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THE SPONTANEOUS IGNITION OF OIL-SOAKED LAGGING

by

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SUMMARY

Test methods for assessing the hazard of spontaneous ignition in oil-soaked lagging on hot pipes have been investigated. One, based on the determination of the critical temperature for ignition of cube-shaped samples of lagging, is suitable for screening purposes and permits a rough estimate of conditions for ignition on a pipe. The other, based on an electrically heated pipe devised for the purpose, yields more directly applicable results but is less suitable for use when a large number of tests have to be performed.

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## INTRODUCTION

Fires resulting from the spillage or leakage of oils and other organic liquids on to the lagging of hot pipes etc., which is otherwise normally non-combustible, occur widely in chemical and allied industries. It appears that most of these fires are small and easily dealt with by plant operatives on the spot, but large fires leading to heavy loss have occurred and all such fires are potentially dangerous - especially on plant handling highly flammable liquids and gases.

In these fires, ignition is typically spontaneous and plant temperatures at which they have been reported to occur range from 200-300°C for mineral oils, 160-250°C for coal tar distillates and 80-150°C for essential oils. Commonly, the first appearance of fire is smouldering and glowing of the lagging; flame may not appear until the lagging is stripped off.

Some experimental studies of the spontaneous ignition of lagging materials impregnated with different oils have been reported by Petkus<sup>1, 2</sup> and Norton<sup>3</sup>. The former author, particularly, concluded that the type of oil and the physical conditions (e.g. permeability to oil and air, conservation of heat) exerted far more influence on ignition than the kind of insulation saturated. More recently, however, Osola<sup>4</sup> has shown that the nature of the lagging is indeed an important factor and Smirnov<sup>5</sup> has found that the self-heating and ignition of 'paraffin' on slag wool lagging can be inhibited by treating the slag wool with boric acid. Therefore, the choice of lagging can be expected to make a significant contribution to the control of the hazard.

The present paper describes a short investigation aimed at devising a test method which can be used to select the safest lagging material for any given situation. In the simplest case a test consisting of a section of heated pipe, simulating the relevant practical conditions, on which contaminated lagging can be tried will yield a 'yes or no' answer on the possibility of ignition. However, when, for example, lagging is being

selected for a new plant having wide ranges of pipe and vessel diameters, hot surface temperatures and lagging thicknesses, an approach capable of giving more generally applicable results is desirable. For this reason an attempt has been made to determine the extent to which recent developments<sup>6-10</sup> in the theoretical understanding of spontaneous heating and ignition of solids are applicable to the ignition of oil-soaked lagging. It was not, however, possible to pursue this aspect of the investigation to a completely satisfactory conclusion.

## EXPERIMENTAL

### GENERAL

Two experimental methods were used to study the ignition of oil-soaked lagging. One of these was based on a section of electrically heated pipe, as above, which was used to determine the lowest pipe temperature which would lead to ignition of a given oil-soaked lagging.

The other method consisted of determining the critical temperature for the ignition of cubes of oil-soaked lagging suspended in a thermostatically controlled oven. This method is capable of yielding results relatively quickly and economically and merits investigation as an alternative method for use whenever there is a need to test a large number of combinations of oil and lagging, the 'pipe test' then perhaps being used as a final check on the conclusions. The relation between the two kinds of test must be sought in the theoretical model for ignition.

The critical temperature for ignition, i.e. 'ignition temperature', was, in both series of tests, defined as the mean between the lowest temperature (of pipe or oven) at which ignition occurred with a given thickness of lagging or size of cube and the highest temperature below this at which ignition did not occur. The recognition of 'ignition' in these tests, however, was not as straightforward as in previous studies<sup>7,9,12</sup>; the criterion adopted, and the reasons for it, are described in the presentation of the experimental results (below).

To the extent that the self-heating is due to oxidation of the oil dispersed in the lagging, self-heating will be limited both at low concentrations of oil and at concentrations of oil which are high enough seriously to restrict the access of air. Thus there should be an optimum concentration of oil for self-heating to ignition. Ignition tests were

therefore carried out for a number of different concentrations of oil in order to locate this optimum.

In this paper, the experimental equipment and procedure are described in outline only. A more detailed account is given in reference 11.

#### MATERIALS

Two types of commercially available lagging were tested on the heated pipe as preformed sections; one a calcium silicate/asbestos type and the other a resin-bonded mineral wool. Cubes for the oven tests were cut from slab stock of the same materials. In order to avoid possible complication due to a modified surface permeability, and also to ensure complete similarity with the corresponding slab stock, a treated fabric coating normally present on the mineral wool sections was removed before test.

The properties of the two lagging materials are given in Table 1. It is convenient to employ c.g.s. units in this paper; the British equivalents are given where necessary. The particle density, required for estimation of the voids in the lagging, was determined by displacement of benzene in a density bottle. The thermal conductivities given in the Table are based on the manufacturers' specifications.

Table 1  
Properties of lagging materials

Lagging	Bulk density g/cm <sup>3</sup>	Particle density g/cm <sup>3</sup>	Voids %	Thermal conductivity (mean temp = 120°C) cal/cm s degC
Calcium silicate/ asbestos	0.19 (12-14)*	2.93	94	1.31 x 10 <sup>-4</sup> (0.39)**
Resin bonded mineral wool	0.13 (9-10)*	2.58	95	1.27 x 10 <sup>-4</sup> (0.37)**

\*lb/ft<sup>3</sup>

\*\*Btu in/ft<sup>2</sup> h degF.

The oil used was low-viscosity transformer oil complying with B.S.148/59 and did not contain antioxidants. The amount added to the lagging was expressed as a percentage of the available voids in the lagging.

## OVEN TESTS

An electrically heated laboratory oven, provided with internal fan circulation and controllable to  $\pm 1$  or  $2^{\circ}\text{C}$ , was used for these tests.

The oven was fitted with four 30 S.W.G. chromel/alumel thermocouples connected, via heavier gauge compensating leads, to a potentiometric multi-point recorder. This allowed three cubes of given size and different oil content to be tested for ignition at any given oven temperature, one thermocouple being inserted in the centre of each cube to detect self-heating, while the fourth indicated the oven temperature in the neighbourhood of the cubes.

The cubes were treated with the desired quantity of oil from a burette. The oil was run slowly on to each face of a cube in turn, and the treated cube allowed to stand overnight, in an effort to achieve a uniform distribution of the oil. It was, however, evident from visual inspection that the uniformity of the oil distribution was poor in the resin-bonded mineral wool; it appeared to be much better in the calcium silicate/asbestos.

By repeating tests with fresh cubes at different steady oven temperatures, the critical temperature for ignition of each size of cube was located.

## PIPE TESTS

The pipe used was an 84 cm length (2 ft 9 in) of malleable iron water pipe, of nominal diameter 2 in B.S.P. (actual diameter 6.0 cm), capped at one end. The pipe was heated by two modified 1 kw pencil type electric fire heaters in series, supported axially in the pipe on a steel rod with spacing discs of asbestos millboard. An electronic proportional controller, for which the sensing element was a thermocouple peened into the surface of the pipe at the middle, gave control of the pipe temperature to within about  $\pm 1^{\circ}\text{C}$  at the control point.

The general arrangement is shown in Fig.1 and also in Plate 1 (in which half of an ignited lagging test piece is being removed). With the heaters arranged as shown in Fig.1, and with lagging 'guard' pieces at the ends, it was found that the surface temperature of the pipe was uniform to within  $\pm 2.5^{\circ}\text{C}$  over the central 25 cm section. With the pipe in the horizontal position, the temperature was uniform to within  $\pm 1.5^{\circ}\text{C}$  over the central 25 cm section.

