

**THE HEALTH EFFECTS OF AIR POLLUTION AND
THEIR IMPLICATIONS FOR CONTROL**

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Reprinted from the symposium on
AIR POLLUTION CONTROL
Published as the Spring, 1968, issue of
LAW AND CONTEMPORARY PROBLEMS
Duke University School of Law
Durham, N. C.

THE HEALTH EFFECTS OF AIR POLLUTION AND THEIR IMPLICATIONS FOR CONTROL*

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INTRODUCTION

Air pollution is particularly interesting, not only in and of itself, but because it is the prototype of problems to come.

It is the prototype because it is intimately linked with the texture, problems, and activity of modern urban life. Where previously we sought the health effects of air pollution by attempting to pin them to the effects of individual pollutants acting separately, we are coming to realize that in a problem of this sort there is no one villain that can be pinpointed, discovered, eliminated, and the problem solved.

We are no longer as much in search of one substance in the atmosphere to account for the health effects of air pollution as we are in search of an understanding of the complex chemistry occurring in our dynamic atmosphere and the results of that chemistry on our health. But simultaneously we have become aware that we are no longer seeking one disease for which air pollution is solely responsible. Rather, there are numerous diseases in part caused by infection, by allergy, by cigarette smoking, by hereditary predisposition, by aging, to which air pollution may be only an added insult in the final outcome—a chain of events initiated by our birth, furthered by our habits, and inexorably linked to the design of our industrial society. The luxury of previous public health research—looking for one cause, one disease—is finally lost to us. And, I believe, with that loss we are ready to progress further in understanding the unquestioned health effects of air pollution and how to control it.

The legal basis for the control of air pollution has progressed from nuisance law to the statutory regulation of specific substances as the sophistication of the sciences involved progressed. But if the multifactorial nature of the problem has stymied the previous research approach, it may stymie legislation based on that research; where simplistic research approaches have failed, so too may simplistic legal remedies. The statutory control of air pollution by pursuing air pollutants one by one as evidence accumulates seems clearly inadequate to a technology producing new pollutants or sources of pollution at an almost geometric rate. Progress in control may require a return to nuisance law, perhaps more broadly based and sophisticated than formerly but still effective in achieving needed abatement.

As a basis for understanding the health effects of air pollution, ensuing sections

* This article is supported in part by the Health Research Council of the City of New York (Contract U-1155), and the Division of Air Pollution, U.S. Public Health Service (Grant No. AP-00266-01).

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of this article deal with the nature of the research problem as well as the lines of evidence that have accumulated.

To maintain a manageable size I have confined myself primarily to air pollution as it occurs in the industrial atmospheres and is typified by the sulfur oxides. This is not to minimize the great importance of the other pollutants and the automobile, but I believe the conclusions that arise from a consideration of one type are applicable to the others.

I

NATURE OF THE PROBLEM

At the outset, let us review the nature of the biological research problem that is posed by air pollution. As John Goldsmith¹ clearly stated several years ago, this is a problem in toxicology, determining for man in his natural setting (now increasingly urban) the relationship between the dose of the noxious agent in the atmosphere and the biological response in man. Classically the toxicologist works in the laboratory and is able to present the dose of the pure toxic agent over such a wide range that he is assured of going from no effect to the most severe effects and can reliably assess the noxious capability of the substance in question. But in air pollution studies that occur in the natural setting, almost none of the ideals of the toxicology experiment are met; conversely, in laboratory studies of the effects of pollutants on man or animals, almost none of the realities of the urban setting are approximated.

What complicates these studies? For simplicity the examples that follow are based primarily on sulfur dioxide, but the problems are almost the same for all the common pollutants.

First, the dose, the sulfur dioxide, except under the most bizarre and rare circumstances, is present in the urban atmosphere in very low concentrations and over a very narrow range. The peaks are rarely ten times the daily averages. The peaks themselves are usually not above one part per million (ppm). One ppm is about the bottom of the range frequently used in the laboratory. The highest levels to which populations are exposed, therefore, are so low that they are seldom used in the laboratory. New York City levels average around 0.15 ppm.²

Second, sulfur dioxide does not exist alone in the atmosphere. When it is present, almost invariably, numerous other substances which may or may not have an effect on man are also present. Because of atmospheric conditions, concentrations of the other substances will be increased at the same time as the sulfur compounds are increased. It is difficult, therefore, for the scientist to know whether an effect he has observed was caused by the sulfur compounds, or by the other materials present—

¹ Personal communication from John Goldsmith, 1961.

² J.R. McCarroll & E.J. Cassell, unpublished data, Christodora Monitoring Station, New York City, 1962-65.

whether, in other words, the sulfur compounds are merely "markers" of the presence of other, more toxic materials.

