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Developments in Air Pollution Measurement

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I. AIR POLLUTION MEASUREMENTS

Developments in air pollution measurement

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The behaviour of plumes from tall chimneys is now fairly well understood. To achieve this understanding it has been necessary to develop high speed recording devices for sulphur dioxide concentration and plume height and to use recorders of atmospheric turbulence and temperature profile at heights up to some hundreds of metres.

Instruments for pollution control, in particular the control of dust, have a different requirement. They must be simple; and in addition must measure meaningful functions of the basic variables rather than a single variable. A dust gauge has been developed which measures in the field a function of dust concentration, dust velocity and particle size, and is also dependent on wind direction. The function is considered to represent the 'nuisance value' of the dust emission. A dust monitor has been developed which measures, before emission, the same function of the dust variables, and can be used for emission control. It supplements the smoke meter type of instrument which measures a different function of dust concentration and particle size. The zero stability of both instrument types has been studied and improved.

The averaging time of a measurement is an important conception both in the investigation and the control of pollution. In monitoring instruments it must be related to the 'integrating time' of each type of complaint. This is the time required for a pollutant to produce its full effect from an arbitrary starting time.

Measurements in the field

The study of air pollution started with field measurements to establish the overall effect produced by a multitude of sources. The sulphur candle and the standard deposit gauge provided the bulk of these early measurements, and although it is both easy and proper to criticize these instruments now, there is no doubt that they were invaluable in their day. More recently the sulphur dioxide bubbler (B.S.S. 1747: 1963) and the C.E.R.L. (Central Electricity Research Laboratories) directional gauge (see figure 1) (Lucas & Moore 1964) have provided more rapid and more meaningful results, but the quantitative understanding of air pollution, and effective action, would have been impossible without the development of methods which permitted the study of individual sources and the build up of air pollution theory.

In the last ten years sulphur dioxide recorders both as single units (Cummings, Redfearn & Roberts Jones 1965) and in geometrical arrays (see figure 2) (Lucas, James & Davies 1967) have been used to establish the pattern of sulphur dioxide ground level concentration around large single sources. The importance of the thermal rise of the plume has been recognized and has been measured by photographic observation, by the use of tracer balloons (Lucas, Spurr & Williams 1957), by the use of instruments based on search lights (Lucas *et al.* 1967), and more recently on lasers (Hamilton 1967). The tracer balloons, followed by a range finder on the roof of the power station, made a remarkably simple and effective technique and first established both the very considerable rises from large sources, and the fact that the rise continued for distances up to 1.6 km (Lucas, Moore & Spurr 1963).

The laser, a very powerful recent development, is considered in the paper by Dr Hamilton (this volume, p. 153).

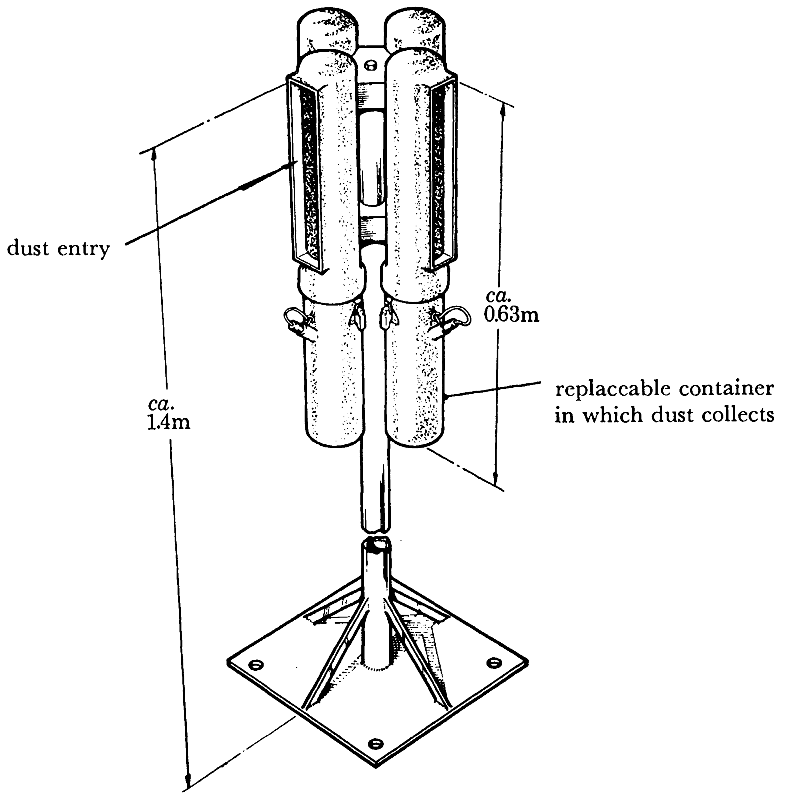

FIGURE 1. C.E.R.L. directional dust gauge.