An oil leak was simulated by pumping oil at a low, measured, rate between the pipe and the inner face of the lagging test piece. In order that the oil should be preheated to near the pipe temperature, it was passed through a coil of 10 turns of  $\frac{1}{8}$  in diameter copper tubing brazed to the surface of the pipe near the end of the lagging test piece (which was recessed slightly to accommodate the coil). For the vertical pipe, the oil was allowed to leak from a series of small holes round the last turn of the coil; for the pipe used in the horizontal position, the oil was fed from a 'tail' on the coil brazed along the top of the pipe and provided with perforations at intervals.

Five thermocouples connected to a potentiometric recorder were used to monitor the tests: one was attached to the surface of the pipe near to the control couple, three were inserted radially in the mid-plane of the lagging test piece to within a short distance of the pipe surface and the fifth attached to the surface of the lagging.

The lagging test pieces were 60 cm (2 ft) long and were held in position on the pipe with the metal straps supplied by the makers. Two thicknesses were tested, 5.1 cm (2 in) and 2.5 cm (1 in). Where necessary, the joints between the sections and at the abutment to the asbestos wood support plates were caulked with magnesia/asbestos cement.

With a test piece in position and thermocouples fixed, the test procedure consisted of first setting the controller to a desired temperature and allowing the system to reach a steady state. Then the oil flow was started at the appropriate rate. Tests were repeated with fresh lagging and different pipe temperatures until the critical temperature for ignition was located.

An oil flow rate of  $3.5 \text{ cm}^3/\text{min}$  was used in most of the tests and was such that a slow drip eventually appeared at the bottom of the lagging when in the vertical position. It appeared to be adequate for self-heating in the 5.1 cm (2 in) lagging used and did not produce saturation. A rate of  $1-1.5 \text{ cm}^3/\text{min}$  was found more suitable for the 2.5 cm (1 in) lagging, since the higher rate led to rapid saturation of the lagging in the neighbourhood of the oil feed.

In order to permit the oil to flow readily at the interface between the pipe and the lagging, and so assist uniform distribution, it was found desirable to avoid the use of a few sections of lagging which were an especially tight fit on the pipe. This applied especially to the 2.54 cm



thick sections of calcium silicate/asbestos.

## RESULTS

### OVEN TESTS

Typical centre-temperature records for self-heating and ignition in cubes of resin-bonded mineral wool are shown in Fig.2. They were all obtained for 5-cm cubes at an oven temperature of 142°C and with oil contents as indicated in the figure. The earlier stages of the records, which have not been included, all showed the centre temperature increasing up to the oven temperature within a period of about 1½ hours; it then remained stationary at this value until self-heating began after a further 4 hours or so.

In one sample, with an initial oil content of 30 per cent, the temperature rose to a value in excess of 500°C (Fig.2) and, at the end of the test, the oil and the resin bonding were found to have burned away in the interior leaving a white friable residue of mineral wool. The loss in weight during this test was approximately equal to the weight of oil added to the cube. In the other tests the cubes exhibited varying degrees of internal charring and the weight loss amounted to 40-50 per cent of the oil added. Cross sections of cubes in which ignition occurred are shown in Plate 2.

Neither in the tests shown in Fig.2, nor in other tests, was there any obvious systematic relationship between the degree of self-heating and the oil content, although it appeared that the highest temperatures were obtained with oil contents in the range 30-50 per cent of the voids. This was the nearest approach that could be made to the determination of an optimum oil content for self-ignition.

It was apparent, especially from the uneven distribution of charring noted on many occasions, that the highly variable behaviour was due largely to the non-uniform distribution of the oil (see, for example, Plate 2). In these tests also, self-heating had clearly to compete with a considerable loss of oil, although in practice, a hazardous oil concentration will tend to be maintained by a leak. In these circumstances, a temperature rise to a maximum of, say, about 50 degC in a test at a given oven temperature may be accepted as an 'ignition' - implying a finite probability that active combustion can occur at that temperature, given a more favourable combination of factors other than temperature (compare Fig.2). For systems obeying the simple thermal ignition model<sup>6,7</sup> (see discussion) the maximum sub-critical temperature rise

in the absence of reactant limitation, is of the order of 25 degC. The criterion of ignition should be set appreciably higher than this but need be no more closely defined than is indicated above.

On the above basis, the ignition temperature for cubes of a given size, is here defined as the mean of the lowest oven temperature at which the cubes tested showed a temperature rise of about 50 degC (sometimes more) and the highest oven temperature at which no ignition (in this sense) occurred, with initial oil concentrations in the range 20-50 per cent. Table 2 lists the values obtained and includes the corresponding temperature rises indicative of ignition.

Table 2  
Ignition of cubes of oiled lagging

Material	Cube size cm	Ignition temperature °C	Temperature rise degC	Time to ignition hrs
Resin-bonded mineral wool	2.54	166 ± 2*	45	$\frac{3}{4}$
	3.8	146 ± 2	83	3
	5.1	140 ± 2	100+	3-7
	10.2	123 ± 6	150	8-20
Calcium silicate/ asbestos	2.54	173 ± 3	98	1
	3.8	168 ± 0.5	116	1 $\frac{1}{2}$ -10
	5.1	160 ± 2	125	4 $\frac{1}{2}$ -5

\*These limits are half the difference between the temperatures for ignition and no ignition.

The times to ignition, measured from the time of introduction of the cubes into the oven to the time at which the temperature rise due to self-heating became rapid, are also given in Table 2 for all tests in which ignition occurred. During a large proportion of these times, especially for the larger sizes at the lower temperatures, the temperature at the centre of a cube remained equal to the oven temperature and indicated the existence of an induction period in the oxidation of the oil.

In general, for any given size of cube for which the induction period showed appreciable variation, the longer periods were associated with the

lower temperatures in the test range. However, the variation of induction period with temperature was sometimes large and not systematic and suggested the operation of other factors such as varying amounts of substances interfering with the oxidation process - either as accelerators or inhibitors. These effects were most pronounced with the calcium silicate/asbestos.

It was also observed in the ignition tests with the calcium silicate/asbestos that, within the periods for which the tests were carried out, usually 14-18 hours, the temperature rise due to self-heating was either large, i.e. 100 degC or more, or zero. This could imply that the estimates of the ignition temperatures are biased on the high side by the presence of very long induction periods in the tests at lower temperatures.

#### PIPE TESTS

A typical temperature record for the self-heating of lagging on the heated pipe is shown in Fig.3. It was obtained with 5.1 cm (2 in) thick preformed sections of the calcium silicate/asbestos on the vertical pipe at a temperature of 194°C. The time was measured from the moment of starting the oil flow.

One of the three thermocouples in the lagging, 1 cm from the pipe, has indicated two periods of self-heating; one to a maximum of 30 degC at 5½ hours and a second to nearly 300 degC above the steady value at about 9 hours. The test was continued for a further 10 hours but no further self-heating occurred near the thermocouples. However, when the lagging was finally removed, it was found to be glowing in an area at the junction of the two sections.

In this particular example, the recorded self-heating evidently occurred near the control thermocouple and interfered with the control of the pipe temperature. In other examples this did not happen and, in others still, all three of the internal thermocouples sometimes indicated self-heating.

Clearly, the distribution of the self-heating and of the oil, was very irregular. This is to be seen also in Plate 3 which shows sections of each type of lagging in which ignition occurred. The lighter patches in the areas of charring are where the char has burned away to ash; the section of resin-bonded mineral wool has been cut transversely to show the extent of burning in the interior.