The third and related complication of such studies is that all the various substances do not co-exist without interaction. The atmosphere is often naively pictured as a large pot in which things are dumped and in which they stay unchanged. But in reality the atmosphere is a dynamically active chemical retort in which substances change themselves and react with other materials to produce new and sometimes unknown substances, with this atmospheric chemical factory variously affected by the wind, sun, humidity, and other weather factors. The meaning of this dynamic chemistry for the Los Angeles oxidant type of air pollution was well demonstrated by Dr. Haagen-Smit and others;³ but we have avoided this same conclusion, that the problems faced in the predominantly sulfur oxide pollution of the northern industrial cities may also derive from the complex interaction of pollutants and weather.

Fourth, how do we know what is really in the atmosphere? Frequently, knowledge is a function of technology. We know about sulfur dioxide because we have instruments to measure it, and have had for some time. But there are substances in the atmosphere of whose nature and presence we know nothing, and the number of such substances is probably increasing as our technology expands. For example, what happens to a plastic bag when it is incinerated; and what is the effect in the atmosphere of gasoline additives?

The fifth complicating feature of the natural experiment is the meaning of what the pollution-measuring instruments say. When a research study reports that the population was exposed to, for example, 0.25 ppm of sulfur dioxide, what does that mean? Generally the instrument did not even really measure sulfur dioxide. If it was of the conductivity type commonly in use, this instrument only reflects sulfur dioxide when that gas exists alone—but as has been pointed out, that ideal is rarely met in the atmosphere. The measurement is interfered with in numerous ways that cast serious doubt on any interpretation of experimental results that are presented as though the exposure was really to sulfur dioxide. In our studies, at one point, we had two instruments side by side, one measuring "true" SO₂ and the other employing the conductivity method commonly in use; not infrequently their readings bore no relationship to each other. In our papers we carefully use the words "whatever is represented by the measurement of sulfur dioxide";⁴ but when we are quoted that important note of caution is left out or forgotten. Similarly, in some studies, the average sulfur dioxide of one area is compared to that of another and then the research findings are causally related to sulfur dioxide. However, sulfur dioxide levels are associated with many things: the weather, type of fuel used in home heating, degree of industrialization, socioeconomic level of population, crowding,

³ Katz, *Physical and Chemical Aspects*, in AIR POLLUTION 97, 149 (World Health Organization 1961).

⁴ E.g., McCarroll *et al.*, *Health and the Urban Environment*, 14 ARCH. ENVIRON. HEALTH 178 (1967).

and probably a host of other factors, all of which have a bearing on disease. Many attempts, some successful (notably the elegant studies of Winkelstein),⁵ have been made to dissociate these related factors from the effects of the pollutants, but in a number of studies these confounding factors are ignored. Legislation of the type which proposes a numerical standard for SO₂ does not deal with "whatever is represented by the measurement of sulfur dioxide"; it deals with the *gas, sulfur dioxide*.

Finally, the effect of pollutants on man is further complicated by the effect of the atmosphere itself. Temperature and humidity have an unquestioned and well known effect on health quite apart from the effect they may have on the pollutants in the atmosphere. The most sharply defined mortality peaks in New York City between 1962 and 1965 occurred during heat waves in two successive summers; and in that three year period there were more than a dozen air pollution episodes.⁶

These additional factors that influence the dose of pollutants appear to be inordinately complicating; but they cannot be dismissed because they are inconvenient. An understanding of them must underlie future approaches to the control of pollution as well as other, similar, public health problems.

The problems that beset the epidemiologist concerned with the dose of the noxious agent in his natural toxicology experiment are no more than the difficulties he confronts in looking for the effect of the pollutants on man.

Briefly stated, there have been no responses in man or animals thus far discovered which are unique to, or solely caused by, exposure to the oxides of sulfur, except perhaps odor. Secondly, there has been no way thus far to get experimental populations who are alike in all respects except their exposure to the oxides of sulfur.

I would like to amplify somewhat on these two points because they lead to an important conclusion. The effects of the oxides of sulfur on man and animals appear to be a consequence of irritation of the mucus membranes. (And to produce this irritation in the laboratory has required levels of SO₂ generally well above those found in the atmosphere.) Cough, airway constriction, increased sputum or mucus are all secondary to the irritant effect of the noxious agent on the sensitive mucus membranes. But these symptoms and research findings are also produced by cigarettes or other irritants, allergy, infections, other pollutants, emotional factors, and so on. Diseases which are, at least in part, contributed to by air pollution are also clearly influenced by other factors. Thus one of the major research tools is denied us, a marker by which we can clearly define an effect of a pollutant on the study population, uncomplicated by any other effects.

The "control population" is dear to the heart of science: a population the same

⁵ Winkelstein *et al.*, *The Relationship of Air Pollution and Economic Status to Total Mortality and Selected Respiratory System Mortality in Men*, *id.* at 162.

