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Measuring the Amenities and Disamenities of Economic Growth

Measuring Social and Economic Change: Benefits and Costs of Environmental Pollution

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INTRODUCTION

Benefits and costs associated with the environment involve not only pollutants and their effects in the usual sense but psychic responses to features of the environment some of which may not even be describable in relevant quantitative terms. Our focus is on pollution in the narrow sense, however, not because the wider and less tractable issues are unimportant, but because of considerations of comparative advantage.

Of the many possible approaches to the measurement of benefits and costs connected with the environment, two are selected for examination here. One possibility is to approach the measurement problem within the framework of the national income accounts. Flows of environmental benefits or costs or responses to them are already partially reflected in the national accounts, and there is a possibility that present deficiencies in their treatment could be remedied. We consider this at some length, with results that are rather negative. Although change in the official definitions does not seem to be warranted, it probably would be useful to prepare some auxiliary series reflecting response to environmental change and control that users could combine with the official series.

NOTE: We are indebted to Henry Peskin, Robert A. Kelly, Clifford S. Russell, and Walter O. Spofford, Jr., for comments on an earlier draft.

Orris Herfindahl died on December 16, 1972, in Nepal, while on a hiking expedition in the Himalayas. This paper reflects the keen interest and concern he had for the natural environment.

Apart from the national accounts approach, a thoroughgoing application of which would involve estimates for the environment of various aggregates corresponding to the series already included—value of service flows, maintenance, environmental capital formation and depreciation (depletion?)—it may be possible to measure environmental benefits and costs on a more limited basis, say, in marginal terms, and this is the approach we have taken. We do not attempt any estimates of benefits and costs as such, but confine ourselves to some general observations on how such estimates might be made and what the data and information requirements are for some of the possible methods.

It is of central importance to any method being used to throw light on environmental benefits and costs that important real external effects are involved with no counterpart money flow. This is in strong contrast to the treatment of ordinary goods for which benefits and costs can be estimated on the basis of market prices. Similar estimates of the changes in environmental benefits and costs that would result from a specified change in pollutant output require the explicit use of a model which can take account of these real repercussions not reflected in market prices or costs or that would be reflected only under some different institutional arrangement.

Several models that can go some distance toward tracing the repercussions of control actions or that can contribute to decisions on the proper control action are discussed. Among these are the adaptation of the input-output scheme to the analysis of pollution problems and a conceptually more elaborate model containing an activity analysis model and other components designed to portray certain physical and biological events accompanying a change in pollution outputs.

The final question to be considered is the kinds of data and information needed for the design and administration of pollution control schemes. The data of the specific models examined in some detail provide substantial guidance here, but since our discussion is necessarily rather general, it has a wider applicability. In effect, the question considered is this: Given that there is to be a pollution control system, what kinds of data and information are needed to make it work? First, it is essential to have baseline or indicator data to know when things have changed for the worse or to get some indication of the possibility that it might be possible to improve things in city A in view of the fact that conditions are better in a similar city B. Second, control requires accurate and comprehensive information on pollutant flows. The possibility of assembling this information as a part of a comprehensive accounting for materials flows is examined. Finally, pollution control requires some change in the way things are now done, but what options are there? What parts of the production function would provide the best compromise between the demands standing behind pollution production and the demands of those who are injured by it, assuming that institutional arrangements permitted the change? The need for systematic information on production possibilities is often neglected, but in fact it is of strategic importance to the design of control schemes that pay at least some attention to the relevant benefits and costs.

I. SOCIAL ACCOUNTS AND ENVIRONMENTAL BENEFITS AND COSTS

The Nature of Social Accounts

An accounting system is a way of systematically describing what has happened between two points in time to the state of a certain group of objects in a system. Ordinarily what happens to the state of the different objects in the system will be associated with various types of flows during the period in question.

We speak of an accounting *system* because the entities involved in the state descriptions and the flows accounted for are members of a proper classification. There is no overlapping of entities or flows, there is some principle of closure which definitely circumscribes the group of entities and flows, and the flows and objects are related in a definite manner. Flows always come from and go to members of the group of entities, and in doing so they behave in accordance with certain relationships that can be specified.

The design of an accounting system requires a selection of the "objects of interest." What phenomena are we trying to account for? The answer to this question determines the nature of the classification of entities and flows. In any practical application of the system, there must be a determination of the boundaries of the system, and this will depend on the phenomena of interest.

One property of an accounting system with boundaries defined in spatial terms is that totals can be broken down by area, as with the income payments series, wealth estimates, and so on. This property is extremely useful if environmental resources are incorporated into an accounting framework, because our interest in these resources usually has a very strong locational component. Unlike, say, the monetary system, there are few aspects of any environmental resource the proper management of which is connected with national totals or any of their national physical aspects. Much of our later discussion stresses the locational aspect.

Weight of flows of physical objects, like money flows between economic units, could form a suitable basis for an accounting system because its components add up to a definite total. While there is merit in an accounting system based on flows of mass—simply to provide an exhaustive means for tracing the flow of different substances—weight in fact may not be very closely connected with the true objects of our interest in connection with the natural environment. We would emphasize, however, the great importance of this exhaustive accounting device, at least for certain areas.

There is a possibility that many of the objects of interest may be such that a system of accounts—defined as above—could make only an indirect contribution to our understanding. For example, one of the things we are interested in is the effects of air pollutants on health—that is, effects on the feeling of well-being a person enjoys, on his performance, on sickness objectively viewed, and on age at death. To study these questions, we need to know the spatial and temporal distributions of concentrations of the different types of air pollutants and the temporal exposures of individuals to the various concentrations. It seems entirely possible, even likely, that the systematic series that we should like to see collected over time to facilitate study of the effects of air pollutants for the most part could not be combined in an accounting system apart from the aspect of mass. There is no point in adding concentrations at different locations, although their comparison in various ways may be of interest. Certain statistical operations can be viewed as the equivalent of adding together the exposures of different individuals at the same location, but there is little point in adding together the exposures of persons at different locations if exposures are different.

Considerations like these lead us to examine the possibility of thinking of social accounts in a looser way. We might, for example, think of social accounts as a systematic series of records over time that will aid us in "accounting" for what has gone on in a certain sphere of interest. Here we are thinking of "accounting" in the sense of describing or explaining rather than in the sense of identifying the numerical components of a total. In the case of the accounting system narrowly viewed, there is an additive unit of measurement which opens the possibility of forming a proper classification and specifying the boundaries of system and subsystem. With the looser system it is still possible to think of system and subsystem, but perhaps with less precision, and the publicly additive property is not present. A weighted sum may be conceivable in certain cases, but the weights usually will be private and more or less subjective.

Series of this kind can be thought of as serving several purposes. They may provide summary indicators of tendencies, they may provide baseline information for future studies, or they may provide important inputs to research studies on specific problems. A major part of our discussion in part III concerns these matters.

Should GNP and NNP Be Modified to Account for Environmental Pollution and Its Control?

The question whether the aggregate output accounts—GNP and NNP—should be modified to reflect the growing generation, treatment, and discharge of residuals from production and consumption activities can be interpreted in two ways. First, should the official definitions be changed, and, second, should auxiliary modified series be presented along with the official series based on unchanged definitions? As a general matter, we feel that the official series should be continued on the basis of the present definitions, both because of the desirability of avoiding breaks in the series and because the advantages and significance of some of the changes that might be made are not yet completely clear. The discussion applies, then, to the second interpretation. Whenever we speak of the desirability of modifying GNP or NNP,[1] we refer not to the official series but to modified auxiliary series. Of course, experience with such series might later be thought to indicate the desirability of a change in the official definitions.

GNP is intended to measure the production of "final" goods and services in the economy. The final "consumers" of these goods and services are taken to be individuals and households (consumers in the traditional sense), government, and nonprofit institutions. It is assumed that these economic agents do not usually use inputs to provide intermediate services (such as, for example, a trucking company would), but rather that they "use up" the utility embodied in the goods and services which the economy produces. This is a working assumption which, in numerous particular instances, is highly debatable.

At any given time there exists a list of goods and services which is officially regarded as final. These goods and services are exchanged

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[1] The discussion always refers to deflated, or "real," gross national product or net national product.

in markets[2] and therefore have market exchange determined prices attached to them in some base year as well as in the current period. As time passes, new goods and services are often "wedged in" to help keep the list more nearly complete. To calculate price-corrected or "real" GNP, the changing amounts of physical units of the final goods and services produced are multiplied by the unchanged base-period set of prices—currently, 1958 prices are used. The system of accounts is of the double entry type. In current prices the total of GNP calculated from the product side must balance GNP calculated as the sum of values added of all activities contributing to GNP. This is not true of real GNP, however, because no deflator has been devised with which the value-added side could be price corrected.[3] Thus, since we are here interested in real GNP, we will refer exclusively to the product-side calculations.

If it were true that all salient goods and services were exchanged in markets; that the degree of competition in these markets did not change; that the programs of government and nonprofit institutions did not change in such a way that they produced substantially altered welfare relative to the final goods and services that they absorbed; that population stayed constant; and that the distribution of income did not change; then alterations in real NNP (GNP minus capital consumption) could be regarded as a good indicator of changes in the economic welfare of the population.

This is an imposing string of assumptions, none of which is ever exactly met in reality. To the extent that they are not met, NNP diminishes in usefulness as a welfare measure. In fact, the distance between reality and these assumptions is large and significant in some cases, thus seriously reducing the practical usefulness of NNP as a welfare measure.

Of course the national accounts, which include much more than total NNP, have been designed to serve a number of purposes. They are intended to provide information useful for economic stabilization policies and programs, and they are meant to provide an estimate of the production of goods and services which the society has available to meet alternative ends. The designers of the accounts thought that at best they would serve to provide only a rough indicator of one dimension of welfare.

But to divorce completely discussion of the accounts from broader questions of welfare, as some would do, would be a serious mistake.

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[2] In fact, some of these transactions are virtual or imputed. For example, the value of owner-occupied housing is estimated by imputation.

[3] Deflated gross national product by industry is calculated by deflating industry outputs and purchases separately and subtracting.

Whether originally intended or not, total NNP or GNP is often explicitly or implicitly viewed as an index of welfare change. Moreover, it is important to recognize explicitly that there are enormous flows of services and disservices, valued by people, which do not enter into the exchange system and therefore are not in the list of final goods and services. Unless care is taken to observe and analyze these flows, the real NNP may become grossly misleading even as to what is happening to production of potentially marketable goods and services in the economy. For example, should there be a large-scale shift from purchases of services (e.g., house painting, grass cutting, construction, household services) to self-provision of these services, the NNP would tend to fall although it would not necessarily be true that production had decreased. The reason that NNP would tend to fall is that the labor going into these self-provided services is not in the list of final products; consequently, working time shifted toward them "disappears" from the account. The reason they are not in the list is that the accountants have found them too difficult and costly to identify and evaluate—although there may be good reason to reconsider this position in view of contemporary techniques of data collection and handling.

It is highly illuminating to view objections of the "environmentalist" to the accounts as involving a question of what is or is not in the list of final products. When the environmentalist contends that GNP overstates growth, he implicitly incorporates in his list of final products many service flows which do not enter into market exchange and consequently are not in the official list. Moreover, he believes that the net effect of including the omissions would be to reduce real product. His list would include the life support, aesthetic, and convenience services of clean air, clean water, and spacious surroundings—all of which in some of their aspects are *common property* resources unsuited to private exchange. The only way a change in these service flows could influence the GNP and NNP as presently measured is if their changed quality or quantity made the production of items which are included in the list easier or more difficult. In reality, such feedbacks on the national accounts from altered quality of the common property resources are probably trivial, up to now, compared with alteration of service flows from these resources direct to final consumers. These are nowhere reflected as such in the list of final products, although they may affect some items that are. It is the marked deterioration of the environmental services not on the list that mainly concerns the environmentalist.

The exclusion of the services of clean air, clean water, space, etc., from the list of final goods probably is not the result of disagreement that the services provided by nature are a factor in true welfare but rather of the judgment on the part of the income accountant that obtaining acceptable estimates for these values would be too difficult and costly. It is clear, however, that any reduction in the service flows of common property resources that is viewed as a loss in real product by consumers means that NNP overstates any increase in final product as compared with the total flow from the truly relevant and larger list of final goods and services. In the extreme case the "true" service flow could actually decrease while NNP rises. Some writers, like E. J. Mishan, believe that this is happening now.[4] This view seems a bit extreme, but whether it is or not is an empirical question.

That burdens on the service flows of common property assets tend to rise with increasing production unless effective, collectively imposed controls are undertaken is obvious from observation. There are also some reasons to believe that this rise will tend to be more than proportional to production growth in developed economies. Conservation of mass requires that all material resources used as inputs to the extractive, productive, and consumptive activities of the economy must appear as residuals which in some manner are returned to the environment—except for changes in the inventory of mass. If the use of material rises faster than production of final goods and services, so must the production of residuals. There are counteracting trends affecting materials use in the economy. However, as lower-quality ores are used greater quantities of unwanted material must be processed to get a given quantity of wanted material; as a result there appears a tendency for residuals to rise faster than final production of goods *and* services "embodying" materials. Also, energy usage recently has been rising faster than real NNP, and so long as it is obtained primarily from conversion of fossil fuels this implies a rapidly rising flow of residual materials and gases. In the absence of effective collective restriction on the use of common property resources like air and water they tend to become the receptacles into which residuals are discharged. Other sources of nonlinearities can be readily identified. Indeed, sometimes discontinuities or thresholds are encountered, as when a water body becomes anaerobic and its functioning changes dramatically for the worse so far as services like recreation and fishing are concerned.

There seems to be considerable agreement among those who have studied the matter that if it were practical to extend the list of final goods and services to include service flows from the natural environment

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[4] See E. J. Mishan, *The Costs of Economic Growth,* London, Staples Press Ltd., 1967.

this should be done. But there also seems to be near universal hopelessness about the feasibility of doing it—at least for a long time to come. Accordingly it is often concluded that the best we can do in this respect is to supplement the real NNP with physical, chemical, or biological indicators of the state of the environment. We discuss this possibility in part III.

But are there any less ambitious adjustments that should be made? One possibility is to deduct consumer "defensive" expenditures from NNP. If environmental service flows remained constant, then "defensive" expenditures made voluntarily by consumers would be on the same footing as any other, being carried to the point where utility gained is equated with alternative cost in utility lost. It would make no difference if environmental service flows are included in the list of final products so far as indication of welfare changes over time is concerned.

If environmental service flows change, however, then it is clear that a list of final products that omits either these or the defensive consumer expenditures may give an incorrect indication of welfare change over time. If defensive expenditures were simply deducted from the present GNP, the necessary implicit assumption would be—if welfare change is to be correctly indicated—that the defensive expenditures exactly offset the decline in value of the environmental services that "ought" to but do not now affect the GNP. Even so, it probably would be of interest to try to estimate consumer defensive expenditures.

