PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Air Pollution in the Locality of Buildings [and Discussion]

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Air pollution in the locality of buildings

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[Plates 11 and 12]

Concentrations of air pollutants at any point in a city are due to contributions from (*a*) the background level of the inflowing 'rural' air, (*b*) the 'overall' urban pollution, and (*c*) the sources 'local' to the point in question. The influence of buildings on the over-all pollution levels is effected through the heat island phenomenon and the geometry and temporal variation of the mixing layer into which the contaminants are dispersing. The enhancement of downwind dispersion of pollutants from local sources upwind is appreciated, but more studies are needed to quantify all factors involved. Wind-tunnel investigations have been demonstrated to be valuable in providing quantitative estimates of the distribution of gas concentrations in the flow field around a building complex.

1. The problem

The tensions and stresses—physical, physiological, and psychological—which stem from the increasing migration to cities of the world's exploding population are being recognized as urgent matters. This is evidenced by the forthcoming United Nations Conference on environmental problems, which will represent a landmark in man's attempt at self-appraisal and concern for his common welfare.

Of these stresses, those brought on by unpleasant odours and by irritating or even more deleterious effects of air pollution are among the more prevalent and insidious to man's health, his welfare, and his social and cultural development. However, it is not the intent of this note to dwell on the effects of air pollution—society accepts them as undesirable—but to present a brief account of what they are and features of their distributions as observed about the building complexes which comprise a city. Some conjecture is also offered on what may be in store in the next decade or so.

2. The pollutants

The air pollutants now of evident concern are the oxides of sulphur and nitrogen, carbon monoxide, hydrocarbons, and particulate matter or 'smoke'. Several of these may also be involved in the formation of 'photochemical smog', whose major components are the photochemical oxidants, a highly reactive species. A host of other substances—organic and metallic compounds, fluorides, and lead—also have been known to give air pollution problems, but their prevalence has not been as widely investigated. Radioactive pollutants do not now present a major practical problem outside test reservations or regions of reactor operations.

Combustion of sulphur-containing fuels for space heating, energy production, smelting, and other manufacturing processes is the predominant source of sulphur oxides in the atmosphere. Combustion of petroleum fuels in cars, buses and trucks accounts for 50 to 75 % of the emissions of hydrocarbons, carbon monoxide, and oxides of nitrogen. Again, combustion and industrial

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processes are the major sources of atmospheric particulates, although every square metre of the Earth's land surface is a potential source of dusts.

It is convenient and informative to classify pollutants into two general groups: (*a*) those emitted directly from identifiable sources and called 'primary' pollutants; and (*b*) those produced *in the air* by interaction among two or more primary pollutants, or by reaction with normal atmospheric constituents (e.g. water vapour), with or without photoactivation (Chambers 1968), and called 'secondary' or 'derived' pollutants.

Most of the more important primary pollutants, with the exception of CO, are known to participate in secondary transformations, either chemical, physical, or both. For instance, SO_2 is converted to sulphuric acid aerosol and particulate sulphur compounds, but little is known of the forms, the reaction times, or the atmospheric conditions involved in the transformations. The half-life of the gas in the atmosphere has been variously estimated from less than an hour to a few days, the lower values being associated with elevated levels of general urban air pollution.

The most important photochemical reaction in smog appears to be the dissociation of NO_2, forming NO and O radicals. Most of the oxygen atoms react with molecular oxygen to produce ozone, but part react with hydrocarbons and other organic compounds to produce a multitude of free radicals noxious to plant and animal life (Cadle & Allen 1970). The reaction times are of the order of 1 to 4 h, and some products such as ozone can continue to form and exist at high concentrations (over 40 $\mu g\,m^{-3}$) well over 100 km from the region of the primary sources.

3. Pollution distributions

The level of pollution at any point among the buildings of a city is the sum of three contributions. The first is due to the background or 'clean air' concentrations of the polluting substances. The second contribution is from the 'overall' urban pollution; and the third, from 'local' sources. A local source is one in which the scale of the diffusing plume has not grown large with respect to the size of the roughness elements (e.g. buildings) about which it is flowing. In other words, for a local source, the bulk transport and diffusion of its effluents are dominated by properties of the aerodynamics of the flow about nearby obstacles; otherwise the effluents become part of the overall urban pollution and their transport and dispersion are governed by larger-scale atmospheric processes. The time or distance required for the dimensions of the plume to become large compared to the roughness elements cannot be precisely stated as a function of the relevant parameters.

To put the above array in prespective, the pollution concentration range involved can be as much as two or more orders of magnitude. For instance, in the near downwind vicinity of a moderate local source of SO_2, observed short-term concentrations of the gas at ground level might be on the order of 3000 $\mu g\,m^{-3}$, the overall urban average on the order of 300 $\mu g\,m^{-3}$, and concentrations in the clean air entering the city on the order of 30 $\mu g\,m^{-3}$.

It is appropriate to discuss separately the state of knowledge on air pollution distributions about buildings gained from wind tunnels and full-scale studies. Although the latter might be expected to provide the more definite data, the lack of environment controls on all scales often render them more difficult to interpret and extrapolate. Further, in considering real air pollution, one is dealing with trace substances in concentrations usually less than 1 $mg\,m^{-3}$, except for carbon oxides. Hence the sampling and analytical techniques must be very sensitive and accurate

in the microchemical or ultra-microchemical range, and thus are highly susceptible to large systematic or random errors. In the case of two identical sampling instruments operating side by side, it has been shown that the correlation between the two sets of data may not be more than 0.7 or 0.8 because of random measuring errors (Mahoney, Maddaus & Goodrich 1969).