The occurrence of the higher temperatures due to self-heating and of the glowing combustion was strongly dependent on the access of air. On many

occasions, lagging which had reached charring temperatures would, when removed from the pipe and allowed to stand vertically with the two halves placed together as on the pipe, continue to self-heat with increasing evolution of smoke and would eventually reach glowing temperatures. This process could be noticeably assisted by placing the lagging in a draught of air. In this connection, it is noteworthy that when the treated fabric coating was left in place on the resin-bonded mineral wool, glowing could not be induced - even with pipe temperatures as high as 300°C (5 cm thickness), and with temperature rises due to self-heating large enough to indicate 'ignition' in the sense described below.

As for the cubes, the ignition criterion could only rarely be associated with a temperature rise up to active combustion at the position of the thermocouples. Based on the order of magnitude of the maximum sub-critical temperature rise expected theoretically<sup>10</sup>, a temperature rise in excess of about 50 degC above the steady value 1 cm from the pipe surface before the oil flow started was taken as indicative of ignition; usually, however, the temperature rise was much higher.

The ignition temperatures obtained, based on the above criterion and defined as previously, are given in Table 3 which also includes the associated temperature rises accepted as indicative of ignition.

Table 3  
Ignition of preformed lagging sections  
on heated pipe

Lagging material	Lagging thickness cm	Pipe orientation	Ignition temperature °C	Temperature rise degC
Calcium silicate/ asbestos	5.1	vertical	191 ± 4	280 (G)
	2.54	"	222*	65 (C)
	5.1	horizontal	192 ± 5	325 (G)
Resin-bonded mineral wool	5.1	vertical	215 ± 3	150 (C)**

Notes:

- (C) Indicates lagging was found to be charred after removal from pipe, (not necessarily near interior thermocouples).
- (G) Glowing combustion occurred.
- \* No test at lower temperature.
- \*\* Temperature rise at surface.

The estimates of critical temperatures for ignition of the lagging on the pipe are less reliable than for the cubes. Owing to the long times involved, up to two days or so per test, it was not always possible adequately to confirm the 'non-ignitions'. However, the 'ignitions' on which the estimates were based were usually clearly marginal.

Induction periods for ignition of the lagging on the pipe are not given here in detail. It is sufficient to note that, at temperatures near the critical values, induction periods varied from 8 to 20 hours and the variation was large enough to obscure any systematic relationship there might have been with the thickness of the lagging.

#### DISCUSSION

The experimental results in Tables 2 and 3 show differences in the ignition behaviour of the two lagging materials but do not permit ready interpretation and generalisation as they stand. For example, the 5.1 cm thickness of resin-bonded mineral wool ignites at a lower temperature than the same thickness of calcium silicate/asbestos on the pipe but, for the 5.1 cm cubes of these two materials the order of the temperatures for ignition is reversed.

However, the significance of the results becomes clearer when they are related in terms of the theoretical model of thermal ignition.

The thermal ignition theory is based on a consideration of the balance between the rate of heat generation in a body of material undergoing chemical reaction and the rate of heat loss to the surroundings. Ignition is associated with a set of quantitative conditions under which a steady state temperature distribution in the body becomes impossible and the temperature rises to high values associated with active combustion. A general account of the theory is given in reference 6 and detailed applications to solids, for body shapes and boundary conditions of interest in the present paper, are given in references 7-10. Here, the relevant equations will be used without preliminary justification, but certain important limitations will be pointed out as necessary. A full list of symbols employed is given at the end of the paper.

On the basis of the theory, a linear relationship is obtained when the results of ignition experiments are plotted in the form  $\log_e (\delta_c T_0^2/r^2)$  vs.  $1/T_0$ .

where here, for cubes,  $T_0$  is the critical temperature, °K, for ignition of a cube of half-side  $r$ .  $\delta_c$  is a dimensionless parameter which defines the critical conditions, and in general, is a function of the geometrical shape of the body and of the boundary conditions. For ignition of the cubes it may here be regarded as constant, its value being 2.53. The slope of the line is  $-E/R$  where  $E$  is an 'activation energy' for the self-heating process and  $R$  is the universal gas constant ( $2.0 \text{ cal mole}^{-1} \text{ degK}^{-1}$ ).

For cylindrical pipe lagging of internal radius  $r_1$ , and external radius  $r_2$ , the corresponding linear relationship for the results is  $\log_e [4 \delta_c^* T_p^2 / (r_2 - r_1)^2]$  vs  $1/T_p$ , where  $T_p$  is the critical pipe temperature for ignition of lagging of semi-thickness  $(r_2 - r_1)/2$ . Here, the parameter  $\delta_c^*$ , appropriate to an infinite hollow cylinder with the inner face at a constant high temperature<sup>10</sup>, is a function of two other parameters  $z_s$  and  $\theta_s$  where

$$z_s = r_2/r_1$$

and

$$\theta_s = \frac{E}{RT_p^2} (T_s - T_p) \quad (1)$$

$\delta_c^*$  must be evaluated for every set of experimental conditions and is given graphically in Fig.4 for a useful range of the parameters  $z_s$  and  $\theta_s$ . The range may be extended as required using equations given in reference 10.

Values of  $T_s$ , the temperature at the outer surface of the lagging, may be determined experimentally or estimated with sufficient accuracy from the heat balance at the outer surface assuming that the lagging is inert. Thus, for cylindrical lagging,

$$h(T_s - T_0) = \frac{K}{r_2} \cdot \frac{T_p - T_s}{\log_e z_s} \quad (2)$$

where the left hand side represents the heat loss to the surroundings at temperature  $T_0$ , by convection and radiation, and is calculable by standard methods<sup>13</sup>. For cylindrical lagging in still air this heat loss is given by

$$h(T_s - T_0) = 9.9 \times 10^{-5} \frac{(T_s - T_0)^{1.25}}{(2r_2)^{0.25}} + 1.37 \times 10^{-12} (T_s^4 - T_0^4) \text{ cal cm}^{-2} \text{ s}^{-1}$$

For lagging on a cylindrical tank of large radius,  $z_s$  approaches unity and it can then be shown that<sup>10</sup>

$$\delta_c^* \doteq \frac{(\theta_s + 1.4)^2}{8} \quad (4)$$

as for a plane slab in contact with a hot surface<sup>8</sup>.

The procedure to be adopted in plotting the results of ignition tests on lagging is, then, first to estimate  $T_s$  for a given test, then to calculate  $\theta_s$  (equation 1) using an assumed value for  $E$ , say 25000 cal/mole, and then to find  $\delta_c^*$  from Fig.4 (or from equation (4) if  $z_s \doteq 1$ ). The value of  $E$  is then determined from the slope of  $\log_e [4 \delta_c^* T_p^2 / (r_2 - r_1)^2]$  vs  $1/T_p$  and, if different from the assumed value, is used to recalculate  $\theta_s$  and obtain a fresh plot. It will be found that this trial procedure converges rapidly onto a constant value for  $E$ .

If the theoretical model is adequate, the results for ignition tests on the cubes and on the lagging should lie on a common line when plotted as above. Indeed, the results for the cubes can be used to determine the value of  $E$  required for plotting the results for the lagging.

The ignition results in Tables 2 and 3 are plotted in the above manner in Fig.5. Straight lines have been drawn through the points for the cubes, and the slopes of these lines provide the values of  $E$  used for placing the points for the pipe tests (for these points the thickness of the lagging is indicated in the Figure). Values of  $T_s$  for the lagging were estimated for an ambient temperature of 20°C.

