac varnish to reduce absorption of oil from the fibre. The cylinders were 3·1 cm diameter and 9 cm long. During the packing of the fibre into a cylinder one end was closed by a cork. After packing, a central hole was made in the specimen with a needle to accommodate the thermocouple. In this series of tests the thermocouple was contained in

a thin pyrex tube of 1-2 mm outside diameter. 2·00 g of oil and 5·00 g of fibre were used and the packing length was 6·5 cm. The packing density was therefore 0·143 g/cm³ (uncorrected for oil loss during mixing). From three to six tests were done at each fixed rate of air flow.

The mean maximum temperature indicated by the thermocouple for the series of tests at each rate of air flow, and the mean time taken to reach the maximum, are given in Table I together with standard deviations. The mean maximum temperature is plotted against air flow in Fig. 3.

TABLE I

Jute batch	Rate of air flow. Q cm³/min	N	Mean maximum temperature. °C	Mean time to maximum. min	Pressure difference ΔP mm water	$\Delta P/Q$ x 10⁴
A	200	6	218 ± 48	91 ± 11	-	-
	300	4	262 ± 18	85 ± 2	-	-
	400	5	186 ± 22	88 ± 9	-	-
	500	3	152 ± 21	83 ± 5	-	-
B	100	3	189 ± 10	84 ± 3	0·19 ± 0·04	19
	250	4	217 ± 16	84 ± 9	0·42 ± 0·03	17
	300	3	217 ± 30	77 ± 5	-	-
	350	4	195 ± 14	80 ± 8	0·65 ± 0·05	19
	400	5	173 ± 21	82 ± 6	0·66 ± 0·09	17

N = number of tests

It will be seen from Fig. 3 that there was an optimum rate of air flow of 250 - 300 cm³/min for the highest temperatures to occur in the oiled jute. Lower maximum temperatures were obtained with jute Batch B, and the maximum tended to occur earlier, than with sample A.

(e) Causes of variation in maximum temperature

It will be seen from the standard deviations given in Table I that there was a large variation in the maximum temperatures obtained at any given rate of air flow. In order to reduce the number of tests required to obtain significant results an attempt was made to discover the reasons for the wide variation. Investigation of the factors under the following headings was carried far enough to reveal gross effects only.

(i) General. Specimens were examined in longitudinal section after each test. When discoloration or charring of the specimen had occurred it appeared, with rare exceptions, to decrease uniformly from the centre to the outside of the specimen. The amount of discoloration for a given rate of air flow was related to the observed maximum temperature. Thus for jute Batch A, with an air flow of 200 cm³/min, the discoloration varied from none in the specimen giving the lowest maximum temperature to dark brown in the specimen giving the highest maximum temperature.

It is concluded that the variation in maximum temperature at a given air flow is not due to variation in the position of the point of maximum heating relative to the position of the thermocouple, and it represents a real difference in the behaviour of the specimen.

(ii) Mixing procedure. The time spent in mixing the oil and fibre was usually about five minutes. Variations in the behaviour of the specimen might arise from variation in the amount of oil lost during the mixing, or from variation in the mixing time in so far as this determined the uniformity of mixing and the amount of oxidation of the dispersed oil at room temperature. Tests were therefore carried out with a fixed time schedule as follows:-

Time taken for mixing = 6 min.
Time taken for packing = 1 min.
Specimen inserted in tester 12 min after start of mixing.

A washed sample of jute Batch A was used (see (iii) below). As above, 2 g of oil was mixed with 5 g of jute and the packing density was $0 \cdot 143$ g/cm^3. The rate of air flow was 300 cm^3/min.

The mean maximum temperature and the mean time taken to reach the maximum are given in Table II with standard deviations. Results are also given for tests with the washed jute in which the procedure was not controlled and which were carried out first. Application of the variance ratio (F) test shows that control of the mixing time produced no significant improvement in the reproducibility of the maximum temperature.

The amount of oil lost during mixing was determined from the change in the total weight of the oil, fibre, and paper tube. The mean loss of oil in four tests was $0 \cdot 20 \pm 0 \cdot 02$ g. Hence the amount of oil on the specimens was actually only $1 \cdot 80$ g and the variation in the amount was about 1 per cent. Further tests are required to show whether this variation in the amount of oil could produce variations in the maximum temperature equal to those observed.