(*a*) *Wind-tunnel studies*

The structure of the airflow about a building has been much studied in wind tunnels, and the limitations of such investigations have been succinctly outlined by Scorer (1963). On the smallest scale of, say, an individual building complex where the turbulence field is dominated by building configuration or perturbations—this is, the effects of atmospheric stability are negligible—model

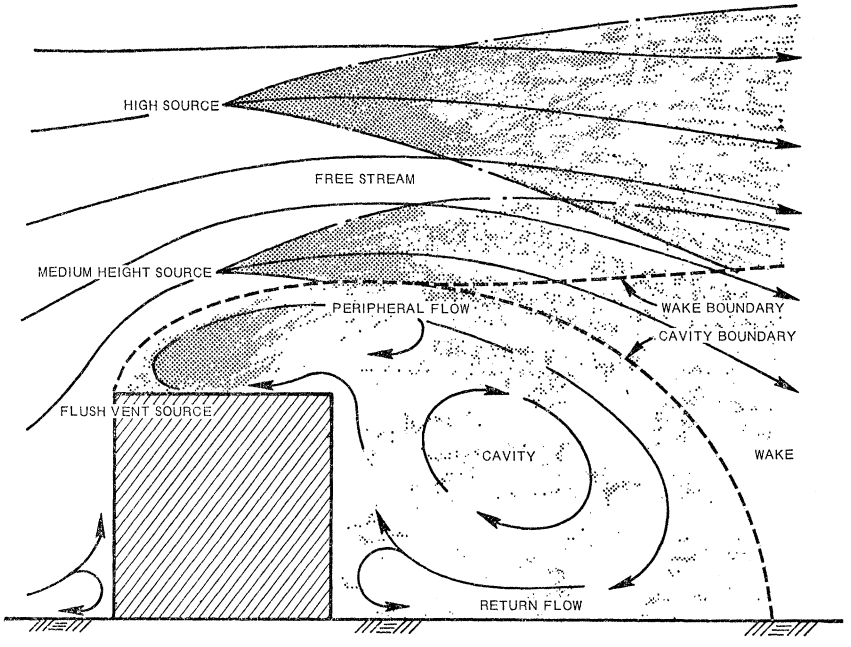

FIGURE 1. Air flow and plume patterns around a building (Halitsky 1965).

experiments on the diffusion of air pollution about the complex from local sources can be quite meaningful. Figure 1, from Halitsky (1965), is a schematic representation of the apparent essential features of the flow around a simple cubical building, and the disposition of pollutants emitted at three different locations above it as determined in a wind tunnel. Taking off from representations such as this, model laws or equations have been developed to predict the pollutant concentration fields around the surface of buildings as well as downwind from sources both internal and external to the buildings. For instance, Halitsky (1965) gives the following general equation to express the distribution of gas concentration in the flow field around a building

$$C = K\dot{Q}/AV,$$

where C is the concentration, $\dot{Q}$ the gas release rate, A the maximum frontal projected area of building, V the wind speed at roof level, and K the non-dimensional coefficient that is a function of space coordinates. It is '...approximately unity on the side walls...' where the gas is released within the cavity on the roof.

Patterns of concentrations within the building cavities derived in full-scale studies with tracer techniques have been reported to compare closely with those predicted from the equations

(e.g. Rummerfield, Cholak & Kereiakes 1967). However, at greater distances downwind in, or out of, the wake, other field data suggest that current wind tunnel modelling limitations (e.g. in density stratification and turbulence spectrum reproduction) are such as to render the technique inadequate for evaluating diffusion under the complete range of atmospheric conditions required (Dickson, Start & Markee 1969; Davies & Moore 1964).

On the intermediate and large scales (as measured in kilometres) where thermally driven circulations or even a wind turning with height must be reproduced, the contradictory hydrodynamic scaling criteria seem to impose unsurmountable obstacles. Wind tunnels with porous walls and roof might offer some elements of successful modelling by enabling horizontal convergence and divergence as well as transport to be achieved. However, the wind turning with height seems to defy reproduction within the present state of the art.

(*b*) *Full-scale studies*

The effect of buildings on the overall pollution levels, or on the dispersion of plumes grown much larger than the dimensions of individial complexes, stem primarily from their role in the determination of the geometry and temporal variation of the mixing layer into which the contaminants are dispersing. The mixing layer is defined as that layer in contact with the ground which is in near-neutral static stability. It comes about due to the diurnal solar heating of the ground and the subsequent convective motions induced in the lower layers of the atmosphere, or to the mechanical turbulence set up by the wind flow over rough surfaces. In rural areas a mixing layer will usually not exist at night except when the winds are strong. However, over cities a mixing layer can usually persist at night as the result of building influences, which give rise to the well-known heat island phenomenon (Myrup 1969). An example is illustrated in figure 2 from Clarke (1969). This is a cross-section of temperature along the direction of the mean wind obtained from helicopter soundings and car traverses near dawn on a late spring morning in Cincinnati, Ohio. Note the well-marked surface-based inversions both upwind and downwind of the city; but the temperature distribution in the lowest levels in the core area is actually about adiabatic! The upper boundary of what Clarke calls the urban mixed layer is indicated by the heavy line. Note also that the layer does not extend above the tops of several downtown buildings (heights are shown to scale), and that it becomes more stable and elevated downwind of the central city, comprising what is called a 'heat plume'. As a matter of interest, there is some evidence that pollutants emitted above the mixing layer may not penetrate down into it, and visible wide plumes of pollution downwind of cities are a common sight to air travellers.

There have been few attempts to derive thermodynamic models of the urban heat island phenomenon. Many more observational data are needed to determine the salient parameters and their magnitude which must be reproduced. As an example, the suggestion by James & Moore (1968) that the urban surface above 150 m should be described in thermal terms rather than by a 'roughness length' is an intriguing one and should be explored. The task will still remain to specify the relationship of model elements in the general distribution of air pollutants about the city buildings—and Summers (1965) and more recently Leahey (1969) have made laudable initial tries.

Fortunately some simple approaches can be revealing and of more immediate application. In situations of comparable ventilation rates by the wind field, the depth of the mixing layer is an index of the volume into which the pollutants will be mixed. The ambient concentrations of most pollutants will then be inversely related to this index, so that its magnitude is an important

parameter of actual or potential urban air quality. The recent experience of London is an excellent case in point. Chandler (1968) reported that as the result of the smoke pollution abatement measures over the past few years, the emissions of sulphur dioxide over London have increased but the ground-level concentrations greatly decreased! G. D. Robinson (personal communication, 1970) has ascribed this anomaly as being brought about by a general increase (in the climatological sense) in the mixing layer depth because of the enhanced convective activity resulting from the solar heating of the ground now provided by the more transparent atmosphere of the city.