⁶ E.J. Cassell *et al.*, *Reconsiderations of Mortality as a Useful Index of the Relationship of Environmental Factors to Health*, a paper presented at the American Public Health Association meeting, Miami, Fla., Oct. 1967.

in all respects except its exposure to the agent in question. But this too is denied us. Air pollution is so ubiquitous that one can never find an urban group that has no pollution. There are such great differences between life in the city and country, besides exposure to air pollution, that it is difficult, if not impossible, to disentangle these factors with any more ease than we can disentangle the differences in the same population between days of high and low pollution.

The problem becomes, therefore, not one of simply deciding on an acceptable numerical level of pollution, but of deciding how to handle a situation of this type where numbers appear to be necessary and where real meaningful conflict exists over the choice of those numbers.

II

LINES OF EVIDENCE

A. The Disasters

Certainly the most dramatic, convincing, and undeniable evidence of the deleterious effects of air pollution on humans has come from the several air pollution disasters. Although the list is not long (Meuse Valley, Belgium, 1930; Donora, Pennsylvania, 1948; London, 1952 and 1962; and Poza Rica, Mexico, 1950) the effects of these unplanned exposures were startling and impressive. The Meuse Valley, Donora and London disasters all have much in common with air pollution episodes which are quite frequent but do not cause the great mortality or morbidity. Considerable knowledge can be gleaned from a careful review of the circumstances involved.

Occurring almost universally in the autumn or early winter, they all have the same meteorologic conditions: the stable air mass of a prolonged anti-cyclonic high pressure system with secondary inversion. The inversion (in which a layer of warm air sits above a layer of cold air, the reverse of the usual situation in which the air gets colder the higher one goes) serves to act as an effective lid retaining below it all the substances that are dumped into the atmosphere and thus preventing their effective dissemination. Fog has been an invariable ingredient of every air pollution disaster.

The Donora, Pennsylvania, episode⁷ occurred in October 1948. Donora is a small town with a population of 14,000 situated on a bend in the Monongahela River about thirty miles south of Pittsburgh. Donora lies in the center of an area of heavy industrial production; there are steel mills, a wire plant, a zinc smelter, and coke plants, all in the immediate vicinity. Also, the hills rise sharply behind Donora to the west and on the other side of the river to the east.

The inhabitants were long accustomed to dirty air but had never experienced a

⁷ See generally H. SCHRENK *et al.*, AIR POLLUTION IN DONORA, PENNSYLVANIA, EPIDEMIOLOGY OF THE UNUSUAL SMOG EPISODE OF OCTOBER, 1948 (Federal Security Agency, Public Health Bull. No. 306, 1949); Ciocco & Thompson, *A Follow-Up of Donora Ten Years After*, 51 AM. J. PUB. HEALTH 155 (1961).

smog like the one which began on October 26, 1948. On Monday, October 25, a stable layer of air formed in the valley area. From then until the smog was broken by rain on Sunday, October 31, this layer acted like a lid clamped over the valley, allowing the build-up of atmospheric pollutants.

Two days after it started, the air was thick and heavy, and visibility was markedly reduced. Although a few persons started to feel ill on Wednesday, October 27, it was on Thursday, October 28, that large numbers became affected. Just as in the other disasters, shortness of breath and cough were the most prominent symptoms, although sore throat, headache, lacrimation, eye irritation, nausea, and even vomiting and diarrhea occurred in some. Between 6:00 p.m. and midnight on Thursday, forty per cent of the affected people reported the onset of their illness. By Friday, October 29, almost every person who became ill during the episode was already ill; seventeen of the total twenty deaths occurred that day. By the end of the episode, a total of 5,910 persons, 42.7 per cent of all persons living in the area, were affected to some degree by the smog. As in the other disasters, the elderly and those with pre-existing heart and lung disease were the most severely affected, although persons in all age groups were affected as well.

In December 1952, a temperature inversion and fog lay over most of southern England, particularly from December 5 through December 9.⁸ It was especially heavy in the Thames Valley, where London is situated. Because the fog occurred in winter, sulfur dioxide and soot from soft coal used in home heating contributed heavily to the usual industrial emissions. By examining the mortality records, it was noted that an increased number of deaths occurred during the episode and in the following weeks. There were approximately 4,000 excess deaths attributed to air pollution. As in the other disasters, the majority of deaths and the greatest number of illnesses occurred in the elderly and those with previous heart and lung disease. However, increased mortality was experienced in every age group and in almost every diagnostic category. It must be emphasized that the assumption that all of these deaths were due to the air pollution episode comes from the coincidence in time of the excess mortality and the increased pollution.

Although most of the attention has been focused on the 1952 London episode, there is also evidence that there have been other similar occurrences in London prior to and since that time. As is so often the case in an acute air pollution episode, the extent of the episode and the amount of illness are often not appreciated at the time of its occurrence. In December 1962 another severe episode of markedly increased levels of pollution was noted in London. On this occasion the excess mortality was estimated to be about 600.

