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THERMAL RESPONSE TO A HEAT SENSITIVE LINE DETECTOR

by

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1. Introduction

Previous studies (1)(2)(3) of the thermal response of heat-sensitive fire detectors, and methods of testing them, have been restricted to the "point" or spot type in which the sensitive element is relatively small and is only affected by the temperature conditions existing in the small area around it.

There are however a number of detectors in which the sensitive element is extended linearly ("line" detectors), and these will be affected by the temperature conditions existing over a fairly large area of the ceiling on which the detector is mounted.

Typical designs of such detectors include those in which a fluid in a thin-walled tube expands on heating and produces a pressure at a sensitive capsule, and others in which the electrical resistance or capacity of a filar conductor or dielectric changes as its temperature increases.

It has been shown (4) that the response of a line detector of this type will depend on the length of detector subjected to the hot gases, and also upon the temperature distribution of the gases over the length of the detector. This note describes some experiments in which various lengths of a line detector have been subjected to an airflow of uniformly-rising temperature. The response times obtained have been analysed and possible methods of testing this type of detector have been deduced from the results.

2. Description of detector

The detector used in these experiments was a modified proprietary detector consisting of two elements in the form of electrical conductors. One element (the detector element R_D) consisted of 3/029 enamelled copper wire and the other element (the compensating element R_c) consisted of 3/029 V.I.R. cable. The two elements formed adjacent arms in a bridge network (Fig. 1) while the remaining arms consisted of a fixed 5 ohm resistor and a variable 0-10 ohm resistor. The bridge voltage was supplied by a 2v. accumulator and the bridge current measured between A & B (Fig.1) by a microammeter.

Two methods of operation can be used with this type of detector. First, the fixed temperature operation, where the compensating element is replaced by a fixed resistance of equal value. Under these conditions any increase in temperature and hence resistance of the detector element, will result in an increase of the bridge current. If the detector is designed to operate on a given current, this will occur when the mean temperature of the detector element R_D has risen by a certain value determined by its temperature coefficient of resistance.

Second, a compensated or rate of rise (3) operation can be used. Here, both the detector and the compensating elements are connected into the bridge and are subjected to the hot gases from the fire. Under these conditions, operation will occur when the difference in resistance of the two elements is sufficient to produce the given bridge current. In this method of operation, the change in resistance of the insulated compensating element, offsets to some extent the change in resistance of the detector element, resulting in a lower bridge current as compared with fixed temperature operation.

The performance of the detector under both these conditions has been examined experimentally and the results analysed.

3. Experimental

The detector elements were mounted parallel to each other in a 7-ft long section of a wind tunnel (Plate 1) which is used for testing the thermal response of point detectors in accordance with British Standard 3116 : 1959(5). Previous measurements had shown that over the length of this section of the tunnel, there was only a small linear reduction in air temperature, and it was therefore suitable for subjecting the line detector to a uniform rate of rise of air temperature over its length. By mounting the detector in the form of a grid parallel to the length of the tunnel it was possible to examine a total length of 16.4 m. Leads were taken from the elements at lengths of 4.1, 8.2, 12.3, and 16.4 m. in order that the response of each of these lengths could be determined. Table 1 gives the resistance of each length of the element at room temperature (18°C).

Table 1

Resistance of detector elements at 18°C

Length of element (Metres)	Resistance (Ohms)
4.1	0.061
8.2	0.118
12.3	0.175
16.4	0.231

The air temperature to which the detector elements were subjected was measured by means of a 40 S.W.G. chromel/alumel thermocouple mounted with its junction on the central axis of the tunnel at the mid-point of the working section.

The response of each length of the detector was first determined under the fixed temperature operation as follows. The compensating element was disconnected and replaced by a fixed resistance, mounted outside the tunnel and equal in value to the compensating element at room temperature. The variable resistance was then adjusted to balance the bridge. The air velocity was adjusted to 80 cm/sec and the temperature was then raised uniformly at 5, 10, 20 and 30°C per minute to about 120°C. This procedure was repeated using the four lengths of detector and in each case the bridge current was recorded at regular intervals throughout the heating period.

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SUMMARY

The response times of a heat-sensitive line detector have been determined under varying conditions. An analysis of the results has suggested a possible method of testing this type of detector.

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Fig. 2 shows the variation in bridge current with time for the four lengths of detector when subjected to a rate of rise of air temperature of 20°C per minute. Similar curves were obtained at the other rates of rise of air temperature.