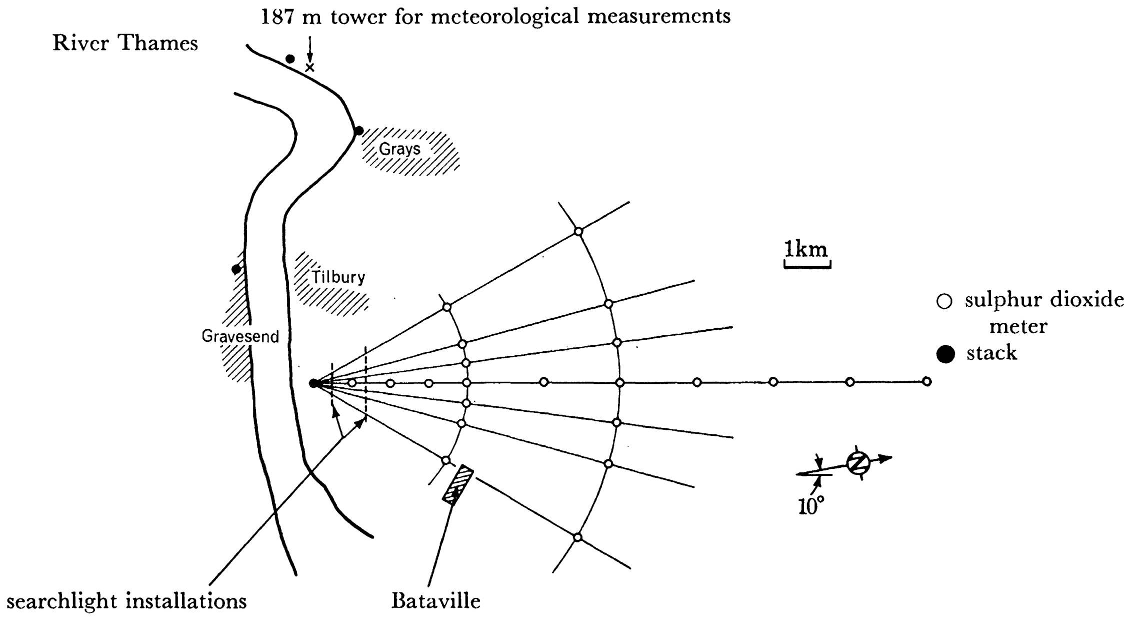

FIGURE 2. Array of sulphur dioxide recorders used at Tilbury power station.

Perhaps the most vital and expensive step in disentangling the mysteries of plume behaviour has been the development of the use of tall masts to carry meteorological instruments at heights which now range up to 385 m. These masts are expensive and in most cases it has been essential to use existing masts: particular cases are the 187 m mast at West Thurrock (see figure 3), used to carry the 400 kV grid lines across the Thames, and the 385 m mast at Belmont (see figure 4) used as a television mast by I.T.A. and B.B.C. The main cost of the mast, which is many hundreds of thousands of pounds, is not a charge on the experiment, nevertheless the cost of instrument wiring and installation runs into tens of thousands of pounds. The variability of temperature,

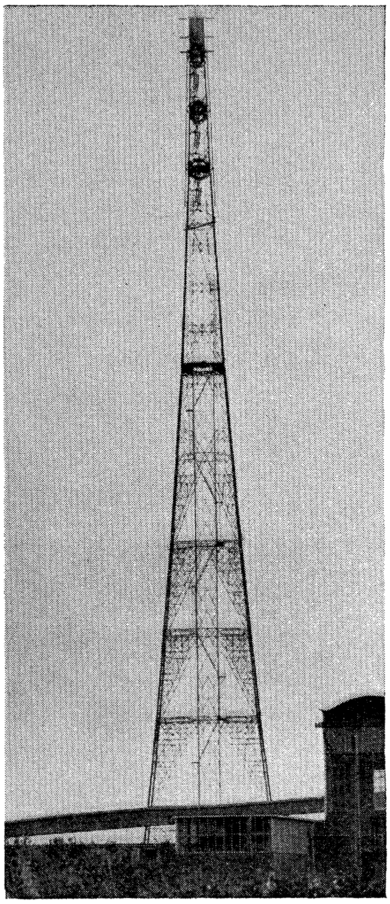

FIGURE 3. The 187 m Thames crossing tower at West Thurrock used to carry meteorological instruments.

