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AIR POLLUTION IN CITIES

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It does not seem so long ago that the earth's atmosphere was assumed to be essentially inexhaustible in relation to the foreseeable demands upon it. Los Angeles' smog and London's dirty fogs were considered exceptional, anomalous local situations but, in general, it seemed obvious that there was no actual scarcity of air.[1] On the contrary, air was one of the classic examples (cited by generations of economists) of a good which is free because there is more of it available than could possibly be sold at any finite price.

The above view has rapidly been supplanted by a different and (hopefully) more realistic picture. Today the air—especially the air above cities—is increasingly seen as a scarce and valuable resource whose price is zero not because it is in oversupply but for the more complicated reason that there exists no social institution of ownership or exchange which would permit an economic balance to be struck between incompatible uses through the operation of a competitive free market. If it were not for this "market failure," a party wishing to use the air as a medium for dispersal and disposal of gaseous wastes, for instance, would have to pay some price for this service. Similarly, an individual wishing to utilize the air for breathing would also pay an appropriate price (just as one pays for food). The first use is incompatible with the second: that is, the utility of the air for breathing is reduced if the atmosphere is used as a sink for residuals of combustion or industrial processes.

A decade or two ago the atmosphere was generally thought of as an immense—virtually limitless—but passive reservoir of air in

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1. For instance, in the report of the President's Materials Policy (i.e., Paley) Commission in 1952, there is no mention at all of air. The same is true of H. Brown, J. Bonner & J. Weir, Man's Natural and Technological Resources (1957); and the monumental Resources in America's Future (1962) by Landsberg, Fischman, & Fisher.

much the same way that the oceans are reservoirs of water. Currently, however, a more sophisticated ecological notion is coming to the fore. The important element in the air is oxygen, without which life cannot exist. Water is constantly being removed from the ocean as vapor and returned to it again as rain or runoff, but water never changes its basic chemical form. However, oxygen is highly reactive. Oxygen in the air is converted to CO_2 by the metabolic processes of animals (as well as by the combustion of fossil fuels), while CO_2 is essential for plants which fix the carbon but release most of the oxygen. Normally the two processes would be in equilibrium, the oxygen-consuming and oxygen-producing activities being adjusted to one another.

Modern (urban) civilization affects this balance in several ways. In the first place, the combustion of fossil fuels—coal, petroleum products, and natual gas—is producing "extra" carbon dioxide and using up oxygen at a staggering rate.

In the United States in 1965 about 1.3 billion tons of fossil fuels were consumed for all purposes along with 2.74 billion tons of atmospheric oxygen—to yield 3.77 billion tons of CO_2 plus immense tonnages of assorted by-products.[2] In comparison, human respiration requires about 60 million tons of atmospheric oxygen (for the population of the United States) and produces 98 million tons of CO_2. Based on biomass, the sum total of all animals—mainly cattle—would require less than five times as much oxygen as the human population alone, or somewhere in the neighborhood of 0.3 billion tons and produce 0.5 billion tons of CO_2 at most. Thus industrialization has multiplied the natural rate of oxygen consumption and CO_2 production by factors of 10 and 7½ respectively in North America. Similar, albeit smaller, multipliers exist in other parts of the world.

There are other factors which may also be tipping the balance in the direction of less oxygen and more CO_2, viz., erosion, deforestation and defoliation of large stretches of countryside, the plowing of grasslands for crops—which leaves the ground bare for part of the year—and the spread of cities and paved areas over sizable areas of productive land. There is evidence also that water pollution may be causing reduced phytoplankton (algae) production in coastal waters.[3] It is far from certain that all the above effects are

2. Carbon and oxygen combine in the ratio of 12 to 32, since the atomic weights are 12 and 16 respectively: coal and natural gas contain approximately 75 per cent carbon by weight and petroleum contains about 85 per cent carbon.

3. *See* Winsten, *DDT Reduces Photosynthesis by Marine Phytoplankton,* 159 Science 1474 (1968).

in the direction of reduced oxygen supply, however. Fertilization of surface waters by organic waste disposal often results in increased alga harvests, and there is even some evidence that higher levels of atmospheric CO_2 stimulate photosynthesis and therefore the oxygen "cycle" and may tend to be self-regulating.[4] Nevertheless, the atmosphere is clearly a finite and extremely valuable resource which is probably being used up or degraded considerably faster than it is being regenerated. It is hardly the unlimited reservoir it was generally imagined to be as recently as a decade or two ago.

As indicated above, the primary use of this resource—to support animal life—is being compromised by other secondary uses of the atmosphere which are not "rationed," as they would be if all such uses were governed by a free competitive market, but are available at no charge to all. The capability of the atmosphere to satisfy all demands put upon it is being exceeded. This is especially so in urban areas where the density of population, as well as commercial and industrial activity, are the greatest.

In the remainder of this paper I shall discuss successively major sources of pollution of the air over cities, physical effects, economic costs, and alternative pollution control policies and technologies.

I
SOURCES OF POLLUTION

As hinted above, the single most important source of air pollution is energy conversion, especially where the combustion of fossil fuels is involved. It is convenient to consider the problem in four segments: (1) utility electric power generation, (2) transportation (especially automotive), (3) industry, and (4) households and commerce in general.

The fuel requirements of each sector are notably different, as shown in Table 1.[5]

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4. There is also the possibility that higher levels of CO_2 may result in higher worldwide temperatures, through the well-known "greenhouse effect," which, in turn, may cause shifts in precipitation patterns. The climatic effects of a temperature rise (or fall) are matters of speculation at present. However, mechanisms have been proposed which might suggest quite drastic effects, not excluding a possible new ice-age (resulting from increased precipitation in the form of snow over the arid land areas of northern Canada and Siberia). *See* Conservation Foundation, Implications of Rising Carbon Dioxide Content of the Atmosphere (1963).