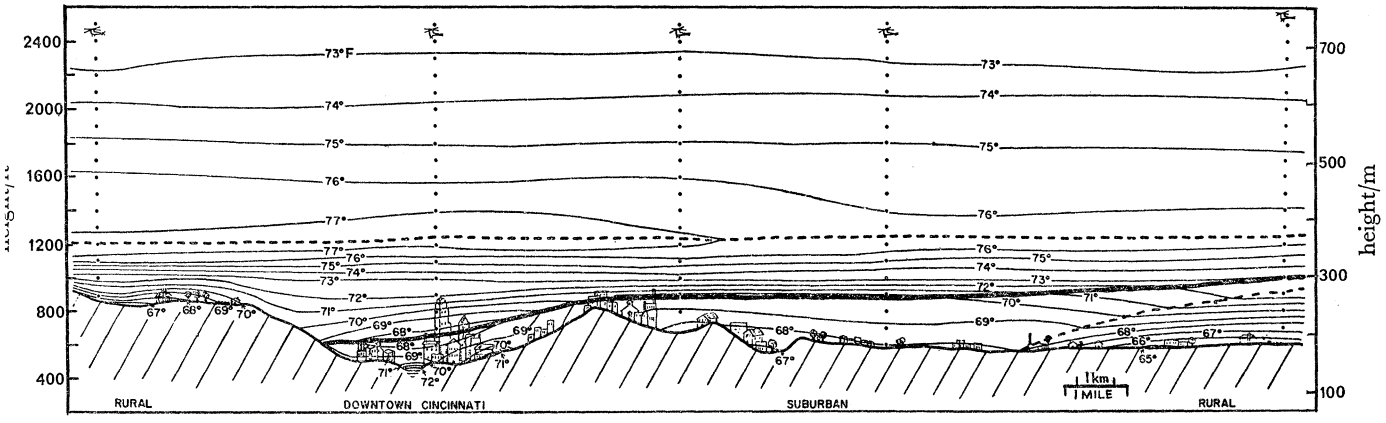

FIGURE 2. Cross-section of temperature structure for 13 June 1967. The top of the urban boundary layer is indicated by the heavy solid line. The dashed lines indicate a temperature discontinuity with less stable air above. The dots alined vertically show the locations where helicopter temperature measurements were obtained. The schematic representation of the height of the buildings is roughly to scale (Clarke 1969).

In another context, by combining the mixing depth with a ventilation factor, meteorologists have operated a successful quantitative air pollution potential forecast scheme for some time in Philadelphia, Pennsylvania. The forecasts correlate well with observed SO_2 data '...representative of city-wide trends' (Finkelstein 1970).

On the other hand, the inverse relationship between the mixing depth and pollutant concentration does not hold well for photochemical smog. Because of the reaction-time requirements, the maxima of the reactive oxidants generally occur near noontime or shortly thereafter when the insolation-driven mixing depth is approaching its maximum.

Gross features of the distribution of primary pollutants over a city usually correspond to the distribution of corresponding sources and wind drift in a manner that might be expected. The details, however, are often not at all straightforward, since the concentrations at any individual site or sampling station can be dominated by diverse local sources. The maxima of the *total* atmospheric burden of pollution are almost invariably to be found in or near the 'core area', although those of individual components may be quite scattered about. The emissions from cars are the most important case in point, as the components are primarily determined by the driving cycle and the total amount by the traffic density. On motorways or through streets where driving is primarily in the cruise mode, the exhausts are low in hydrocarbons and CO but high in nitrogen oxides. On the other hand, in the central parts of the city where stop-and-go driving is predominant (i.e. mostly in the idle mode), the exhaust is high in hydrocarbons and CO (Ludwig 1967).

The distribution of ground-level maxima of secondary or derived pollutants, which are formed

in the atmosphere, can be far removed from the principal source regions of the primary reactants. The formation of photochemical smog, for example, involves processes of vertical diffusion, horizontal advection, and finite-rate photochemistry with characteristic times on the order of 1 to 4 h. This would allow a downwind drift of perhaps many kilometres before the reactions would be complete. Conversely, the decay of SO_2 in a heavily polluted urban atmosphere by oxidation or absorption would tend to bring the maximum from an elevated source closer to the place of origin than would be true of a stable contaminant.

As was mentioned, pollutants emitted above the mixing layer may remain aloft during transit of the city. During settled weather conditions elevated plumes travelling in the stable region can maintain their integrity for tens of kilometres, again as every observant air traveller knows. The course of the plumes can be reasonably steady, and problems can result if they fan across tall buildings projecting high enough above the mixing layer. In addition, there may be elevated heteorogeneous patches of pollutants drifting about of fairly broad extent but only of several metres depth, formed by circumstances of elevated emissions and wind shear and stability. Measured concentrations of SO_2 (Davidson 1967; Georgii 1969) and particulates (Barrett & Ben-Dov 1967) in such plumes or layers over cities have exceeded 2 and 3 mg m^{-3}, respectively. Hence the coincidence of such with the level of air intake of a building could have most unpleasant consequences; it has been known to seriously interfere with work schedules for construction of tall buildings (I. A. Singer 1970, personal communictation).

Few systematic investigations of the three-dimensional distribution about buildings of pollution from *local* sources have been undertaken. In part this has been due to the primary concern by air pollution agencies in concentrations at the street or 'breathing' level; in part it is due to the technical difficulties and high cost of obtaining representative and adequate data in the vertical. One of the most significant studies was conducted above and among the streets of Frankfurt/Main on the distribution of CO from car exhaust (Georgii, Busch & Weber 1967). The investigation showed a '. . . significant relation between the ventilation of the streets and wind speed and direction'. This relation is shown in figure 3 from Georgii (1969), which gives the mean circulation patterns and CO distributions for wind speeds less than, or greater than, 2 m s^{-1}, respectively. Note the marked horizontal and vertical gradients of the gas, particularly under light wind conditions. It was concluded that while the accumulation of pollutants also depend upon the heights of the buildings and the width of the streets, wind velocity was the most important factor in their dispersion. In Frankfurt, a wind speed of at least 5 m s^{-1} was said to be required to achieve a 'complete ventilation' of the streets. The extent to which the Frankfurt results can be generalized is a matter for speculation, but certainly they are indicative and can provide qualitative guidelines. The decrease of CO with height, for instance, was found to be exponential, in agreement with similar data obtained to 25 m above the streets of West Berlin (W. Fett 1968, personal communication). It has been found that aerosol materials decreased with height in that manner over Cincinnati (McCormick & Baulch 1962). On the other hand, concentrations of CO and 'photo-oxidants' measured on the balconies of the eight and twelfth stories of apartment houses located on major streets in Moscow did not differ significantly from those at street level (Fel'dman & Lampert 1968). Other fragmentary data on the vertical variation of pollutants also exist, but in total they are not sufficient to allow a comprehensive picture of cause and effect to be extracted.