TABLE II

Effect of treatment and nature of fibre

Fibre	Rate of air flow Q cm^3/min	N	Mean maximum temperature. ^{o}C	Mean time to maximum. min	Pressure difference. Δ P mm water	Δ P/Q x 10^4
Washed jute.	300	5	244 ± 38	58 ± 2	$0 \cdot 89 \pm 0 \cdot 01$	30
Same, with controlled preparation.	300	3	248 ± 24	68 ± 1	$0 \cdot 85 \pm 0 \cdot 03$	28
Glass fibre.	300	3	270 ± 16	25 ± 1	-	-

N = number of tests

(iii) The nature of the fibre. Differences in the behaviour of jute samples might arise from one or both of variation in physical factors, such as specific surface, and variation in chemical factors affecting the reaction. An example of the latter is the proportion of hemicelluloses which, as Saha [3] has shown, can act as antioxidants.

The effect of mild treatment of the jute was determined for a sample of Batch A which was washed with boiling distilled water and soap, rinsed in four changes of water, and dried at 105°C. After drying it was exposed to the atmosphere for a few days, mixed, and stored in a tin. The final moisture content was $3 \cdot 4$ per cent.

The results of self-heating tests carried out with the washed jute are given in Table II. The mean maximum temperature does not differ significantly from that obtained with the unwashed jute at an air flow of 300 cm³/min (Table I, Batch A). The time taken to reach the maximum temperature is less with the washed jute; this is probably due to the reduced moisture content. The reason for the difference in these times for the two series of tests on the washed jute (Table II) is not known. The difference between the standard deviations for the maximum temperatures for the washed and unwashed jute is not significant.

Tests were carried out with 2·0 g of oil mixed with 5·0 g of glass fibre. The results (Table II) show that the mean time taken to reach the maximum temperature was much less than with jute as oil carrier, but the mean maximum temperature and the standard deviation were similar to those obtained with Batch A of the jute.

(iv) Specific surface and porosity of the specimen. The Kozeny equation for the flow of fluids through granular beds has been applied to the flow of air through packings of jute with parallel fibres by Roy, Mukherjee, and Sen [4]. This equation may be written as follows:

$$\frac{\triangle P}{Q} = \gamma \frac{\eta L}{A} \cdot S^2 \cdot \frac{(1 - \epsilon)^2}{\epsilon^3} \qquad \dots (1)$$

Where Q is the volume rate of flow with a pressure difference of $\triangle P$ across a packing of length L and cross-sectional area A. S is the particle surface area per unit volume of the packing, and ϵ is the porosity of the packing (i.e. fraction of voids). η is the viscosity of the air. K is a constant, at least at porosities below 0·7, which depends on the geometry of the voids; at higher porosities K varies with porosity. The equation may be expected to apply to a random packing of fibres but with a different value for K. In determinations of the fibre diameter of wool, Anderson and Warburton [5] found that K had a higher value for plugs of random fibres than for parallel fibres and, also, the coefficient of variation of K was much smaller for the random fibres than for the parallel fibres.

As a first step in determining a correlation between the variation of maximum temperature and the specific surface of the specimen the air pressure difference across the specimen was measured in all the tests on jute Batch B (Table I) and on the washed jute (Table II).

Until the temperature of the specimen exceeded 100°C the pressure difference across the specimen remained almost constant and then began to increase as the self-heating increased.

In Fig. 4 the maximum temperatures obtained in the tests with washed jute are plotted against the mean pressure difference, expressed in mm water gauge, for the first 30 min of test, during which the temperature rose to about 100°C. There appears to be no correlation between the maximum temperature and this pressure difference.