5. Presentation by W. A. Vogely and W. E. Morrison, World Power Conference, Oct. 1966, Patterns of Energy Consumption in the United States 1947-65 and 1980 Projected.

TABLE 1
Sources of energy used by various sectors
(in percent)

	Utility	Trans-portation	Industry	Households and Commercial
Coal	55		29.4	0.4
Petroleum	6	99.85	22.8	38.8
Natural gas	22		39.3	42.8
Utility electricity	[a]	0.15	8.5	14.4
Other	17			3.6
	100	100	100.0	100.0

[a] Not applicable.

In the case of electric power production, minimum cost per British thermal unit (BTU) is of paramount importance: thus, natural gas is dominant in the west and southwest, water power in the upper northwest, coal in the midwest and east, and residual oil imported from Venezuela on the east and Gulf coasts. Natural gas is comparatively clean and contributes very little in the way of unwanted emissions (other than CO_2) except for minor quantities of oxides of nitrogen. Coal and residual oil, on the other hand, both normally contain a considerable amount of sulfur (~2.5 per cent) which burns to form sulfur dioxide (SO_2) and sulfur trioxide (SO_3).

Electric utilities produced an estimated 13.6 million tons of sulfur oxides in 1965, plus 3.7 million tons of oxides of nitrogen, 2.5 million tons of carbon monoxide, and 2.4 million tons of particulates (soot).[6] Oxides of sulfur are toxic in themselves; they also combine with water to form acids (H_2SO_3 and H_2SO_4) which are highly irritating to lungs and bronchial passages as well as to plants, painted surfaces, bare metal and—not least—stone (especially limestone or marble, which are rapidly eroded in the presence of atmospheric sulfur oxides).

In the transportation sector, the prime consideration is that the fuel be liquid, for ease of storage and handling. Thus, petroleum products account for all but 0.15 per cent of the total (over 300 milmilion tons in 1965) and about 90 per cent of this is gasoline—the fuel used by conventional spark-ignited (Otto-cycle) internal combustion engines for automobiles and all except the largest trucks—the remainder being jet fuel (similar to kerosene) and diesel oil.[7]

All of these products are distillates and therefore relatively free of inherent contaminants such as sulfur. However, in order to prevent pre-ignition and "knocking" in internal combustion engines

6. R. Ayres & A. Kneese, *Environmental Pollution* in New Resources in an Urban Age (Perloff ed. 1969).
7. W. Vogely & W. Morrison, *supra* note 5.

without sacrificing engine performance (by reducing compression ratios) or utilizing more costly aromatics such as xylene and toluene, it is standard practice to add a small quantity of tetraethyl lead to increase the so-called "octane number." However, on a national basis, this amounts to 200,000 tons of lead per year (one sixth of all annual lead production), practically all of which appears as very fine particles in automotive exhausts and is dispersed into the air. Its subsequent pathway through the ecosphere is, at present, largely unknown in detail, although presumably accumulation must be taking place in soil, in plants and animals, and in surface waters.

In addition to additives such as lead, the internal combustion engine is so inefficient that prior to the 1968 model-year as much as 10 percent of the fuel used in automobiles, or 20 million tons on a national basis in 1965, was wasted and dissipated in the atmosphere unburned or partially burned. Carbon monoxide is produced by uncontrolled vehicles, i.e., those without smog-control devices, at the rate of about one pound (equivalent to 7.5 cubic feet of gas) for each two pounds of fuel burned.[8] Assuming the lethal concentration of CO is somewhere in the range of 200 parts per million or 0.02 per cent, and assuming each automobile in a city drives 10,000 miles per year and obtains 14.7 miles per gallon—the national average figures[9]—each car will produce roughly 2500 pounds of carbon monoxide in a year, while trucks produce considerably more. This adds up to a national total in the neighborhood of 100 million tons for 1965. This is enough to contaminate nearly one hundred million cubic feet of air to the point of lethality. If we further assume an urban population density of 10,000 per square mile with one car or truck for every two persons, a little arithmetic indicates that such a community produces enough carbon monoxide each year to poison *the entire atmosphere above itself*. Clearly, if the carbon monoxide simply accumulated without being dispersed or oxidized to CO_2, cities could not co-exist with automobiles.

Fortunately, due to natural processes, the half-life of carbon monoxide in the atmosphere is apparently fairly short, but peak concentrations as high as 140 parts per million (ppm) have been observed over city streets during periods of heavy traffic.[10] Levels of 40 ppm are thought to be sufficient to have an adverse effect on

8. *See* President's Science Advisory Comm., *Restoring the Quality of Our Environment* (Nov. 1965).

9. *See* Automobile Manufacturing Association, Automobile Facts and Figures (1966 ed.).

10. Subpanel on Air Pollution, Report on The Automobile and Air Pollution: A Program for Progress (1967).

physiological and mental functions and may be contributory causes of many accidents.

Oxides of nitrogen (NO and NO_2) are also produced by the high-temperature, high-pressure combustion processes characteristic of internal combustion engines—about 5.7 million tons in 1965.[11] These are toxic in themselves, and, together with unburned hydrocarbons, are the main ingredients in the photochemical mixture which constitutes Los Angeles-type "smog."

In addition to gaseous emissions, automotive vehicles are significant sources of particulates. Minor quantities originate in the engine exhausts; others come from mechanical wear, especially rubber from tires and asbestos particles from brake linings. The latter are not directly by-products of combustion, although they are produced mainly because the kinetic energy of vehicular motion is converted into heat as the vehicle is slowed down or brought to a stop.