There is some evidence (see, for example, Peterson, Paulus & Foley 1969) that the mean size of aerosol particles increases with height in the mixing layer, although the mechanism which

brings this about is uncertain. Aside from the effect which such a distribution change might have on optical properties of the atmosphere such as visibility, there might be toxicological consequences on people living in high-rise apartments since size is important in determining the irritant potency of some submicrometre particulates.

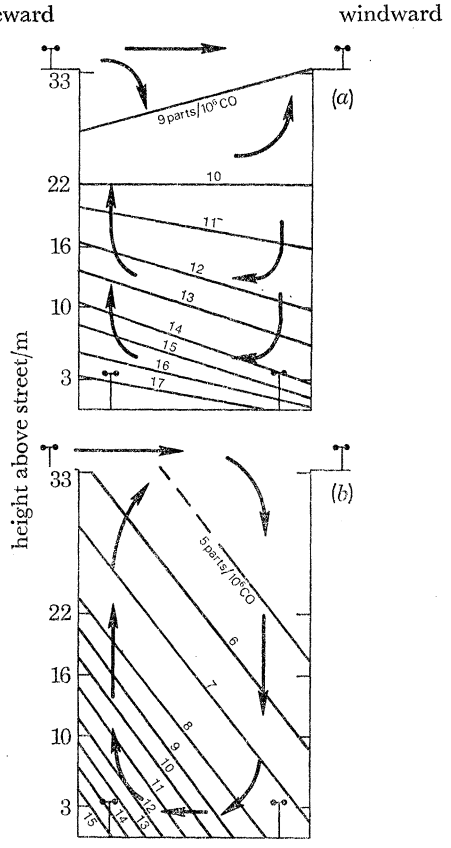

FIGURE 3. Air circulation and CO distribution above streets at wind speeds (*a*) $< 2\,\mathrm{m\,s^{-1}}$ and (*b*) $> 2\,\mathrm{m\,s^{-1}}$. (After Georgii 1969.)

In relation to the effect of buildings in dispersing local sources, a study of tracer material released for 1 h periods near the ground in a major city showed that the urban setting affected the cross-wind diffusion primarily by enhancing the size of the initial plume (McElroy & Pooler 1968). At 1 km from the source, which was the distance to the first arc of sampling, the plume was already large compared with the vertical dimensions of the buildings it was passing over. The standard deviations of the tracer material in the cross wind and vertical directions (the latter derived, not directly measured) were of the order of 100 m. The subsequent mixing was also enhanced such that at 10 km the surface concentrations were about one-third lower than those which might be expected over smooth terrain.

The role of buoyance forces in the dispersion process at the longer distances of travel over heteorogeneous buildings is not clear. Their importance probably depends on height and on the degree to which heat-island manifestations have developed. Clarke's data and others' hold strong inference that in the core areas a ground-based, near-neutral stability layer might be expected most of the time in the lower 50 to 100 m or so.

(*c*) *Indoor–outdoor relationships*

The study in Moscow disclosed that the '...one time maximum permissible concentrations...' of NO_2 and CO were persistently exceeded on the eight- and twelfth-story balconies of the apartment houses, as well as at street level, and O_3 concentrations were '...double the olfactory threshold'. The CO 'excess factor' was nearly an order of magnitude. Reports such as this bring up the important question of the pollutant concentrations to which the building *occupants* may be exposed. Essentially three classes of factors determine the relative concentrations affecting building occupants: (*a*) those influencing the outdoor concentrations about the buildings which have been outlined; (*b*) those influencing the exchange of outdoor and indoor air; and (*c*) the amounts and types of pollutants generated within the building by cooking, heating, etc.

Provision of filters in the air inlet or recirculation systems can give partial protection against some pollutants, particularly aerosols. Most buildings are not so equipped, however, and Calder (1957) has analyzed the susceptibility to aerosol penetration of several classes of common buildings, i.e. private dwellings and public facilities. He concluded that '...the inside dosage depends primarily on the magnitude of the total outside dosage, and not on how the latter quantity is accumulated as a function of time'. I have not found any relevant studies that contradict that conclusion. Most reports of indoor–outdoor measurements are based on grab-samples or 'instantaneous' concentrations. The results of these studies are highly variable but, in total, they show no significant differences that are not influenced by sources or sinks of pollutants in the buildings.

Present trends in construction of buildings with multi-level parking garages, which constitute large volume sources, and air-rights structures over motorways do not help matters. Both can creat increased risk situations within the buildings in which established air quality standards can be exceeded (National Air Pollution Control Administration 1967).

4. Outlook

Much work must be done to uncover all we would *like* to know about the interrelationships among building topography, source distributions, meteorological factors, and air pollution concentration fields. If the present state of knowledge is only indicative, it has, nevertheless, revealed no mysteries. As in other fields of science and technology, advances will come after the right questions have been posed and investigated. Not all of the questions that we have asked in air pollution survey and research studies have been outstandingly perceptive or imaginative. We would be better advised perhaps to be less concerned with obtaining statistical correlations among data of sometimes questionable relevance and more concerned with studies offering promise of providing physical insight. Understanding of the whole problem of secondary pollutants is an outstanding example of where this shift in research emphasis is desirable. Here, as elsewhere more comprehensive efforts are required that have *cooperative* input in design and execution by chemists, engineers, meteorologists, and physicists commensurate with the real scope of the complexities. In questions of air resource management, air pollution control officials should also be consulted in order that no effort is wasted on attempts to answer questions that no one asks. In this connexion, one can distinguish between what one needs to know to answer questions relative to the dispersion of pollution from local sources, and what one needs to know about the overall distribution of pollution over a city to answer questions related to air

resource management on the larger scale. The former may never be completely generalized in quantitative analytical terms because of the varying complexities, whereas the modelling of mean pollutant distributions over a city on time scales of a few hours or longer has been demonstrated to be possible (see Wanta 1968).

Within the course of the next ten years it is quite possible that vehicles powered by diesel and petrol fuels will be prohibited by law from operating in the core areas of major cities. Although such a step may be taken for several reasons, it would eliminate major sources of primary air pollutants in such areas. One can also hope that the incentives will be great enough that the present engine will be essentially 'clean' or that a new type of engine is developed or other fuels brought into use, so that all new vehicles will be 'pollution free' in the not too distant future.