The results for the cubes of the two lagging materials lie on lines of different slope and it is immediately clear how the relative hazard, as measured in terms of the critical temperatures for ignition of cubes of given size, can be reversed in the range of higher temperatures required for ignition of the lagging.

To a first approximation, the temperatures for ignition of the lagging which would be consistent with the results obtained from the cubes can be read directly from the lines in Fig.5 at the levels of the experimental points for each thickness of lagging. In this way it may be estimated that the critical pipe temperatures observed for ignition of the 2.5 cm thickness of calcium silicate/asbestos and the 5.1 cm thickness of resin-bonded mineral

wool are respectively about 17°C and 30°C higher than is to be expected from the tests on the cubes. Part of these differences may be due to the experimental estimates of the critical temperatures for ignition on the pipe being too large - owing to inadequate replication of 'non-ignition' tests as indicated earlier.

Earlier studies of the ignition of solid materials (wood sawdust and fibre insulating board) have shown that, for practical purposes, there is a good correlation, on the basis of the thermal ignition model, between ignition results for cubes in an oven and for plane slabs in contact with a heated surface on one side. The further extension of the model from a plane slab to a hollow cylinder heated on the inner face is a less important step, and one may expect to be able to make reasonably reliable predictions of ignition temperatures for solid combustible lagging materials from ignition data obtained for cubes. In a typical case, the increase in critical temperature for ignition in going from a plane slab to cylindrical lagging for which  $z_s$  is as high as 4, is 30°C<sup>10</sup> compared with the increase of about 60°C in going from the cube in the oven to the plane slab heated on one face<sup>9</sup>.

However, for the ignition of oils dispersed in incombustible lagging, as studied in the present paper, the position is more uncertain. An effect which could constitute a major complication for ignition of the lagging on the pipe is distillation of the oil down the steep temperature gradient in the lagging.

This effect could modify both the intercepts and slope for ignition results obtained for lagging on pipes when plotted as in Fig.5, but need not seriously invalidate predictions for other pipe diameters and lagging thicknesses involving linear interpolation or, limited, extrapolation of the results so plotted. However, the discrepancy between the lagging on the pipe and the cubes in the oven could then be even greater than is apparent for the present results as plotted in Fig.5, for which a common value for  $E$  has been assumed.

Unfortunately, it has not been possible to obtain sufficient results for the ignition of oiled lagging on the pipe to evaluate the real importance of this difficulty. To this extent, the value of the cube tests for the purpose of the detailed prediction of the behaviour of lagging on pipes remains in doubt, and would merit further investigation when opportunity occurs.



Finally, it may be pointed out that, under certain conditions<sup>6,7</sup>, a system may exhibit an appreciable temperature rise due to self-heating without, however, being capable of attaining a state of active combustion in the conventional sense. In such systems, a definite 'ignition' does not occur. There may be certain oil/lagging combinations showing this behaviour and which will be free from the risk of fire - although the self-heating may be objectionable for other reasons. It should not, however, be concluded, without further exhaustive tests, that a given oil/lagging combination is of this type because of some initial difficulty in inducing active combustion during oven tests or pipe tests.

### CONCLUSIONS

Whichever test method is adopted for assessing the self-ignition hazard of different lagging/oil combinations, considerable replication of the tests is likely always to be necessary for obtaining reliable estimates of the critical ignition temperatures and dimensions.

The test based on the ignition of cube-shaped samples in an oven is most suitable for the performance of large numbers of tests. Determination of the critical temperature for ignition of a single size of cube will provide a coarse screen for a range of lagging/oil combinations and could be used to assess the value of, for example, additives designed to reduce the ignition hazard. In detail, such a test would not necessarily place all combinations tested in the correct order of hazard for use as lagging on a pipe.

Further information on this can be obtained by testing cubes of different sizes and examining the results on the basis of the theoretical model for thermal ignition. This will also permit an estimate to be made of actual pipe temperatures for ignition, but the error may be large - perhaps even larger than the 30°C noted in this paper.

The pipe test will furnish checks on the predictions from oven tests. Used to determine critical temperatures for ignition of at least three thicknesses of a given lagging/oil combination it should provide data capable of being used to make reasonable estimates for ignition of any thicknesses on any diameter of pipe. However, unless a number of heated pipes can be built for simultaneous use, estimates of critical ignition temperature will take much longer to determine than with oven tests. If a readily controlled supply of steam is available, a steam-heated manifold test rig of the kind

used by Osola<sup>4</sup> will be preferable, for this purpose, to the electrically heated pipe used in the present work.

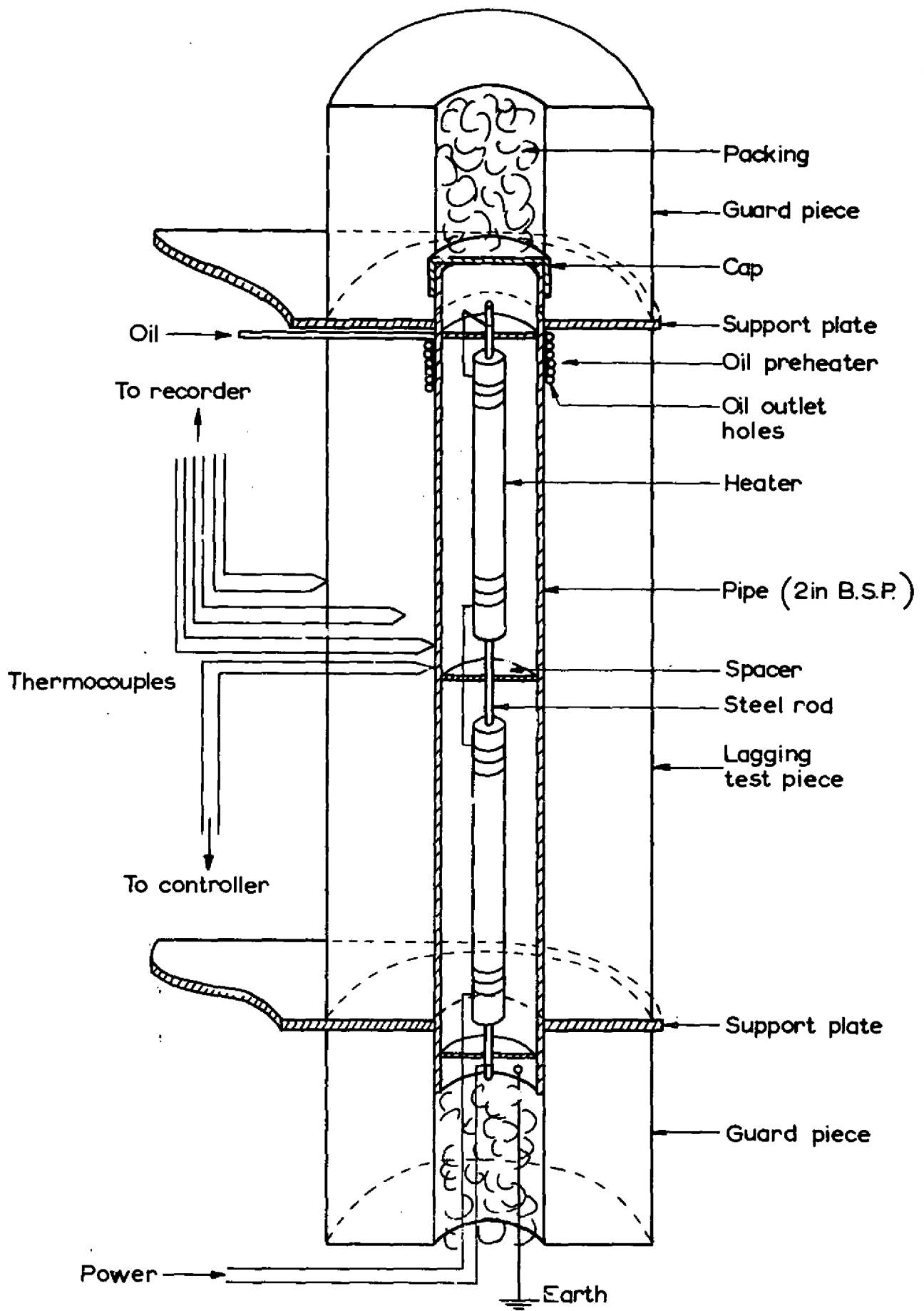
As indicated at the outset, the choice of test will depend to a large extent on circumstances. The limits within which an ignition temperature will need to be known will be conditioned by the limits within which the relevant plant temperatures are normally controlled. Again, for purposes of insulation, the thicker layers of lagging are usually associated with the higher pipe temperatures. This is the most adverse situation for the occurrence of ignition and may often be the only one that needs to be tested for a given plant. At the same time, however, an examination of other thicknesses could reveal the extent to which, at the expense of increased heat loss, the fire hazard could be overcome simply by reducing the thickness of the lagging at especially vulnerable points on the plant.