Although people living in densely populated cities travel by automobile somewhat less than people living in suburbs or smaller towns, the differences on the average are not great. Only in New York City is a significant fraction of total passenger-miles attributed to railroads or rapid transit. Generally speaking, it can be assumed that local trips (50 miles or less) are distributed geographically roughly in proportion to population—which means most of them occur in urban areas—although longer trips would be more likely to utilize intercity or rural routes. However, automobile trips over 100 miles in length account for only 20 per cent of total automobile passenger-miles and, presumably, a comparable fraction of overall emissions.[12]

Industrial processes, especially metallurgy, cement and glass manufacture, and refractories, plus space-heating in households and other buildings, account for the remaining fossil fuel consumption in the United States. All three types of fuel are significantly represented. Thus 188 million tons of coal were used in industry in 1965, of which 96 million were first carbonized, yielding 77 million tons of coke plus coal gas, coal tar, and coal tar derivatives.[13] Low sulfur coal is necessary to produce metallurgical quality coke and the output of low sulfur Pennsylvania and West Virginia sources by the coking industry is mostly tied up by long-term contracts. Coal is no longer used to an appreciable extent for space heating purposes. Thus industry and households together contribute less than electrical utilities to the overall sulfur problem—8.4 mil-

11. R. Ayres & A. Kneese, *supra* note 6.
12. Automobile Manufacturing Association, *supra* note 9.
13. R. Ayres & A. Kneese, *supra* note 6.

lion tons of SO_x from these sectors was estimated for 1965. In addition, these sectors yielded 7 million tons of nitrogen oxides (NO_x) and 7 million tons of particulates (soot) and were the major single source of both.[14] Smoke control is, of course, particularly difficult in small heating plants for homes or apartments.

Residuals contributing to urban air pollution arise from two other principal sources: (1) production and processing wastes, and (2) consumption wastes. In the first category one must include such major items as evaporative losses in natural gas production, petroleum refining and petrochemicals, ore beneficiation, and so forth. In the second category must be included not only "final" goods whose ultimate disposal results in combustion (e.g., trash burning), but also a large number of "intermediate" products which never appear physically in a product for final consumption and which are actually dissipated and dispersed into the environment in normal usage. Among this category of products are many which contribute in a major way to air pollution, such as cleaners, solvents, pesticides, explosives, aerosol propellants, and so forth.

Fortunately, a number of the most obnoxious airborne industrial wastes, such as the fluorides which arise from the processing of phosphate rock into "superphosphate" fertilizer, and the sulfur oxides associated with copper, zinc, or lead ore reduction, are not produced in heavily populated areas. Petroleum refining, too, is sometimes restricted to fairly remote locations, although there are also large refineries to serve the local market in most metropolitan areas. Chemical plants in general, however, tend to be situated in or near cities and these are among the most prolific producers of evil-smelling,[15] corrosive, and irritating fumes.

Among the dissipative intermediates, solvents are the most noteworthy contributors to urban air pollution. This category includes turpentine, benzene, xylene, naphtha, methyl-, ethyl-, and isopropyl alcohols, glycol ethers, acetone, methyl-ethyl-ketone, carbon disulfide, carbon tetrachloride, vinyl chloride, and various other chlorinated hydrocarbons. Most of these substances have a variety of basic chemical uses, so that one cannot simply add up the total quantities produced and assume that it all contributes to air pollution. Nevertheless, this is the ultimate fate of very large tonnages of dry-cleaning agents, paint-removers, diluents and thinners used in many fast-drying paints, varnishes, and lacquers, among others. The function of a solvent is to selectively separate and remove solid substances from places where they are not wanted and/or to

14. *Id.*
15. Particularly, the mercaptans (RHS) including hydrogen sulfide.

permit solids to be deposited easily and uniformly in places where they are needed. The solvent itself may or may not be deliberately thrown away (i.e., allowed to evaporate) after such use, but even if it is distilled and re-used, there is bound to be some loss. If the cycle is repeated frequently, as in commercial dry-cleaning plants, the cumulative loss will be large.

The disposal of "final" goods, such as garbage, household trash, demolition wastes, and junk, may or may not contribute to air pollution, depending on how it is handled. Garbage and trash—about 4 pounds per capita per day, or 150 million tons per year, nationally—are largely ($\tilde{}$80 per cent) combustible,[16] whence refuse collection costs can be significantly reduced by incineration at the point of origin. However, local incineration is extremely inefficient and there is virtually no way to control smoke production, in particular. Many cities haul trash and garbage to central locations for processing. Again, to reduce bulk, open burning has been practiced at many such sites—with concomitant ill-effects on the surrounding area. Incineration in enclosed furnaces under controlled conditions is somewhat more efficient, but even so, a significant fraction of the fly ash (and all of the SO_x and NO_x) tends to escape into the atmosphere. Detailed statistics on emissions from refuse incineration are not currently available, but it is clear from materials-balance considerations that if only 100 million tons are burned annually in an uncontrolled manner, of which 20 per cent is incombustible, then somewhere in the neighborhood of possibly several million tons of soot is being injected into the atmosphere annually. In New York City about 75 tons of particulates a day are attributed to municipal refuse burning and a further 61 tons a day are attributed to dwellings and apartment houses—of which a significant fraction is also due to incineration.[17] All in all, probably half of all particulates (soot) come from this source.

II
EFFECTS

This is not the place for a detailed explanation of the physical, physiological, and socio-psychological effects of air pollution. It may be of interest, however, to summarize briefly the multitude of ways in which externally induced changes in the chemical composition of its atmosphere may affect the inhabitants of a city.

16. Aerojet General Corp., California Waste Management Study, Report No. 3056 to the State of California, Dep't of Public Health (1965).