There has been much discussion of the reasons for the differences in mortality between the two episodes. The Donora and London 1952 disasters focused attention

⁸ See generally MINISTRY OF HEALTH, MORTALITY AND MORBIDITY: THE LONDON FOG OF 1952 (No. 95, London, 1954).

on sulfur dioxide as the causative agent, and were in part responsible for the large volume of research into the health effects of sulfur dioxide. However, reconsideration of these episodes themselves has helped show that for effects to be manifest, more must be present in the atmosphere than sulfur dioxide alone.

In London in 1952 the highest concentration of sulfur dioxide was 1.34 ppm. In London in 1962 with fewer excess deaths, there was a higher hourly concentration of sulfur dioxide (1.98 ppm) but a considerably lower level of particulate matter or soot than in the 1952 episode. At the same time that London was experiencing the 1962 episode, the Netherlands was visited by similar weather conditions and had, as a consequence, markedly increased levels of both sulfur dioxide and particulate matter.⁹ Little increased illness or mortality was reported. In general, sulfur dioxide levels were slightly lower than the English values but the amount of particulate matter was very much lower in the Netherlands.

The interrelationship between SO₂ and particulate becomes more manifest the more closely the disasters and episodes are examined. As will be seen later, this interrelationship of one pollutant to another is crucial to understanding the problem and, I think, developing a control philosophy.

That a high concentration of a specific common pollutant alone is probably not sufficient to cause increased mortality is clear from the fact that while there have been few air pollution disasters (periods of high mortality) there have been many episodes during which concentrations of air pollutants reached very high levels.

Several authors have investigated a number of episodes in New York City and have come to the conclusion that there was an increase in mortality during those periods of increased pollution. Greenburg¹⁰ and his group have stated that increased mortality was present during episodes in New York City in 1953, 1963, and more recently in 1966. McCarroll and Bradley¹¹ have commented upon increased mortality occurring during several periods of increased pollution in New York City. However, more critical examination of mortality statistics and air pollution levels in New York City by the author and his colleagues¹² has thrown considerable doubt on the previous observations. What is apparent is that, if on occasion increased mortality is associated with increased air pollution, those occasions are considerably less frequent than increased air pollution without attendant changes in mortality. This latter note of caution does not detract from the fact that air pollution episodes have un-

⁹ See generally Tesch, *Air Pollution in the Netherlands*, 57 PROCEEDINGS OF THE ROYAL SOC'Y OF MEDICINE 997 (1964).

¹⁰ Greenburg *et al.*, *Report of an Air Pollution Episode in New York City, Nov. 1953*, 77 PUB. HEALTH REP. 7 (1962); Greenburg *et al.*, *Intermittent Air Pollution Episode in New York City, 1962*, 78 PUB. HEALTH REP. 1061 (1963); Greenburg *et al.*, *Air Pollution, Influenza, and Mortality in New York City*, 15 ARCH. ENVIRON. HEALTH 430 (1967).

¹¹ McCarroll & Bradley, *Excess Mortality as an Indicator of Health Effects of Air Pollution*, 56 AM. J. PUB. HEALTH 1933 (1966).

¹² E.J. Cassell *et al.*, *supra* note 6.

questionably occurred during which there was increased illness and death. As Lawther has noted in the past, "the mortal results of high concentrations of urban pollution are recognized though much work still needs to be done to elucidate the mechanism by which it exerts its effects."¹³

The basic requirement for a potential air pollution episode, the concentration of numerous and active sources of smoke and gas, is not unique to Donora, London, or even New York. This requirement is met by many of our cities and industrial areas. The meteorologic conditions necessary to produce an episode also are not unique to these areas but are found in many cities and encompass many regions of this country. The meteorologic conditions necessary to produce an episode cannot be prevented although they can usually be predicted. While there may be considerable argument about the need to control this or that specific pollutant, there is no question about the need to prevent the occurrence of air pollution episodes. All the technology necessary to accomplish this exists today. The ability to predict the occurrence and duration of the meteorologic conditions that promote air pollution episodes has made possible effective episode control. In addition, it is possible to cut back the emission of pollution from major sources. An increasing number of cities have episode control mechanisms already in force and in some areas they have been written into law.

B. Laboratory Studies

As noted earlier, determining the health effects of air pollution is a problem in toxicology, and toxicology is classically a laboratory science. Many studies on the health effects of specific pollutants have been carried out over the years. Generally speaking, these investigations have been used to determine the following things: basic physiologic response to specific pollutants; the dose-response relationship; factors within the host which modify the response; factors affecting the pollutant which modify the response. As mentioned earlier, laboratory studies are generally unable to approximate the realities of the urban situation. It is often difficult to know the degree to which laboratory results apply to the real setting. The most striking difference between most laboratory studies and "real life" is the use of animals rather than man to determine the effects of the pollutant involved. Although there are very real ethical and medical limitations to the use of man as an experimental animal in determining the effect of air pollutants, there have been a number of studies utilizing man as well as studies utilizing animals. The footnote references include studies involving other pollutants, but the discussion here will deal primarily with the oxides of sulfur.