#### LIST OF SYMBOLS

- E = 'Activation energy' for self-heating process.  
h = Surface heat transfer coefficient (sum of radiation and convection)  
K = Thermal conductivity of lagging  
R = Universal gas constant  
r = Half-side of cube  
r<sub>1</sub> = Radius of inner surface of lagging  
r<sub>2</sub> = Radius of outer surface of lagging  
T<sub>0</sub> = Ambient air temperature (or oven temperature) °C or °K as text  
T<sub>p</sub> = Temperature at hot (inner) surface of lagging °C or °K as text  
T<sub>s</sub> = Temperature of outer surface of lagging °C or °K as text  
z<sub>s</sub> = r<sub>2</sub>/r<sub>1</sub>  
 $\theta_s = \frac{E}{RT_p} (T_s - T_p)$   
 $\delta_c^* = f(\theta_s, z_s), \text{ Fig. 4.}$

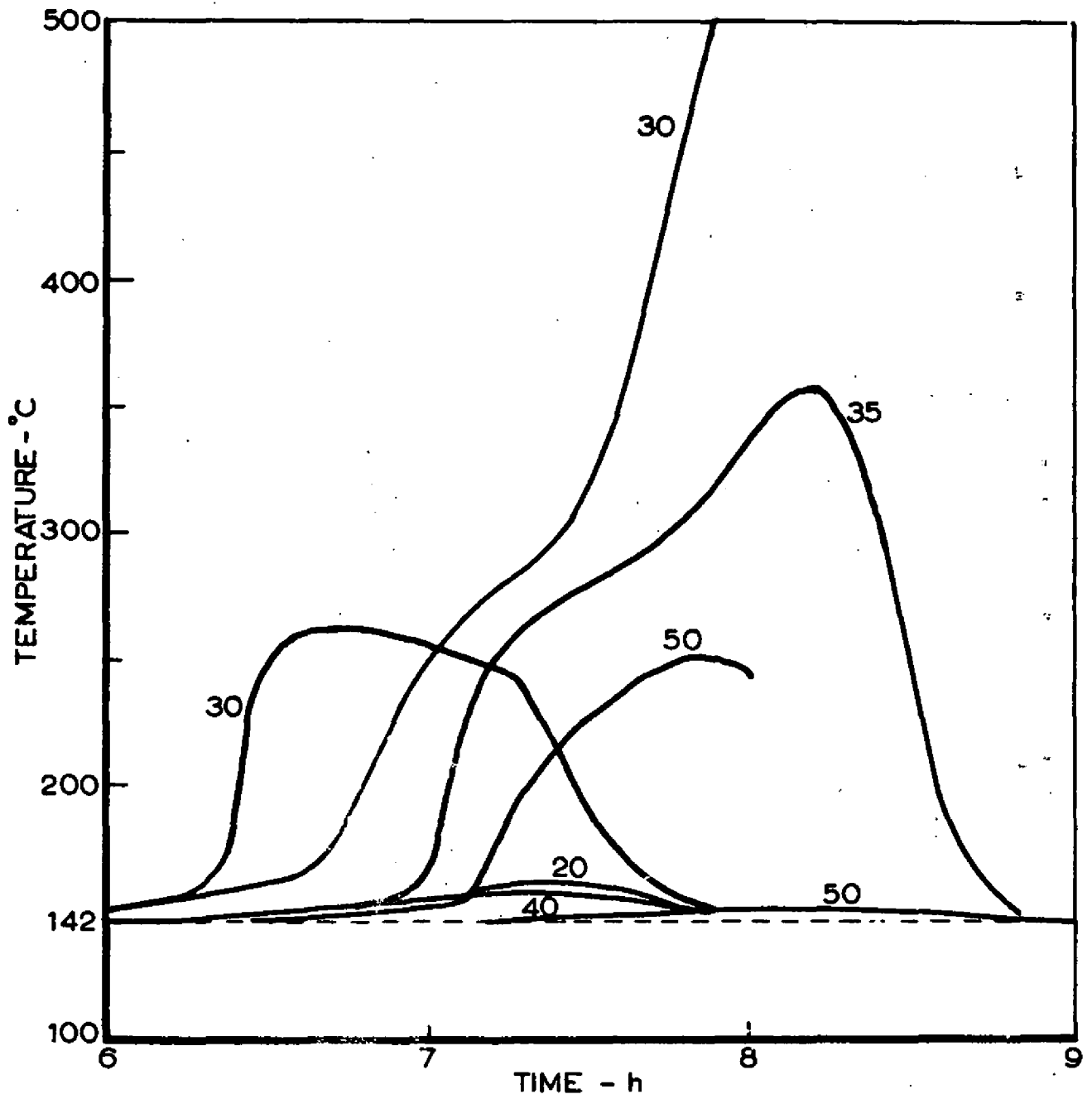
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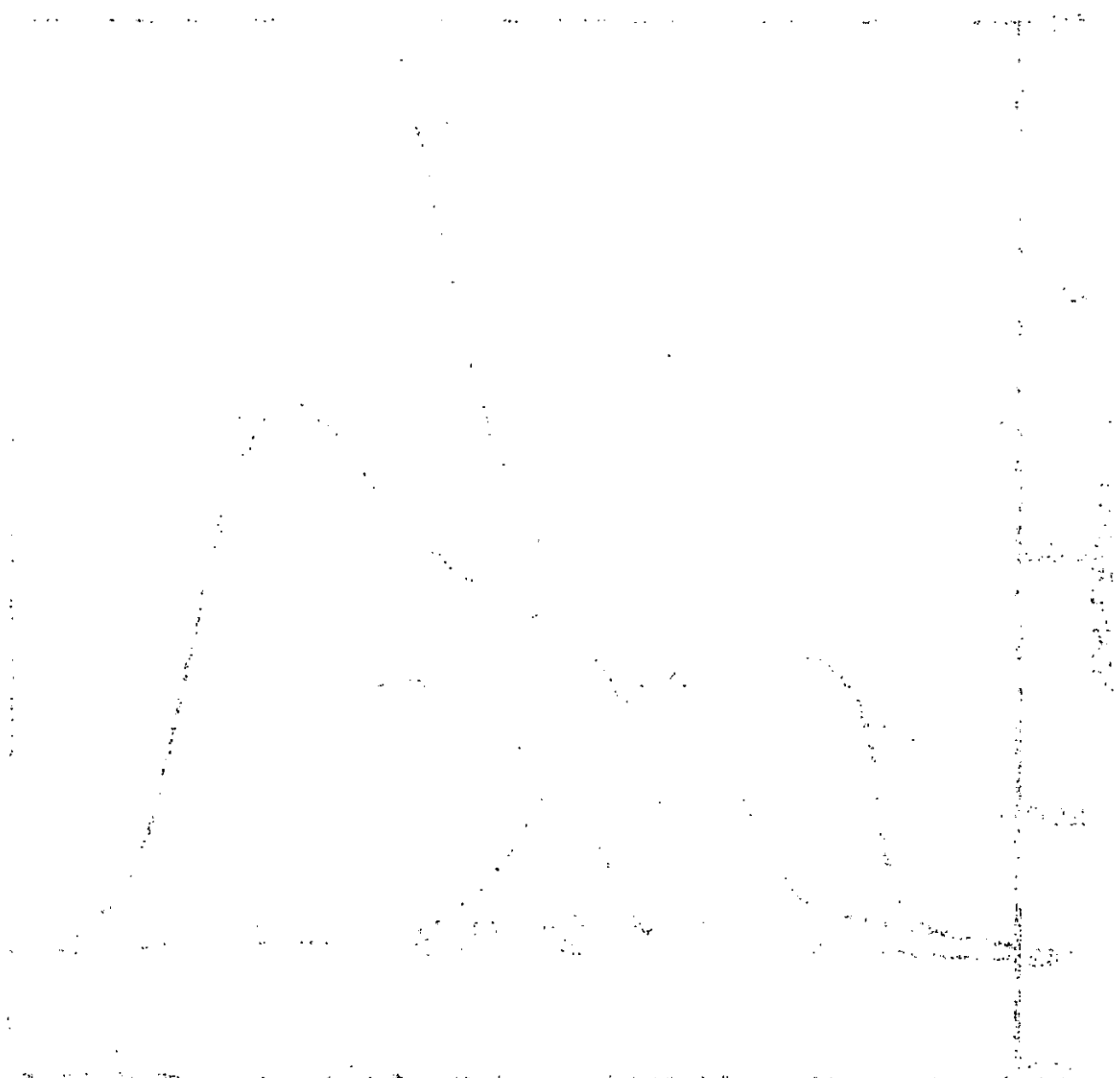
SECTIONAL VIEW  
(not to scale)