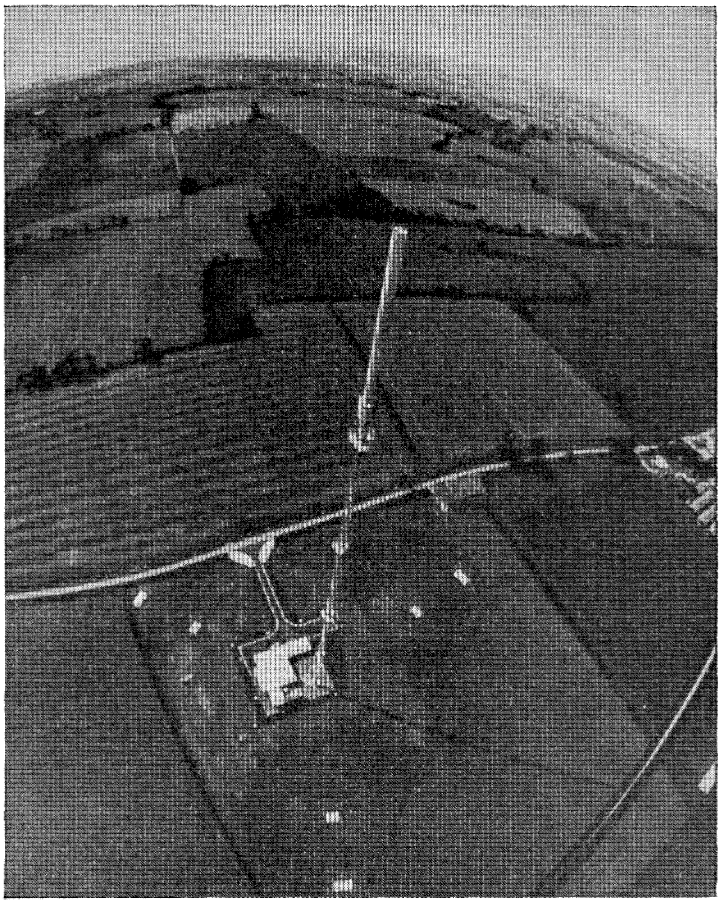

FIGURE 4. A 385 m television mast similar to one at Belmont used to carry meteorological instruments.

wind velocity and turbulence with height is so important in the rise and dispersion of a plume that detailed knowledge of the variation is essential to a proper study.

When the wind and temperature profiles of the atmosphere are known up to heights of about twice the chimney height, it is usually possible to make a scientific correlation between emission from the chimney, the thermal rise of the plume and the concentration of sulphur dioxide at ground level. I feel that our work in this field (Lucas 1967; Moore 1967; Hamilton 1967) is reasonably reliable, and it is to be regretted that there is still considerable disagreement internationally about the dependence of plume rise on the wind velocity and the rate of heat emission from the chimney. I think this is mainly due to the uncritical acceptance of plume rises measured too near the chimney. I would like to suggest that future analyses should comply with the following conditions:

(1) The rise should be measured at, or extrapolated to, a horizontal distance of ten chimney heights from the source.

(2) That for wind speeds below 3 m s^{-1} the temperature profile of the atmosphere should be known up to the height of the plume.

(3) That in any regression analysis of the data from different sources, the height of emission should be recognized as a variable.

If these conditions were observed, I would expect good agreement between different observers and good agreement with at least one current theory.

Averaging times

In specifying observed or permissible pollution concentrations it is important to take account of the extreme variability of the signal. Concentrations are commonly specified without indicating whether the concentration is a mean value or a maximum value and often without realizing that even a maximum value is an average over a time determined by the measuring method. If one takes sulphur dioxide concentrations as an example, there may be peak concentrations lasting for periods of seconds, but it is not practicable to measure these values, and the value actually recorded on sulphur dioxide recorders is averaged over about 3 min. In specifying an acceptable concentration it is usually implicit that the level is the *maximum* reading obtained over a period of several hours using an instrument with an averaging time of 3 min. By the use of arithmetical methods or instruments with longer averaging times it is possible to assess the maximum concentration from a particular source with a wide range of averaging times. Table 1 gives the

Table 1. The effect of the averaging time on maximum concentrations

averaging time	max. concn for 1 *a* from large single source	max. concn for 1 *a* from large area source
3 min	C	C
1 h	$\frac{1}{2} C$	$\frac{1}{2} C$
24 h	$\frac{1}{12} C$	$\frac{1}{3} C$
1 a	0.01 C	$\frac{1}{25} C$

relation between the maximum concentrations obtained from a large source with different averaging times based on the experimental results obtained at Tilbury (Moore 1967), and also an estimate of the relation between maximum concentrations for the same averaging times which would be obtained in the middle of a large city. It is important to select and specify the appropriate averaging time for a stated concentration, whether it is a measured value or an allowable level.

Plant measurements

Measurements made in the plant are very different from measurements in the field.