The experiments were repeated with the detector in its compensated form and the variation in bridge current with time for a rate of rise of air temperature of 20°C per minute under these conditions is shown in Fig. 3. Again, similar curves were obtained at the other rates of rise of air temperature.

Comparison of Figs. 2 and 3 show that the performance under the two forms of operation of the detector differ in two respects. First, the form of the variation of bridge current with time is different and second, the bridge current reached at any given time is less with the detector operating in its compensated form than with the fixed temperature operation. It is therefore necessary to analyse the performance of the detector in more detail.

4. Bridge circuit theory

Using the notation of Fig. 1[*] the bridge current i_g will be given by

$$i_g = \frac{E(R_1R_D - R_2R_c)}{R_g(R_1 + R_c)(R_2 + R_D) + R_1 R_2(R_c + R_D) + R_cR_D(R_1 + R_2)} \tag{1}$$

where R_g is the resistance of the microammeter.

In these experiments however, $R_g \gg R_1\ R_2\ R_c$ and R_D and $R_1 = R_2$.

Hence equation (1) reduces to

$$i_g = \frac{E\ (R_D - R_c)}{R_g\ R\ (1 + \frac{R_D}{R})(1 + \frac{R_c}{R})} \tag{2}$$

where $R_1 = R_2 = R$

Table 1 shows that $\frac{R_D}{R}$ and $\frac{R_c}{R}$ are small compared with unity and thus the bridge current is given approximately by

$$i_g = \frac{E\ (R_D - R_c)}{R_gR} \tag{3}$$

The bridge current is therefore proportional to the difference in resistance of the elements of the detector. If then R_0 is the resistance per unit length of the elements at room temperature the bridge current which occurs when the mean temperatures of the detector and compensating elements have risen by θ_D and θ_c °C respectively will be given by

$$i_g = \frac{E\ R_0 \gamma\ L}{R_gR} (\theta_D - \theta_c) \tag{4}$$

where L is the length of the elements and

γ is the temperature coefficient resistance

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[*] The symbols $R_1\ R_2\ R_c\ R_D$ etc. used in the following theory denote the resistance of the elements referred to by these letters in Fig. 1.

5. Discussion of results

a) Fixed temperature operation

Under these conditions the value of R_c remains constant and in effect θ_c is zero. Thus equation (4) becomes

$$i_g = \frac{E R_o \gamma L}{R_g R} \theta_D \qquad (5)$$

It has been shown (1) however that the mean temperature rise of the detector element when subjected to a rate of rise of air temperature of α °C per minute for a period of t minutes is given by

$$\theta_D = \alpha \left\{ t - \tau_D (1 - e^{-t/\tau_D}) \right\} \qquad (6)$$

where $\tau_D = \frac{C}{HA}$ and

C is the thermal capacity of the element per unit length

H is the convective heat transfer coefficient

and A is the area per unit length of the element

Combining Equations (5) and (6) we obtain

$$i_g = \frac{E R_o \gamma \alpha L}{R_g R} \left\{ t - \tau_D (1 - e^{-t/\tau_D}) \right\} \qquad (7)$$

If therefore the detector is designed to give an alarm when a chosen bridge current I_g is reached and the time taken to reach this current is large enough for $e^{-t/\tau_D} \ll 1$ then the response time t_R will be given by

$$t_R = \frac{K}{\alpha L} + \tau_D \qquad (8)$$

where $K = \frac{R_g R I_g}{E R_o \gamma}$

Thus, except for small values of t a linear relation between t_R and $1/\alpha L$ should exist. This relation has been plotted in Fig. 4 from the experimental results, taking a value of $I_g = 6 \mu A$. This line gives a value of $\tau_D = 30$ sec and K = 305 m°C. For comparison the value of K calculated from the physical properties of the element and the component values of the bridge is 285 m°C.

Equation (8) shows that at any given rate of rise of air temperature the response time of the detector will depend upon its length. Thus if the response time of the detector has to lie within specified limits as is required by B.S. 3116 : 1959, then there is a maximum and minimum length of detector which can be used for any given "setting" i.e. K in the example quoted above.

It follows from Equation (8) that if the response time of a length L_o of the detector at any rate of rise of air temperature is t_o then the length of detector L_c which will give a critical response time t_c at the same rate of rise of air temperature, is given by

$$L_c = L_o \frac{(t_o - \tau_D)}{(t_c - \tau_D)} \qquad (9)$$

This suggests that a possible method of testing a fixed temperature line detector is to subject a given length of the detector to a range of rates of rise of air temperature, and to use the response times obtained to derive the value of τ_D. The critical lengths of the detector can then be readily obtained.