Defensive expenditures by industry are already appropriately treated from this point of view since they never appear in real NNP. We will not develop the rationale for these points here since it is quite analogous to that developed in some detail for residuals control expenditures, below.

Costs of meeting environmental standards. Up to this point we have been discussing common property environmental resources as though their use were completely unrestricted. In the United States, this was a fairly good approximation of reality until recently, but public policy development is now proceeding rapidly to regulate their use for residuals disposal. The policy path we are taking seems to be leading toward ambient *environmental* standards which are to be achieved by enforcement of *emission* standards or, in a few cases, through the incentives provided by emission charges or taxes. If these policies become effective they should give rise to large expenditures for the control of residuals generation and discharge. The time pattern these will follow is uncertain, but probably they will "hump" in the next five to ten years during a clean-up phase, possibly then declining slightly for a time, following which they may tend to rise nonlinearly with increasing input. Table 1 gives some idea of the outlays which might be involved in the period 1970–75 if objectives are pursued very vigorously, although actual expenditures probably will be much less. The question arises, How should these expenditures be treated in the NNP?

Before trying to answer, we should review how such expenditures would be treated under present procedures. The fact is that they would be handled differently depending on whether they are incurred by consumers or government on the one hand or by industry on the other. In the following discussion we will neglect direct expenditures for pollution control by consumers, because we think they will be small (with one major exception which we discuss later), and in any case no different principles are involved.

The differential effect of industrial and governmental expenditures can easily be illustrated by a very simple example. Assume an economy in which only two commodities are produced in the base period, haircuts and bread (the citizens will be nude but well clipped). Accordingly the list of final products will consist of haircuts and bread (see Table 2). Let us assume that the production of haircuts generates no significant amount of residuals but that the production of bread does. Suppose also that barbers can be diverted to control residuals if that is desired (the bread can be produced with less waste if more labor is used).

In the base period there is a standard for the discharge of residuals, but the production of bread is just low enough to avoid violating it. In period 1, a change in family composition causes a shift in demand from haircuts to bread together with an increase in residuals. If there were no standard for discharge of residuals, the situation would be that labeled 1a. That is, $500 of productive services would have been diverted from the production of haircuts to bread, and residuals discharge would have increased.

There is a standard for residuals discharge, however, and it is not being met in situation 1a. If it is met by a diversion *within the industry* of barbers to residuals control, NNP will register a decline as compared with period 0, as shown by 1b. The decline in the flow of residuals is not recorded, of course. In contrast, if the government hires these same men to limit the discharge of residuals to the standard level, NNP will show no decline, as in 1c. The reason is that there is nothing in the list of final products corresponding to residual controls, and so the activities directed toward that end cannot be reflected in NNP evaluated

TABLE 1

A Collection of Rough Estimates of Increase in Costs to Achieve "Substantial" Reductions in Environmental Pollution, 1970–75

	Billions of Dollars[a]
Water	
Treating municipal sewage	12
Reducing nonthermal industrial wastes	6
Reducing thermal discharges	3
Sediment and acid mine drainage control	3
Reducing oil spills, water craft discharges, and other miscellaneous items	1
Added reservoir storage for low flow regulation	1
Separating storm and sanitary sewers	40
Total	66
Total without last item	26
Air	
Controls on stationary sources	5
Mobile sources	
To modify refining and distribution of gasoline	2
Engine modifications	2
Added fuel costs	1
Total	10
Solids	
Increased coverage of collection	1
Increased operating cost, including environmental protection costs	3
Total	4
Other	
Control of heavy metals (mercury, cadmium, etc.), stopping use of persistent pesticides, improving water treatment, control of pollutant-bearing soil runoff, control of feed-lot operations, etc.[b]	15
Grand total	
With storm-sewer separators (about 35 per cent increase of GNP)	95
Without storm-sewer separators (about 20 per cent increase of GNP)	55

SOURCE: Allen V. Kneese, "The Economics of Environmental Pollution in the United States," in Allen V. Kneese, Sidney E. Rolfe, and Joseph W. Harned, eds., *International Environmental Management: The Political Economy of Pollution*, Proceedings of Atlantic Council–Battelle Memorial Institute Conference of January 1971, Washington, D.C., forthcoming.

[a] Estimates include investment and operating costs.

[b] A sheer guess.

TABLE 2

The Haircuts and Bread Economy

		Q	P_0	NNP
Period 0	H	100	$10	$1,000
	B	100	10	1,000
				2,000
Period 1a (as it would be without residuals control)	H	50	10	500
	B	150	10	1,500
				2,000
Period 1b (as it would be if industry had to control residuals by diverting 25 extra barbers)	H	25	10	250
	B	150	10	1,500
				1,750
Period 1c (as it would be if government hired the extra bakers and set them to controlling residuals)	H	25	10	250
	B	150	10	1,500
	G	25	10	250
				2,000

H = haircuts.
B = bread.
G = government.

at base-year prices. However, since government is in effect regarded as a final consumer, its expenditure for the barbers (or rather residuals controllers) is included in NNP.[5]

Observations on Treating the Costs of Environmental Standards. If we visualize a situation in which the government establishes effective environmental standards which must be continuously met, the present NNP treatment of industry outlays to comply with them would seem to indicate welfare change more appropriately than the present treatment of similar governmental outlays. The reason is that the outlays made for residuals control can be viewed as simply being necessary to maintain, at some specified level, the service flow naturally provided by the common property assets. In that sense they are expenditures necessary to

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[5] A more formal justification of these points is included in a forthcoming study by Karl-Göran Mäler of the Stockholm School of Economics.

maintain the unproduced capital stock. Failure to treat them this way could result in an anomalous situation in which a progressively larger share of production would have to be devoted simply to environmental quality maintenance with NNP continuing to rise. It would be hard to claim that this rise could in any way be regarded as indicating increased welfare. Viewed this way the appropriate procedure would be to treat industry outlays for control as at present and to change procedures so that government outlays for control could be treated similarly.[6] This would require identification of government expenditures for residuals control, which we think would not be too difficult, and their subtraction from the present NNP for presentation as an auxiliary series.

The one major exception to the view that consumer expenditures to control residuals will be small is in the control of emissions from automobiles. The approach adopted in the official series is essentially to add items called control devices to the list of final products. If this were not done, the price deflator would tend to indicate a reduced real production of automobiles.

The better approach, it seems to us, is to treat this case—again in an auxiliary series—symmetrically with the way industry is now treated. The consumer would be regarded as producing a service for himself, the production of which generates residuals. He is required in the interest of maintaining the service flow from common property assets to incur a cost. To add such costs to NNP over time would have the same anomalous results as already described in the case of industry.

As we have already indicated, our view appears to be contrary to the views of some experts in national income accounting. Their position apparently rests on two major considerations. The first reflects the special problem of dealing with a catch-up phase such as we are now experiencing in connection with the control of environmental pollution. When effective standards of higher than prevailing quality are first set, some of the expenditures made will result in actual improvements in environmental quality. Thus, the anomalous situation would arise that the population actually experiences an improvement in welfare while the associated influence on NNP is downward. To avoid this situation it has been proposed that the list of final products be expanded to include industrial outlays for residuals control. For reasons already explained we do not think this is the appropriate approach for the longer term welfare indicator. It would be preferable not to add the outlays but to

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[6] We are still assuming, we think correctly, that consumer expenditures for residuals discharge control will be minor.

prorate them over a longer period of time, especially from earlier periods when NNP tended to be understated as an indicator of welfare.

The second argument relates to the accounts as measures of production. If it is argued that the GNP is an important measure of the production that might be diverted in periods of national emergency (wartime, for example) for overriding national ends, then the production going into residuals control should be included in GNP. This is because it could be diverted at the cost of permitting deterioration of the service flows from common property assets. In this sense it is quite analogous to running down private capital during such periods. But this does not argue that these expenditures should ever be included in NNP.

The argument is also made that not including production directed toward residuals control would distort labor productivity series which are obtained by dividing NNP by man-hours worked. One's point of view on this seems to be highly contingent on what one regards as measured by labor productivity. If one regards it as the output per man-hour net of the output needed to maintain the service flows of all assets—private and common—then it is wholly appropriate that productivity should tend to fall if a larger proportion of total effort has to go for meeting environmental standards. On the other hand if one regards productivity as pertaining only to conventional production processes, then one would wish activities devoted to environmental maintenance to be in the list of final goods.

Conclusions on national accounts. Since the character of the national product and income accounts is not directed very closely to the single objective of measuring changes in social welfare and uncertainty surrounds some of the changes that have been discussed—both as to implications and practicality—we feel that the official definitions should not be changed. However, series should be prepared that reflect, at least in part, the growth of activities that would indicate decreases in an idealized list of final products or that offset, at least to some degree, the apparent increases registered in, say, NNP.

To this end, we suggest the regular preparation and publication of the following series:

1. Industrial expenditures for residuals control;
2. Government expenditures for residuals control;
3. Consumer expenditures for residuals control;
4. Consumer, industry, and government defensive expenditures.

None of these is prepared currently, and all offer considerable difficulty. If they can be put together, however, the accounts could be adjusted to reflect various preferences and points of view. It probably would be desirable to publish auxiliary series modifying the official series. The following are some of the possibilities, with all series assumed to be price corrected:

1. GNP—including all residuals control in the list of final products;
2. NNP_1—GNP minus net depreciation of private assets;
3. NNP_2—GNP minus net depreciation of private assets and minus the nonindustry cost of residuals control and defensive expenditures (and in principle all other costs which may be induced by the growth process itself).

In no case, however, should the mistake be made of thinking that adjustments of these types can come very close to indicating changes in "true" welfare so far as flows of environmental services are concerned. The essential ingredient that is lacking is a valuation for the environmental services themselves and, on capital account, an expression for decreases or increases in the value of the corresponding natural assets.

Apart from this general caveat, the definition of some of the series is not very precise. This is especially true of industrial outlays made for pollution control to meet standards of environmental quality. This is evident immediately merely by considering the possible responses of industry to an increase in these standards. True, it may make some outlays, both capital and operating, which would be designated as pollution control outlays. These might include equipment for extracting substances from stack gases or fluid effluent, for example. There are other responses, however. A material may be substituted which is not regarded as a pollutant when emitted in gaseous, fluid, or solid waste. A basic process may be changed which cuts emission of pollutants. Total emission of pollutants may be cut by a combination of ordinary pollution control equipment which in turn causes a reduction in consumption of the article in question by increasing cost and price. There is little hope for estimating the latter types of response on any comprehensive basis.

Thus the whole problem cannot be solved. Even though the suggested adjustments are partial, however, they ought to be made, for they may permit some sharpening of conclusions on what has happened to real product.

II. MODELS FOR ACCOUNTING AND ANALYSIS

To go beyond the rather simpleminded compilation of series on expenditures made in connection with pollution change or control and estimate the net benefits associated with changes in pollutants emitted requires the use of a model that will simulate, at least in part, the real repercussions that result from a change that is imposed. There are many models of widely varying degrees of complexity and adequacy that might be and are used for this task.[7] Several models have been presented in recent literature which lend themselves to rather detailed forecasting and policy analysis. They include rather straightforward extensions of open input-output models, analytical-type accounting models which balance materials flows as well as money flows, and activity analysis models embodying important features of natural environmental systems. In discussing them we will proceed from the simpler ones which are relatively easy to implement to those which encompass more significant elements of reality but are harder to implement. We discuss three, a national input-output model, models to account for all materials flows, and a linear programming model adapted to the analysis of regional pollution problems.

The National I-O Model

In recent papers, W. Leontief has proposed an extension of the basic national open I-O model which would permit forecasting of residuals emissons and of the effects of certain types of policy measures. The following exposition of his proposal is based on the mathematical appendix of Leontief's article in the *Review of Economics and Statistics.*[8] Although interpretation of the mathematics is rather straightforward, we shall describe the system in some detail because pollutants are handled somewhat differently from ordinary commodities and also because some readers may not be familiar with matrix representation of a system of equations.

The physical input-output balance with pollutants included in the system is shown by matrix equation (1) in Exhibit 1. We have m ordinary goods and $n - m$ pollutants, making a total of n inputs and outputs.

Each of the A matrices is a matrix of input-output coefficients. For example; a_{ij} is the amount of ith ordinary input required per unit of jth ordinary output (submatrix A_{11}); a_{ik} is the amount of ith ordinary input required to produce a unit of the kth pollutant reduction output (submatrix A_{12}); a_{ki} is the amount of the kth pollutant resulting from producing a unit of ith ordinary output (submatrix A_{21}); a_{kl} is the

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[7] It is an interesting exercise to try to specify the model that is implicit in some of the current "analyses" of pollution problems.

[8] Wassily Leontief, "Environmental Repercussions of the Economic Structure: An Input-Output Approach," *Review of Economics and Statistics,* August 1970, pp. 262–271.

EXHIBIT 1

Physical Input-Output Balance

$$
\begin{array}{rc}
 & \begin{array}{cc}\text{Ordinary inputs} & \text{Pollution reduction activities}\end{array} \\
\begin{array}{r}\text{Ordinary inputs}\\[2ex] \text{Pollutants produced (can be regarded as "inputs")}\end{array} &
\left[\begin{array}{c:c} I - A_{11} & -A_{12} \\ \hdashline A_{21} & -I + A_{22}\end{array}\right]
\end{array}
\left[\begin{array}{c} X_1 \\ \hdashline X_2 \end{array}\right]
\begin{array}{l}\text{Ordinary outputs}\\[2ex] \text{Pollution reduction "outputs"}\end{array}
= A^{*}X =
\left[\begin{array}{c} Y_1 \\ \hdashline Y_2 \end{array}\right]
\begin{array}{l}\text{Ordinary goods remaining for final demand}\\[2ex] \text{Pollutants remaining for final demanders}\end{array}
\tag{1}
$$

Commodities, or industries, are indexed as follows:

$$\underbrace{1, 2, \ldots, i, \ldots, j, \ldots, m}_{\text{Ordinary goods}} \qquad \underbrace{(m+1), \ldots, k, \ldots, l, \ldots, n}_{\text{Pollutants}}$$

amount of the *k*th pollutant produced as a result of a unit reduction in the *l*th pollutant (submatrix A_{22}).

To see what is involved in this system of equations, let us separate out one of them and write it out in full. Assume that we have three ordinary commodities and two pollutant reduction activities,[9] a total of five outputs, or "inputs," in all. Take, for example, the first equation, (2), which is formed by multiplying each member of the first row of A^* by the corresponding members of the X vector of industry outputs and adding these products together, thereby obtaining the first member, y_1, of the vector of final outputs, Y:

$$[1 \quad -a_{12} \quad -a_{13} \quad -a_{14} \quad -a_{15}]\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} = y_1 \tag{2}$$

or,

$$x_1 - a_{12}x_2 - a_{13}x_3 - a_{14}x_4 - a_{15}x_5 = y_1.$$

Note that in the matrices of input-output coefficients we have regarded a_{ii} and a_{kk} as zero so that industry output is always net of its own output that *it* uses.