The rate of heating per unit volume of the specimen, and therefore the maximum temperature reached, would be expected to depend on the oiled surface per unit volume exposed to oxidation, i.e. on the specific surface. The absence of a correlation between the maximum temperature and the pressure difference across the specimen therefore leads to the conclusions that the observed variation of pressure difference, at constant air flow, between specimens was due to differences in the porosity rather than the specific surface of the specimens, and that these differences of porosity were not responsible for the variation in maximum temperature. Alternatively, the lack of correlation may have been due to a random variation of the porosity and specific surface together. The variations in porosity could have arisen from variations in mean packing density within the limits of measurement (estimated at about ± 3 per cent) or from local variations in the uniformity of packing. The conclusion that the effect of porosity predominated is supported by the following calculation.

By differentiating equation (1) with respect to S and ϵ the change in pressure difference at constant air flow resulting from simultaneous small changes in specific surface and porosity is found to be

$$\delta\left(\frac{\Delta P}{Q}\right) \approx C\left(2S\frac{(1-\epsilon)^2}{\epsilon^3}\cdot\delta S - S^2\frac{(1-\epsilon)(3-\epsilon)}{\epsilon^4}\cdot\delta\epsilon\right),\ldots (2)$$

where $C = \frac{\eta KL}{A}$ = constant.

Taking the density of jute fibre as $1\cdot48$ g/cm^3 (Roy et al [4]) the porosity of the specimen at a packing density of $0\cdot14$ g/cm^3 is $0\cdot91$. The specific surface of the jute (on a volume basis) may be taken as approximately 1,000 cm^2/cm^3 [4]. Inserting these values in (2) we have

$$\delta\left(\frac{\Delta P}{Q}\right) \approx C\left(2\cdot2\times10\,\delta S - 2\cdot8\times10^4\,\delta\epsilon\right). \quad\ldots (3)$$

For a one per cent increase of the specific surface and porosity ($\delta S = 10$, $\delta\epsilon = 1\times10^{-2}$) we have (preserving the order of terms)

$$\delta\left(\frac{\Delta P}{Q}\right) \approx C\left(2\cdot2\times10^2 - 2\cdot8\times10^3\right)$$

The change in the pressure difference resulting from a one per cent change of porosity is thus about thirteen times the change produced by a one per cent change in the specific surface.

The mean pressure differences during the initial heating to about 100°C are given for each rate of air flow for jute Batch B in Table I and for the washed sample of Batch A in Table II, and the ratio $\Delta P/Q$ is given in the final column. This ratio is nearly constant for each batch of jute but the value for Batch B differs widely from the value for the washed sample. As the nominal packing density and the method of packing was unaltered this difference in the ratio for the washed jute and Batch B may be due to a difference in porosity, arising from a difference in mean fibre density, or to a difference in mean specific surface.

For a packing density of $0\cdot143$ g/cm^3 and a fibre density (ρ) of $1\cdot48$ g/cm^3 it can be shown that

$$\delta\epsilon \approx 0\cdot064\,\delta\rho$$

Inserting this in (3) we have

$$\delta\left(\frac{\Delta P}{Q}\right) \approx C\left(2\cdot2\times10\,\delta S - 1\cdot8\times10^4\,\delta\rho\right)$$

For a one per cent change in specific surface and fibre density ($\delta S = 10$, and $\delta\rho = 1\cdot5\times10^{-2}$) we have

$$\delta\left(\frac{\Delta P}{Q}\right) \approx C\left(2\cdot2\times10^2 - 2\cdot7\times10^2\right)$$

That is, the ratio $\Delta P/Q$ is about equally sensitive to changes of specific surface and of fibre density. Although the difference between the mean maximum temperatures for the washed jute (Batch A) and Batch B, attained with an air flow of 300 cm^3/min (Tables I and II), are not statistically significant they are at least consistent with the washed jute having a higher specific surface than Batch B. The washing treatment probably resulted in a higher degree of separation of the jute fibres and so increased the specific surface. At the same time, however, the increased fibre separation may have resulted in a packing which was different in structure or degree of randomness to that obtained with the unwashed fibre and which, therefore, had a different value for the Kozeny constant K. Hence the reason for the difference in the ratio $\Delta P/Q$ for the washed and unwashed jute cannot be decided without further investigation.