17. R. Ayres & A. Kneese, *supra* note 6.

To begin with, there are direct effects on people, ranging in severity from the lethal to the merely annoying. Fatalities are not, as a rule, traceable individually to the impact of air pollution, primarily because most of the effects are synergistic. Thus, air pollution is an environmental stress which, in cooperation with a number of other environmental stresses, tends to increase the incidence and seriousness of a variety of pulmonary diseases, including lung cancer, emphysema, tuberculosis, pneumonia, bronchitis, asthma, and even the common cold. Statistical studies suggest that most or all of these are definitely correlated with long-term exposure to polluted air.[18] The most dramatic proof of the lethal capabilities of air pollution is the sharp rise in death rates (mainly from the elderly or those already suffering from one or more of the above complaints) during each major air pollution "episode" in a major city. Oft-cited examples include the Meuse Valley, Belgium 1930 (60 deaths); Donora, Pennsylvania 1948 (20 deaths); London 1952 (3500-4000 deaths); New York City 1965 (400 deaths).[19]

For every actual fatality attributable to the effects of pollution, there are many persons who are affected to the point of physical illness and a larger number who may not require medical treatment but who suffer significant annoyance, such as coughing, wheezing, pains in the chest, smarting eyes, and so forth. Finally, there is a still broader class, which probably includes nearly everybody living in an urban area, who object to the soot, bad smells, and other visible or sensory manifestations of pollution. Unfortunately, there are no good yardsticks to measure the disutility experienced by each group or the number of people who belong in each classification. However, one rather significant point deserves emphasis. The disutility arising from minor discomfort and essentially aesthetic objections to air pollution is probably the most underestimated and certainly the fastest-growing component of the total problem. This arises from two inter-related factors: (1) the rising level of education on the part of the population and even more rapid rate of increase in the means and possibilities of communications, all of which results in an explosive increase in the level of awareness and general perception of the pollution problem as compared with a few decades ago, and (2) the fact that comfort and aesthetic satisfaction are "superior goods," as many economists have pointed out, and the demand for them grows nonlinearly with general prosperity and affluence, which are themselves rapidly increasing.

18. They also may be correlated with smoking, malnutrition and other forms of stress. This makes statistical analysis extremely difficult.

19. *See* Goldsmith, *Effects of Air Pollution on Health*, 1 Air Pollution (2d ed. 1968).

Here lies the explanation of the superficially paradoxical fact that a generation ago belching smokestacks were welcomed, as indicators of full employment, whereas today they are more likely to be taken as symbols of technological obsolescence and management irresponsibility.

Direct effects on humans have parallels in the animal and plant worlds. Animals of economic importance (livestock) are not colocated to any appreciable extent with cities and can safely be overlooked in the present context. Effects on pets (dogs, cats and birds) almost certainly exist, although they have not been much documented. To the extent that the effects are chronic, perhaps resulting in discomfort and life-shortening for the animal, the disutility to humans may not be very great in most cases. In fact, since more kittens and puppies are born than are needed to satisfy the demand for pets, replacements of nonpedigreed animals can be had at virtually zero price.[20]

As far as plants are concerned, much the same situation holds. Crops are mostly some distance away from cities, and hazards are likely to be rather special in nature (e.g., fluorides from superphosphate plants, or sulfur oxides from copper smelters). However, there are some districts where truck crops—mostly fruits and vegetables—are grown in close juxtaposition to major cities. This is particularly true of Connecticut, Long Island, New Jersey, eastern Pennsylvania, and Delaware, and of southern California between San Diego and Santa Barbara where citrus groves still exist in considerable abundance. Agricultural damage in the citrus belt of southern California seems to be due mainly to oxidants, such as ozone and peroxy-acyl-nitrate,[21] which are produced by the interaction of unburned hydrocarbons, oxides of nitrogen, and strong sunlight. In the mixed truck-farming region of the Middle Atlantic states (potatoes, tomatoes, leafy vegetables, green peas, sweet corn, apples, peaches, dairy and poultry farming), the major cause of damage seems to be sulfur which often causes leaf-spotting and discoloration—reducing the market value of the product—and sometimes stunted growth or worse. In suburban gardens and city parks, there are deleterious effects on shrubs, flowers, and shade trees.

As with direct effects on human health, it is difficult to unambiguously trace a given symptom or a case of stunted growth to a par-

20. Pets are valued highly once they become "part" of a family, but their value declines later on as they become elderly and decrepit.

21. Brandt & Heck, *Effects of Air Pollutants on Vegetation,* 1 Air Pollution (2d ed. 1968).

ticular air pollutant. Again, air pollution must be considered an environmental stress, along with drought, extremes of temperature, or pest outbreaks. Very often—in fact, probably in the majority of instances—a healthy organism can withstand a single moderate stress but not two or three different stresses at the same time. Another way of looking at the matter is to say that exposure to constant stress from air pollution tends to weaken the plants' resistance to other environmental stresses, such as cold winters or dry, hot summers. Thus part of the excess mortality associated with events of the latter type should be attributed to the abnormal stress of air pollution, just as part of the excess mortality which might follow a very severe air pollution "episode" might fairly be attributable to the extra cold winter or an extra wet spring. Again, there are no satisfactory methods of allocating the observed damages among a number of synergistically interacting multiple causes, nor can the damages themselves be adequately measured and reduced to economic terms.

A third category of effects comprises damage to property. Here again, sulfur and oxidants are perhaps equally potent. As noted previously, sulfur oxides combine with water to form sulfurous acid (H_2SO_3) and the much more corrosive sulfuric acid (H_2SO_4). These acids will damage virtually any exposed metal surface and will react especially strongly with limestone or marble (calcium carbonate). Sulfur oxides will also cause discoloration, hardening and embrittlement of rubber, plastic, paper, and other materials. Oxidants such as ozone will also produce the latter type of effect. Of course, the most widespread and noticeable of all forms of property damage is simple dirt (soot), which has some secondary effects of its own. Thus, if shirt collars can be worn twice, the shirt itself will last approximately twice as long as if the shirt requires laundering after only one day—since a shirt's useful life is essentially measured in terms of the number of washings it undergoes, rather than the number of days it is worn.[22] Of course, airborne dirt also affects other clothing, furniture, carpets, drapes, exterior paintwork, and automobiles. It leads to extra washing, vacuum cleaning, dry-cleaning, and painting; and, of course, all of these activities do not entirely eliminate the dirt, so that people also must live in darker and dirtier surroundings.