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[9] We speak of pollutant reduction activities rather than industries because in any application the pollutant reduction activities often will be a part of an ordinary industry. In some cases it may be desirable to account for these separately.

This equation simply says that the total output of the first commodity minus the amount used in the production of x_2, x_3, x_4, and x_5 is equal to the amount of the first commodity, y_1, going to final demanders. The last four terms account for all of the x_1 used in production, whether for ordinary goods or pollution reduction.

Now consider equation (3), in the bottom part of the square matrix, A^*, say the last one for the nth commodity, which is a pollutant. Note that since the output of the pollution-processing industry is here measured as pollution reduction, the signs of the elements of the two lower quadrants are reversed from those of the two upper ones:

$$[a_{51} + a_{52} + a_{53} + a_{54} - 1]\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} = y_5 \tag{3}$$

or,

$$a_{51}x_1 + a_{52}x_2 + a_{53}x_3 + a_{54}x_4 - x_5 = y_5.$$

This says that the pollutant, which is commodity number five, that is generated in the production of x_1, x_2, x_3, and x_4 *minus* the amount by which this pollutant is reduced equals the amount which goes to final demanders.

Thus, in abbreviated matrix form, the physical input-output balance is $A^*X = Y$, where X and Y are vectors of industry outputs and deliveries of final goods, respectively. Industry outputs include pollutant reduction, and final goods include pollutants received.[10]

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[10] So far, no account has been taken of pollutants generated by the final demand sector. To do so, form a "household" pollution generation matrix, A_y, of the coefficients a_{gy_i}, showing the amount of pollutant g generated per unit of commodity y_i consumed.

Then the vector of pollutants generated by household consumption will be, say, $Y_H = A_yY_1$.

If Y_E is the vector of pollutants reaching the "environment," we have:

$$Y_E = \boxed{A_{21} \;\vdots\; -I + A_{22}}\begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + Y_H$$

$$= \underbrace{[A_{21} \quad A_{22}]\begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + Y_H}_{\text{Total generated by industry and households}} \quad \underbrace{- X_2}_{\text{Pollutants processed}}$$

$$= Y_2 + Y_H.$$

[Cont. on p. 459]

EXHIBIT 2

Input-Output Balance Between Prices and Values Added

$$\begin{array}{r|c:c|}
 & m \text{ Goods} & (n-m) \text{ Pollution control activities} \\
\hline
m \text{ Ordinary goods} & I - A'_{11} & -Q'_{21} \\
\hdashline
(n-m) \text{ Pollutants} & -A'_{12} & I - Q'_{22} \\
\hline
\end{array}
\begin{array}{|c|l}
\hline
P_1 & \text{Prices of ordinary goods} \\
\hdashline
P_2 & \text{Prices for pollution elimination} \\
\hline
\end{array}
= Q^* P =
\begin{array}{|c|l}
\hline
V_1 & \text{Value added for } m \text{ ordinary goods} \\
\hdashline
V_2 & \text{Value added for } (n-m) \text{ pollution control activities} \\
\hline
\end{array} \tag{4}$$

The system of equations, $A^*X = Y$, can be solved for the vector X, industry outputs, by premultiplying each side by the inverse of the matrix, $(A^*)^{-1}$, obtaining $X = (A^*)^{-1}Y$. Thus, if $(A^*)^{-1}$ has been calculated for a given industrial structure, the industry outputs, X, that would be associated with any specified bill of final goods, Y, can be calculated very easily, given, of course, the peculiar assumptions of the input-output scheme as commonly formulated. The main one is that the input coefficients, the *a*'s, are fixed no matter what the size of an industry's output. That is, there is only one way to produce an output, a way that is completely described by one column of *a* coefficients. It is this assumption that facilitates calculation of economy-wide effects of certain policy changes or changes in final demands.

If the value added in the production of a unit of a commodity is known,[11] this schema can be used to calculate the prices of the commodities that will rule under certain specified conditions. First we express the input-output balance between prices and values added, as in equation (4) in Exhibit 2. **P** is a vector of prices of outputs, partitioned into ordinary goods and pollutants, as before, and *V* is a vector of values added, partitioned in the same way. The square matrix is different, however, in

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[Cont. from p. 458]

Thus, if (1) is to hold, the lower part of the Y vector must be net of household pollution since these equations express relations between pollutants generated by industry, processed by industry, and delivered by industry to households:

$$\begin{array}{|c|}
\hline
Y_1 \\
\hdashline
Y_B - Y_H \\
\hline
\end{array}$$

If $Y_H = 0$, this reduces to the original formulation with $Y_B = Y_2$.

[11] For example, if labor is the only factor input and the labor input coefficients, analogous to the input-output coefficients, a_{ij}, are known and a wage rate is specified, value added can be calculated for each good.

that A^* has been transposed, that is, its columns and rows have been interchanged so that, for example, element a_{ki} is now where element a_{ik} used to be.

In addition, the coefficients involving pollution generation [those in A_{21} and in $(-I + A_{22})$] have been modified. They have been reduced by a factor which reflects the proportion of pollutant generated by an industry the elimination of which is paid for by it. Thus, if industry i generates a_{ki} pollutant per unit of output (a_{ki} is in A_{ki}) and pays for the elimination of $100r_{ki}$ per cent of it, we replace a_{ki} by $q_{ki} = r_{ki}a_{ki}$. A similar modification is made for pollutants produced by the pollutant control industries, that is, of the a_{kl} found in the quadrant $(-I + A_{22})$.

After these modifications, A_{21} becomes $-Q_{21}$ and $(-I + A_{22})$ becomes $(I - Q_{22})$. Note that signs are changed in order to have the price of the product minus the sum of required inputs times their prices be equal to value added for each industry.[12]

In matrix form, the price–value-added balance is expressed as $Q^*P = V$. As before, we can premultiply both sides by $(Q^*)^{-1}$ and in this way determine the prices that must rule for a given set of values added *and* q's: $P = (Q^*)^{-1}V$. Note that if each industry pays for the

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[12] Consider now an equation involving the top portion of the large square matrix, Q^*, in Exhibit 2, say the first. Assume a five-commodity economy as before.

Since A^* has been transposed (as indicated by the prime to the upper right of A_{11}, etc.), the first column of A^* is now the first row of Q^*, with the coefficients a_{ki} and a_{kl} modified as just explained. Thus the first equation, using *original* subscripts, is:

$$[1 - a_{21} - a_{31} - q_{41} - q_{51}]\begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \end{bmatrix} = v_1$$

or,

$$p_1 - a_{21}p_2 - a_{31}p_3 - q_{41}p_4 - q_{51}p_5 = v_1.$$

This says that the price of commodity number one minus the cost of ordinary inputs numbers two and three minus that *portion* of the per unit cost of eliminating pollutants four and five generated in the production of good number one to be borne by industry number one is equal to the value added of industry number one.

Similarly, the equation involving the last line of Q^* is:

$$-a_{1n}p_1 - a_{2n}p_2 - a_{3n}p_3 - q_{4n}p_4 + p_5 = v_n.$$

This says the same thing, with the industry in question a pollution control industry.

whole per unit cost of pollutants eliminated that it has produced (i.e., if r_{ki} and r_{kl} equal 1), then $Q_{21} = A_{21}$ and $Q_{22} = A_{22}$.

By using the relationships established in these equations, various interesting analyses can be performed. For example, calculations can now be made of changes in residuals resulting directly and indirectly from a change in final demand[13] or of the net increase in production needed to achieve a specified reduction in residuals while holding final goods production constant. This analysis accounts not only for the resources needed by the residuals control sector but the resources used indirectly to control residuals from the supplying industries.

Equation (4) and those derived from it balance the system in value terms and admit the possibility of some residuals being controlled by the manufacturing industries themselves (but still in activities separable from their normal production process) rather than only by the residuals control sector.

The appeal of the I-O approach as extended to include residuals generation and control lies in the ease with which it can be implemented. At least two efforts are already underway. Leontief reports on one in this volume, and at our own organization, Resources for the Future, an effort is being made to project resource use and residuals generation several decades into the future by means of a mathematical model which embodies a national input-output matrix.[14] This model contains techniques for projecting the "exogenous" final demands in the I-O model and also techniques for projecting the technical coefficients based on technological change and substitutions induced by relative price shifts. The model also projects residuals from government activities and final consumption.

The economy-wide I-O approach is best suited for residuals problems where location of discharge does not matter, or at least is not a dominant consideration, either for natural or policy reasons. For example, should the increase in atmospheric CO_2 become a problem of real concern, the I-O approach would permit testing the influence of different patterns of final demand on CO_2 discharge, given that the production technology of the economy did not change or changed in accordance with the projections of technical and residual coefficients. In this case the specific loca-

[13] When the change in final demand is a unit increase in the ith good or service, ordinary inputs required and residuals generated are the elements of the ith column of $(A^*)^{-1}$.

[14] This work is being conducted by Ronald G. Ridker and Robert U. Ayres.

tion of the discharge does not matter, because more or less uniform dilution occurs globally—at least in a given hemisphere.

In those cases where concentration, exposure, and assimilative capacity do vary with location, an "ideal" policy would take account of these differences, but certain considerations, cost of implementation, for example, may point to the desirability of national emission standards even in these cases. In this circumstance, the national I-O model will still be of some use. For example, the implications for residuals and industry outputs of alternative patterns of final demand and levels of residuals control can be played out, although the linkage with environmental effects must then be extremely loose.

As of September 1970, performance standards for new facilities had been established by the Environmental Protection Agency (EPA) for nitric acid plants, contact sulfuric acid plants, portland cement plants, large incinerators, and fossil fuel steam plants. In addition, emission standards applicable to all sources will shortly be established for asbestos, mercury, and beryllium.[15] The national I-O approach would be of considerable help in analyzing these and similar cases.

Another calculation that can be made is one in which patterns of final demand are projected under the assumption of no residuals control and with present or projected production technologies, including residuals generation coefficients, going into the future. One can get an impression of alternative possible futures by means of these "projections," as will be possible with the Ridker-Ayres model already mentioned.

The I-O approach as we have described it so far has some notable shortcomings, however:

1. The system as suggested up to this point is on a national scale whereas pollution "problem sheds" tend to be on a regional scale, and sometimes the region is quite small.
2. It has not accounted in a logically complete manner for the residuals generated in production and consumption in the initial attempts at application. In principle, however, the pollutant categories could be expanded to include *all* residuals. If the classification were rather detailed, there would be many pollution "control" industries with zero output.
3. It is usually not correct to think of residuals control as taking place in a separate residual control sector or even in separate residual control activities—especially in the case of industrial activities. In most indus-

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[15] *Environmental Quality*, second annual report of the Council on Environmental Quality, August 1971, p. 9.

tries, process changes resulting in residual control and greater production of usable products are important alternatives to separate residual control activities either outside or within the industry. The only way such changes resulting either from new application of existing technology or development of new technology can be inserted into the I-O approach is by changing coefficients relating residuals generation to output. There is no internal optimizing method for selecting industrial processes in view of their residual generation characteristics and other economic attributes—unless I-O analysis is abandoned for activity analysis, its close relative.

4. The model focuses on residuals generation and discharge. It does not analyze what happens to residuals once they enter into the environment, nor does it incorporate any consideration of damages. The processes of transportation and transformation in the environment, as affected by hydrological, meteorological, biological, and other natural system conditions have a significant bearing on the damaging effects of a given amount of residuals discharge.
5. The model focuses on residuals control costs but gives no attention to the value of the loss in function of common property resources when their quality deteriorates due to the effects of residuals discharge.

Some of the deficiencies of the I-O approach as just described can be remedied within its framework, but only at the cost of considerable complication. For example, the limitation of national scale of the model immediately suggests regional I-O models. However, even this extension would leave two important limitations: the linearity of the system, which limits the extent of the changes with which it can deal, and the one-to-one relationship between process and product.

Regional and Interregional I-O Models

National boundaries seldom describe a satisfactory area for the analysis of pollution problems. They tend to conform more nearly to natural regions ranging from the entire globe (as with CO_2 and DDT) to small stretches of river or highly localized airsheds. In principle this fact could be accommodated in the I-O approach by developing a set of linked interregional models for the nation. There is not much logical or mathematical difficulty in converting the national to an interregional model. The extensions are straightforward, and consist primarily of adding rows and columns specifying imports to and exports from the various regions. The problem lies rather in data requirements.

There are many reasons for wishing to have a set of coherent I-O models for subnational regions. Many tables have been constructed for individual states and regions, but no consistent set exists for the nation as a whole. The pollution issue adds another argument for developing such a system. We propose that discussions be initiated leading to the design of a national system of regional I-O models for analysis of various problems, including residuals generation and discharge.[16]

Accounting for Residuals in a Logically Complete Manner

The residuals generation aspect of the present I-O models does not completely account for all materials flows, including residuals, that are generated by the various parts of the real-world system. There is no environmental sector, and all residuals not processed are viewed as ending up in the final demand sector. Moreover, interdependencies among solid, liquid, and gaseous residuals in production, consumption, and transformation (treatment) processes are not identified or accounted for.

In a recent study by Ayres, d'Arge, and Kneese,[17] models have been explored which provide for a logically complete accounting of materials flowing into production and consumption processes in the economy and thence to the environment. The approach proceeds by specifying a set of equations representing materials balances in conjunction with the equations representing an interdependent economic system. We will treat it only briefly because so far it has had little empirical application. It has called attention to the importance of the conservation of mass in considering residuals processes—both as to the amounts produced and the limitations of treatment processes with respect to them. Essentially all raw materials (in terms of mass) which enter the extractive and materials-processing activities of the economy must be returned to the environment as residuals. This fact is not controverted by the application

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[16] A substantial amount of work has already been done on regional environmental problems involving the I-O approach. See John H. Cumberland, "A Regional Interindustry Model for Analysis of Development Objectives," *Regional Science Association Papers*, 1966, pp. 65–94; Cumberland, "Application of Input-Output Technique to the Analysis of Environmental Problems," prepared for the Fifth International Conference on Input-Output Techniques, Geneva, January 11–19, 1971; and Walter Isard et al., "On the Linkage of Socio-Economic and Ecologic Systems," in *Regional Science Association Papers*, 1968, pp. 79–100.

[17] Allen V. Kneese, Robert U. Ayres, and Ralph C. d'Arge, *Economics and the Environment: A Materials Balance Approach*, Washington, D.C., Resources for the Future, Inc., 1971. For later comments on this approach, see Roger G. Noll and John Trijonis, "Mass Balance, General Equilibrium, and Environmental Externalities," *American Economic Review*, September 1971, pp. 730–735; and A. O. Converse, "On the Extension of Input-Output Analysis to Account for Environmental Externalities," *American Economic Review*, March 1971, pp. 197–198.

of treatment processes, since they only transform materials and do not destroy them. Some estimates of residuals generated in the U.S. economy have been made based on materials balance concepts, and other applications in analysis and forecasting are being explored.