In the case of sulphur dioxide, it is possible to estimate its rate of emission and in the light of existing knowledge to specify a chimney height. From then on there is little point in making further measurement except for confirmatory purposes.

In the case of other pollutants, however, notably smoke and dust, the *reduction of emission* is an *additional* important part of achieving clean air and it becomes desirable to make continuous measurements of emission.

A monitor for smoke—black condensed hydrocarbon—has indeed existed for many years. It can also be used to monitor fine dust up to about 20 μm. In my opinion it has proved a disappointing instrument and I would like to consider the reasons for this.

A typical smoke meter chart obtained in a pulverized fuel power station is shown in figure 5—ignore the smoother line for the time being. It shows a signal with a very large high frequency component. It is fairly obvious that a management instruction to maintain this signal below a given level will be difficult to observe because of the extreme variability of the signal and the transitory nature of the high readings. This difficulty can be resolved by the consideration of measurement averaging times. The phrase 'averaging time' has in fact a number of different meanings. It has been used by Pasquill (1962) in the study of atmospheric diffusion to indicate the time constant of the measuring instrument which excludes the contribution of high frequency variations from the determination of the variance of the signal; and in this context he is more concerned to determine the *variance* than the mean. It can also be used when instrument time

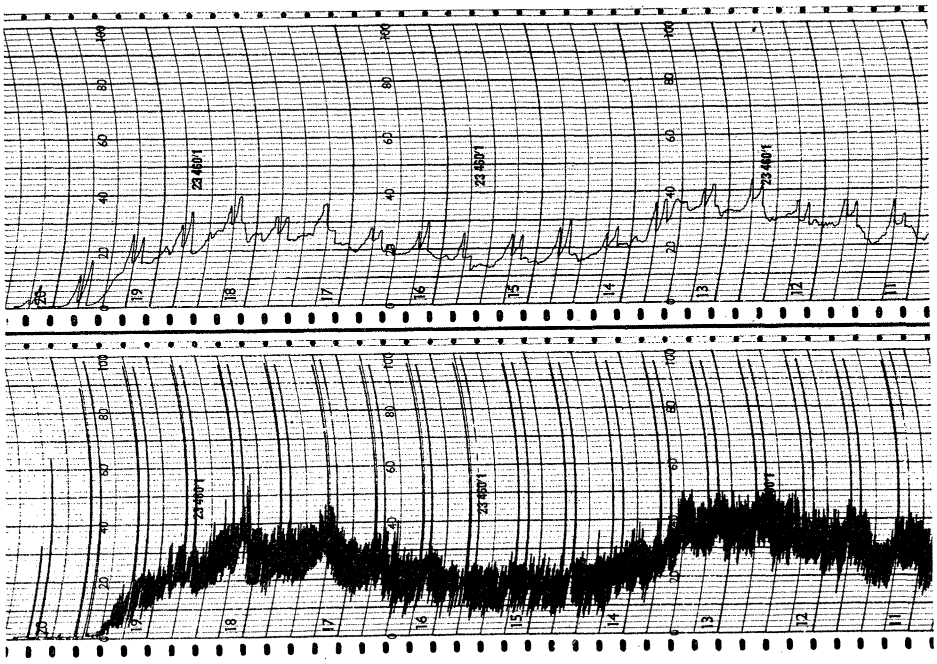

FIGURE 5. A typical record obtained from an optical density recording meter, and the same signal with an instrument averaging time of 2 m.

constants or arithmetical averaging are applied to reduce the variance of the signal so that a more useful *mean* can be determined. However, before it can be objectively applied in this way it is necessary to introduce a further conception, based on the fact that the effects of a pollutant accumulate for some period of time to produce their maximum effect. For instance, if a chimney starts to emit smoke, the plume becomes more and more visible as the length of the smoke plume increases, but after a period of time the plume reaches the limit of visibility and then ceases to appear to grow longer. The effect of the smoke is therefore integrated over a time which will be something between 1 and 15 min, let us say 5 min to indicate the order of magnitude. Similarly, if dust is being emitted and is settling on objects in the neighbourhood, the dust layer will build up either continuously or intermittently, according to the steadiness of the wind direction, to a certain level, but will then return to zero when the object is cleaned either by strong winds or by rain or by manual cleaning. The dust nuisance therefore has an integrating period which can be assessed as being on the average about 8 h.

Integrating times for other types of complaint are shown in table 2.

The integrating time of a pollutant is a guide to the appropriate averaging time for the monitoring instrument. If the two are made equal, the retrospective examination of the record is simplified without the loss of any significant information. In general the averaging time may sometimes be less than the integrating time by a small factor so that corrective action can be taken at the earliest possible moment.

If we return to figure 5 we see that if the averaging time of the instrument is increased to about 2 min from about 1 s, as shown by the second trace, a more useful record is obtained which is more likely to be taken seriously by the plant operator.