In practice the rate of rise of temperature to which a line detector is subjected may vary over its length (6). It has been shown (4) however that in many cases the response under these conditions is identical to that of a detector subjected uniformly to the mean rate of rise of air temperature over its length. Thus, if an exponential decrease in rate of rise of air temperature about the centre of the detector is assumed the critical length will be given by

$$1 - e^{-\beta\frac{Lc}{2}} = \beta\frac{Lo}{2}\left\{\frac{(t_o - \tau_D)}{(t_c - \tau_D)}\right\} \qquad (10)$$

where β is the exponential decay constant.

Table 2 gives the maximum and minimum lengths of the detector used in these experiments which would ensure that the response time would be within the limits required by B.S.3116 : 1959, for a bridge current setting of $I_g = 6 \mu A$. These critical lengths are shown for a uniform and exponentially decreasing rate of rise of air temperature. The value of β has been taken as 10^{-3} cm $^{-1}$ (4).

Table 2

Minimum and Maximum lengths of detector

Rate of rise of temperature oC/min	Limits of response time set by B.S.3116 : 1959 (min)		Length of detector assuming a uniform rate of rise of temperature over whole length (m)		Length of detector assuming an exponential variation in rate of rise of temperature (m)	
	Upper	Lower	Minimum	Maximum	Minimum	Maximum
1	56	37	5.5	8.4	6.4	10.8
3	20	9.5	5.2	11.3	6.0	16.6
5	13	5	4.9	13.5	5.6	22.4
10	7.5	2	4.3	20.3	4.8	-
20	4.75	0.75	3.6	-	4.0	-
30	3.75	0.5	3.1	-	3.4	-

It can be seen from this table that the maximum and minimum lengths of detector are not independent of the rate of rise of air temperature. This arises from the fact that neither the upper nor the lower limit of response time specified in B.S.3116 : 1959 is strictly inversely proportional to the rate of rise of air temperature. Further, the maximum allowable length of detector, when subjected to a uniform rate of rise of air temperature has not been determined for rates of 20 and 30°C per minute since the lower limit of response time at these rates is too small for the approximation $e^{-t/\tau_D} \ll 1$ to be valid.

Finally, with a line detector subjected to a varying rate of rise of air temperature of the form assumed in these examples, there will be a minimum response time at any given maximum rate of rise of air temperature which can be achieved and which would require an infinite length of detector. Equation (10) shows that this minimum time t_m will be given by

$$t_m = \frac{\beta L_0}{2} \left\{t_0 - \tau_D\right\} + \tau_D \qquad (11)$$

Thus at rates of rise of air temperature of 10, 20 and 30°C per minute, the minimum times would be 2.03, 1.27 and 1.01 minutes respectively for the detector used. Table 2 shows that these are greater than the lower limits of response time required by B.S.3116 : 1959 and thus the maximum length of detector when subjected to a varying rate of rise of air temperature has been omitted from Table 2 for rates of rise of 10, 20 and 30°C per minute.

b) Compensated Operation

Combining Equations (4) and (6), the bridge current under these conditions is given by

$$i_g = \frac{E R_0 \gamma \alpha L}{R_g R} \left\{\tau_c(1-e^{-t/\tau_c}) - \tau_D(1-e^{-t/\tau_D})\right\} \qquad (12)$$

where τ_c refers to the compensating element and will generally be much greater than τ_D. With the same notation as previously, it can be shown that provided the response time is large enough to make $e^{-t/\tau_D} \ll 1$ then the response time of the compensated form of detector is given by:

$$t_R = \tau_c \log_e \frac{\tau_c}{(\tau_c - \tau_D) - K/\alpha L} \qquad (13)$$

There is thus no simple relation between the response time and αL which suggests that a similar approach to that suggested for testing the fixed temperature type is not possible with the compensated form of line detector. However Equations (12) and (13) yield a certain amount of information on the expected performance of this type of detector.

It can be seen from Equation (12) that the bridge current will become independent of time after long periods of heating. This is shown by the form of the curves in Fig. 3. Also, the bridge current at any given time will be less than that of the fixed temperature type, which can be seen by comparing Figs. 2 and 3.