The model developed by the above-mentioned authors is essentially an extension of the Walras-Cassel-Leontief general interdependency analysis with explicit introduction of the concept of mass balance. Theoretical welfare economic aspects of the model have also been examined, but these are of no particular interest to us here. Extensions of a model comparable to the one presented here have also been examined from a welfare economics point of view by Karl-Göran Mäler.[18]

There are a number of ways in which a comprehensive materials balance might be illustrated. Perhaps the simplest and most direct would be an adaptation of the activity analysis format, as in Exhibit 3. Row headings indicate particular goods or services. Activities (which could be industries but do not have to be) are indicated by column headings. Final consumption activities (here combined into one column) are also included in the format.

A negative entry in a cell indicates the quantity of the good (measured by weight except for services, which must be measured in conventional units) in that row that is used as an input by the corresponding activity. A positive entry in a cell indicates the amount of the good in that row that is produced by the corresponding activity.[19] For example, suppose that on row 3 a −22 appears in column 6 and a +37 in column 9. This would mean that 22 units of good 3 are used as an input to activity 6 and that 37 units of good 3 are produced by activity 9.

Resources coming from the environment are always inputs; hence the negative signs as indicated. Purely intermediate goods and services are used only within the industrial sector. Hence, all rows sum to zero for this sector.

Final goods and services have net positive balances for the industrial sector, but the totals for all economic units are zero, since goods and services going to the final consumption sector are regarded as inputs into the consumption activity.

Residuals may go into an activity that transforms them, perhaps producing some salable product (reclamation) along with other residuals or they may go to the environment. The destination might be indicated by a subscript, say *A* for atmosphere or *W* for water. In the case of

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[18] *Op. cit.*

[19] All entries are per unit of time.

EXHIBIT 3

Format for Materials Balance

Outputs and/or Inputs	Industrial Activities				Final Consumption Activities (e.g., households)	Total for All Economic Units	Total to Environment from:		Total from Environment to:	
	1	2	. . .	Total			Industry	Final Consumption	Industry	Final Consumption
Resources 1. 2. , ,	–		–	–	–	–	0	0	–	–
Intermediate goods and services 1. 2. , ,	–	+		0	0	0	0	0	0	0
Final goods and services 1. 2. , ,	–	+		+	–	0	0	0	0	0
Residuals (including pollutants)				0 or ±	0 or +	0 if all is processed; + if not (some goes to environment)				
1. 2.	-5 0	0 -2	$+3I$ $+2I+4A$	-2 $+4$	$+2I+3W$ $+3A$	7	4	$3H$ 3		
, ,										
Column total (excluding services)	0	0	0	0	0	0	B		C	

residual 1, for example, five units are "processed" by activity 1, of which three come from industry and two from households. These units contribute to the production of the outputs of activity 1, which may include other residuals. Households also discharge three units of residual 1 to water bodies.

In the case of residual 2, two units are used as input by activity 2, all of them coming from industrial activities. Industrial activities also discharge four units to the atmosphere along with three discharged by households.

Residual row totals for all activities will be zero if all of a given residual produced is processed. If not, the row total will be positive, with some of the residual going to the environment.

Neglecting inventory changes, column totals of tangibles should be zero for each activity, as should also the totals coming from and going to the environment ($B = C$).

Needless to say, the practical implementation of a materials balance accounting system would encounter a host of difficulties that have not been touched on here. This format is useful for thinking about pollution problems, however, since it provides the basis for viewing the choice of production and consumption activities and their levels as a programming problem that treats the production and processing of residuals as an integral part of the whole.

An interesting extension of the economic-materials balance model has been made by James E. Wilen.[20] The connecting link between Wilen's model and the economic-materials balance model is the r vector of resources inputs. In broadest overview, the linkage is as follows: via fixed coefficients, a Y vector of final demands determines the vector of resource materials (r) needed for their production. Next, a matrix D is defined such that $D^{-1}r$ yields a vector, m, of the mass and energy inputs necessary to produce r in nature. The use of these inputs to produce ecosystem products going to the economy (r) results in a reduction of ecosystem products available as production inputs into the ecosystem. This reduction is given by Cm, where C is a matrix converting mass and energy inputs into ecoproduct. The return of mass and energy from the economy to the ecosystems can be handled in an analogous fashion and a net impact on the ecoproduct derived.

This formulation is an interesting extension of the model in a highly

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[20] James E. Wilen, "Economic Systems and Ecological Systems: An Attempt at Synthesis," paper presented at the Symposium on Economic Growth and the Natural Environment, April 26–28, 1971, University of California, Riverside.

desirable direction—the incorporation of the ecological impacts of production and consumption activities. However, the formulation does suffer from extreme abstraction and neglects the nonlinearities and interactions that are of central importance in ecological systems—as Wilen recognizes. The problem of linking ecological systems to economic systems will be pursued further in the discussion, below, of the Russell-Spofford model, which exhibits a somewhat greater concreteness and realism.

The Russell-Spofford Model

We have seen that in principle the interindustry-type models can be regionalized, made to account for materials flows to the environment in a logically complete fashion, and, at least in a rough way, to incorporate ecological impacts of production and consumption. We turn now to an operational model of quantitative residuals management devised by Russell and Spofford [21] which to some extent meets all five of the criteria implied by our above discussion:

1. It is regional and location-specific within the region. Its results can be translated into an accounting entity such as gross regional product. In this, it is similar to the I-O models.
2. It can account for residuals in a logically complete manner and does so in some of its submodels.
3. It can treat process, input, and product changes as well as residuals treatment in an integral manner.
4. It traces residuals discharged to the environment through processes of diffusion and degradation and specified concentrations of them at receptor locations. It incorporates an ecological model which translates these concentrations into impacts on higher organisms of direct interest to man.
5. It explicitly considers economic damages to receptors resulting from residuals discharge. In contrast to the I-O type models, it is an optimizing model which can be used to analyze a wide range of policy alternatives.

The Russell-Spofford model deals simultaneously with the three major general types of residuals—airborne, waterborne, and solid—and reflects the physical links among them. It "recognizes," for example, that the decision to remove waterborne organic wastes by standard sew-

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[21] Clifford S. Russell and Walter O. Spofford, Jr., are the authors' associates at Resources for the Future, Inc.

age treatment processes creates a sludge which, in turn, represents a solid residuals problem; the sludge must either be disposed of on the land or burned, the latter alternative creating airborne particulates and gaseous residuals. Second, it can incorporate the nontreatment alternatives available (especially to industrial firms) for reducing the level of residuals generation. These include input substitution (as of natural gas for coal); change in basic production methods (as in the conversion of beet sugar refineries from the batch to continuous diffusion process —see Chart 1, below); recirculation or residual-bearing streams (as in recirculation of condenser cooling water in thermal-electric generating plants); and by-product recovery (as in the recovery and reuse of fiber, clay, and titanium from the white water "waste" of papermaking machines). Third, the model incorporates and can handle environmental simulation models if necessary, as well as analytical transformation functions which translate quantities of discharge (mass and energy—for example, heat) at particular (source) locations into concentrations at other (receptor) locations. Moreover, it incorporates an ecological model which translates residuals concentrations into impacts upon various species.

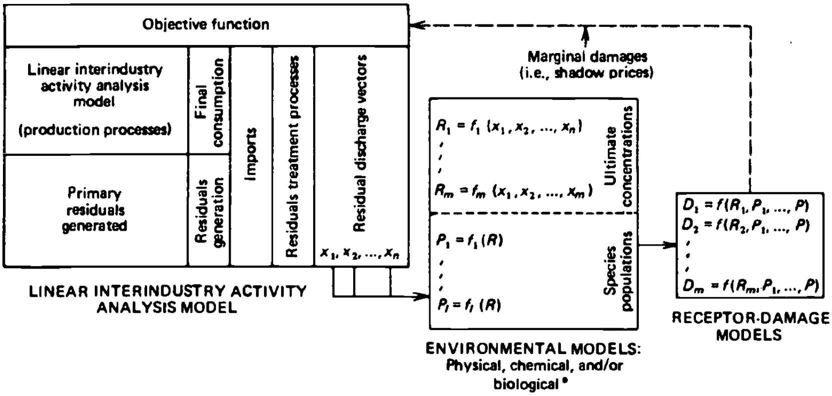
The model containing these features is shown schematically in Exhibit 4. The four main components of the over-all framework may be described as follows:

1. A linear programming interindustry model that relates inputs and outputs of selected production processes and consumption activities at specified locations within a region, including the unit amounts and types of residuals generated by the production of each product; the costs of transforming these residuals from one form to another (as of gaseous to liquid in the scrubbing of stack gases); the costs of transporting the residuals from one place to another; and the cost of any final discharge-related activity such as landfill operations.

The interindustry model permits choices among production processes, raw material input mixes, by-product production, recycling of residuals, and in-plant adjustments and improvement, all of which can reduce the total quantity of residuals generated; that is, the residuals generated are not assumed fixed either in form or in quantity. This model also allows for choices among treatment processes and hence among the possible forms of the residual to be disposed of in the natural environment and, to a limited extent, among the locations at which discharge is accomplished.

EXHIBIT 4

Schematic Diagram of Residuals—Environmental Quality Planning Model



[a] Linear and nonlinear analytical expressions as well as simulation models are implied by these expressions. For simplicity, the functions in the figure reflect only one type of pollutant.

2. Environmental diffusion models which describe the end of various residuals after their discharge into the physical environment. Essentially, these models may be thought of as transformation functions operating on the vector of residuals discharges and yielding another vector of ambient concentrations at specific locations throughout the environment. Between discharge point and receptor locations, the residual may be diluted in the relatively large volume of air or water in the natural world, transformed from one form to another (as in the decay of oxygen-demanding organics), accumulated or stored (as in the accumulation of organics in benthal deposits) and, of course, transported to another place. Fortunately, for many situations the equations characterizing the transformation of residuals between discharge and receptor locations reduce to simple linear forms for steady-state deterministic conditions so that the linkage sometimes can be made via a coefficient.[22]

3. Ecological models analogous to the more familiar physical diffusion models are models of ecological systems which reflect the changes (as through a food chain) following on the introduction of a particular

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[22] It should be noted, however, that physical, chemical, and/or biological interactions among residuals in the environment cannot be handled quite so easily.

residual discharge or on moving to a different set of ambient concentrations. Instead of residuals concentrations as the end products of this type of model, we might obtain estimates of the populations of species of direct interest to man, such as sport fish or rare and endangered animals.

4. Ideally, a set of receptor-damage functions relating the concentration of residuals in the environment and the impact on species to the resulting damages, whether these are sustained directly by humans or indirectly through impacts on material objects or the medium of such receptors as plants or animals in which man has a commercial, scientific, or aesthetic interest. Ideally, the functions relating concentrations and impacts on species to receptor damage should be in monetary terms. Actually, adequate damage functions have not been estimated for any phase of the residuals problem. Consequently, in the computations so far, which have been aimed at testing the whole framework, it has been necessary to use arbitrary functions.

As an alternative to the use of damage functions in the analysis (or in their absence), constraints, or standards, could be specified for emissions or for concentrations at points where receptors are exposed to the pollutant. In practice, this will be a very important type of analysis because of the many difficulties in estimating damage functions.

The linkage between the components and the method of optimum-seeking may be explained in an illustrative way as follows. Solve the linear programming model initially[23] with no restrictions or prices on the discharge of residuals. Using the resulting initial set of discharges as inputs to the diffusion models and the resulting ambient concentrations as the arguments of the damage functions, the marginal damages can be determined (damage associated with a unit change in discharge). These marginal damages may then be applied as interim effluent charges on the discharge activities in the linear model, and that model solved again for a new set of production, consumption, treatment, and discharge activities. The procedure is repeated until the optimum is found.

This procedure can be looked at as a steepest ascent technique for solving a nonlinear programming problem. The objective function is linearized locally, using the provisional marginal damages as "fixed" residuals discharge prices. Because the constraint set is also linear, the resulting problem may be solved using standard linear programming

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[23] There are a number of different ways in which the objective function and constraints might be formulated.

methods. This linearized subproblem is solved subject to suitable bounds on the allowable distance that a decision variable may move in a single iteration. The objective function is then linearized again around the new temporary solution point, and so on until a local optimum is reached.

The problem for which the model is intended to provide an approximate solution could also be stated in a completely general manner not suitable to numerical solution, as the above described version is, but perhaps easier to understand. The objective is to maximize, for a region, a complicated economic criterion function reflecting the costs of regional production, the benefits from regional consumption, the costs of residuals treatment, and the external damages resulting from residuals discharges, with allowance for the "assimilative" capabilities of the regional environment.[24] In this form, the regional residuals management problem is a general nonlinear programming problem, with both objective function and some constraints being nonlinear. But since the solution of a nonlinear problem as complicated as this one may be very difficult, if not impossible, it is useful to make the changes required to get rid of the nonlinearities. The problem then appears as sketched earlier.

The Russell-Spofford model was designed for the analysis of residuals management in regions where the scale and severity of the problems justify a considerable investment in data and analysis. The model is now in the process of being applied to the lower Delaware River basin. As a result, we shall know a good deal more about the precise form the model should take and about the volume and nature of the data required to provide a useful tool.

The model does not completely portray all aspects of the simultaneous economic production of goods and services and the handling of residuals. As it now stands, it does not incorporate adaptations at the consumer or household level. In principle, the consumer can be viewed as choosing among "consumption processes" to maximize utility in a manner entirely analogous to the choice among production processes that is an integral part of the solution of the linear programming part of the R-S model.[25] Specification of the consumption processes would

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[24] For more detailed explanations of the model, see Clifford S. Russell and Walter O. Spofford, Jr., "A Quantitative Framework for Residuals Management Decisions," in Allen V. Kneese and Blair T. Bower, eds., *Environmental Quality Analysis: Theory and Method in the Social Sciences,* Baltimore, Johns Hopkins Press, 1971; and Clifford S. Russell, "Regional Environmental Quality Management: A Quantitative Approach," paper presented at the California Institute of Technology Conference on Technological Change and the Human Environment, October 19–21, 1970.

[25] See Kelvin Lancaster, "A New Approach to Consumer Theory," *Journal of Political Economy,* April 1966, pp. 132–157.

be enormously difficult, but the omission no doubt is quantitatively important for some problems. The cheapest way to reduce exposure to some pollutants is by substitution in the consumer budget.

Another partial limitation is the way in which the locational aspects of the problem are handled. As pointed out above, the model is location-specific in that locations of emission sources and receptors play an essential role in determining the concentrations to which receptors are exposed. The model does not optimize for location, however. That is to say, the effects of different specified locational configurations must be compared by successively solving models incorporating them. Apart from these limitations, the R-S model presents a pattern for considering analysis of environmental pollution problems that provides valuable guidance for the collection and organization of pertinent data.