Another reason for the limited usefulness of the smoke meter has been its lack of zero stability. This has been mainly due in the past to the obscuring of the observation windows through which

Table 2. Integrating and averaging times

complaint	typical integrating time	detector averaging time	detector
smell	1 s	1 s	nose
		3 min	SO_2 recorder
visible plume	5 min	1 s	smoke meter
		1 min	Ringelmann chart
dust contamination	8 h	10 s } 15 min }	C.E.R.L. dust monitor
		1 month	directional dust gauge
plant damage	1 a (cycle of growth)	1–8 h	plant appearance
		3 min	SO_2 recorder
corrosion of metals and stone	1–10 a	1 month	sulphur candle
		1 month	corrosion specimen
		3 min	SO_2 recorder
damage to health	?	?	?

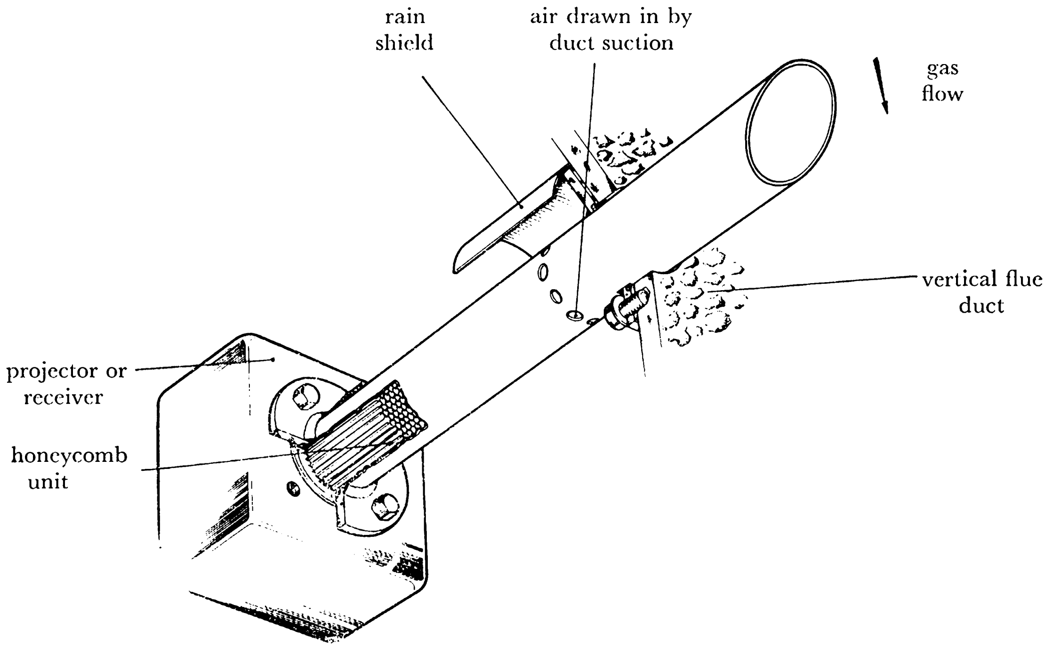

Figure 6. The Everclean window used for the observation of optical density of flue gases.

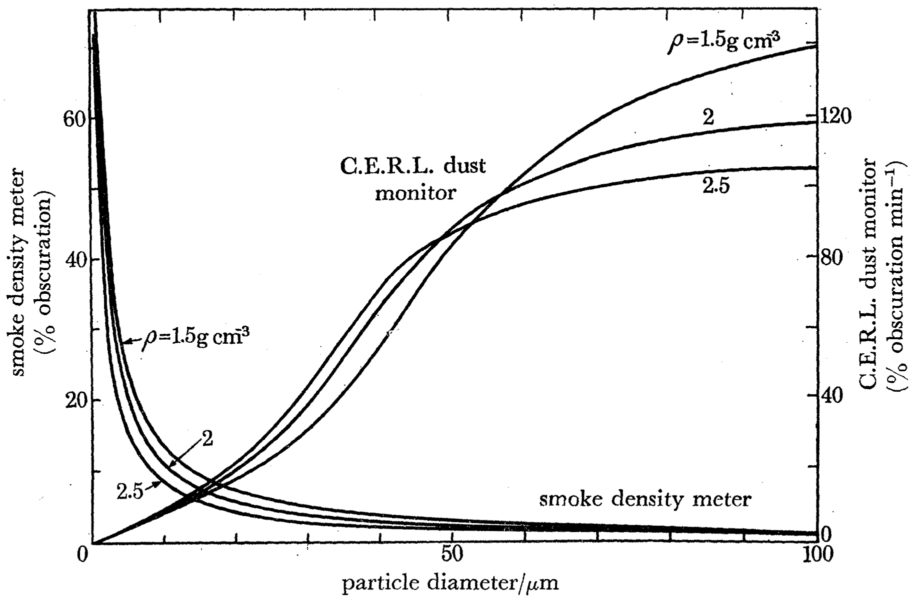

FIGURE 7. The size dependence of the response of smoke recorders and C.E.R.L. dust monitors. All curves are for a dust concentration of 225 mg m^{-3} at a gas velocity of 12.2 m s^{-1}.