A final category comprises bio-climatic and ecological effects. On

22. Our grandfather's generation got around this difficulty by utilizing detachable collars, but this frugal custom has disappeared in the United States. It still survives, to some degree, in coal-burning London—where the celluloid "white collar" was once the universal badge of a clerical—and hence middle-class—job.

the urban scale, it is known that there are distinct, measurable differences between the climate in a city and in its environs. Thus temperatures and humidity are higher, precipitation and cloud cover are slightly more frequent, fog is much more common (especially in winter), and so forth.[23] These differences are almost certainly due in part to the large amount of waste heat generated in cities and very likely also owe a debt to the concentration of particulates (which can serve as condensation nuclei for fog, for instance) and possibly some of the other residuals which are commonly dispersed in the air over cities.

On the continental scale, of course, one must begin to worry seriously about major perturbations to the climate which might be caused by the (apparently) rising level of atmospheric CO_2, as noted earlier. If, as has been suggested, the "greenhouse effect" leads to higher temperatures and results in melting the massive accumulations of ice in Greenland and Antarctica, one obvious consequence would be a distinct rise in the sea-level and a considerable problem for low-lying coastal cities. The rise would occur gradually, over centuries, permitting either evacuation or the building of dikes and protective walls, but in either event the consequences would be quite important for many urban dwellers. On the other hand, it has also been suggested that higher temperatures might trigger a new ice age which would have precisely the opposite effect. If this were to happen, a number of seaports would be stranded, like gasping fish, away from deep water.

III
COSTS

The notion of pollution "cost" is somewhat more elusive than it might at first appear to be. Although one may be forced by practical considerations to take a very simplistic view of the matter in the end, it seems worthwhile to mention some of the underlying difficulties in the concept. Quantitative national estimates of the cost of air pollution are relatively few and, with rare exceptions, not very illuminating.[24]

The usual approach is to add up dollar expenditures, such as extra cleaning or hospital bills, which would not be necessary if there were no pollution, plus lost future income and call these the "cost"

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23. *See* Lowrey, *The Climate of Cities,* Scientific American (Aug., 1967).

24. This literature has been reviewed and summarized in the presentation "How Much is Air Pollution Costing Us?" by A. V. Kneese, National Conference on Air Pollution, in Washington, D.C., Dec. 12-14, 1966.

of pollution. There are two immediate and cogent objections to this procedure, however. The first is that many, if not most, of the most important disutilities of pollution are not reflected by any such dollar expenditures. Clearly, hospital or burial costs, or even the present value of lost future income, are a poor measure of the value of a human life.[25] In the very large number of cases where the disutilities are sensory and aesthetic, no dollar value at all is allowed by such a measure.

Clearly, what is wrong here is that the real benefits which air pollution has deprived us of—life, health, and clean fresh air—are provided free. But they are free *not* because they exist in over-supply,[26] but because there exists no market in which they can be exchanged and priced. We have, at present, no satisfactory way of attaching a dollar sign to the loss of a free benefit. However, it is misleading and quite incorrect to assume explicitly or implicitly that the loss should be counted as zero.

The second fundamental objection to equating pollution costs with dollar expenditures which would not otherwise be made is the elementary fact that, in an exchange economy, an expense to one individual results in an income to another. Thus the extra cleaning costs noted previously result in extra income for the laundry. There is no *a priori* way of balancing the utilities and disutilities resulting from such a transaction since they depend upon the alternatives which exist for each party. For the person forced to spend more of his income on cleaning than he otherwise would, the welfare loss to him is the difference between the amount of satisfaction he would have received from spending a few cents per day in other ways *vis-à-vis* the satisfaction received from spending it on laundry.

For the economy as a whole, the question is more complicated: it boils down to the comparison of alternative patterns of expenditure and forms of employment for capital and certain categories of labor. If unskilled labor is in short supply, the use of it in a laundry is wasteful of resources, but if it is in over-supply, the alternative might be unemployment. There is no easy universal formula for measuring the marginal social utility of money spent on a particular good or service. Each case would have to be judged on its merits.

However, in a society such as the United States where neither

25. The absurdity of this measure is clear if we note that according to it men are "worth" 70 per cent more than women at age 20, but men and women have equal expectations at age 60, with the relative values reversed by age 70. Again, by this measure, an individual is "worth" much more if he dies slowly and agonizingly in a hospital than if he dies at home in his sleep.

26. The population explosion notwithstanding. Each individual only has one life to live, some threescore and ten years (give or take a few) in length.

labor nor capital is fully utilized under normal circumstances, it seems likely that, *ceteris paribus,* extra costs imposed by pollution do have some compensating economic benefits in creating employment for otherwise hard-to-employ workers. This is not to say that other forms of socially useful employment may not be found in the future, but at the present time it is probable that money now spent on extra laundry, cleaning, and maintenance produces more jobs for unskilled and semi-skilled labor than alternative modes of expenditure (e.g., on durable goods) would do. This being so, the sum total of dollar expenditures would have to be reduced by the net (dollar) benefits thereby produced to arrive at an estimate of net dollar costs.[27]

The fact is that any change in the pattern of consumption and expenditure has its effect on production and prices also. The example given above postulated that a change in expenditure patterns might result in a reduced demand for certain types of labor which are currently in oversupply.[28] Similarly, in another sphere, it must be pointed out that the economic distortion resulting from the fact that residuals can be disposed of into the environment without cost —or at too little cost—implies that certain products and services are probably being sold too cheaply, whereas others may be more expensive than they would be if *all* goods and services—including those provided by the environment—were exchanged only in a free competitive market.[29]

Electric power is a good case in point. It is produced as cheaply as it is in certain areas only because the electric utilities are allowed to use the air as a place to dispose of smoke and excess heat, without cost. If an economic price were charged for this service, the cheapest means of producing electric power might involve a different technology, and it might conceivably be more expensive.[30] Since electric power is an input to essentially all other industries, pro-

27. It is not impossible that the dollar benefits actually exceed the dollar costs, although this may seem a bit far-fetched at first.