III. DATA NEEDS SUGGESTED BY THE MODELS FOR ANALYSIS OF ENVIRONMENTAL POLLUTION

The models for analysis of environmental pollution discussed above could be implemented in various degrees of complexity and detail. They could be complicated or extended, as, for example, by a more elaborate treatment of the location factor or by giving direct attention to consumer response to changed conditions (including price changes) resulting from pollution controls.

Clearly, the types and depth of data that will be needed are going to depend on the particular forms of these and other possible models that will be found to be useful in grappling with pollution problems. Useful guidance for practical data decisions will be provided by efforts under way to implement the national I-O model, the Russell-Spofford model, and possibly others. Without waiting for substantial progress on these efforts, however, it is possible to make a few detailed suggestions for data on the basis of what we already know and to make a number of more general suggestions on types of data whose compilation should be initiated or expanded.

Our suggestions on needs for continuing data will be considered under two categories. First, baselines need to be established and maintained, the general idea being that departures from baselines serve as warning signals. Two types of baseline data will be considered: first, measures of a summary or indicator nature which will be useful for the general public, and, second, more detailed or sophisticated baselines useful to technicians. The second general category consists of data more directly needed for the design, analysis, and administration of pollution control schemes.

The idea behind use of the term "baseline" seems to be that in the absence of interference the system under examination—for example, an ecological system—continues to function in a manner approximating a steady state. This must be understood to include the case of nonexplosive oscillatory behavior, too. A definite departure from this baseline situation indicates that a new element has been introduced into the operation of the system. The resulting change may or may not be desirable with respect to human objectives. In any case, departure from the baseline calls for investigation. If the effect of the intrusion is benign, it would be good to know what has happened, for we might be able to turn the mechanism involved to our account. If the effect has been undesirable, we ought to understand what has happened, for the observed deterioration may presage more serious effects unless the disturbing factor is properly dealt with.

Baseline and Indicator Data for the Citizen

It is unlikely that any problem involving deterioration of the "environment" can be handled by public action unless a substantial part of the public understands that a particular type of deterioration actually has taken place. This is necessary if there is to be any consideration at all of the desirability of remedial action by members of the public and its elected representatives.

The general characteristics of baseline measures that might fill this need are suggested and limited by the level of technical understanding of the general public of the various physical and biological systems. Although the level of comprehension no doubt is rising gradually, the types of measures needed can best be characterized as indicators. The indicator itself may not be a part of the group of variables that are significant for control or manipulation of the system, although it will be closely associated with the variables that the expert might view as expressing best the state of the system in question.

With this in mind, it is possible to suggest some of the characteristics that a system of indicators useful to the general public should have. First, and very important, the number of indicators should be limited, for there is no useful result to be expected from asking the ordinary citizen to take the time to determine the significance of several hundred series even if he could. Indeed, even for the expert the very idea of changes in the state of a system that have significance for man seems to imply the view that there are some variables that perform the function of summarization. This function should be the main basis for choosing the limited number of indicators. In systems with living organisms, the measure should be chosen with a view to its properties as an integrator of effects over time and over a variety of intrusions. This suggests that indicators probably should be chosen from the higher trophic levels of the various types of ecosystems in which we are interested, since in many cases substances are concentrated as the successive members of the food chain eat each other, thereby revealing adverse effects or intrusions more clearly.

To give concreteness to these general considerations, a few candidates for general indicators are suggested here. Our purpose is only to provide illustrations and not to suggest that these ought to be among the indicators that should be adopted, this determination being one that we gladly leave to the experts in these matters.

In the case of water bodies, changes in the various types of fish populations are a good summary indicator of changes in many aspects of the aquatic environment. The complete disappearance of certain types of fish is easily understood to signify a major change in the condition of the water body, perhaps a large change in dissolved oxygen content or the introduction of substances incompatible with the species in question.

In water bodies of various types, especially estuaries, changes in the distribution of the populations of different types of shellfish or in their density at particular locations can serve as summary indicators of effects flowing from a variety of sources.

A physical aspect of water bodies that is of direct concern to the nonexpert is turbidity, a quality that is measured in an easily understood standard way. Changes in turbidity—on the average, seasonal, after rains, etc.—may be caused by a variety of factors, which is the same as saying that this is an integrative indicator, a property we believe to be desirable. Note that the emphasis here is on changes in turbidity. In some cases natural conditions produce a permanently high but harmless level of turbidity.

Changes in bird populations are indicative of changes in soil and vegetation. That these changes can register effectively the introduction of pesticides into the soil and other parts of the environment (as, for example, with the introduction of the poison compound 1080 into carrion eaten by birds) is widely understood. The whole web of relations involved is very complex, of course, but the summarization of the effects on birds is just the kind of indicator that is needed to lead the nontechnician to an awareness that something important may be happening which will affect other things that may be more important to him than the birds themselves.[26]

In the case of the atmosphere, some of the pollutants that may have adverse effects on health are not visible nor do they have a distinctive odor. Still, because the presence of this type of pollutant is associated with the presence of other pollutants that are directly detectable by persons, an indicator of detectable pollutants can serve the double purpose of warning of the perceptible changes as well as those not directly accessible to human perception. What types of measure might qualify? There are various ways to measure haze, but many of the methods have no immediate significance for the nonexpert. Again, merely to indicate the *type* of measure needed, one possibility easily understood by the nonexpert would be an adaptation of a procedure used to test the quality of a camera lens. In this test a standard test card with various numbers of lines per inch on it is photographed under standard conditions (distance, light, etc.). Perhaps it would be possible to use a somewhat similar test to measure haze, for example, by photographing a test card under standard conditions at rather long distances. Whatever the method of measurement the technical expert might finally recommend, it is desirable that the procedure and the way in which the results of the test are expressed have a ready meaning for the ordinary person.[27]

The particulate content of the air is of rather direct significance for the nonexpert and would qualify as a suitable measure if translated into a form or forms with simple meaning, perhaps by a simple model of the respiration process or as calculated deposition per year under standard conditions.

Is the miner's canary the prototype of an indicator of the general severity of air pollution for health? Ideally several types of indicator, which might be insects, plants, or animals, would be useful. Some indicators are especially sensitive to particular pollutants, and the same indicator may not serve equally well to register acute episodes and longer-

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[26] Leaving aside aesthetic or recreational interest in a wild animal or bird, the view of some—that extinction of a species is nothing very significant since extinctions have been occurring throughout all natural history—begs the question. This question is whether the observed imminent or actual extinction is the result of a change that will produce adverse effects in addition to the observed extinction.

[27] One of the authors was told of a similar and even simpler test conducted in Tokyo, Japan, over a period of many years. It appears that one gentleman kept a record each day of whether Mount Fuji could be seen or not. Over the period of rapid industrialization, the number of days per year on which it could be seen declined from about 90 to less than 1. What more dramatic indicator of air pollution for a Tokyo resident could be found?

term changes in pollutant levels. In any case, the desideratum is that a change in pollutant level increase mortality or produce other easily observable and quantifiable changes in appearance or function. Colonies of indicator plants, insects, or animals could be maintained in various cities and other environments with the members having a standard genetic composition and receiving standard care. The resulting data would serve as indicators of differences in pollution in time and space, thus suggesting when and where additional investigation should be undertaken.

Note that there is a locational aspect to all of the baseline indicators discussed to this point. Although some of them probably could be combined into state, regional, or national measures, there is little reason to do so. The effects are not national as are those, for example, of so many economic phenomena whose effects are dispersed and homogenized by the market mechanism. The appropriate remedies often appear to be mainly local, granted that it is possible and in some cases may be desirable to apply measures that require uniform action across the nation regardless of variation between locations in the damages produced and in the cost of reducing pollutants to reduce damages by a given amount.

Baseline and Indicator Data for the Experts

The rationale for baseline data useful to technical experts on various aspects of the physical environment is the same as that for indicators useful to the nonexpert. Movement of a measure outside the range of values it has taken in the past serves as a warning that something important may have happened. If the causative factor can be identified and its effect was adverse, it may be possible to develop corrective measures.

There is no need that data collected on a regular basis for possible use by experts have an immediate or obvious significance for the nontechnical person. Nor is it necessary that all of them should be rather summary and/or integrative. Detail is no bar to data being useful to the expert, for if he truly is expert he will know how to use it and put it to work, but it is important to realize that he, too, can be overwhelmed by the enormously high rate at which some types of data can now be generated. This category of data should include a number of "basic" physical, chemical, and biological characteristics of the various environments.

Physical and chemical data. A good illustration of a data system for basic physical characteristics of an environment is provided by the present data system for water quality in the United States. The label "water quality" is somewhat misleading, of course, since what is involved are characteristics which do not indicate generalized quality in and of themselves. This depends on the values attached to physical qualities by water users.

The water data system includes a large number of variables, generally expressed as concentrations, including several families of chemicals (e.g., phenols, chlorinated hydrocarbons), pH, individual metals (e.g., mercury, chrome, cobalt, lead), temperature, various aspects of flow behavior, and so on.

The system of baseline measurements for air pollution is far less well developed, reflecting in part the much shorter period over which interest has been strong enough to lead to formation of a measuring system. Pollutants are but part of a desirable system of atmospheric baselines; others include elemental and basic compound measurements and various meteorological characteristics such as cloud cover—a complex phenomenon in itself.

Baseline measures are needed for all the major natural systems, and in many areas systematic measures have been collected for a long time. What is needed at this time is to examine the scope and adequacy of the various systems of measurement to insure that important areas are not neglected and that the measurement programs meet proper sampling requirements.

Of what use are these seemingly isolated series, multiplied in number to a point that must seem otiose to the nontechnician? If a control system already exists or if the need for one should arise, these series very often will have a direct relevance for design or administration of the control system. More fundamental than this, research on the large-scale behavior of these systems cannot be very productive without data.

It ought to be possible to characterize the major changes in ways that would be meaningful to the nonexpert. Some small beginnings are made in the 1971 report to the Congress of the Council on Environmental Quality, but a larger effort is warranted. One essential is that the summary presentations contain references that will direct the interested person to the basic data sources for continuing series.

Biological data. Biological or ecological baseline data for expert use are needed, too. By and large, the detailed series that ought to be collected for different types of situations must be left to the experts for decision, just as in the case of the physical and chemical series on water quality and in other areas of interest. However, we venture to suggest discussion of one type of more general series, namely, studies of ecosystems. The results of these studies should perhaps be included eventually in an augmented system of social accounts.

Studies of ecosystems. Every location in and bordering the country is a part of an ecosystem of one type or another. How can we get some indication that something important may have gone wrong with the way one of them functions, something that may have serious consequences for humans directly or indirectly? A possible method is a systematic program of repeated studies of different ecosystems at different locations in all parts of the country, including the study of populations of the different species and changes in their characteristics such as size, function, appearance, chemical composition, and so on. The discussion proceeds in terms of populations, since that is an aspect of the studies that is easily understood by the nonexpert.

By population study of an ecosystem we mean a study of the levels or densities of the populations (which could be measured by biomass) of the different species (or larger groups) of living beings in the system. We discuss first the general rationale of such a system and then the factors constraining its implementation.

The rationale of population studies of this type is simple. The basic ideas of ecology tell us that the size of an ecosystem—as expressed, say, by biomass—will depend on the energy and nutrients available to the system, other characteristics of the physical environment, and the species constituents. Ecology can be viewed as the study of the relations among energy, nutrients, and living things that determine the size of the system as measured by the rate of biomass production and the relative numbers (or masses) of the different species.

A fundamental concept here is that of the steady state. That is, if the system is subjected to a temporary disturbance, it will (usually) return to its original equilibrium position after a time. The equilibrium position might actually be one of nonexplosive continual oscillation, and these oscillations might be very complex. If the disturbance is permanent rather than temporary (for example, as with the continued inflow of a degradable pesticide into the system), the system will move to a *different* steady state characterized by a different total biomass and different relations among the numbers (or masses) of the various species originally present. Some may disappear altogether. In the larger and longer view, of course, the idea of a steady state to which ecosystems tend to return is bound to be erroneous because of the presence of natural forces producing progressive alteration of the system. Over decades, ecological succession is a major changing force. On the evolutionary time scale, mutations are an important source of change. Our concern, however, is with shorter periods of time to which the concept of steady state has more relevance. Even from a shorter perspective, an "ecosystem" that is so small that it is not well separated from the influences of surrounding systems (that is, a system that is not large relative to the forces coming from the neighboring systems) is likely to evolve progressively, as may be the case, for example, with some of our national parks.

The steady state concept suggests that periodically collected population data for an ecosystem possibly could provide a comprehensive and sensitive indicator of the introduction of foreign substances and also of damage to some of the species therein, thereby indicating possible damage of significance to humans if we eat things related to the ecosystem, if we value it for its beauty or other qualities, or if we ingest things which, although not from this particular ecosystem, have been exposed to or contain the same substance. If the population census were quite detailed, it would direct our attention automatically to the most sensitive parts of the ecosystem, thereby increasing the probability of early warning. Whatever may be the species or group most susceptible to damage by, say, a pesticide, or whatever species that rapidly increases to fill the gap thus created, it would be forcefully brought to our attention by the change in its numbers. Furthermore, low concentrations of the foreign substance would in some cases be brought to our attention by being concentrated in organisms as it passes up the food chain. Some of these organisms near the end of the chain will be affected adversely. For example, reproduction may be impaired or death rates may rise. In other cases, however, the foreign substance may be concentrated in certain tissues without evident adverse effect.

Ideally, a system of population censuses like this would embrace all types of living things in the particular ecosystem including microorganisms, ranging from those on the surface, such as plants, mammals, or birds, those in the soil, those in water bodies, and those in the sediments underlying water bodies. In general, more frequent censuses would seem to be desirable where there already is a large flow of pollutants to an ecosystem, because the composition and quantity of the effluents could change over a comparatively short period of time. In certain cases where man's activities greatly simplify the "natural" ecosystem, as with agriculture, stability of the system is often diminished. It would be desirable that the censuses be more frequent in these cases, too. The period between studies would not have to be the same for every location, although a study ought to be made at the same time of year for a given location and probably should be made at the same time of year for the same type of ecosystem at different locations.

The difficulties. All of the above is a rather idealized version of how a system of studies of ecological systems might work. Unfortunately, there are many difficulties that prevent its realization, not the least of which is cost, which would rise rapidly as the attempt is made to cover each ecosystem site more completely and in more detail. After all, there are critters on critters, some critters have others inside them, and these have others on and in them—not ad infinitum, as a well-known limerick has it, but far enough in that direction to make the complex world of man-made objects seem simple by comparison.