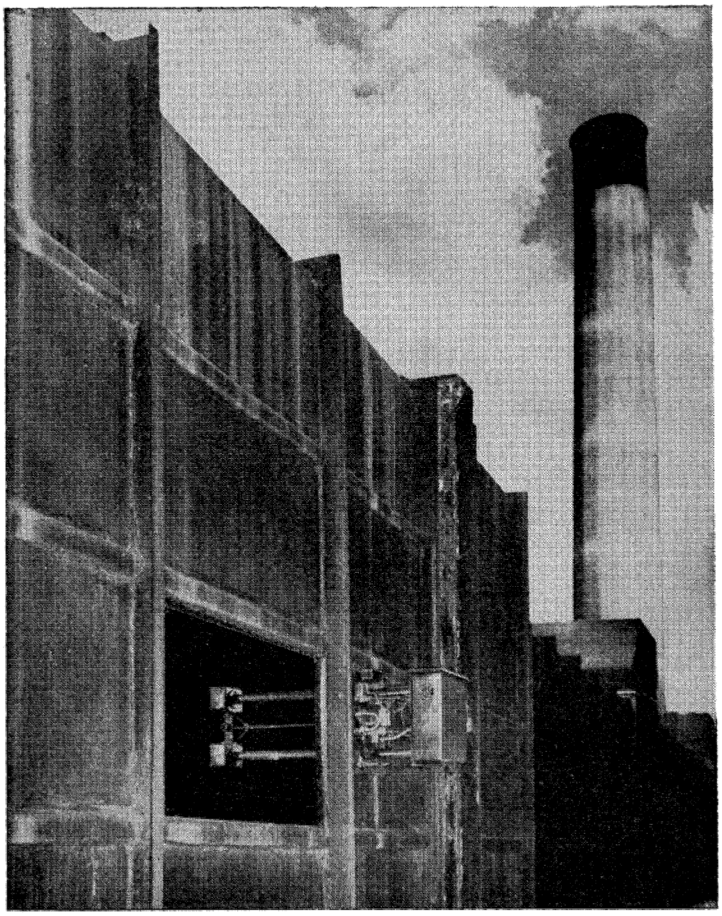

FIGURE 8. The C.E.R.L. flue dust monitor.

the light passed into and out of the duct. This can be overcome by the use of Everclean windows (see figure 6) (Crosse, Lucas & Snowsill 1961 *a*). The transport of dust by turbulent diffusion is cut down by an adequate length of tubing and the diffusion of extremely fine dust and vapours is finally attenuated by a honeycomb sealed to the glass.

The smoke meter has also been disappointing in the control of dust emission because it is insensitive to coarse dust. It responds to a function of dust concentration and particle size which is exactly the right function to indicate plume visibility at the chimney mouth. This function of particle size and particle density is shown in figure 7 (Lucas & Snowsill 1967). However, the function of dust size which corresponds to complaints of dust pollution at *ground level* is shown by the other family of curves and shows the dominance of coarse dust.

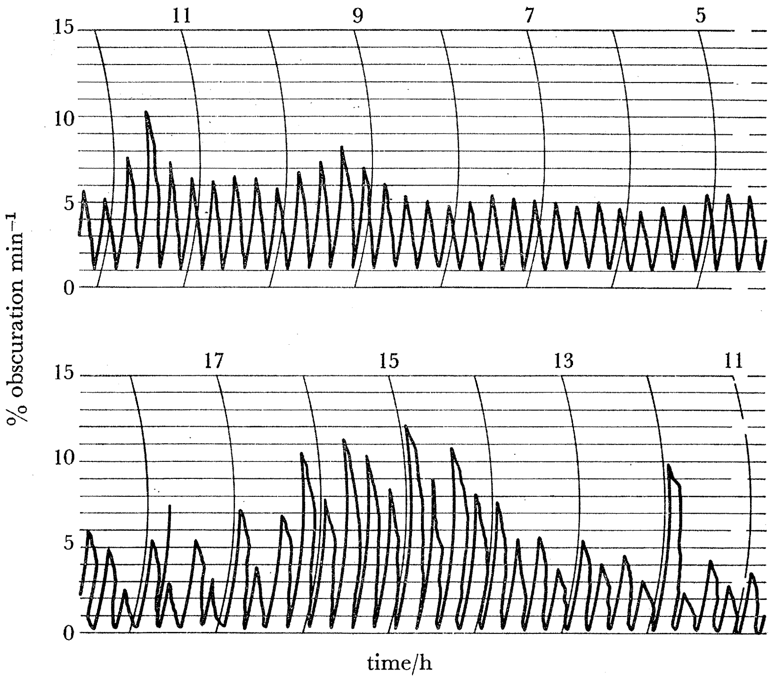

FIGURE 9. Typical records obtained from a C.E.R.L. flue dust monitor.