(v) <u>Thermal properties of the specimen.</u> Tests were carried out to
determine whether the rate of the initial heating of the specimen by
the oven, before self-heating began, would reveal any variation in the
thermal properties of the specimens which could account for the
variations of maximum temperature. For this purpose a number of specimens
were tested with nitrogen passing through the apparatus to ensure the
absence of oxidation. When the temperature of the specimen had reached
95°C the nitrogen was replaced by air and self-heating proceeded as
usual. The specimen consisted of 5·0 g of jute which had been dried at
105°C, and 2·0 g of oil. The rates of nitrogen and air flow were 300 cm³/
min.

The temperature in the specimen rose rapidly to 60°C in about 5 min,
and then more slowly to reach 90°C in about 30 min. This behaviour was
probably due to the presence of forced convection through the specimen
and to the fact that the thermocouple indicates mainly the temperature
of the air in the voids. Thus it seems reasonable that the temperature
indicated by the thermocouple should rise rapidly, after insertion of
the specimen in the tester, to some value intermediate between the entry
and exit temperatures of the air passing through the specimen; then the
further rise will depend mainly on the rate at which the temperature of
the specimen increases.

The times taken for the temperature to cover specified intervals are
given in Table III. The results for each test are arranged in order of
increasing temperature maximum reached during the self-heating stage.

<center>TABLE III</center>

<center>Initial heating of oiled jute in nitrogen</center>

Maximum temperature °C	Time to 60°C min	Time to 90°C min	Time 60°C - 90°C. min	Time 95° - max. min
175	5·5	31·5	26	39
183	3·8	26·0	22	33
219	6·5	30·0	23	35
274	4·8	29·0	24	32

There appears to be no correlation between the variation of maximum
temperature and the variation in thermal properties of the specimens as
indicated by the temperature-time data in Table III.

<center>Conclusions</center>

The state of this investigation may be summarized as follows:-

1. A modification of the Mackey Tester has been designed in which
materials may be tested, for their tendency to spontaneous
heating and ignition, with a controlled current of air passing
through the specimen;

2. It has been shown that there is an optimum rate of air flow
for the self-heating of linseed oil on jute at a given packing
density in the new apparatus;

3. As in the Mackey Tester, the maximum temperature reached under
a given set of conditions in the new apparatus is subject to
rather wide variation;

4. An attempt to identify causes for the variation in the maximum
temperature was unsuccessful.

The new apparatus is preferred to the Mackey Tester for the laboratory examination of the spontaneous heating and ignition tendencies of materials in general because it is more versatile; thus, materials may be examined under conditions of natural or forced aeration of the specimen, in atmospheres containing any desired concentration of oxygen, and at a number of different temperatures. Furthermore, the Mackey Tester is associated with a standard test which is used for assessing the hazard of textile oils, and which employs a criterion found by experience to be satisfactory for this limited purpose. It is desirable that the Mackey Tester should be reserved for this purpose and that no opportunity should be provided for interpreting the result of tests on other materials in terms of the criterion adopted in the standard test for textile oils.

Acknowledgements

Most of the experimental work described in this note was carried out by Miss M. Ward and Mr. G. Skeet.

References

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2. "Prescribed method for testing textile oils for liability to spontaneous heating," Fire Offices' Committee, London, 1938.