The layman may believe that it is a simple matter to count the numbers of each species, but the unfortunate fact is that the biological world is not so simple nor is species identification or classification into higher groups an easy thing. Perhaps some 10,000 new species are found each year. Among large creatures that are abroad during the day, the number discovered each year is much less. Perhaps only some two or three are added to the list of birds (now about 8,600), but six to seven thousand insects are added each year to the present list of three-quarters of a million. Nor are species easy to identify. Some groups of organisms have no specialists currently studying them, for example.[28]

Having recognized the cost difficulty and the impossibility of taking a complete count by species, we encounter the fact that there is far from a consensus on classification or on what ought to be measured if budgets are limited. This has an important bearing on the effectiveness with which the diagnostic scheme outlined in the discussion of the idealized system can operate. In this case the detection of changes in the functioning of ecosystems depends on changes in relative populations, not of species—which would be too costly—but of larger groups. But the changes that are observed will depend on the type of measures and the classification used, and classification cannot be said to be the object of a very strong consensus. The difficulty is closely related to the problem of inferring changes in the stability of an ecosystem from changes in species diversity. As is so often pointed out, however, measures of species diversity are very sensitive to the particular scheme of classification that is used.

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[28] See Philip Handler, ed., *Biology and the Future of Man,* New York, Oxford, 1970, p. 518ff.

Classification difficulties are but one of many in determining when a permanent change has taken place in the system. Populations of ecosystems do fluctuate. As one investigator states, "All populations of organisms fluctuate in size. For any population the only assertion that can be made about it with certainty is that its size will not remain constant." [29] For example, variations in weather affecting vegetal food supply are sufficient to induce changes in populations which will reverberate throughout the whole system, and these will be not only seasonal in nature but very likely annual, too, and of a rather complicated pattern.

In short, how is the usual noise of the system, consisting of fluctuations of populations within the range of past experience, to be distinguished from changes in populations that are associated with a genuine change in the structure of the system that determines its mode of functioning? Clearly there is a distinct possibility that a genuine change—perhaps one with ultimately important consequences—may be evidenced by population movements well within the range of fluctuations that have occurred in the past and that perhaps have been observed. More accurate interpretation of such fluctuations in populations will require much additional research on many aspects of the behavior of pertinent types of ecosystems.

These several difficulties diminish considerably the value that a system of ecosystem studies might at first sight appear to have, but they are far from sufficient to warrant an easy conclusion that a useful system cannot be formulated. What can be done?

One possibility would be to concentrate on some of the many known sensitive indicators.[30] Egg shells, for example, appear to be rather sensitive to the presence of certain pesticides in the environment. In addition, measurement might concentrate on those species or groups of species that are cheaper to identify, count, and/or weigh. Census efforts might be concentrated, for example, on the higher species. Birds would be preferred to mammals, the former being cheaper to count for various reasons. The principal species of fish, shellfish, and insects in an

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[29] E. C. Pielou, *An Introduction to Mathematical Ecology*, New York, Wiley-Interscience, 1969, p. 7. Of course the sentences quoted were not intended to deny the existence of forces producing strong tendencies to equilibria.

This excellent work would be quite accessible to the economist with a modest preparation in mathematical statistics and matrix algebra.

[30] Dale Jenkins, director of the ecology program of the Smithsonian Institution, has provided a discussion of a possible biological environmental monitoring system in a paper entitled, "Biological Monitoring of the Global Chemical Environment," June 1, 1971 (processed). Many of the potential monitors are plants.

area might be included in the count. And of course in some cases important change may be reflected by an easily observable characteristic other than numbers or mass.

Every act of economy has its cost, of course, and a decision to concentrate on higher species or classes is no exception. It *is* possible that effects of the greatest significance to man would first and most clearly be evident in the detailed functioning of systems of microorganisms. Perhaps a suitable compromise in view of our great ignorance would be to make the censuses of a small number of systems rather complete, extending down to the important microorganisms of the system.

We advocate intense discussion looking forward to a larger, more systematic, and better integrated program of ecosystem studies. It would be extremely useful to have a more adequate system of biological indicators of a number of types in many different locations to give us warning of possible adverse changes that would be detected in other ways only with costly delay.

These suggestions—made very diffidently by nonspecialists—are put forward only to give other nonspecialists a sense of the potential usefulness that we feel such a system may have. Actually, the monitoring systems already in operation, both physical and biological, go a substantial distance in the directions suggested. Apart from the water and air quality systems mentioned earlier, a multiagency pesticide monitoring program has been in operation for a number of years under which residues in foods, feed, people, birds, animals, water, and soil have been measured. Many important changes—and decisions not to change—have been effected through these programs.

There is, of course, a multiplicity of monitoring programs. In the federal government alone, there are some *56* in sixteen agencies, costing about $40 million per year.[31] The mere multiplicity of programs raises the problem of coordination. While there may be good reasons for this multiplicity, it seems clear that the enormous quantity of data being generated is not being distilled into a form that will tell the interested layman what is happening. It ought to be possible for a citizen of, say, Washington, D.C., to find out what has happened to any of the various aspects of the environment in the area around his city over the last one, five, or ten years. At present he cannot possibly do this without calling on the services of not one but several specialists and even then will find many lacunae. To get out of the impasse will require an expanded monitoring effort on many fronts and a much

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[31] Kneese and Bower, eds., *Environmental Quality,* p. 210.

stronger effort to convert the technical data into series that will speak to the nontechnician. The annual report of the Council on Environmental Quality would certainly seem to be the first point of reference. It does give some signs of eventually fulfilling this role.

Data for the Design, Analysis, and Administration of Control Schemes

When it becomes evident through the baseline-monitoring system or other means that something has gone wrong in the environment, the next question is whether remedial action is possible and should be taken. In short, what is needed to design a control scheme and to predict its operation in a way that will facilitate the decision to put it into operation? Three types of data are essential to this task: first, materials balance data; second, production function information—what types of action are possible; and, third, information on the benefits associated with the possible courses of action.

Materials balance accounts. One thing that seems to us to emerge rather clearly from the experience to date is the desirability of a genuinely complete accounting for material inputs and outputs of all economic units, including households, governmental units, and nonprofit institutions, measured in weight, and including those that are sold or paid for as well as those that are not. We discuss first the desirable characteristics of these data without reference to the current status of data collection efforts along these lines.

A materials balance accounting system certainly merits being called basic. These data are essential to almost any approach to the management of unsold residuals flowing from economic units. At a minimum, they permit the identification of sources and locations of emissions and provide the fundamental basis for estimates of transfer and ultimately of exposure. In those cases where a substance is suddenly recognized as an important and perhaps dangerous pollutant, the system would be of immense aid in tracking down the sources of emissions. Finally, if we do find it possible and desirable to move in the direction of models of the sort that have been discussed earlier, the process of implementing them could make very good use of such data. They would be essential for any calculations involving the national input-output system or regional systems that may be constructed in the future. This materials balance accounting system, therefore, should be integrable with the present I-O system, although in some cases a more detailed industrial classification would be desirable.

Classification of the noneconomic output (the residuals or effluents) poses a very difficult problem, and here there is no escape from trying to anticipate later data needs. A considerable body of experience and thought on these matters is reflected in the current classifications of water and air pollution data that are now being collected on a regular basis. An important general question with respect to the classifications now used is whether in certain cases data should be gathered in more detail, as, for example, where one member of a family of pollutants is thought or known to have more serious effects than its relatives.

The products of economic units that are not sold include many things not included in the categories presently regarded as pollutants. One consideration relevant to their classification is the possibility that in the future the substance may be treated in some way (including reclamation) or that it may come to be recognized as a pollutant.

The materials balance accounting system would be more detailed than the I-O system in that discharge data would be for industry *by location.* A location tag for the discharges is an absolutely essential part of the system, although the degree of precision in the location designation need not be the same for all effluents. For those now regarded as important pollutants, the degree of required precision is very high, however. It would be advisable to record initial destination of the effluent in question—whether to an effluent-processing industry or to another disposal site such as atmosphere, water body, or land. In some cases it would be useful to have data not only on final discharges of effluents but also on certain pollutants produced in a plant and processed in that plant.

The data for such an accounting system would be organized by some type of geographical unit. The designation of geographical units should be such that county totals could be formed which could then be related to all the other data presently available on this basis. Probably the geographical unit should not be larger than the county in any case, but where an industrial complex is concentrated in an area, the basic geographical unit should be quite small.

The various censuses will be helpful in developing these balances, but where there are many similar firms in operation, sample coverage would be adequate. The required totals could be estimated on the basis of sample relations between the various materials flows and other variables which are already collected on a comprehensive basis.

Since so many other data with which materials balance data may be associated in the future are available on an annual basis, the calendar year seems to be the appropriate time unit for which the data should be prepared for the system as a whole. In the case of many pollutants, however, there are strong seasonal, weekly, daily, or even hourly variations that carry important implications for measurement by control authorities and for the production of damages. Where sample inquiries are made, presumably of firms that emit important quantities of pollutants, it would be convenient simultaneously to collect more detailed data on the temporal variation in these flows. Existing knowledge is probably sufficient to allow a proper determination of firms falling in this category.

Use of a materials balance accounting system does not mean that every economic unit will literally have to weigh every transaction and split it into the various components dictated by the classification scheme. Although the system is an accounting system which in principle implies complete balance for each economic unit, for all subunits of the system, and for the system as a whole (just as is implied by the national income system), the basic data for the system could be built up from a variety of sources.

Emissions of residuals are currently the target of data collection programs of at least three federal agencies: the Water Quality Office and the Air Pollution Control Office of the Environmental Protection Agency [32] and the U.S. Army Corps of Engineers. The first two are using questionnaires and other means to assemble data on quantities and patterns of pollutant emissions. The Corps of Engineers is using the Refuse Act of 1899 (33 U.S. Code 407) as authorization to collect a quite elaborate body of data on industrial and various other discharges to navigable water bodies.

It is not yet clear just how extensive a body of data will result from these efforts, which are of course closely tied in with the current content of control programs in the case of the two EPA agencies. In any case, it seems clear that the existing programs will fall short of providing data by industry (i.e., all sectors of the economy) by location of pollutants emitted, let alone sufficient data to permit construction of a materials balance system of accounts.

It seems to us that the appropriate first step is to assign some statistical agency of the government the task of attempting to construct a system of materials flows on an annual basis. Only by making the attempt will it be possible to coordinate the pollution emission data activities already underway and to identify the gaps that must be filled

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[32] Formerly Federal Water Quality Administration and National Air Pollution Control Administration.

before a complete set of accounts can be constructed. That the system of accounts be complete is not of importance in and of itself. The overwhelmingly important reason is that the possible repercussions of changes in residuals flows in one part of the system can be traced only if complete materials flow data are available on a rather detailed basis. This is true whether sufficiently detailed I-O systems are available for use or not. Any simpler procedures, such as catch-as-catch-can tracing of principal materials impacts, will require the same sort of data.

A possible result of the attempt to construct the complete system may be the integration of data-gathering activities directed principally at substances presently designated as pollutants. The cost of amplifying the body of basic data that will be available shortly to the point where a periodic accounting of the *whole* materials flow can be made may not be very great if the collection of the additional data needed is integrated with data generation activities already in existence.

Information on control techniques and costs. Historical I-O data, baseline data, and information on materials flows all have an important role to play in the comprehension and analysis of pollution problems, but they provide little direct help in deciding what, if anything, should be done. To make headway on this question, we need to know what options are open. For example, we need to know what the possibilities are for processing an effluent containing pollutants or for changing processes so as to alter the composition of effluents together with the costs associated with these different options. The question of what technical options are available arises not only in connection with industrial effluents, but also in connection with residuals coming from households. Similarly, we need also to know what technical options are available for intervention in a given type of environment to raise its assimilative capacity or to improve its condition and thereby the flow of service coming from it.

Assembly of information of this type does not necessarily entail going far beyond the range of experience. As is well-known, industrial processes often exhibit sizable geographical variations. The fact that processes are changing through time means that at any one time there will be processes recently adopted that may not be widely known. In many cases, it is possible to transfer or adapt processes from one industry or function to another, earlier conditions simply not having been such as to encourage the transfer. Thus there is often a rather wide range of choice simply from among already existing and quite well-known options.

Techniques and costs of controlling industrial residuals. Control of residuals may take a number of different forms. One possibility, perhaps the most obvious to the nontechnician, is to process the present flow of effluent, that is, to alter the composition of the final effluent so that it is less harmful. Additional inputs will be required, but whether the new effluent will be larger in mass than the old will depend on the extent to which salable products are recovered as a result of the new effluent treatment. In any case the main objective of effluent processing is to change the form of residuals so that they are less harmful or more concentrated and therefore more readily disposed of in comparatively harmless ways. Removal of sludge from sewage and putting it in landfill is a good example.

Most of the estimates of the cost of pollution control one finds in official documents like *Clean Water* and *Clean Air* are based solely on the processing alternative and therefore tend, as we shall see below, to be too high. On the other hand they also tend to be low because they neglect the interrelations among liquid, solid, and gaseous residuals. A more integrated approach embracing a wider range of options is needed. This is illustrated below with a study of the beet sugar industry.

As just indicated, tacking on additional processes is only one of the possibilities. The composition and size of the effluent stream can also be changed by changing inputs (e.g., by substituting a nonpersistent for a persistent pesticide or by substituting low- for high-sulfur fuel) or by changing basic processes before the stage at which the present effluent is emitted. In addition, it may be possible to change the location of processes so that the concentration of the pollutant-reaching receptors is reduced. Finally, the quality characteristics of the final product can have a large bearing on the amount of residuals generated. For example, production of high brightness paper creates far more chemical residuals than that of low brightness paper.

The type of information on technical options and cost that is needed can be illustrated very forcefully by an examination of the operations of the beet sugar industry in the United States.[33] Here, as in many other industries, the most important of the possible responses to emissions control is not the adding on of separable effluent-processing devices, the technology conventionally considered by engineers and policy makers, but rather process change which results in fuller use of materials either

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[33] The discussion in this section is based primarily on George O. G. Löf and Allen V. Kneese, *The Economics of Water Utilization in the Beet Sugar Industry,* Baltimore, Johns Hopkins Press for Resources for the Future, 1968. The materials balance described in later pages was calculated by George Löf.

by producing more of the primary product or by generating salable by-products.

As shown in Table 3, one of the major residuals causing water quality deterioration—the organic materials residuals load expressed in pounds of BOD (biochemical oxygen demand) per ton of beets processed—has been reduced greatly in the beet sugar industry as a whole in the last two decades by comparatively simple and economical alterations in processes. The main changes have been substituting beet pulp drying for storage of wet beet pulp in silos and the use of Steffens waste for the production of by-products. These changes reduce BOD generation by about 60 per cent. The other process change, i.e., a shift from cell type to continuous diffusers, is integrally related to recirculation of screen and press water. This further reduces the BOD generated by about 10 per cent.

Chart 1 indicates the main processing and waste water residuals streams in representative beet sugar plants. Chart 2 shows residuals streams in a plant practicing no material or by-product recovery and discharging all of its liquid residuals into a watercourse. A few cases approaching this still exist. Chart 3 shows a plant in which all water is fully recirculated, and there is no external discharge of waterborne residuals. There is one plant in the United States which uses basically this system; the others fall into intermediate positions. Charts 2 and 3 are not only helpful for understanding Table 3, but also the materials balance for a beet sugar plant, presented below.