FIG. 1. APPARATUS FOR IGNITION TESTS ON PIPE LAGGING



Figures on curves represent oil content as percentage by volume of voids

FIG. 2. SELF-HEATING OF 5-cm CUBES OF RESIN BONDED MINERAL WOOL AND OIL AT 142 °C



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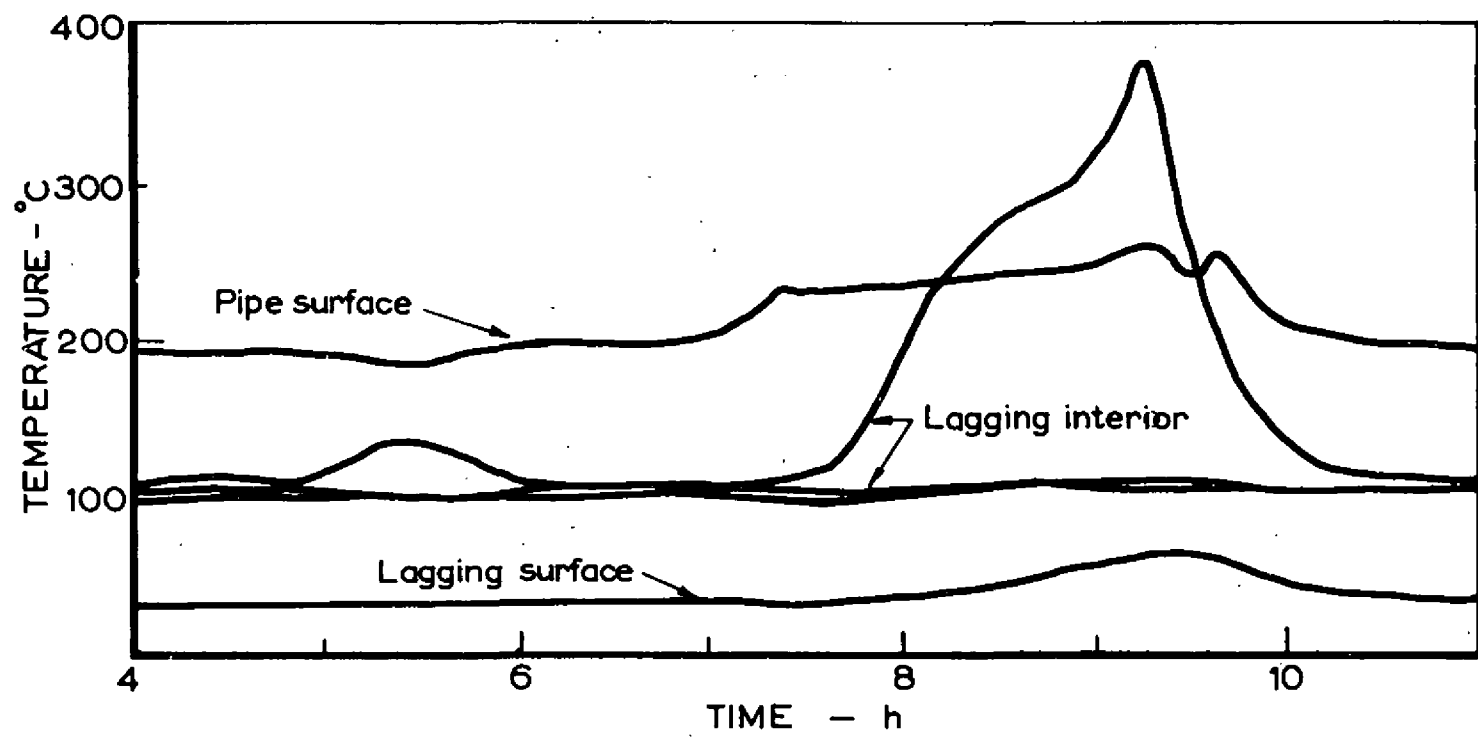