28. Of course, in principle, the reverse could also happen, which would be no less important (but with opposite implications) if true.

29. In this context, the availability of assimilation capacity for residuals is a service rendered by the environment, for which an appropriate price should be paid, while the provision of unwanted residuals (such as soot or gaseous effluents) constitutes a disservice for which there should be a compensation corresponding to a negative price.

30. Actually, it would necessarily be more expensive under the altered ground rules only *if* the present technology were the cheapest one available. This is probably not the case in most big cities, however, since nuclear plants are now cheaper than almost any existing fossil fuel plants, except where coal or oil is available locally. New facilities are overwhelmingly nuclear and if all doubts regarding safety and radioactive waste disposal were resolved, most existing fossil fuel plants in big cities would be replaced by nuclear power plants.

duction costs would rise in other sectors of the economy. If aluminum production, for instance, depended to any extent on electric power from coal or oil-burning plants (which it does not), the price of aluminum would, in turn, have to be raised. This would affect the price of kitchenware, aircraft, and other products.

Speaking generally, the effects of air pollution on the economy include the sum total of all distortions[31] and implicit readjustments of the above type. To estimate these quantitatively would involve first knowing what the entire economy would be like if these distortions did not exist. A rather elaborate analysis of each industry would be required to estimate what its production costs would be on the basis of an altered set of input costs, including hypothetical payments for environmental services. From the revised set of prices (based on existing demand and elasticities), a new set of demands would have to be derived. From these, in turn, further revisions in calculated prices would be made. Thus, by iteration, a picture of the hypothetical undistorted economy could be derived—assuming one had a reasonable method of assigning virtual prices to the environmental services which are currently free.[32]

Assuming full employment (or making any other reasonable assumption about labor utilization), the GNP of the hypothetical "undistorted" economy could be computed by a linear programming model and compared with the actual one. However, this does not necessarily bring us closer to a realistic estimate of the cost of air pollution, since what counts is the *welfare* output—i.e., the total satisfaction provided—by the two economies. Once more we are reminded that welfare or satisfaction includes many things which are not bought or sold in a competitive market, and it is entirely possible, although not necessarily true, that the "undistorted" economy would produce fewer material goods or a smaller GNP, but greater welfare than our present one.

In summary, the overall costs of air pollution would be the sum of three terms, as follows:

disutility or losses of non-market ("free") benefits (life, health, aesthetics)	+	disutility or net direct dollar expenditures (e.g., laundry medical costs, etc.)	+	disutility (or utility) of net indirect dollar costs(or benefits) to society (e.g., employment, distorted prices, etc.)

31. Again, this refers to the fact that certain economic services rendered by the environment are exchanged at zero price, which would not be the case in a perfectly operating free competitive market.

32. This problem is discussed in Ayres & Kneese, *Production, Consumption, and Externalities* to be published in The American Economic Review (1969).

Of these three terms, the first has implicitly been assumed to be zero, although most analysts realize that this is unrealistic. The second term has been computed although the existing studies still leave much to be desired.[33] The third term has been ignored completely, possibly because first-order approximations may well be negative (i.e., beneficial to society in dollar terms) and no economist has wished to appear to say that "air pollution is good for you," however qualified that statement would be. Actually the numerical comparison of dollar costs and benefits appears to be unimportant in comparison with the glaring omission of the first term of the three: the physical and psychic losses for which we have no convenient dollar price tags. It is not acceptable to say that these kinds of losses are not zero, or even to say that they are large but inherently unquantifiable. The problem remains, however, to estimate them quantitatively *in terms of dollars,* which is the only existing available measure of utility (or disutility).

Fortunately it is not quite accurate to say that there exists no marketplace in which the services and/or disservices provided by air pollution are exchanged. Literally speaking, this is so, but there is one market where the impact of these services/disservices is felt and can be measured: real estate. To quote Ridker,

> If the land market were to work perfectly, the price of a plot of land would equal the sum of the present discounted stream of benefits and costs derivable from it. . . . Since air pollution is specific to locations and the supply of locations is fixed, there is less likelihood that the negative effects of pollution can be significantly shifted onto other markets. We should, therefore, expect to find the majority of effects reflected in this market, and can measure them by observing associated changes in property value.[34]

To the above, it should be added that the real estate market, like others, is very imperfect. In this case, the crucial flaw is the lack of perfect information on the part of purchasers. It would have been equally accurate and more appropriate to say that the price of a plot of land reflects the sum of present values of *anticipated* (i.e., perceived) future benefits and costs derivable from it. The point of this remark is that the vast majority of real estate buyers have essentially no knowledge at all of the more acute medical effects of air pollution—which are still being argued in highly

33. The best estimates are those by R. Ridker, Economic Costs of Air Pollution: Studies in Measurement (1965).

34. Ridker, *Strategies for Measuring the Cost of Air Pollution,* The Economics of Air Pollution (1966).

abstruse terms even among doctors. Hence, it is apparent that the latter are not being taken into account in land prices. What the real estate market primarily reflects is the tangible, experiential aspects of pollution: more rapid deterioration and extra cleaning and maintenance costs, the milder medical symptoms, such as shortness of breath and smarting eyes, plus bad smells and dirt. Ridker assumed —justifiably, no doubt—that these problems would be closely correlated with sulfur dioxide emissions. Eight "sulfation zones" were identified in St. Louis, and it was found by survey that average property values varied by about $250 per lot, per zone, other things remaining equal.[35]

Assuming an annual discount rate[36] of 6-8 per cent, this presumably can be interpreted to mean that the marginal utility of a shift from one sulfation level to the next is about $15-$20 for a lower middle-class or middle-class city-dweller. The marginal utility of a shift from the highest to the lowest sulfation level was evidently about $150 or $200 per year, on the basis of the rather narrow spectrum of tangible disservices (maintenance, odor, soot) mentioned above.