Equation (13) shows that for a given value of K there is a critical value of αL below which the detector will not operate given by

$$\alpha L = \frac{K}{\tau_c - \tau_D} \qquad (14)$$

To derive this critical value it is necessary therefore to determine the value of τ_c. This was done in a manner similar to that used for determining τ_D, by subjecting the compensating element alone to a range of rates of rise of air temperature. The value of τ_c was found to be 1.5 min. Thus if the detector is assumed to operate on a bridge current of 3 μA the predicted value of K is 140°Cm and the critical value of αL is 140°C min^{-1}m.

Using Equation (13) the response time of the detector has been predicted for this value of K and is plotted in Fig. 5 against αL together with the experimental results obtained over the same range. The agreement between the predicted and measured values of response time is reasonable at the larger values of αL but the discrepancy is high for the lower values. This is probably due to the small values of resistance involved at the low values of αL making reliable measurements difficult. However, it can be seen from Fig. 5 that close to the critical value of αL the response time is very sensitive to αL while at higher values the response time is small and not markedly dependent on αL. Further it can be shown using Equation (13) that for the values of τ_C and τ_D to be expected it is unlikely that a compensated line detector can be designed such that its response time lies within the limits set by B.S.3116 : 1959 over the range of rates of rise of air temperature from 1 to 30°C per minute even assuming a fixed length were used.

Compensated line detectors have however been installed in situations where only the detection of rapidly developing fires is required and under these conditions Fig. 5 shows that the effect of the length of the detector used on the response time is likely to be small.

6. Conclusions

The response time of a fixed temperature and compensated line detector has been predicted theoretically and compared with the values obtained experimentally. This has shown that with the fixed temperature type of detector its thermal response can be adequately assessed by subjecting a given length of detector to a range of rates of rise of air temperature from which the maximum and minimum lengths of detector such that its response lies within prescribed limits can be deduced.

An analysis of the performance of the compensated type of detector has shown that while no simple relation exists between the response time and length of detector it is probably best suited for use in situations where only the detection of rapidly developing fires is required, under which conditions its performance is not markedly dependent on the length of detector used.

Acknowledgements

The experimental work described in this note was carried out by P. A. Donohue and T. Ivin.

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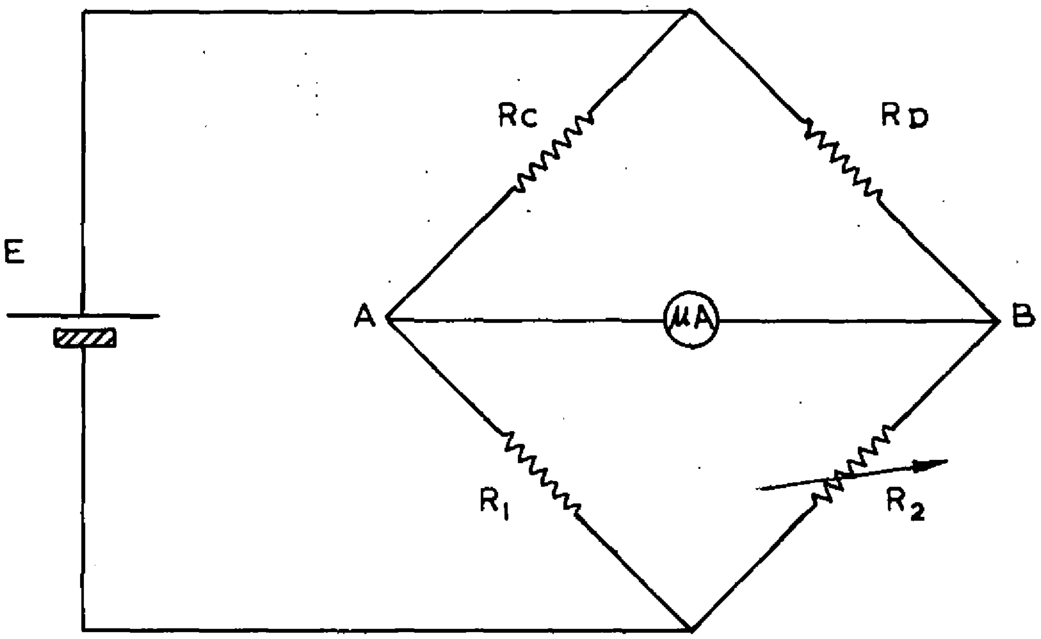

RD — Detector wire
Rc — Compensating wire
R_1 — Fixed 5 Ω resistor
R_2 — 0-10 Ω variable. resistor