Reid exposed rats to sulfur dioxide at a level of 400 ppm and was able to produce

¹³ Lawther, *Symposium on Air Pollution—Summary*, 57 PROCEEDINGS OF THE ROYAL SOC'Y OF MEDICINE 1040 (1964).

a secretion of mucus analogous to that found in human bronchitis.¹⁴ Earlier, Dalhamm had shown that an exposure to high concentrations of sulfur dioxide effectively stopped the ciliary activity (which is part of the mechanism for removal of foreign particulate matter introduced to the lung) within the tracheo-bronchial tree.¹⁵ Humans are intolerant to atmospheres containing 400 ppm of sulfur dioxide.

Over the last number of years, Amdur and her colleagues have carried out a series of experiments on guinea pigs in an attempt to determine the mechanism of effect of sulfur dioxide.¹⁶ It was early shown that sulfur dioxide in sufficient concentration was able to increase airway resistance. This broncho-constriction is a feature of chronic bronchitis and other chronic diseases of the lung. While the effect in guinea pigs required concentrations of sulfur dioxide considerably above those found in ambient atmosphere, Amdur found that the addition of an inert particle (sodium chloride) seemed to produce a synergistic effect; an increase in airway resistance greater than could be accounted for by the sulfur dioxide or the sodium chloride particles alone. In the ensuing years, the group has used particles which are not in themselves inert, but interact with the sulfur dioxide to produce sulfuric acid or sulfur trioxide. With these more active particles the dose of sulfur dioxide required to produce a physiologic effect has more nearly approached the levels that might be found in urban air. Amdur has reported some effects in men exposed to relatively low (one to eight ppm) concentrations of sulfur dioxide.¹⁷ Frank, in experiments on healthy humans,¹⁸ was generally unable to show any change in airway resistance (the most sensitive indicator of effect at hand) at concentrations of sulfur dioxide below five ppm. However, in his experiments one individual responded to the range one to two ppm. In studies over many years, Lawther has been unable to demonstrate any effects in man of realistic concentrations of sulfur dioxide although an occasional experimental subject has reacted in a more sensitive manner.¹⁹ Sim and Pattle, while showing similar lack of response to the usual ambient concentrations, also demonstrated the phenomenon of the sensitive individual.²⁰ If such "sensitive" individuals exist in large numbers in the population, then ambient concentrations of sulfur dioxide, thought now to be harmless, might represent a greater threat.

¹⁴ Reid, *An Experimental Study of Hypersecretion of Mucus in the Bronchial Tree*, 44 BRIT. J. EXPERIMENTAL PATHOLOGY 437 (1963).

¹⁵ Dalhamm, *Mucous Flow and Ciliary Activity in the Trachea of Healthy Rats and Rats Exposed to Respiratory Irritant Gases*, 36 ACTA PHYSIOLOGICA SCAND., 123 SUPPLEMENTUM (1956).

¹⁶ Amdur, *The Effect of Aerosols on the Response to Irritant Gases*, in INHALED GASES AND PARTICLES (C. Davies ed. 1961).

¹⁷ Amdur, Melvin & Drinker, *Effects of Inhalation of Sulfur Dioxide by Man*, [1953] 2 THE LANCET 758.

¹⁸ Frank & Speizer, *Uptake and Release of SO₂ by the Human Nose*, 7 THE PHYSIOLOGIST 132 (1964).

¹⁹ Lawther, *Effects of Inhalation of Sulfur Dioxide on Respiration and Pulse-Rate in Normal Subjects*, [1955] 2 THE LANCET 745.

²⁰ Sim & Pattle, *Effects of Possible Smog Irritants on Human Subjects*, 165 J.A.M.A. 1908 (1957).

Initially, studies by Frank,²¹ Dalhamm and Strandberg,²² and others showed that almost none of the sulfur dioxide that is inhaled enters the deepest reaches of the lung; that it is virtually completely removed by absorption in the nose or pharynx. Nadel, trying to explain why the sulfur dioxide should cause bronchoconstriction if it did not reach the lower lung passages, demonstrated that the effect was a reflex from irritation in the upper airways.²³

More recent studies by Amdur have resolved some of the conflict by showing that the higher the concentration of inhaled sulfur dioxide the higher the percentage absorption in the upper airways.²⁴ At very low concentrations of inhaled SO₂ (0.16 ppm) very little is absorbed in the upper airways and almost all reaches the lung itself. In addition, the absorbed sulfur dioxide has been shown to enter the blood stream.

The use of sulfuric acid mists in experiments similar to those quoted above has shown this substance to be a potent irritant of the respiratory tract. Here again, concentrations larger than those experienced in the worst air pollution have been required to produce an effect. However, sulfuric acid mist is not a gas but rather a particle. In appropriate particle sizes as much as sixty to eighty per cent of the inhaled particulate reaches the alveoli.

Once a solid particle reaches the small airways and alveoli, its residence time is measured in weeks, months, or years. The effects of some particles are well known; the occupational disease silicosis results from the long-term inhalation of silica containing particles.