FIG. 3. SELF - HEATING OF OILED PIPE LAGGING  
CALCIUM SILICATE / ASBESTOS PREFORMED SECTIONS

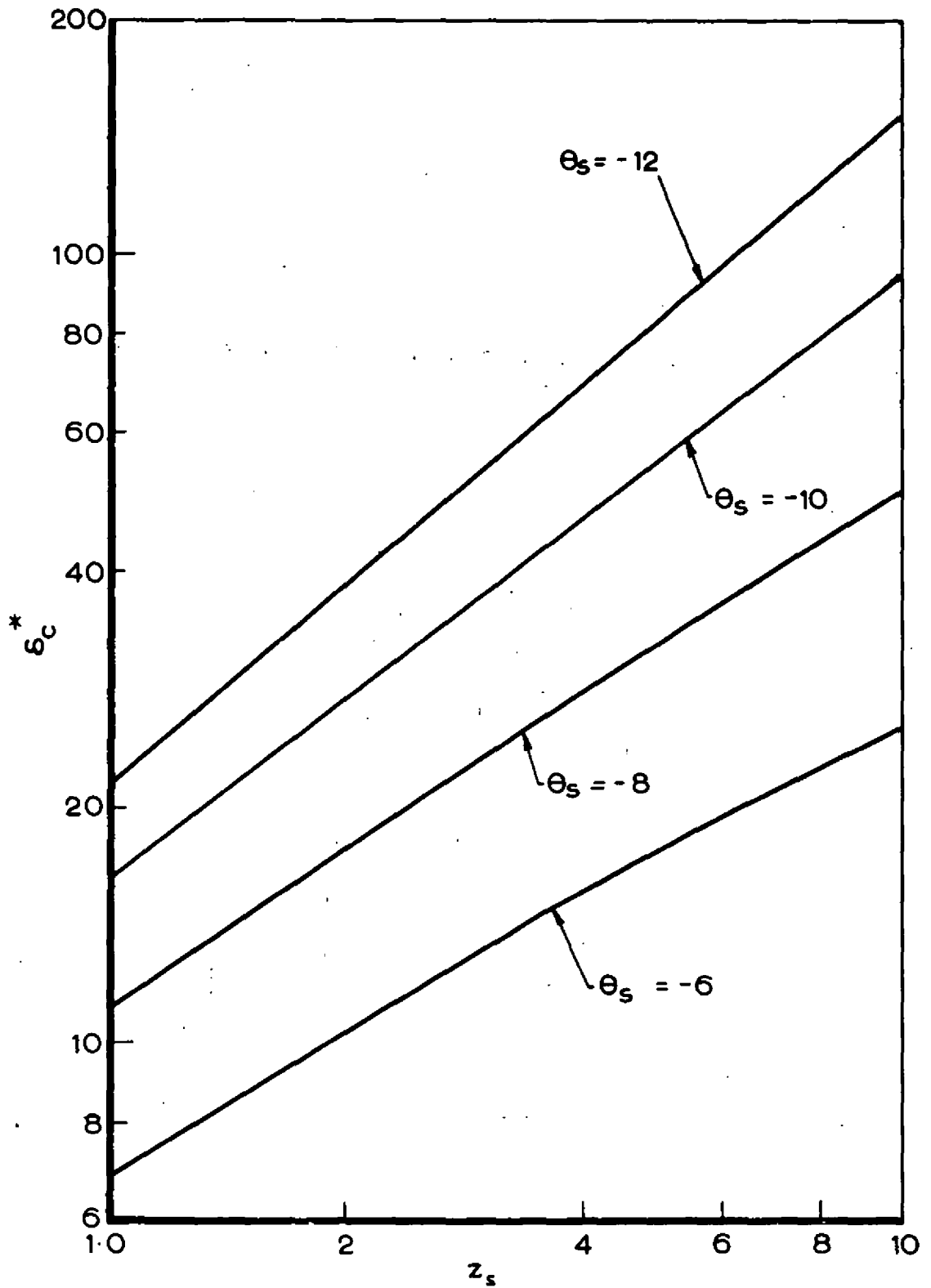
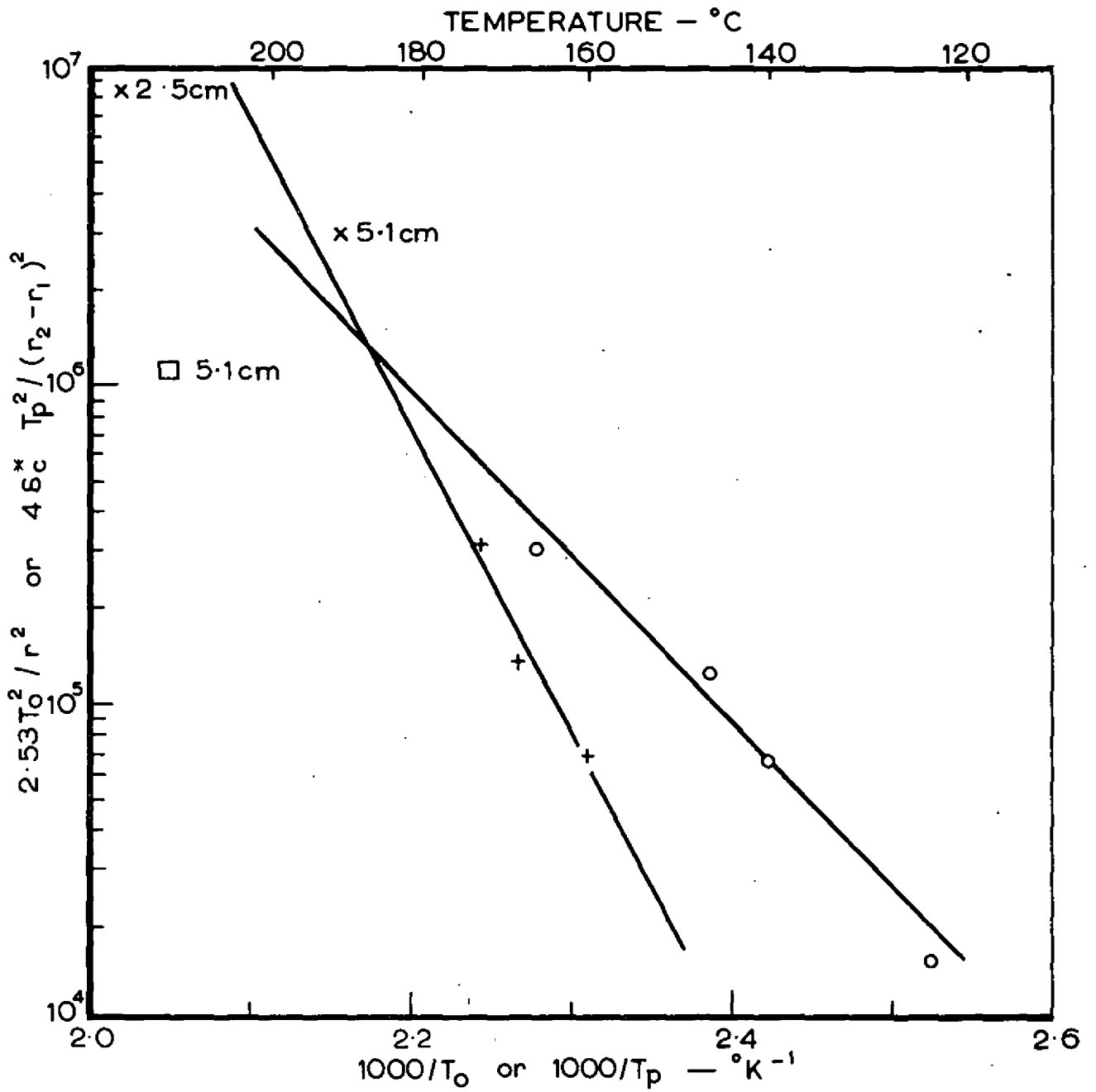