FIG.1. CIRCUIT DIAGRAM OF LINE DETECTOR

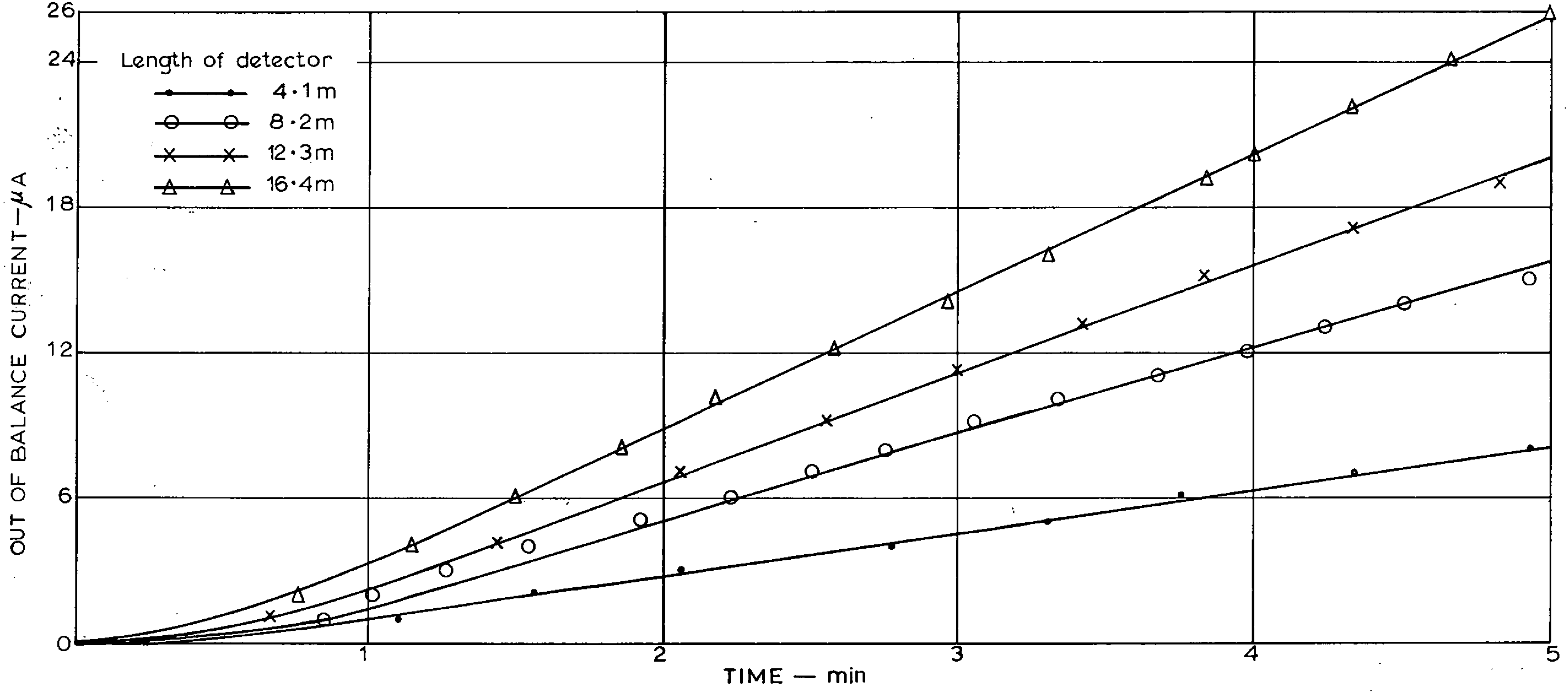

FIG. 2. RESPONSE OF FIXED TEMPERATURE LINE DETECTOR AT 20°C/min

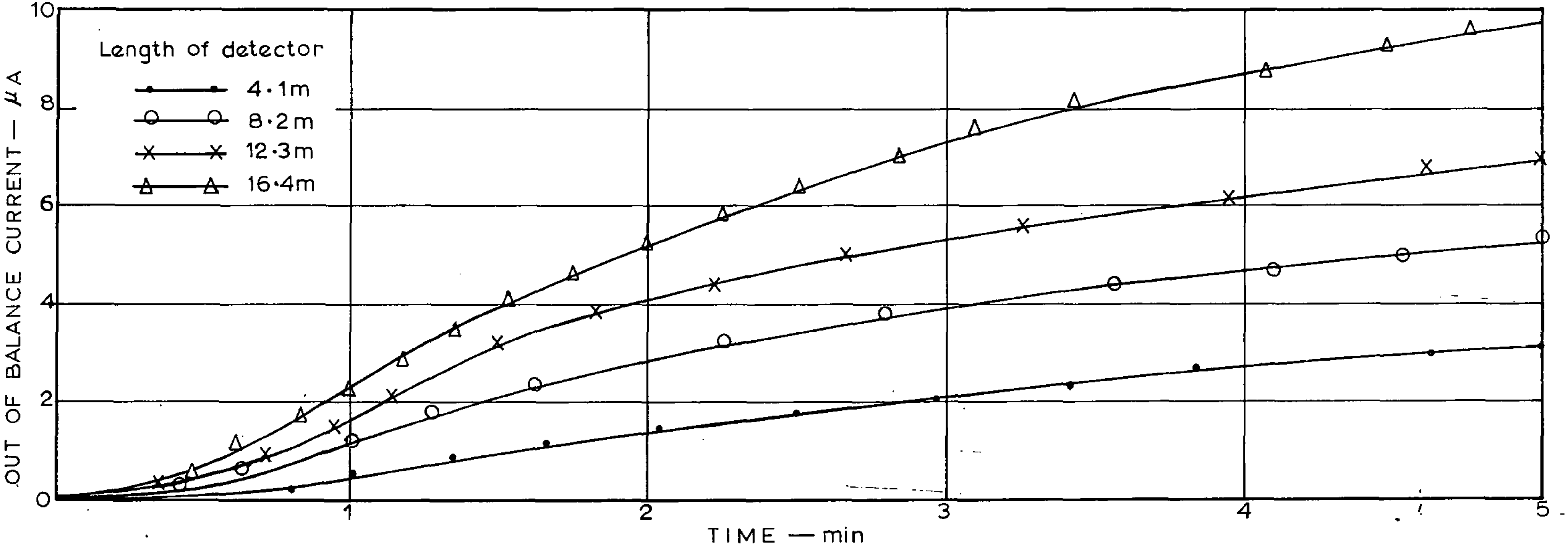