3. Saha, A. N., J. Text.Inst., 1951, 42, T 207.

4. Roy, M. M., Mukherjee, R. R., and Sen, M. K., J. Text. Inst., 1950, 41, T 249.

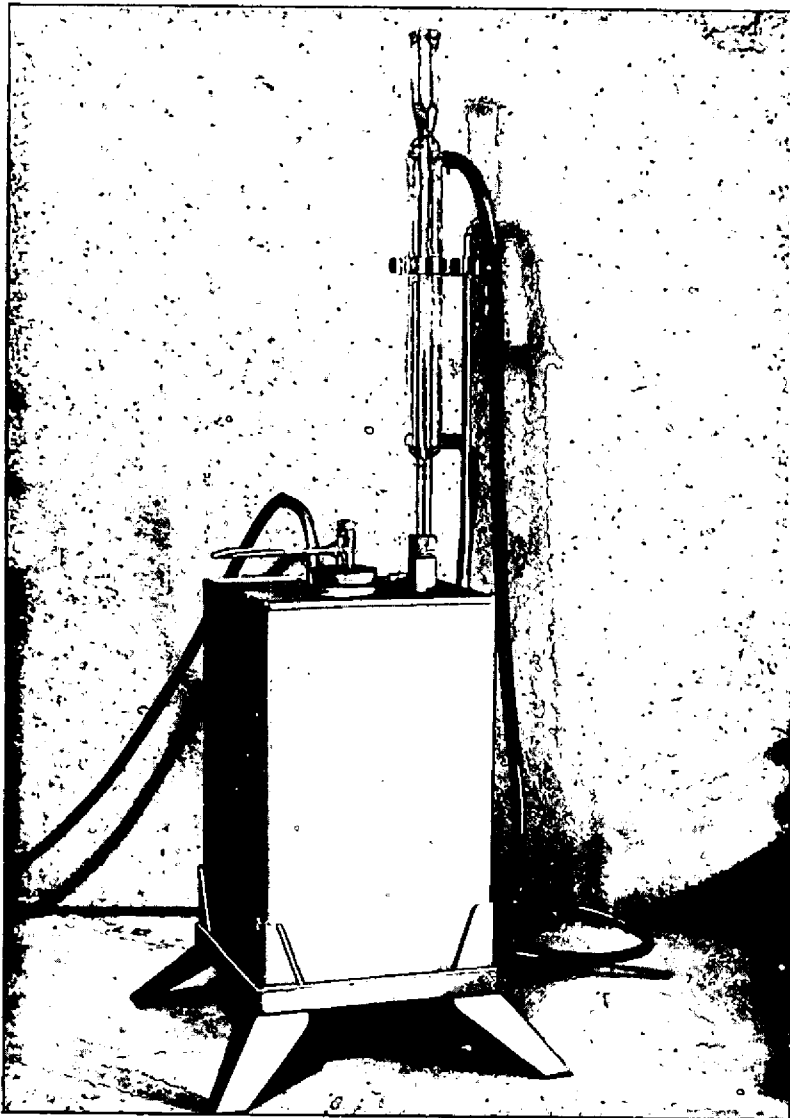5. Anderson, S. L., and Warburton, F. L., J. Text.Inst., 1949, 40, T 749.
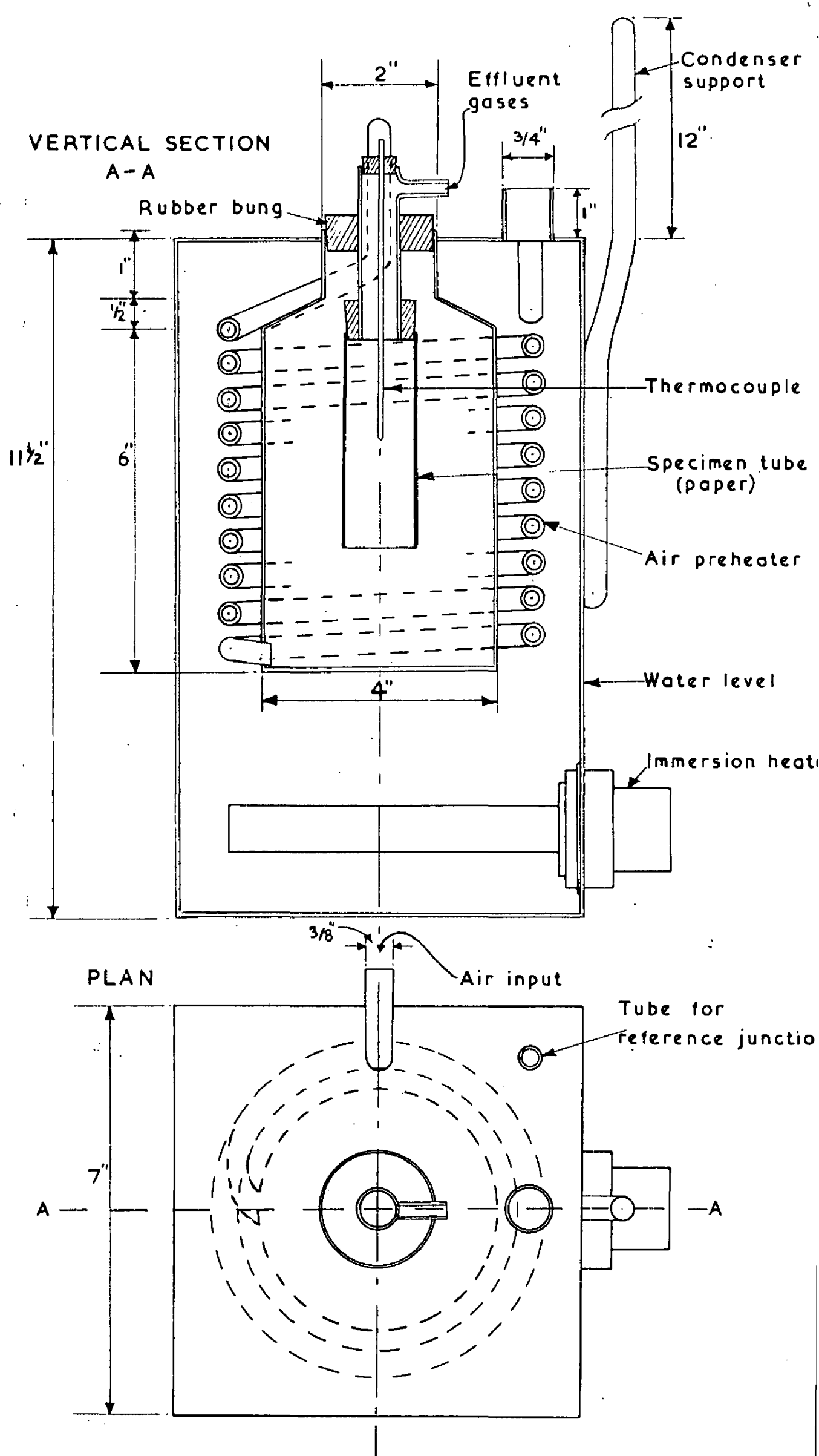
FIG. I. APPARATUS FOR STUDY OF
SPONTANEOUS HEATING