The studies of Johnstone over many years have demonstrated that the interaction of the gas sulfur dioxide with catalyzing particles such as manganese, iron, vanadium, and titanium, for example, can result in the formation of sulfuric acid in the presence of the particle.²⁵ While it is only speculation, it appears likely that under certain conditions where both sulfur dioxide and catalyzing particle nuclei are present in the same atmosphere, the gas will be adsorbed onto the particle and sulfuric acid will be produced. In the proper size range such particles can be inhaled and retained in the lung. Under those circumstances one would be inhaling what is, in essence, a tiny sulfuric acid manufacturing plant.

Such catalytic particles are a common constituent of urban atmospheres. They result from the burning of fuel oil and coal, and they are increasingly used as gasoline additives. The kinds of particles and the type of catalyst may vary widely from region to region. The "London particle" is different from the "New York

²¹ Frank & Speizer, *supra* note 18.

²² Dalhamm & Strandberg, *Acute Effect of Sulfur Dioxide on the Rate of Ciliary Beat in the Rabbit*, 4 INT'L J. AIR & WATER POLLUTION 154 (1961).

²³ Nadel *et al.*, *Mechanism of Bronchoconstriction*, 10 ARCH. ENVIRON. HEALTH 175 (1965).

²⁴ Amdur, *Respiratory Absorption Data and SO₂ Dose-Response Curves*, 12 ARCH. ENVIRON. HEALTH 729 (1966).

²⁵ Johnstone, *Properties of Aerosols Related to the Effects of Inhaled Particles and Vapors*, in INHALED GASES AND PARTICLES 95 (C. Davies ed. 1961).

particle." It is intriguing to speculate whether these particle differences may play a role in the apparent differences between the effects of air pollution in London and, for example, New York. Differences in weather are also likely to contribute to differences in the reactive chemical retort that is now the urban atmosphere.

The laboratory has provided evidence that the common constituents of air pollution are capable of producing adverse effects in both man and animals. Such a demonstration of adverse effect has also been made for virtually all the common pollutants, including those in the oxidant atmospheres, such as that of Los Angeles.²⁶ In general it has required amounts of pollutants far above those generally found in the atmosphere to produce effects. Again, one is forced to conclude that because of the multiplicity of factors at work, the whole is greater than the sum of its parts.

C. Chronic Pulmonary Disease

Even a cursory perusal of morbidity and mortality data shows that chronic bronchitis is more commonly found in large towns than in sparsely populated areas of Great Britain. In Great Britain it is a common disease, accounting for a significant percentage of the total mortality and morbidity. The apparently obvious association between the urban situation and chronic bronchitis led to great interest in its study as a means of demonstrating the health effects of air pollution. The interest was widened by the increasing prevalence of chronic respiratory diseases in the United States and Europe. The studies of Reid and others seemed initially to incriminate sulfur dioxide as a causative factor in the production of chronic bronchitis.²⁷ As sophistication increased in the study of this disease it became clear that the problem was not so simple. One of the first victims of the increasing sophistication was the definition of the disease. Investigators in the United States were talking about a different thing than the British when they used the words chronic bronchitis. After many years the definition has become standardized and studies that are comparable have now been done on an international scale. It is now called non-specific lung disease, chronic obstructive pulmonary disease, chronic respiratory disease, and several other names, but all of these names are descriptive of an illness which is characterized by cough, the production of variable amounts of phlegm, and broncho-constriction (an obstruction to the easy passage of air through the bronchial tubes). The relationship of this disease to emphysema is unclear except that while emphysema is a disease in which cough and phlegm may not be present, several of the physiologic features are shared by both. The end state in either is a respiratory cripple.

Within limited and climatically fairly homogeneous areas, for example in London, the distribution of bronchitis mortality has been shown to reflect the varying

²⁶ See, e.g., 1 AIR POLLUTION *passim* (2d ed. A. Stern 1968).

²⁷ E.g., Reid & Fairbairn, *The Natural History of Chronic Bronchitis*, [1958] 1 THE LANCET 1147.

concentrations of smoke and sulfur dioxide in the local atmosphere. A marked gradient exists between country districts and urban areas which correlates well with local pollution levels. However, as noted above, elevated levels of sulfur dioxide and smoke are more than indicators of air pollution. Therefore, it may be unwarranted to assume a cause and effect relationship between air pollution and bronchitis. Sophisticated techniques, however, have been used to show that there is a positive correlation between local air pollution levels and bronchitis death rates that are independent of such social characteristics as population density and overcrowding. Other approaches are possible to delineate the various factors in the production of the disease. The investigation of industrial cohorts has been widely used. Reid, in England, studied postmen,²⁸ and Cornwall and Raffle, in England, studied bus employees.²⁹ These studies, done on occupational groups where job and pay are uniform throughout the area, have demonstrated an excess in bronchitis morbidity in the most heavily polluted districts. Postal employees working much out of doors, for example, have a higher bronchitis morbidity than postal employees who work inside.