It is not realistic to believe that air pollution considerations alone will be sufficient to discourage the erection of air-rights structures or multi-level garages in apartments and office buildings, even in the face of the potential hazards. We can expect that vehicle-use regulations of the type anticipated will help mitigate these problems in the core areas. It is a different story in suburbia, and the air pollution from cars and trucks will continue to be a problem until the pollution-free energy converter is a practical reality. I see no evidence of a tend by the public to give up private cars in the foreseeable future. As a point of interest here, many voices in the United States are urging a prohibition of the manufacture of 'big' cars. However, the abatement of air pollution is not among the merits such a step might have. Comprehensive tests among all sizes of cars have shown no significant relationship between vehicle weight and mass emission of pollutants per kilometre of travel (Rose 1970).

Another major air pollution problem facing us and our children—and perhaps our grandchildren even more seriously—is that presented by fossil-fuel-burning electric power generation stations. The trend over the world to spend millions building tall stacks and only thousands for research to eliminate the noxious effluents is to be deplored. A tall stack gives license to pollute the atmosphere in unprecedented quantities without regard for the consequences beyond the back garden fence. The greatest apprehension right now is because of the fact that the ultimate consequences of the enormous emissions of SO_2 are unknown. Sulphur dioxide is converted to sulphuric acid aerosol and particulate sulphur compounds, and more studies are needed on the effects of these products on man, animals, plants, materials, visibility, haze formation, and precipitation composition on regional to global scales. We need to know how much of the world-wide increase in atmospheric turbidity is associated with particulate sulphur originating from pollution sources.

The role of architects and engineers who design buildings and plan complexes must continue to be that of avoiding or correcting problems of pollution from local sources. Wind tunnel studies are quantitatively informative in evaluating the distribution of gas pollutant concentrations in the flow field around a building. The effect of a building complex in enhancing the downwind dispersion of effluents from upwind local sources is recognized, but further studies are required to express the phenomenon in terms of atmospheric diffusion parameters appropriate to the boundary conditions of building geometry and meteorological factors.

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Discussion

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One aspect of architectural aerodynamics which has not been mentioned is the blackening of buildings. Architects have found it desirable in recent years to break up large flat areas of wall with arbitrary designs in order that their intended plainness should not be spoiled by streaks and blotches of darkening by pollution.

The blackening is usually organic in origin, and is not a simple deposition of black material. Some buildings show that areas which are well washed by rain and quickly dried are kept clean; places where wetting occurs but drying out takes place slowly, such as shadowed areas, or areas which are wetted but not washed, and not well dried by wind, turn black. North-facing walls and areas under sills are particularly susceptible.

In figure 4, plate 11, the Daily News building in Chicago is seen to be most blackened in the middle of its flat face where the air presumably stagnates more than at the edges which are more quickly dried. In figure 5, plate 11, the corner of the Chicago Opera House shows discrimination on the scale of a few centimetres. I suspect that the clean area close to the corner is produced by the blowing of rain to the corner after which it runs down in the calmer area of the eddy

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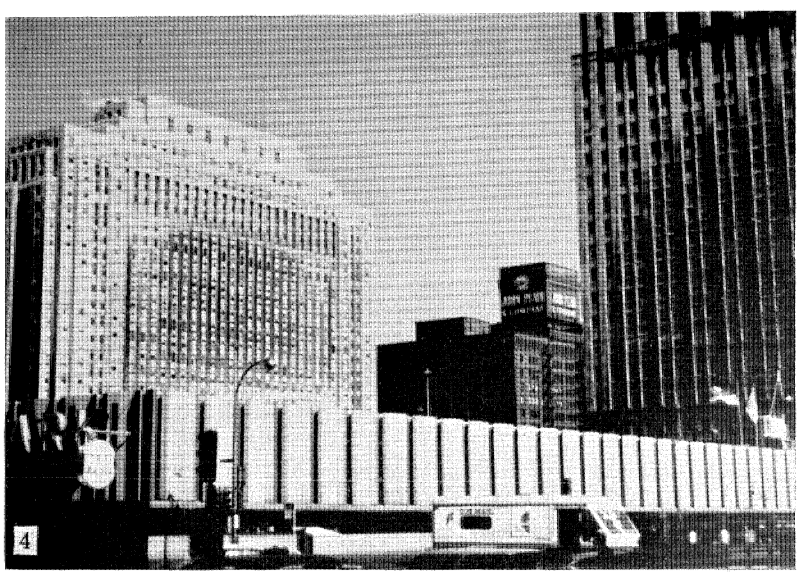

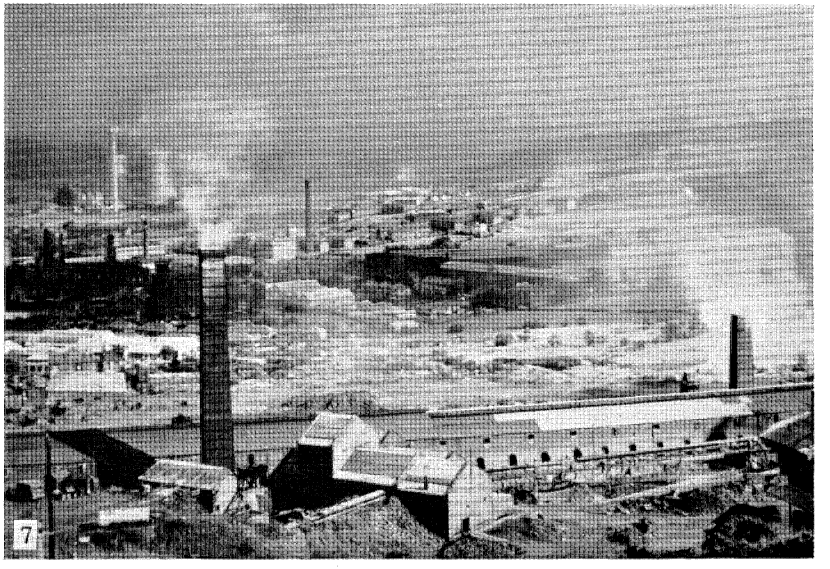

(*Facing p. 524*)

FIGURE 4. Darkening of the Daily News building in Chicago.

FIGURE 5. Darkening of the corner of the Chicago Opera House. The stone close to the corner is washed by running rain concentrated there by the airflow which separates at the corner.

FIGURE 6. Haze accumulated over Tyrone, next to Bald Eagle Mountain, Pennsylvania, from the pulp mills.