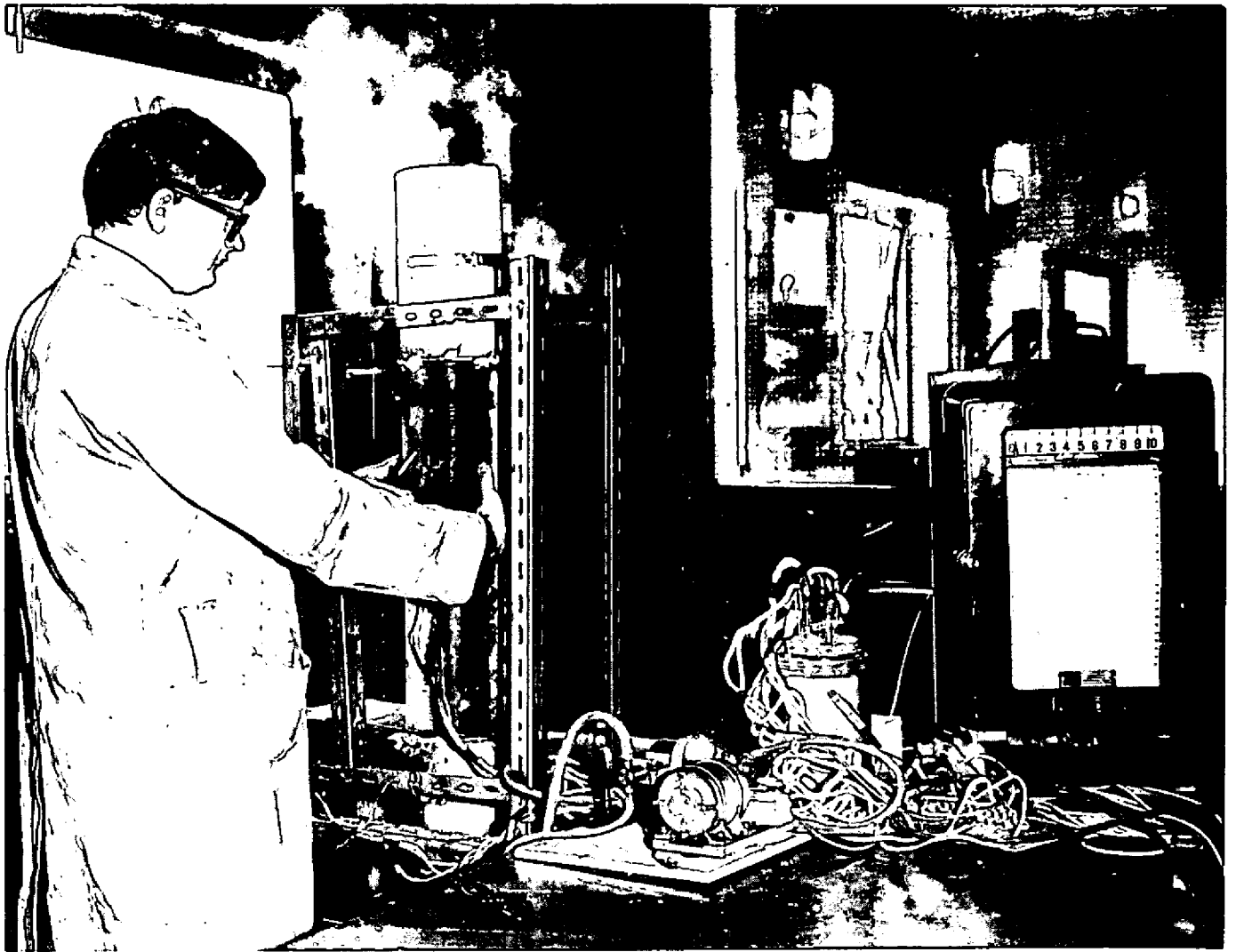
FIG. 4. CRITICAL IGNITION PARAMETER FOR PIPE LAGGING





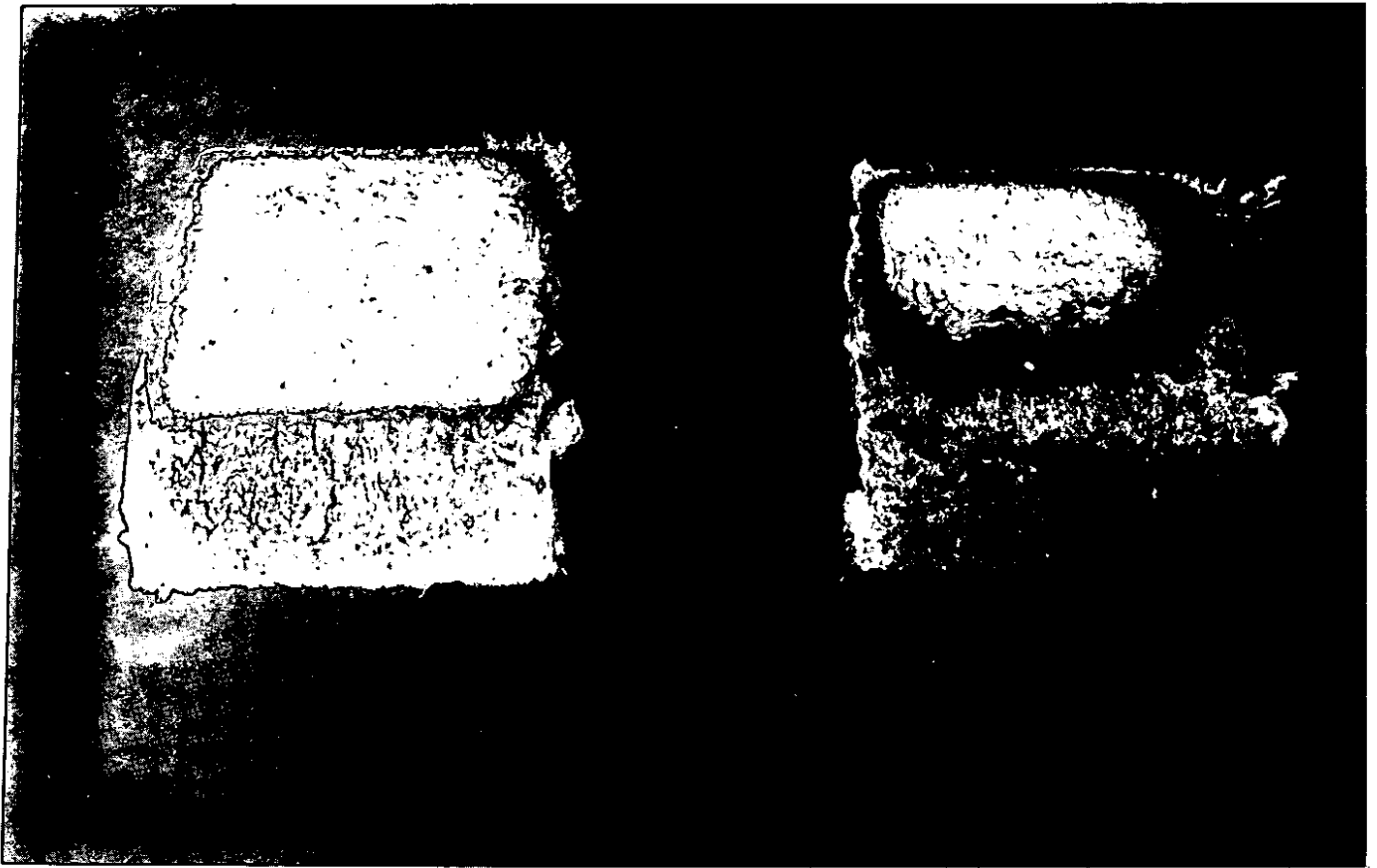
Calcium silicate / asbestos	}	Cubes in oven	+
		Lagging on pipe	x
Resin - bonded mineral wool	}	Cubes in oven	o
		Lagging on pipe	□

FIG. 5. THEORETICAL CORRELATION OF IGNITION DATA



IGNITION OF OIL-SOAKED LAGGING  
ON HEATED PIPE

PLATE 1



IGNITION OF CUBES OF RESIN-BONDED MINERAL  
TREATED WITH TRANSFORMER OIL  
(Cross-sections of 5.1 cm cubes)

PLATE 2



Resin-bonded  
mineral wool



Calcium silicate/  
Asbestos

IGNITION OF OIL-SOAKED  
PIPE LAGGING

PLATE 3