VERTICAL SECTION
A – A

Effluent gases

Condenser support

Rubber bung

2"

3/4"

12"

1"

11½"

1"

½"

6"

4"

Thermocouple

Specimen tube
(paper)

Air preheater

Water level

Immersion heat

3/8"

Air input

PLAN

Tube for
feference junctio

7"

1"

A

A

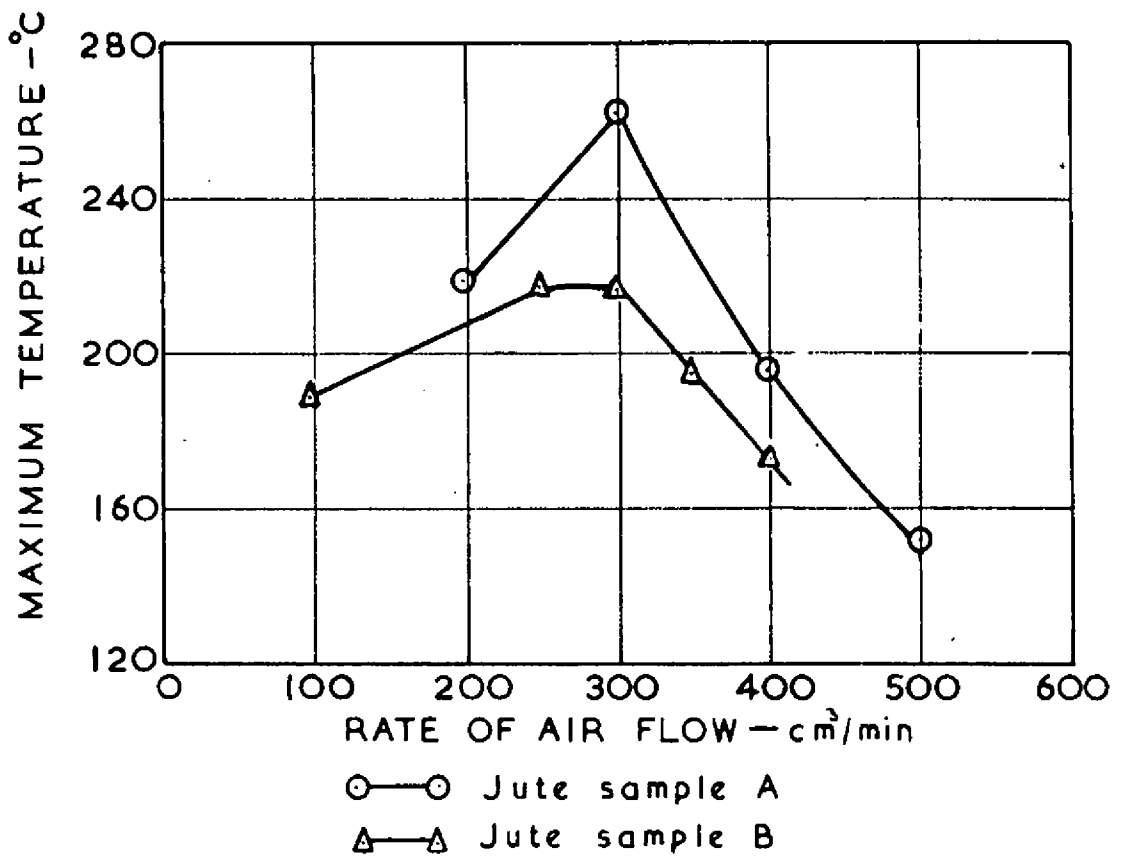FIG.2. APPARATUS FOR STUDY OF SPONTANEOUS