The requirement to monitor this complaint has been met by the development of the C.E.R.L dust monitor (Crosse *et al.* 1961 *b*) which is shown in figure 8, installed in a duct. Its response has been deliberately tailored to the second family of curves of figure 7.

The chart produced by the monitor is shown in figure 9. The saw tooth type of record is fairly novel in instrument recording. It is in fact used in at least two British and two continental air pollution instruments. The rising line shows the dust emission being integrated by the instrument until, after 15 min, the accumulated dust is blown away and the instrument reads zero. The upper peaks of the saw teeth are true 15 min integrals of the variable. The lower points are the effective instrument zero at the time. Hence even if the zero wanders it causes no error. Using the peaks of the saw teeth, the averaging time of the instrument is 15 min. The average is a true average. The 'average' of most other instruments is a weighted average, with the weighting decreasing exponentially with the time which has elapsed from the original signal to the 'present'. The averaging time is in fact the time constant of the exponential. The 15 min period is much shorter than the 8 h integrating time recommended. For the plant operator this gives the earliest possible anticipation. For the supervisor, for retrospective control, the information rate is too rapid. It is intended to print out an 8 h integral so that only three readings need be checked per day.

Conclusion

Measurement has proved vital in achieving an understanding of air pollution and in discriminating between the many theories which have been adduced. In future the emphasis will tend to shift from field measurements to plant measurements if real pollution control is to be achieved. Instruments installed in plants, besides meeting the requirements of zero stability, robustness and reliability in industrial environments must: (1) be aimed at a particular cause of complaint; (2) respond to the right function of the variables; (3) have averaging times which bear a proper relation to the integrating time of the complaint.

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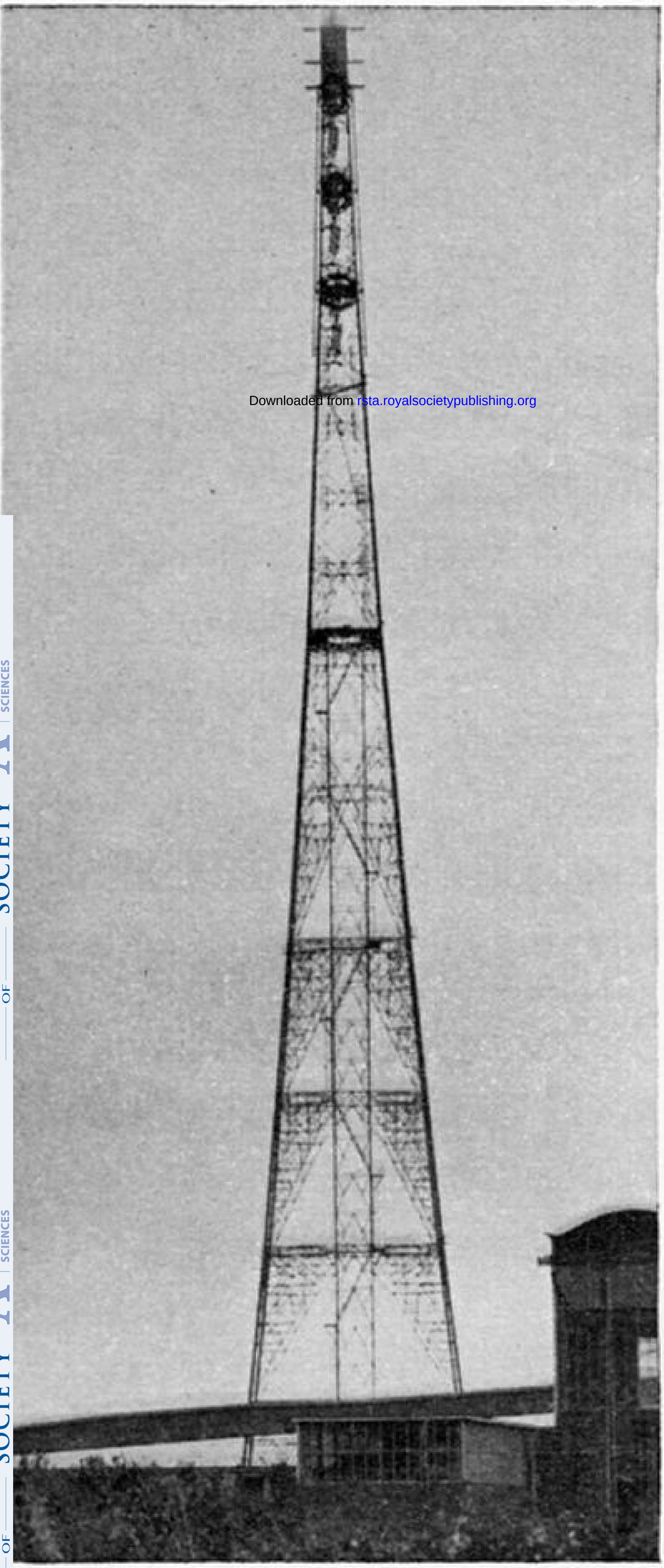