FIGURE 7. The power station, whose chimney is level with the surrounding hills, and a brickworks were the low efflux velocity causes entrainment of effluent into the chimney wake, at Elland, Yorkshire.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

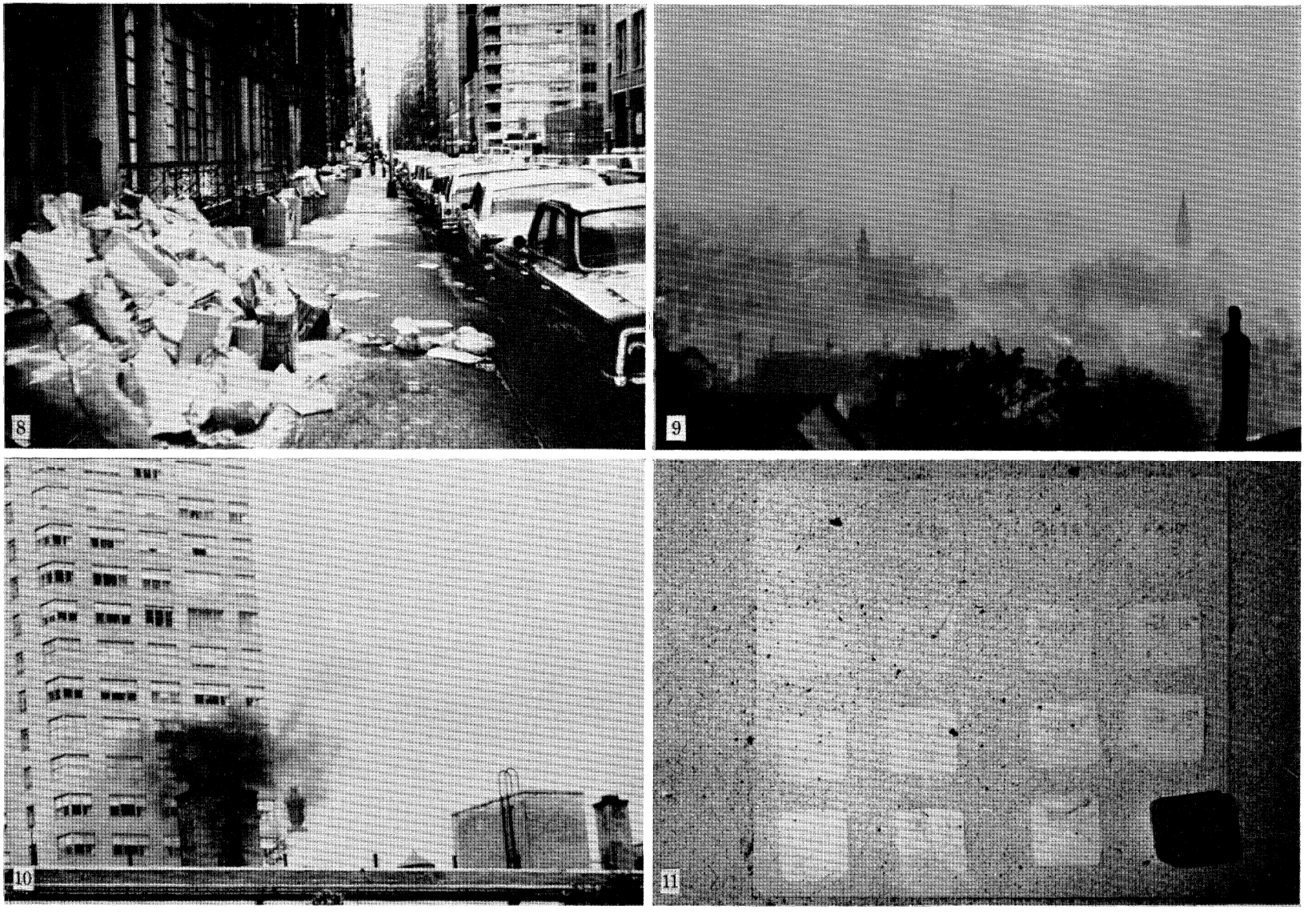

FIGURE 8. A Manhattan street during the Garbage Strike of 1968. Cars parked to maximum density.

FIGURE 9. Domestic smoke accumulated over Lincoln. Most of the pollution observed in the streets comes from sources within 200 metres or so, and dilution is mainly by upward diffusion.

FIGURE 10. Smoke, dust, and ash, from domestic incineration in Washington Square, New York.

FIGURE 11. Carey's dinginess experiment in Washington Square showing the large particle size of the deposit.

produced by separation at the corner. The effects are thus a combination of wind, wind-blown rain, and sunshine.

The discoloration of surfaces in this manner is certainly not intended. The chemistry of the blackening is unknown in detail, and it can be radically altered by drips from lead or copper pipes, roofing, and fillets, iron nails, plasters of varying chemistry, and stone of various stratification in relation to the face. Nevertheless, the aerodynamic effect is equally a major factor in determining the shapes that emerge.

Dr Craxford has mentioned with justified satisfaction the reduction of smoke. In addition to the medical reason he mentioned, this is important because particulate material alters the radiation balance of the air and makes the layers below the top of a haze cooler. The chief effect of this is to increase the accumulation of pollution emitted below a haze top and to reduce the incidence of thermal convection which is the main agent for dispersal upwards, which is much more important than any other mechanism of dispersion because only after upward dispersion can the pollution be rained out. This effect is most pronounced in valleys enclosed by hills and figure 6, plate 11, shows an example of this—the haze due to the pulp mills at Tyrone in an Appalachian valley in Pennsylvania. Quite frequently the air in this valley is made several degrees colder than in the neighbouring valleys, and often a wet cloud is formed, which makes things worse. Thus the local climate is altered significantly.

In order to avoid this result it is desirable for chimneys to emit their plumes above the surrounding hills. This is not practicable at the Tyrone mills but has been achieved at Elland power station, near Halifax, seen in the distance in figure 7, plate 11.

This picture also shows a brickworks which illustrates the entrainment of the plume into the wake of the chimney when it is too wide and has too small an efflux velocity. This kind of effect is very suitable for wind tunnel investigation.