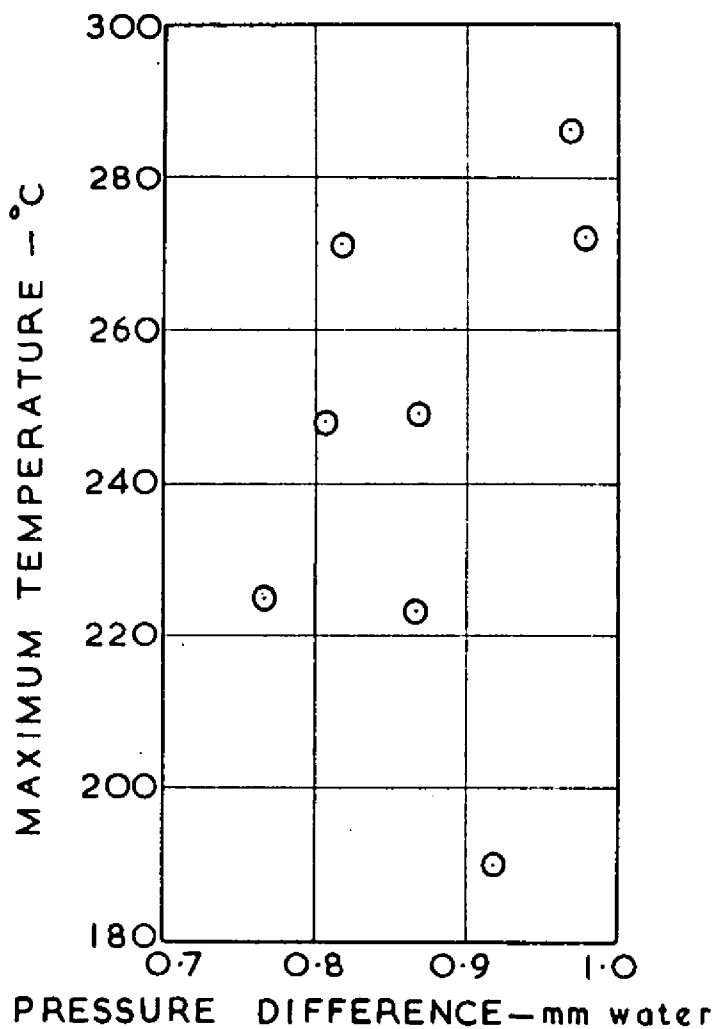FIG. 3. EFFECT OF AIR FLOW ON SELF-HEATING
OF LINSEED OIL ON JUTE

FIG. 4. CORRELATION OF MAXIMUM TEMPERATURE
AND PRESSURE DIFFERENCE