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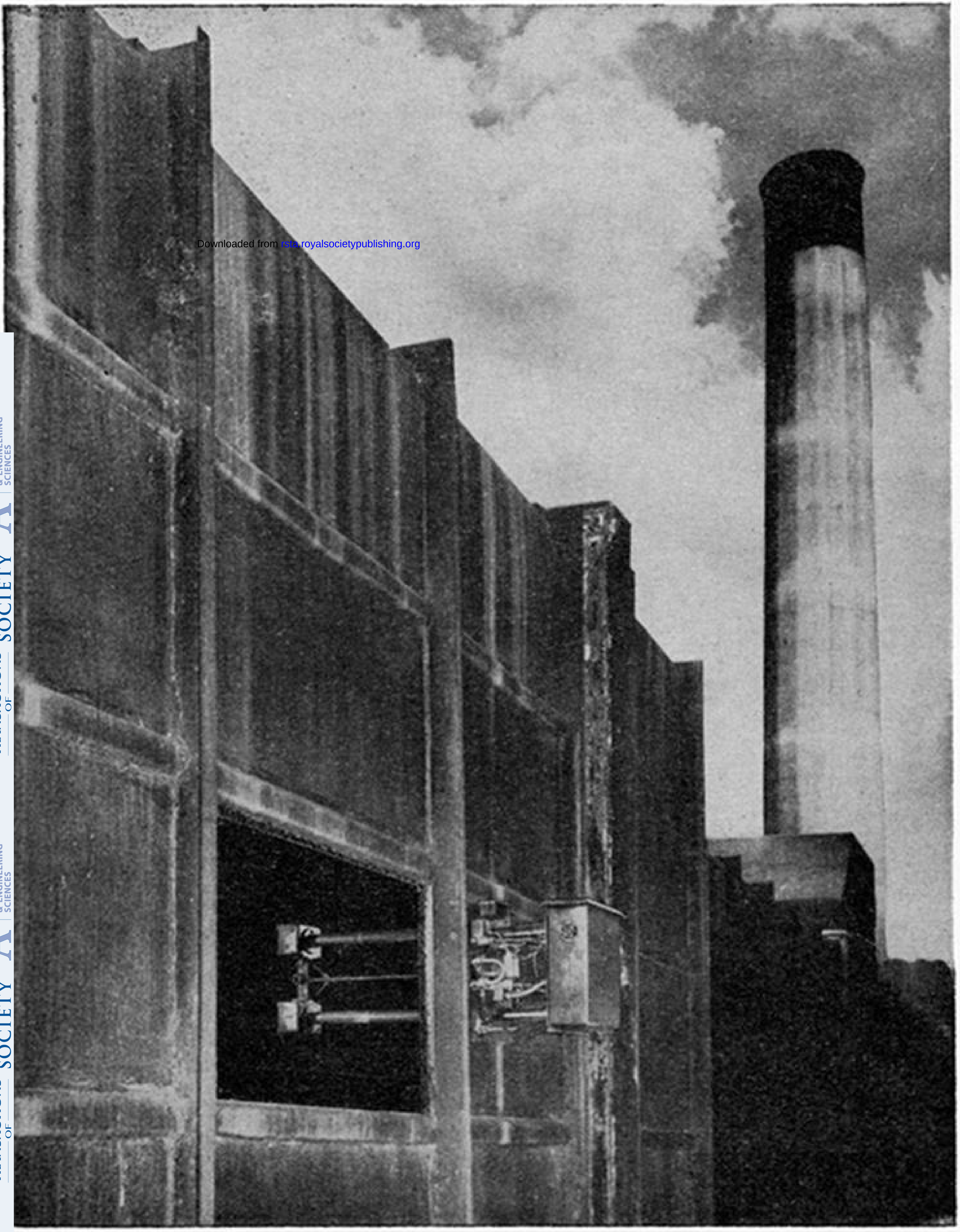

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