The amount which a fully knowledgeable real estate buyer would add to this to allow for the more serious, but rarer conditions, such as lung cancer and emphysema—whose link with air pollution is apparent statistically but not causally—is much harder to estimate. It has been observed that a human life is worth more to society than the simple discounted present value of future earnings, and acknowledged, also, that its value must nevertheless be finite, rather than infinite.[37] Limited guidance may perhaps be derived from the upper range of awards of juries in cases of accidental injury or death in cases where the negligent party is insured and can be presumed to have unlimited resources. Such awards nowadays often run above $250,000.

In the future, better information may come from sophisticated polling techniques, designed to elicit "willingness to pay." It is well known that simple questions, like "what would you be willing to pay to avoid (or gain) so and so," yield misleading answers.[38] However, there are methods of reducing, if not eliminating, some of

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35. *Id.*

36. The "discount rate" is equivalent to the average annual increase in value of alternative investments. To find the present value of a dollar-benefit to be received some years in the future one asks "what is the dollar amount which, if we invested it at 6-8%, would equal the specified amount at the appropriate time?"

37. Notwithstanding the irreplaceable uniqueness of each personality and each soul.

38. Since the person queried actually pays nothing to have his opinion recorded, he can make very extreme statements in the hope of indirectly influencing policy makers.

these secondary interactions between the pollster and the person being polled. It is possible that more meaningful answers can be obtained to questions like "would you accept a 1-in-10 chance of dying within 5 years in exchange for X thousand dollars?" Indeed, there are several professions—such as bullfighting and auto-racing —which offer opportunities (but not certainties) of large rewards in exchange for very high risks of injury or death. By analyzing data from polls, together with actual statistics for risky professions, it should be possible to cast much more light into this area of ignorance.

Whether by these methods, or others, only when the problem of putting a dollar value on illness and death has been grappled with, will it be possible to estimate the costs of pollution and the benefits of pollution control.

IV

ALTERNATIVE CONTROL POLICIES AND TECHNOLOGIES

This topic is a broad one which can only be skimmed in an overview such as this. As regards basic policies, there is a continuum of possibilities, depending largely on where the policy-maker stands with respect to one basic philosophical issue: the value of the free market as a method of allocating resources and incomes in our society. If the free market is deemed to be a mechanism worth preserving and improving, then the appropriate method of minimizing the disutilities[39] arising from air pollution is to recognize the fact that most of them arise from market failures and thus to attempt to eliminate these failures or find means of compensating for them. If, on the other hand, the free market *per se* is not felt to be important, then there is no basic objection to strictly pragmatic *ad hoc* responses, even though the latter may perpetuate or worsen the fundamental market failures. As a matter of observation, existing approaches to the problem of control tend to be of the latter type.

A classic market-preserving approach essentially attempts to eliminate externalities by "internalizing" them. On the government level this approach leads to regional compacts and "super agencies." In the private sector, however, the standard method of internalization—merger—is not available in most cases.[40]

39. As distinguished from *effects*, which are strictly physical.

40. The most extreme example would be public ownership of all sources of pollution (which essentially means all productive facilities and all energy-converting devices). This eliminates externalities as such, by merging the producers and consumers into one unit, but it also eliminates competition— another important feature of the free market— and has a very serious problem with respect to its "internal" operation, including the question of allocation of resources. Thus public ownership essentially begs the question rather than solving it.

The next alternative is to eliminate the effect of the market imperfections (if not the imperfections themselves) by attaching prices to *all* services—and disservices—which are now rendered "free" by the atmosphere. This means dollar exchanges, positive or negative as the case warrants, would be imposed for:

(1) private use of air as an input for any purpose,
(2) private use of the assimilative capacity of the atmosphere, for any purpose,
(3) inadvertent or unwanted material inputs *from* the air.

A formal scheme for incorporating such exchanges in the general equilibrium theory of economics has been described elsewhere.[41] In practice, the charges for air used for breathing would be very low since the quantity available greatly exceeds any possible near-term demand for this purpose. Charges for oxygen used for combustion might be the same, per unit, but would be greater in total. Charges for accepting CO_2 might be waived (as being covered by the charge for oxygen) but there would be additional charges for using the atmosphere as a sink for other products of inefficient combustion. On the other hand, persons inadvertently receiving unwanted inputs from the atmosphere, such as smog or soot, would receive appropriate compensation.

The important point is that if all these services and disservices were exchanged on a market, there would be *finite* prices attached to them. While such a market cannot exist in actuality as long as the air is held in common as a public good, there may be means of simulating the relevant effects of such a market: namely, the exchanges of money and the adjustments in productive processes and technology which would inevitably follow. One such simulacrum is the proposed "effluent tax," which would require a residuals producer to pay the government (as a surrogate for the public) in proportion to the quantity of residuals dispersed in the environment.

Without belaboring the point unduly, an illustration may be worthwhile. At the present time, in the absence of either a market exchange mechanism or an effluent charge, an electric utility may produce any amount of soot it pleases.[42] Its products are: (1) electricity and (2) soot (disregarding other effluents for the moment). It buys fuel, sells electricity, and "gives away" its soot, and chooses the cheapest possible fuel. Suppose, however, that the utility is no longer allowed to give away its co-product, soot, but must pay its

41. Ayres & Kneese, *supra* note 32.
42. Except as limited by *ad hoc* smoke control laws.

neighbors a price to accept it. Then it can do one of two things: it can continue to use the same fuel and the same combustion technology and simply charge more for the electricity, or it can shift to a cleaner fuel, use precipitators in the stacks, and reduce the output of soot. Since the demand for electricity will decrease if the price rises, profit considerations dictate that the electric utility will seek to keep the price of power low by finding cheap ways of eliminating the soot. Within a few years the "price" of eliminating soot will fall drastically, since many people will have a positive incentive to reduce it.