FIG. 3. RESPONSE OF COMPENSATED LINE DETECTOR AT 20 °C/min

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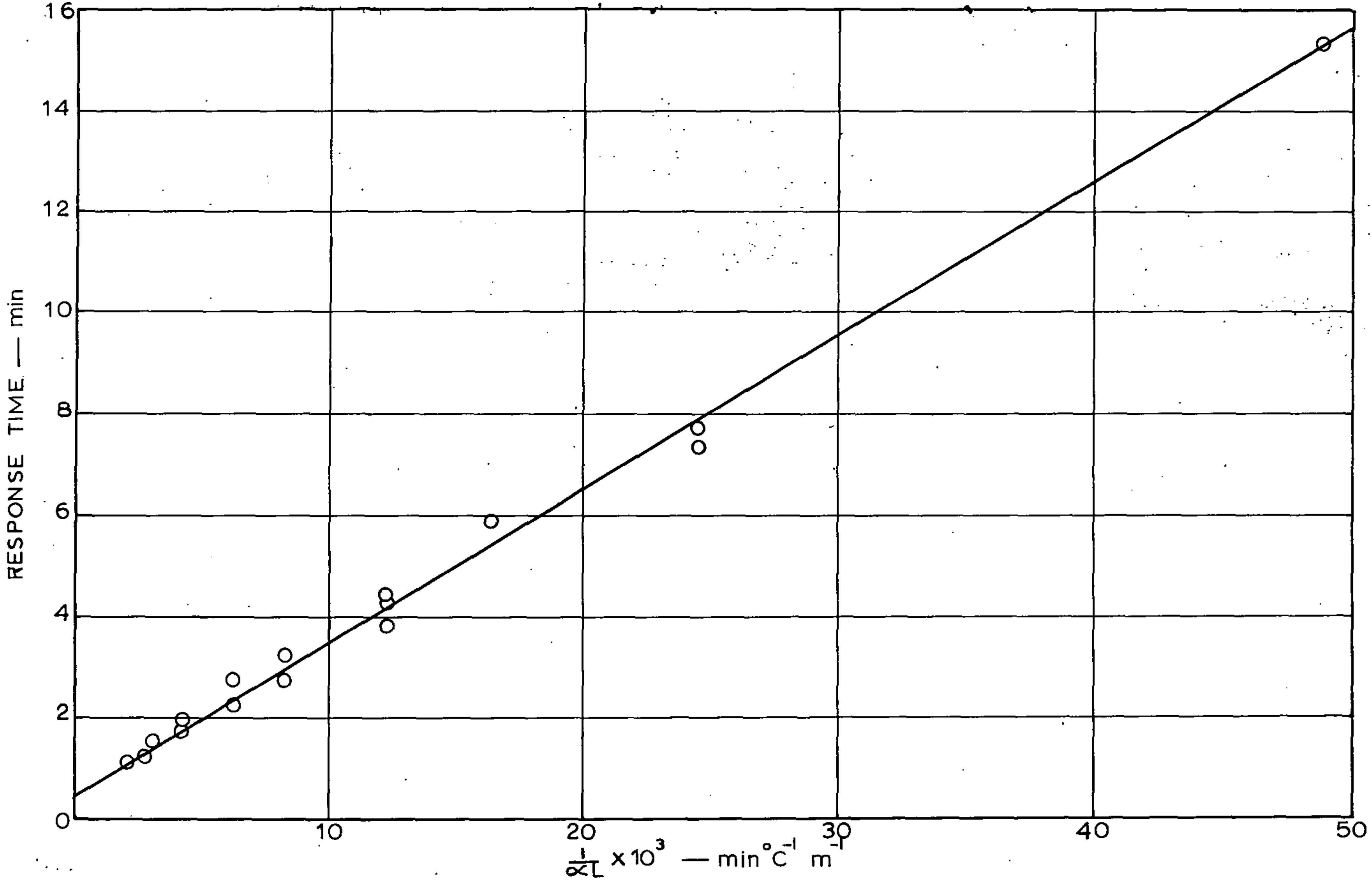