Investigations using the same techniques as those used in England have been carried out in the United States.³⁰ The greater frequency of chronic respiratory disease in Britain as compared to the United States that was indicated by the reported death rates was confirmed in these studies of respiratory symptoms. The results also confirmed previous indications of more serious respiratory disease in British cities than rural areas of that country. In addition, although there was a smaller urban-rural difference in the United States, the prevalence of chronic respiratory disease was not as high in the United States as in England, and even more significantly, did not vary greatly from New York to San Francisco or Los Angeles. The most important finding of these studies, however, is that the overwhelming factor that correlates with chronic bronchitis is cigarette smoking. The contribution of the cigarette to this disease appears to be so great, that at least in its production it is difficult to indict another agent. However, even differences in smoking do not appear to account for the differences in prevalence of chronic bronchitis between the United States and England. It may be significant that although there are several areas (which were included in the studies) in the United States which have sulfur dioxide levels as high as those occurring in London, the amount of suspended particulate matter is almost invariably very much less.

There may be some question about the role of air pollution in the production of chronic respiratory disease, but there can be no question that it is a factor in

²⁸ Reid, *General Epidemiology of Chronic Bronchitis*, 49 PROCEEDINGS OF THE ROYAL SOC'Y OF MEDICINE 767 (1956).

²⁹ Cornwall & Raffle, *Bronchitis Sickness Absence in London Transport*, 18 BRIT. J. INDUSTRIAL MEDICINE 24 (1961).

³⁰ E.g., Holland *et al.*, *Respiratory Disease in England and the United States*, 10 ARCH. ENVIRON. HEALTH 338 (1965).

the aggravation of pre-existing symptoms or disease. Dr. Lawther and his group in England have studied the problem extensively and have shown fluctuations in the state of well-being of a group of patients with chronic pulmonary disease that are clearly associated with changes in air pollution.³¹ C. M. Fletcher's group in London came to the same conclusion while following an industrial population, the majority of whom had some evidence of chronic bronchitis.³² Spicer used advanced techniques for evaluating day-to-day variations in pulmonary function in a group, some of whom had chronic obstructive pulmonary disease and others of whom were normal.³³ While he was unable to demonstrate that the observed variations were due to any particular pollutant or meteorologic variable, it was clear that the group tended to react together and therefore appeared to be responding to some common, presumably environmental, stimulus.

In addition to what other factors may contribute to the production or exacerbation of chronic pulmonary disease, occupation may be important. Enterline's studies on the prevalence of chronic pulmonary disease in miners³⁴ has shown distinct variations from mining community to mining community although the evidence seems to indicate that coal miners in general have a far higher prevalence of chronic lung disease than the "normal" population in the United States.

From all the data we must conclude, with Professor Reid, that although air pollution is "certainly not the only cause, nor perhaps even the major initiating cause, it is almost certainly a promoting or aggravating factor in the evolution of serious chronic lung disease."³⁵

For the purposes of this discussion, consideration of chronic pulmonary disease should bring sharply into focus the multifactorial nature of the public health problem before us. What appeared at first to be a simple direct cause and effect association between air pollution and an easily identifiable disease soon lost that attractive simplicity. The disease itself turned out to be more complex than was thought at first. The association of cigarette smoking, so clear and undeniable; the role of infection in worsening the course; the effect of air pollution in producing exacerbations; the greater prevalence among lower socioeconomic groups; and the real differences in the disease between the United States and Britain make chronic respiratory disease a model for the concept of the complex interplay of factors in diseases associated with air pollution.

³¹ Lawther, *Climate, Air Pollution and Chronic Bronchitis*, 51 PROCEEDINGS OF THE ROYAL SOC'Y OF MEDICINE 262 (1958).

³² Angel, Fletcher *et al.*, *Respiratory Illness in Factory and Office Workers*, 59 BRIT. J. DIS. CHEST 66 (1965).

³³ Spicer & Kerr, *Variation of Respiratory Function: Studies on Patients and Normal Subjects*, 12 ARCH. ENVIRON. HEALTH 217 (1966).

³⁴ Enterline, *The Effects of Occupation on Chronic Respiratory Disease*, 14 ARCH. ENVIRON. HEALTH 189 (1967).

³⁵ Reid, *Air Pollution as a Cause of Chronic Bronchitis*, 57 PROCEEDINGS OF THE ROYAL SOC'Y OF MEDICINE 965 (1964).

D. Epidemiology of Air Pollution in Normal Populations

It is in normal populations that the importance of the health impact of air pollution on the general population must be sought. The finding of a meaningful effect on the health of normal citizens would provide greater impetus in the control of air pollution. On the other hand, studies in normal populations should also make it clear whether the effects found are the result, in so far as can be determined, of one pollutant or of the total complex.