It should be noted that the "closed" plant requires treatment (in the form of clarification) for its recirculating water stream, even though materials recovery and by-product production have greatly reduced waterborne residuals. Even where opportunities to utilize process changes and increase recovery are favorable, some residual material usually remains. The stream containing this residual may be treated, thus producing a solid or gaseous residual or changing the chemical composition of the waterborne residual. However, the treatment in this case is different from the usual add-on devices in the sense that it is an integral part of a recirculating water stream which permits the external discharge of waste water to be closed off completely. Admittedly this is an extreme situation, but note that in this instance cost information about add-on devices would yield *no* information about what has been done to control residuals. On the other hand, attributing the cost of all process changes to residuals reduction would be erroneous because many valuable salable products have been generated as a result.

TABLE 3

Estimated Reduction of Biochemical Oxygen Demand (BOD) in Beet Sugar Processing, 1949 and 1962 (1,000 pounds per day)

	1949					1962				
Type of Waste	BOD Generated[a]	BOD Removed by Process Changes[b]	BOD Removed by Waste Treatment	Total BOD Removal	BOD Discharged	BOD Generated[a]	BOD Removed by Process Changes[b]	BOD Removed by Waste Treatment	Total BOD Removal	BOD Discharged
Flume and washer water	510	–	–	100	410	710	–	–	270	440
Cooling water and condensate	80	–	–	10[c]	70[c]	110	–	–	30	80
Pulp screen and press water	550	50	70	120	430	840	630	60	690	150
Silo drainage	1,390[d]	660[e]	140	800	590	1,940[d]	1,920[e]	10	1,930	10
Lime cake slurry	730	0	350	350	380	1,030	0	960	960	70
Steffens filtrate	610	160[f]	80	240	370	770	560[f]	160	720	50
Total BOD	3,870			1,620	2,250	5,400			4,600	800

Notes to Table 3

NOTE: Based on 158,000 tons of beets per day processed by 58 plants operating in 1962. In 1949, 113,000 tons per day were processed. To enable direct comparison, the data for 1949 were extrapolated to production of 158,000 tons per day, assuming constant proportions.

SOURCE: George O. G. Löf and Allen V. Kneese, *The Economics of Water Utilization in the Beet Sugar Industry*, Baltimore, Johns Hopkins Press for Resources for the Future, 1968.

[a] Based on BOD per ton of beets sliced in an "unimproved" plant, from U.S. Public Health Service, "Industrial Waste Guide to the Beet Industry," December 1950.

[b] By process changes and recirculation.

[c] Based on estimated 10 per cent reuse as diffuser make-up water.

[d] BOD which would be generated if all spent pulp were handled in silos, i.e., no pulp drying.

[e] BOD not generated because of use of pulp driers.

[f] By recycle-to-production process and production of concentrated Steffens filtrate.

To conclude this section we present a detailed materials balance calculation for two beet sugar production processes. One of these we term "high residual" and the other "low residual." Charts 4 and 5, showing the materials flow and residual materials, correspond to Charts 2 and 3 above, which show the water circulation streams. In a wet-process industry like beet sugar the two are closely related. Table 4 summarizes a few salient figures from the materials balance.

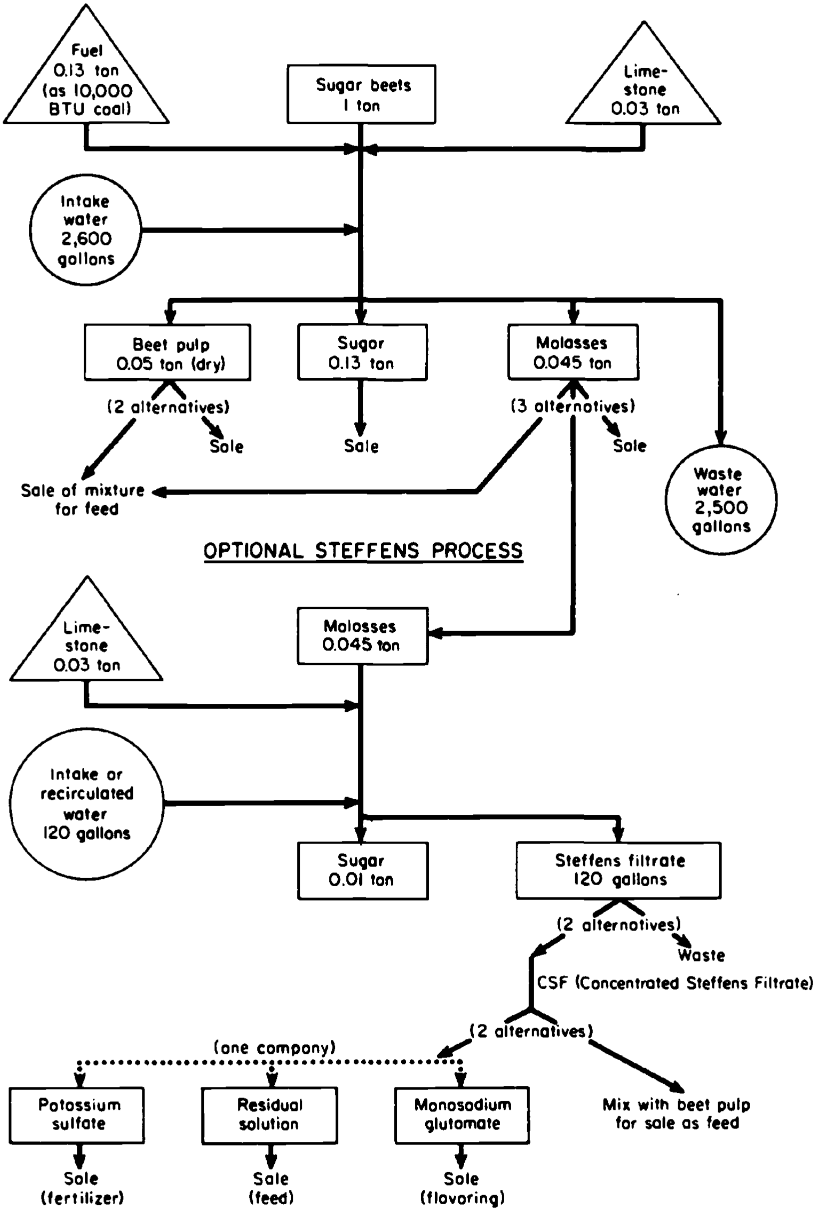
It will be noted from the table that a large reduction in organic residuals was purchased at the expense of a comparatively small increase in potentially harmful gas and inert solids. The interdependence among the residual waste streams going to different environmental media is revealed by these calculations. Considering the environmental circumstances in which most beet sugar factories operate—away from large cities but near small streams with very limited capacity to assimilate organic wastes—the trade-off shown is probably favorable, a conclusion that would not be evident if emission control policies for different media are considered in isolation, as has been the conventional practice.

To sum up, this example illustrates that control of emissions to one environmental medium may come at the expense of increased discharges to another. Consequently, an adequate study of the technology and costs of residuals control must consider the *sets* of emissions levels of interest as being simultaneously imposed for each type of stream. In this case, as probably in others, adjustment to emissions control would also result in greater production of salable output, and the value of this output must be subtracted from the expenditure to get a net cost of control.

Several studies of industrial residuals control taking these factors into account are now in process at Resources for the Future.

CHART 1

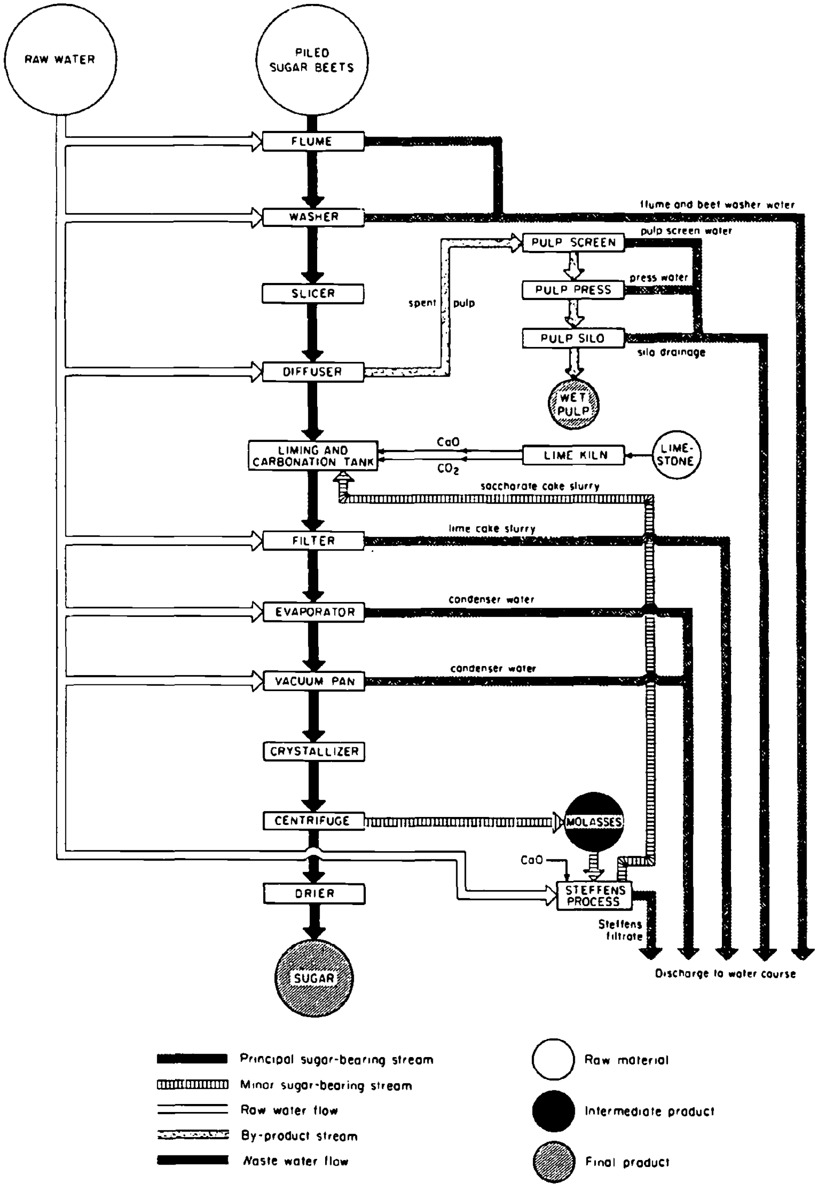
Main Processes in a Beet Sugar Plant



SOURCE: Allen V. Kneese, Robert U. Ayres, and Ralph d'Arge, *Economics and the Environment: A Materials Balance Approach*, Baltimore, Johns Hopkins Press for Resources for the Future, 1970.

CHART 2

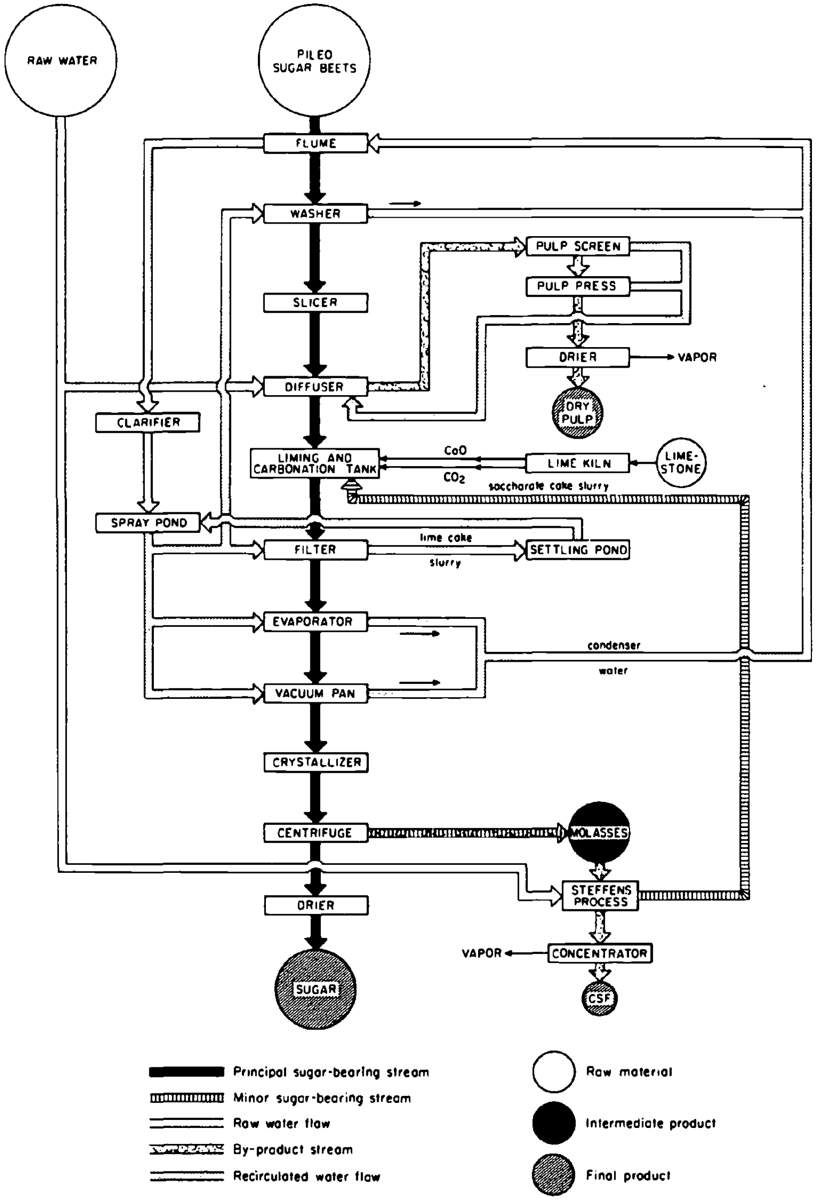
High Residual Beet Sugar Production Process



SOURCE: See Chart 1.

CHART 3

Low Residual Beet Sugar Production Process



SOURCE: See Chart 1.

CHART 4

High Residual Beet Sugar Production Process Without Recirculation (in pounds per ton of beets processed except where otherwise stated)

Intake: 5,250 gallons per ton of sliced beets—regular; 175 gallons per ton of sliced beets—Steffens additional.