FIG. 4. RELATION BETWEEN RESPONSE TIME (t), RATE OF RISE OF TEMPERATURE (∝) AND LENGTH OF DETECTOR (L) (FIXED TEMPERATURE)

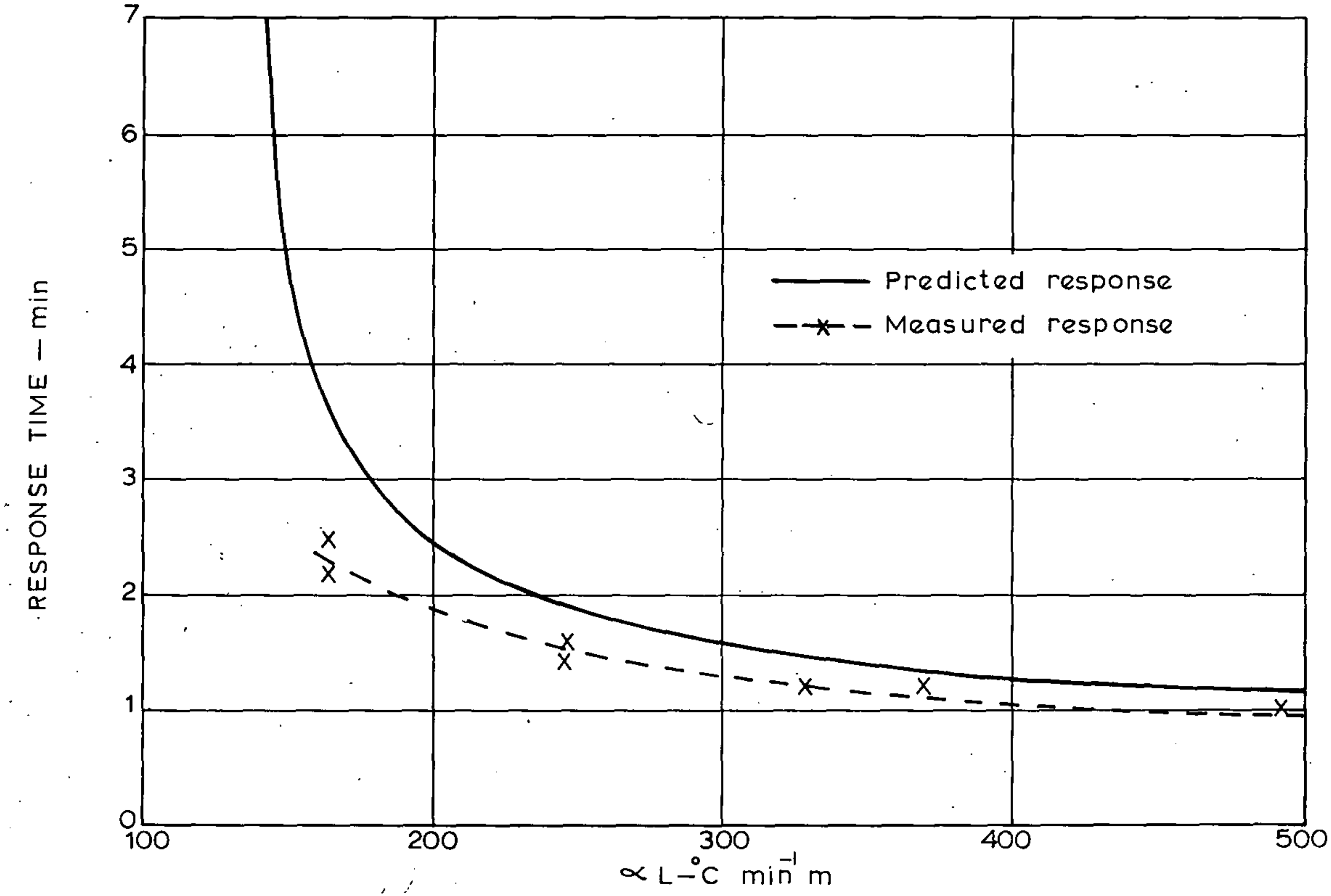