The *ad hoc* approach, which does not seek to preserve or improve the free competitive market, encompasses any number of variants, although the most common are the enforcement of arbitrary standards and subsidies. The first is a simple statement that emissions from such-and-such a process or engine shall not exceed a given amount, together with an appropriate amount of enforcement. Theoretically, this method might result in standards being set unrealistically low (or even at "zero"), although in practice the proposed standards are invariably modified by considerations of what the affected industry says is feasible. Unfortunately, the industry never really knows what it could do, at what price, and neither does anybody else. Worse, there is an historic tendency on the part of industry to grossly exaggerate the costs of any change whatever. The result is that standards are almost invariably much too lenient.

The most popular approach, with industry, is government subsidy, or—equivalently—tax credit. Unfortunately, by over-estimating the cost, it is sometimes possible to make a sizable windfall profit.[43] On the other hand, it is the case that certain industries would be severely damaged by a strict application of an effluent tax or even by the imposition of a realistic standard of emissions. While it seems difficult to justify making exceptions in favor of established interests, it is also inequitable, in some pertinent sense, to hurt or eliminate an industry by suddenly changing the rules of the game. This problem is not hypothetical: for example, the leather industry, for one, can probably not afford to clean up and remain competitive with synthetics.[44] In time, other industries based on

43. A typical method is to ascribe entirely or mostly to pollution control a large capital investment which would have been made anyway. It takes a very alert and knowledgeable bureaucrat to detect this sort of cheating.

44. However, it must be remembered that if hides had no market, they would be a disposal problem for meat packers; hence, the equilibrium market solution would involve an appropriate payment from the meatpackers to the leather industry (in lieu of disposal costs), thus eliminating the need for a public subsidy, but probably raising the price of meat.

natural products (sugar refining, paper, etc.) may face the same problem. Thus a case could be made for a public buy-out or a temporary subsidy to ease the period of transition.

Passing from policy to technology, there are two basic approaches: symptomatic treatment and process change. The first approach comprises the gamut of smoke precipitators, stack gas absorbers, filters and washers, afterburners and catalytic mufflers for automobiles, etc. These devices add complexity and cost to residuals-producing processes. Moreover, since the quantity of residuals is not actually decreased by add-on devices, the problem is very often merely shifted from one medium to another. Thus sulfur dioxide can be removed from stack gases by "washing"—but the sulfur-laden water still constitutes a disposal problem which may not be any less serious in magnitude. However, in some cases—as in the case of seaports—disposal in this manner may be preferable to use of the the air as a sink. Disposal as a solid, as with fly ash precipitated from stacks, would virtually always be advantageous. (Indeed, this material has several potential markets, e.g., as insulation or filler). In the case of automobile exhausts, the main problem arises from inefficient combustion, rather than impurities in the fuel, and afterburners do perform a useful service if they simply reduce the amount of unburned or partially burned material which escapes.

The alternative basic approach is, in the long run, more promising, however. It is to decrease the amount of residuals produced by fundamental process changes. In the case of electric utilities, this may be done by shifting from high sulfur to low sulfur oil; or by using natural gas or gassified desulfurized coal. Conversion to electricity may also be carried out nearer the mine, thus reducing transportation costs as well as reducing residuals load (which includes heat as well as combustion waste products) on the urban airshed. A shift to nuclear power also will reduce the problem of combustion-by-products, although the thermal pollution problem will be worse and a new problem of radioactive waste disposal must still be faced. Ultimately, however, controlled thermonuclear reactions (fusion power) promises to eliminate most of the presently envisaged residuals problems, including the latter.

Combustion wastes from automotive vehicles can also be drastically reduced by changing the basic technology. The least disruptive change would involve a switch from the internal combustion engine (ICE) to an external combustion engine (ECE). It has been concluded elsewhere that a modern Rankine-cycle reciprocating ECE using steam or a synthetic working fluid with appropriate

characteristics—such as one of the Freons—would provide very satisfactory service in all automotive applications with no sacrifice in power, weight, effective range, smoothness of operation or fuel consumption efficiency. Indeed, the evidence suggests that such an engine, mass-produced, would be simpler, cheaper to manufacture, longer-lived, and more economical to operate than the ICE.[45]

In the longer-term, electric propulsion for vehicles may be in the cards, since there is very rapid progress in battery and fuel cell technology, under the stimulus of military and space requirements. Extrapolating the recent rate-of-change in battery and fuel cell capabilities for another decade or two suggests that by 1985 or so, an electric car, using a fuel cell for primary power and batteries for peak power needs, will be economically and technologically competitive if marketed in such a way as to take advantage of its very low operating costs.[46]

Either an external combustion engine or the battery/fuel-cell option would reduce the emissions problem very drastically even from levels contemplated for 1985 by the large automobile manufacturers. To explore the circumstances under which a process-change of this magnitude might occur in an industry as massive and entrenched as the automotive industry is a major topic in itself and cannot be undertaken here.

However, there is good reason to believe that expenditures of government money may be most effective when, and to the extent that, they help to bring about process changes or large-scale technological substitutions such as the above. Thus, the technology of utility electricity generation has begun to reflect the massive federal government support of nuclear research. The government also can exert leverage by taxing a socially "undesirable" activity, or by explicitly creating a market for a desirable one through its own purchases. Indeed, the most likely way of encouraging the creation of a modern "steam-power" industry would be to specify that procurement for government agencies, the Post Office, police and so forth must utilize external combustion engines rather than internal combustion engines for propulsion. This strategy has not yet been tested, but it appears promising enough to warrant very serious consideration.

45. *See* R. Ayres, *supra* note 8. For a more thorough exposition, *see* R. Ayres, Technology and Urban Transportation: Environmental Quality Considerations, to be published for Resources for the Future by Johns Hopkins University Press, 1969.

46. This probably implies rental on a mileage basis in a manner analogous to the way Xerox copiers and electronic computers are rented currently. *See* R. Ayres, Technology and Urban Transportation, *supra* note 45.