The type of investigation used has varied from the crudest search for differences in mortality between polluted and less polluted areas to repeated surveys of normal populations using the most sensitive physiologic measurements of lung function. The early hope that a survey of mortality patterns in the United States would clearly show a difference that might be attributed to air pollution was not sustained by the evidence.⁸⁶ More recently, and with considerable elegance, the studies of Hammond on a large population in California have not shown differences in mortality that could be attributed to air pollution.⁸⁷ What has repeatedly shown itself in all such surveys is an urban-rural difference which is now acquiring the popular label, "the urban factor."

Some studies in special populations have been mentioned earlier in the section on chronic bronchitis. There it was noted that the examination of special industrial populations in England had clearly demonstrated a difference in the prevalence of chronic bronchitis which was thought to be associated with the air pollution of the region of employment. Less satisfactory correlations have resulted from the similar studies in the United States. An earlier study established a positive correlation between respiratory absenteeism and the sulfation levels of a number of cities in which one large company had employees.⁸⁸

Because young children can be expected not to smoke and to have relatively normal pulmonary function, free from the effect of long-term disease or aging, they would appear to be ideal populations in which to determine a difference between those living in polluted and non-polluted atmospheres. Several studies employing such populations of children have been conducted in the United States and abroad. Toyama and Tomono studied the pulmonary ventilatory capacity of primary school children in Kawasaki.⁸⁹ They compared 245 students aged ten to eleven in a polluted area with 163 students of the same age in a school located in a clean air area of the same city. They were able to show that the average pulmonary function

⁸⁶ See Prindle, *Some Considerations in the Interpretation of Air Pollution Effect Data*, 9 J. AIR POLLUTION CONTROL ASS'N 12 (1959).

⁸⁷ C. Hammond, *Epidemiological Evidence on the Effects of Air Pollution*, a paper presented at the Annual Meeting of the Air Pollution Control Association, Cleveland, Ohio, June 1967.

⁸⁸ Dohan *et al.*, *Variations in Air Pollution and the Incidence of Respiratory Disease*, 12 J. AIR POLLUTION CONTROL ASS'N 418 (1962).

⁸⁹ Toyama & Tomono, *Pulmonary Ventilatory Capacity of School Children in a Heavily Polluted Area*, 8 J. JAPANESE SOC'Y OF PUB. HEALTH 659 (1961).

measurements fluctuated with a striking parallelism to the monthly dustfall in the children in the school in the polluted area. The pulmonary function of students in the school in the cleaner environment was invariably better than that of the children in the school in the polluted area. A questionnaire survey of the same children confirmed the differences with symptoms such as coughing and expectoration occurring in greater numbers in those children in the more highly polluted area. Similar results were reported by Watanabe from Osaka where again it was shown that students attending two schools in a polluted industrial area in Osaka had worse pulmonary function values than students attending a school in a rural area with little pollution.⁴⁰ There was in both of these studies, of course, a large effect of weather and season. In neither study was it possible to separate the effects of sulfur oxides from those of particulate matter of other pollutants.

Lunn and his group reported on a group of 819 infant school children living in areas of Sheffield, England, with widely ranging air pollution levels.⁴¹ Upper respiratory tract illness and lower respiratory tract illness showed differences between the areas which were attributed to differences in pollution exposure. When several other socioeconomic factors were accounted for, the difference remained. Therefore, from the studies cited, it would appear that in children there is a distinct difference in the illness experience and certain pulmonary functions which appears to be related to the degree of pollution in the area in which they reside or go to school.

The ideal epidemiologic experiment would be one in which two populations the same in all respects except for their air pollution exposure could be compared to determine the effects of the air pollution. Such a "natural" experiment was studied by Prindle and his associates in the Public Health Service.⁴² Seward and New Florence, Pennsylvania, are towns only a few miles apart. Their inhabitants are similar but, because of the prevailing winds, a power plant situated between them unloads most of its effluent onto Seward. Seward has three times as great a dustfall, six times as much sulfation but almost equivalent amounts of suspended particulate (the size range that is breathed deep into the lungs). Studies of pulmonary function, chest x-rays, and surveys of bronchitis failed to show major differences between these two towns that might be attributed to air pollution. There did seem to be a greater frequency of increased airway resistance in Seward, the dirtier town, than in New Florence. However, other extremely important factors which bear on this difference, such as smoking habits, and occupational differences, were not taken into account in the original conclusions. Subsequent examination of the data has failed to support a marked difference in illness experience between the polluted and

⁴⁰ Watanabe *et al.*, *Effects of Air Pollution on Health*, 26 OSAKA CITY INSTITUTE OF HYGIENE 32 (1968).

⁴¹ Lunn *et al.*, *Patterns of Respiratory Illness in Sheffield Infant School Children*, 21 BRIT. J. OF PREV. & SOCIAL MED. 7 (1967).

⁴² Prindle *et al.*, *Comparison of Pulmonary Function and Other Parameters in Two Communities with Widely Different Air Pollution Levels*, 53 AM. J. PUB. HEALTH 200 (1963).