Figure 8, plate 12, shows a street in New York after one week of the garbage men's strike of February 1968. It illustrates two urban problems, cars and rubbish. It is nonsensical to extrapolate the car density from past trends without reference to the maximum which would be reached either because traffic density makes the possession of a car no advantage or because the population has as many cars as it wants or can park overnight. Since we have reached one or both of these limits part or most of the time in some parts of some cities we actually know what the worst pollution will be because the pollution from sources within the city where the inconvenience due to them is felt is almost entirely due to sources within 400 m or less of the point of observation. Thus more distant sources do not account for much and the maximum achievable pollution is achieved in the areas where maximum car density is already reached. On this basis we can plan new street development, and it is important not to increase the density of fully used roads in such a neighbourhood.

The fact that most of the ground-level pollution from densely distributed ground level sources is due to the sources in the immediate neighbourhood (in some cases even 80 % might be due to sources within 100 metres upwind of the observation point) is illustrated in the picture of Lincoln, figure 9, plate 12, which shows the rapid diffusion upwards. Of course the area significantly contributing is larger the lower the source density because of the increase in the average distance of the observation point from the nearest source.

Incineration of domestic garbage is practised regularly in New York apartment blocks, and figure 10, plate 12, shows what is typically visible for 10 min or so when this is done. The immediate neighbourhood is showered with small ash particles, and domestic incineration is the source of most of the particulate material which falls out.

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To see the contribution from gravitational deposition we may perform Carey's experiment to measure dinginess. This consists of placing toy bricks (or, if you are more sophisticated, rubber bungs) on a white card, and removing one each day. The results, shown in figure 11, plate 12, is to show how long it takes to achieve various levels of dinginess. The example shown was obtained by placing the card in a bathroom with the window slightly ajar, in February 1968 in Washington Square. Most of the deposition consists of particles which are individually visible to the naked eye.

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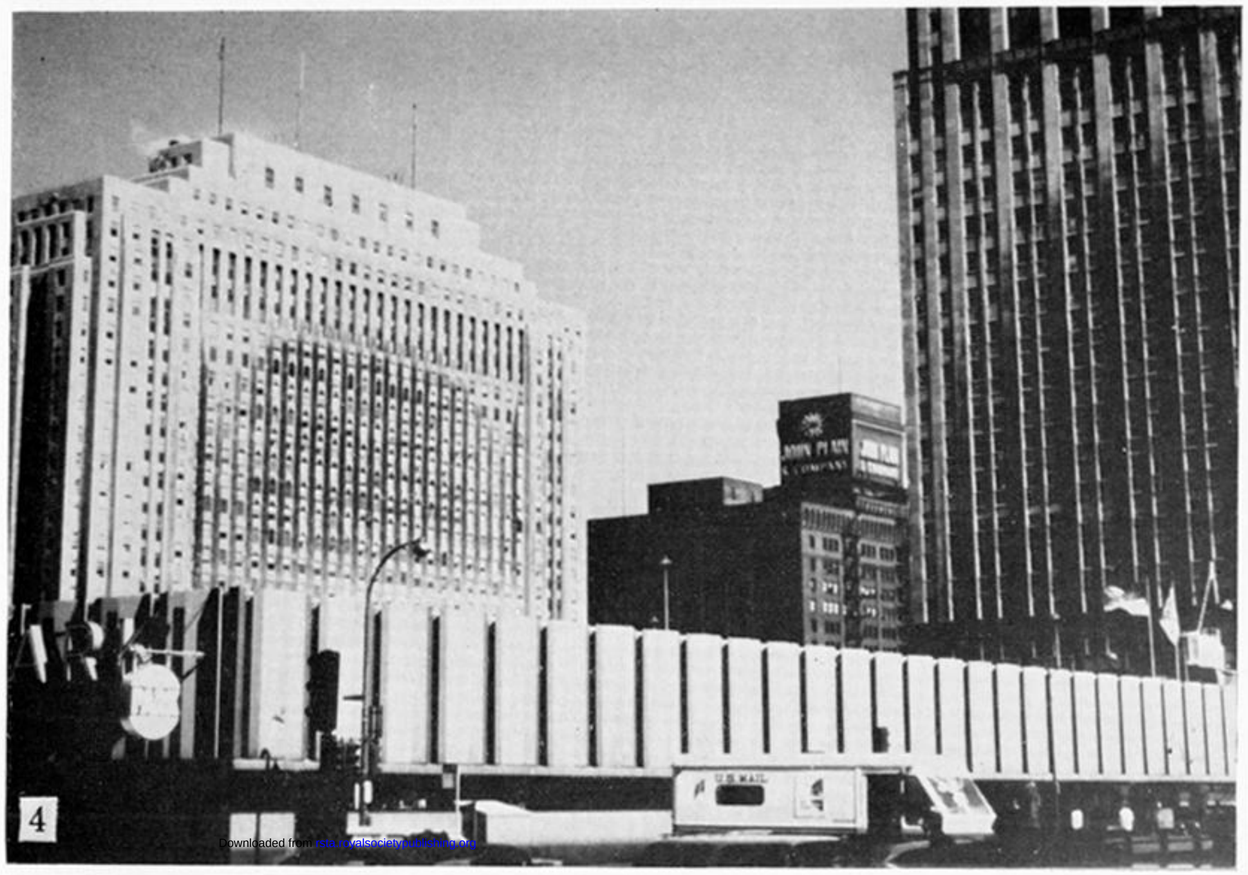