FIG. 5. VARIATION OF RESPONSE TIME (t) WITH RATE OF RISE OF TEMPERATURE (∝) AND LENGTH OF DETECTOR (L) (COMPENSATED)

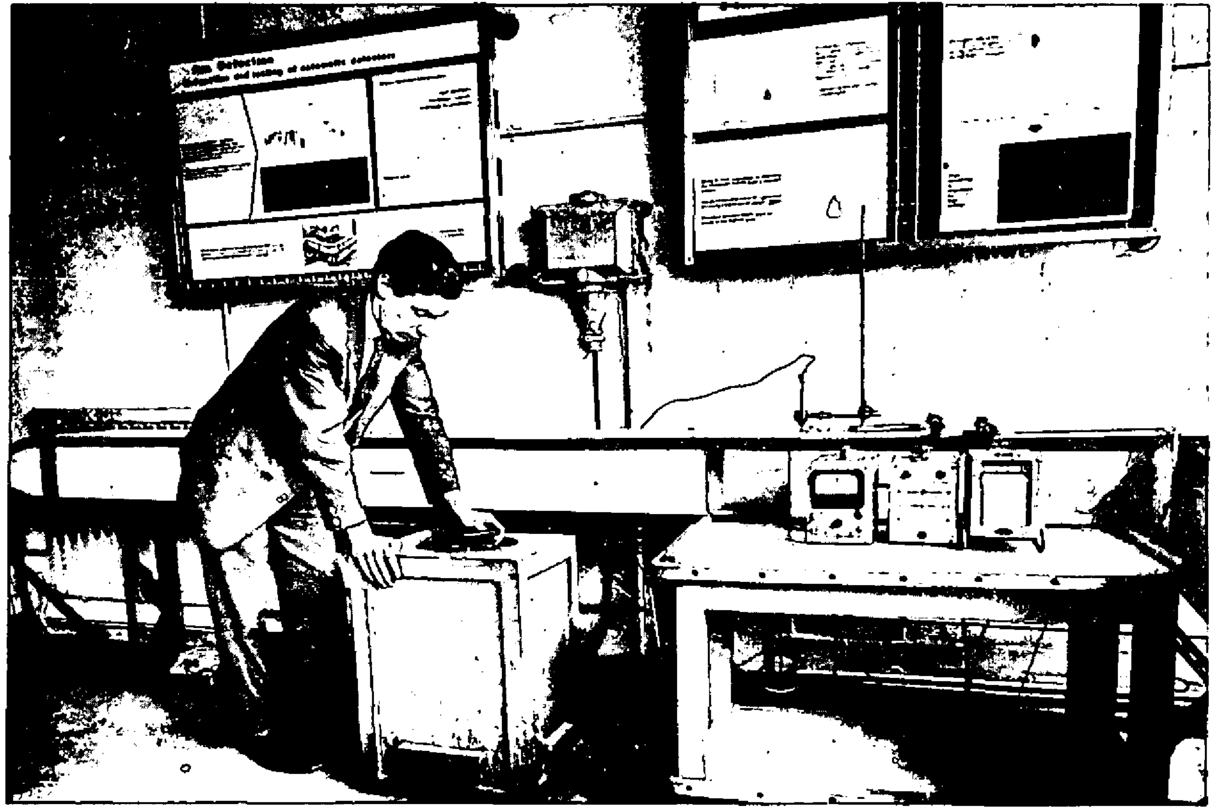

PLATE 1. WORKING SECTION OF WIND TUNNEL