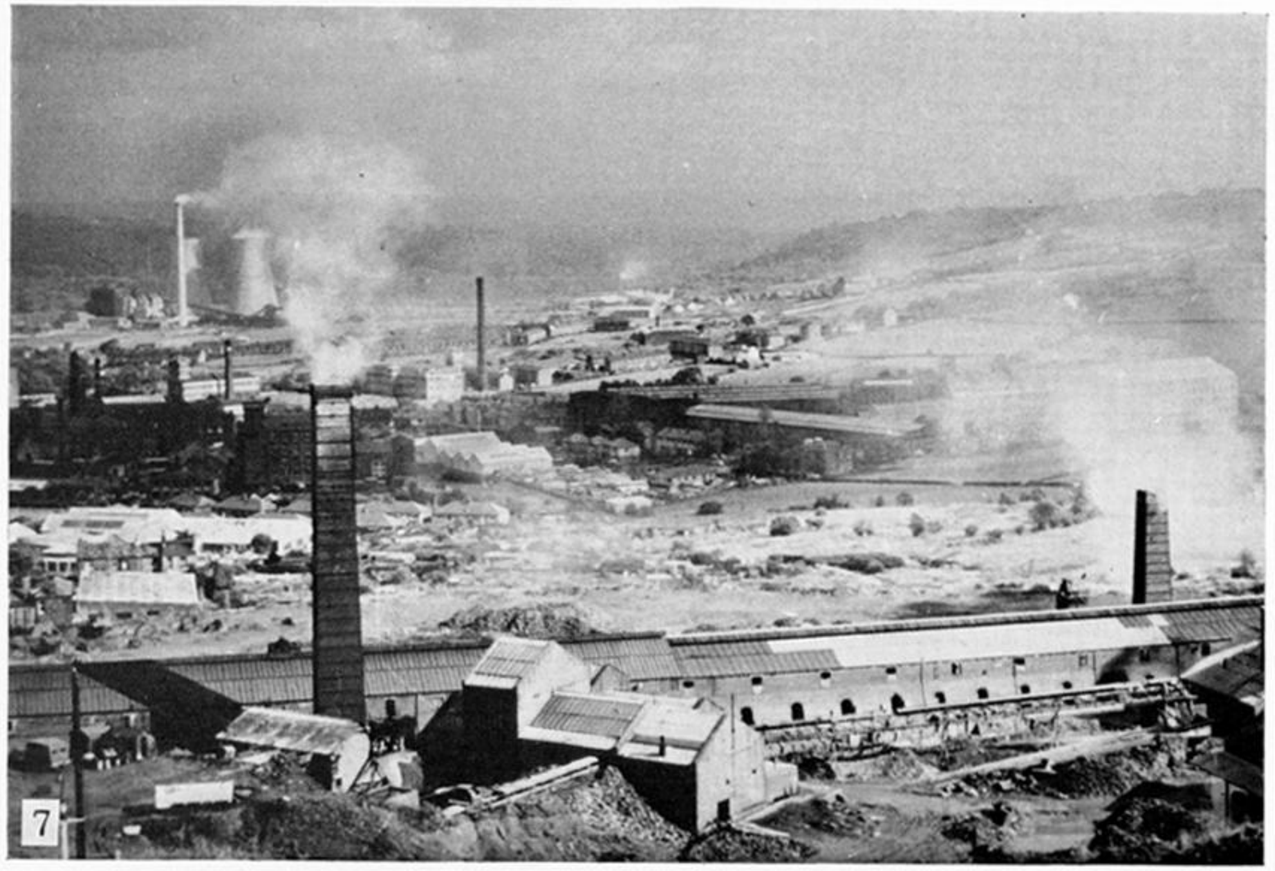

FIGURE 4. Darkening of the Daily News building in Chicago.

FIGURE 5. Darkening of the corner of the Chicago Opera House. The stone close to the corner is washed by running rain concentrated there by the airflow which separates at the corner.

FIGURE 6. Haze accumulated over Tyrone, next to Bald Eagle Mountain, Pennsylvania, from the pulp mills.

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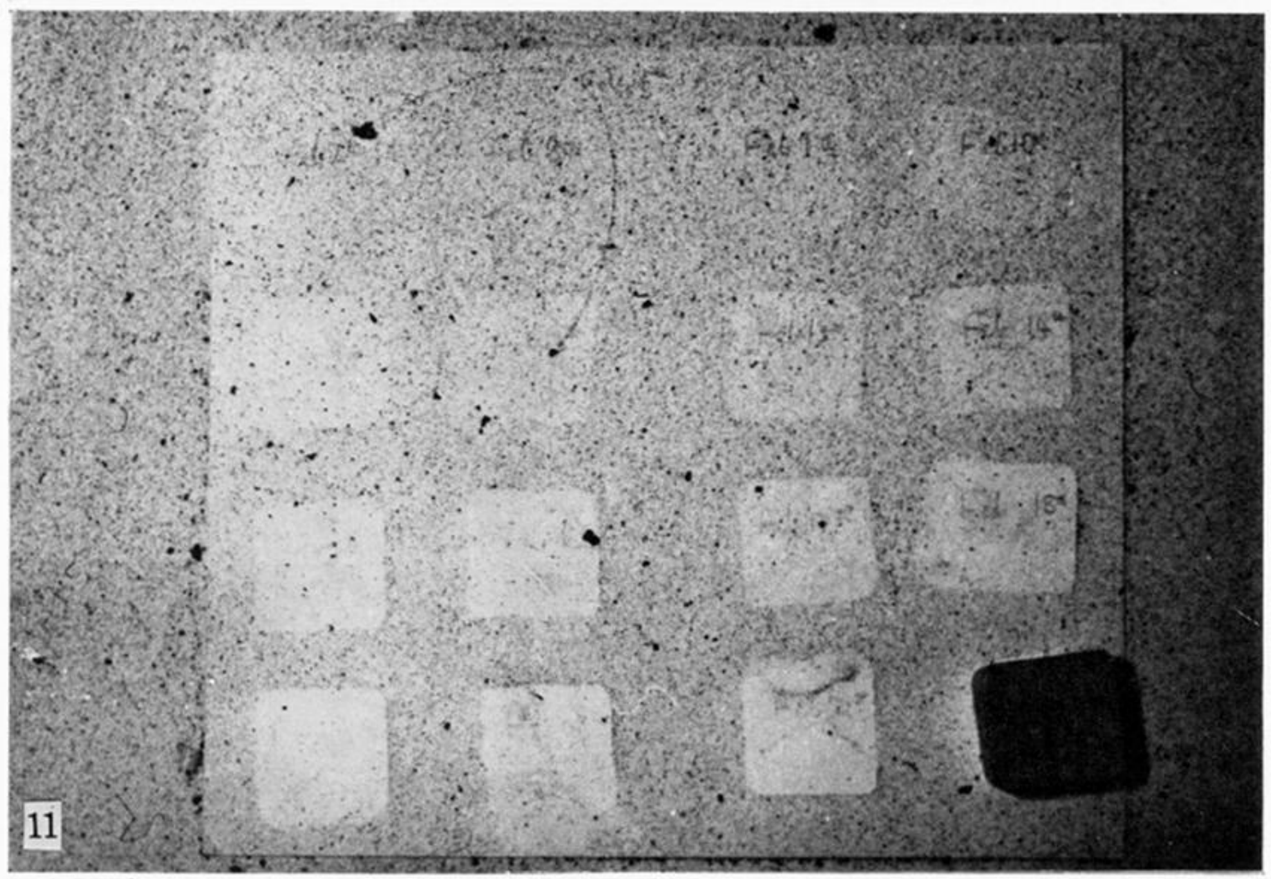

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