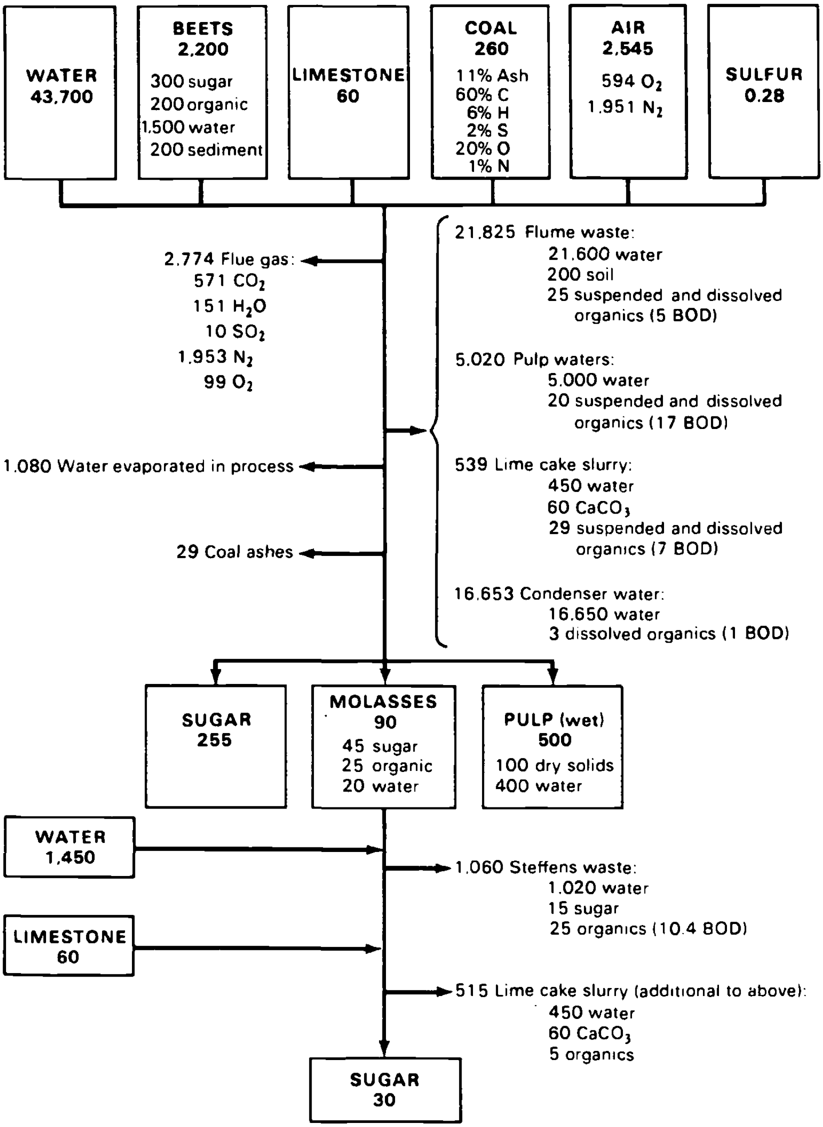


CHART 5

Low Residual Beet Sugar Production Process with Extensive Recycling (in pounds per ton of beets processed except where otherwise stated)

Intake: 270 gallons per ton of sliced beets—regular; 128 gallons per ton of sliced beets—Steffens.

Coal quantity based on 200 for simple plant plus 60 for pulp drying plus 25 for CSF production (evaporation). Coal assumed 10,000 Btu per pound, 11 per cent ash, 60 per cent carbon, 6 per cent hydrogen, 20 per cent oxygen, 2 per cent sulphur, 1 per cent nitrogen. Coal assumed to provide all the plant heat requirements, including pulp drying.

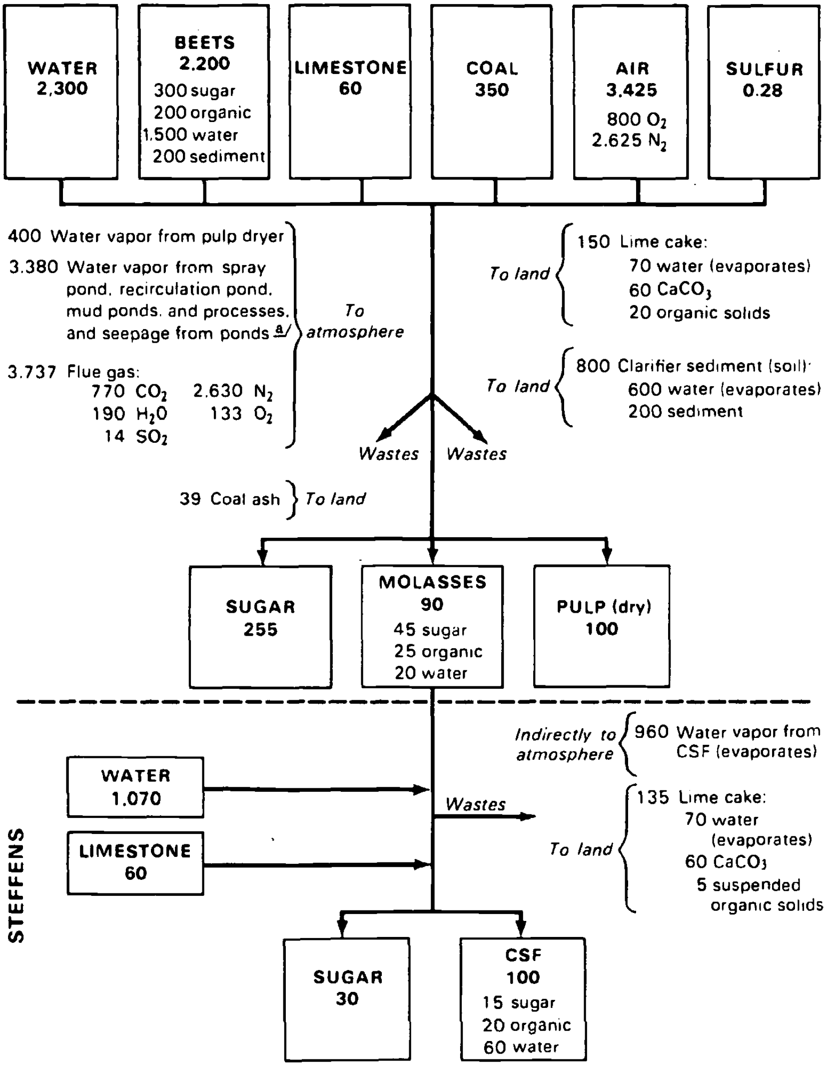


TABLE 4

Selected Figures from Materials Balance for Two Beet Sugar Processes (pounds per ton of beets processed)

Inputs and Outputs	High Residual Process	Low Residual Process
Raw material inputs		
Beets	2,200	2,200
Limestone	60	60
Coal	260	350
Sulfur	0.28	0.28
Product outputs		
Sugar	285	285
Pulp	100 [a]	100 [b]
Concentrated Steffens filtrate [c]	0	100
Waste residuals		
SO_2	10	14
$CaCO_3$	120	120
Coal ashes	29	39
Organics	122	25
Soil	200	200

SOURCE: Allen V. Kneese, Robert U. Ayres, and Ralph C. d'Arge, *Economics and the Environment: A Materials Balance Approach*, Johns Hopkins Press for Resources for the Future, 1970.

[a] Dry weight of wet pulp.

[b] Dry.

[c] Used for stock feed to recover monosodium glutamate and potassium sulfate.

It seems clear that information on alternative processes is a *sine qua non* for evaluating the implementation of any control scheme, whether this involves effluent charges, emission standards, or outright prohibitions.

Technical options and costs: household residuals and alteration of environmental states. Household residuals are on a par with industrial wastes as regards the need to know the technical options for management. The quantities of such residuals moving into sewers and into present channels of solid waste disposal are very large. Household consumption activities are an important direct contributor to air pollution since transportation, consisting primarily of passenger automobiles, is the main source of carbon monoxide, hydrocarbons, and nitrous oxides sent to the atmosphere (71, 53, and 47 per cent, respectively).[34] Large quantities of waste heat are discharged in connection with home heating and cooling. A variety of effluents not entering the usual disposal channels comes from numerous consumption activities, an especially important one for water bodies being oil from motor boats with two stroke motors.

In general terms, the options available for the control and management of household effluents are similar to those for industrial effluents. It is possible to add on treatment devices at the effluent end, as is usually done with domestic sewage and solid waste. Other options are just as important, however, as in the case of industrial effluents. That is, "consumption processes" can be altered and inputs can be changed in ways that will alter the composition of effluents in a less harmful direction and perhaps reduce their quantity. Changes of this type are well illustrated by those already introduced for automobile motors, including closed crankcase ventilation circuits, which result in a more complete burning of hydrocarbons, elimination of atmospheric venting of gasoline tanks and carburetors, the use of unleaded gas with associated changes in motors (such as fuel injection), and alteration of timing in the tuning of motors.

A more fundamental process change would be to abandon the internal combustion engine altogether and substitute for it an inherently low emission engine type like the Rankine cycle. This looks like an option that should be taken very seriously.[35]

Another shift of inputs is exemplified by the changes that have taken place in the last few years in the types of household detergents used.

Clearly there is a need for a large body of up-to-date information on the options available for the management and processing of household discharges to sewers, for gathering, transporting, and processing or disposing of solid wastes, and for discharges going directly to the atmosphere from consumption activities.

Almost needless to say, this type of information on technical options and costs at both the levels of the firm and household is also essential for the effective application of analytical models such as those discussed in part II above. In fact, the building of these models and efforts

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[34] Kneese and Bower, eds., *Environmental Quality*, p. 212.

[35] See Robert U. Ayres and Richard P. McKenna, *Alternatives to the Internal Combustion Engine: Impacts on Environmental Quality*, Baltimore, Johns Hopkins Press, forthcoming.

to bring them to empirical application has probably been the chief stimulus and guidance for structuring the proper approaches to information gathering. The research and information-gathering efforts in this area are, however, tiny in relation to our need to know. Leaving aside scientific and engineering work on details, they amount to no more than a few hundred man-years per year.

The "environment," or particular environments, are the final place for disposal of effluents. Here, too, there are options for control that should be available for consideration. In some cases it may be possible to alter the state of a particular environment so as to increase its assimilative capacity or to reduce adverse effects flowing from it to receptors. Perhaps the most familiar example is the augmentation of low-stream flows through releases from reservoir storage to increase the assimilative capacity of streams. Artificial stream aeration has a similar objective and has proved to be practical in some cases. Another example—not yet brought to fruition—is provided by the schemes that have been proposed to break up temperature inversions in the Los Angeles basin. Sometimes ecological systems can be altered in favorable ways as with the introduction of the coho salmon in the Great Lakes.

Amount and value of damages from different levels of residuals in the environment. It is not enough to know that a pollution control scheme will produce certain physical results at a specified cost. The decision to adopt it or reject it ought to be based on a more or less definite answer to the further question of what difference the change makes to the people concerned. The question we should like to have answered is: How much would the beneficiaries be willing to pay for the change (with what income constraint?) if they understood its nature and significance and if they had the opportunity to buy it? Failing estimates of the value of the change to them, it would be desirable to describe the impact of the change on humans in quantitative or otherwise communicable terms so that some judgment can be made on the desirability of the change. In many cases, it will be found that some of the effects of the change can be quantified and perhaps that values can be attached to them, but some of the effects will not permit this, in which case reliance must be had on a reaction to the proposal based on experience with similar conditions in other areas.

Note that a serious complicating factor is that the damage (or benefit) functions are often not linear, that is, the value of a marginal unit of reduction in a pollutant is not constant, since the initial reductions from a very undesirable situation are more significant than similar changes initiated from an already favorable situation. While this characteristic of damage functions means that there will be many cases in which it can be demonstrated that a certain proposed change should be made since it may be possible to establish that the benefits are likely to be much greater than the costs, the question of the extent to which pollution control should be carried requires more precise estimates of the damage functions.

This is in full recognition of the fact that the final decisions concerning the use of common property resources must and should be made through our processes of collective choice, i.e., political processes. The effectiveness with which these work to aggregate preferences is itself an important topic for research and data collection.[36] The collective choice-making process cannot proceed rationally unless usable information about benefits and costs can be made available to it.

Of all the types of information required for formulation of a rational control scheme, the benefit functions are probably in the worst state. Without at least rough estimates of them, there is danger that control measures costing substantial sums will be introduced with little or no benefit, or, on the other side, that we will fail to take relatively cheap steps that could produce benefits far in excess of cost.

The work of Lave and Seskin provides an indication of the state of affairs in one sphere, namely, air pollution.[37] Limiting themselves to the effects of air pollution on human health, they surveyed a large number of studies attempting to relate air pollution to health (mainly epidemiological studies), reworked some of these, and also did a cross-sectional study of mortality, air pollution, and certain socioeconomic factors in 114 standard metropolitan statistical areas. Their summary conclusions are that the evidence is extremely good for association between air pollution and bronchitis and lung cancer but only suggestive for other ailments such as cardiovascular diseases and nonrespiratory tract cancers. They estimate that a 50 per cent reduction in air pollution might produce a 25 to 50 per cent reduction in morbidity and mortality from bronchitis at a saving in cost (direct earnings forgone) of $250 million to $500 million per year; lung cancer mortality would be reduced by 25 per cent with a saving of $33 million per year; all respiratory disease would be reduced by 25 per cent with a saving of $1,222 million per year. In sum, a 50 per cent reduction in air pollution levels in

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[36] See Edwin T. Haefele, "Environmental Quality as a Problem of Social Choice," in Kneese and Bower, eds., *Environmental Quality*.

[37] Lester B. Lave and Eugene P. Seskin, "Air Pollution and Human Health," *Science*, August 21, 1970, pp. 723–733.

major urban areas might save about $2 billion per year. Whatever the particular costs assigned, they estimate that 4.5 per cent of the morbidity and mortality associated with air pollution would be saved by a 50 per cent reduction.

Their estimates are significant in indicating the importance of the air pollution problem, and if one believes the coefficients they have estimated, the equations can be applied to local and regional areas, but what is mainly of interest here are the limitations of the estimates. While two major classes of pollutants are distinguished in the Lave-Seskin study (particulates and sulfates), more detailed information would be very useful. A general difficulty afflicting most of the studies examined is the approximate nature of the exposure assigned to the individuals in the samples, the major weakness generally being the implicit assumption that the residents of an area have experienced the current levels of air pollution—as measured—for a long period of time. In fact, even within a city there are often significant variations in exposure. Finally, the availability of data for making such studies is revealed by the fact that they had to limit their own estimates to mortality, although morbidity and other loss of function are probably even more important. There is a great need for a program to generate health statistics that are truly usable for this type of problem.

While we are far from being completely at sea about the costs of air pollution, a great deal more work is warranted to provide more precision, greater detail, and a larger body of evidence. The need is fully as great for other types of pollution control.

IV. CONCLUSIONS

The national accounts approach for measuring benefits and costs resulting from environmental pollution was the first to be considered. While the treatment of industrial outlays for pollution control or defensive expenditures in the present official series is reasonably satisfactory, the consumer end of the problem is not. The difficulty lies in our inability to provide estimates of the value of environmental service flows, positive or negative, not reflected in ordinary transactions, and until this is done, any attempts to doctor the official series are likely to produce new errors to replace those corrected. However, outlays for pollution control and defensive expenditures are of interest in their own right and should be assembled. It can do no harm to see what the official series would look like if they were modified by these series in various ways.

If benefits and costs from environmental pollution cannot be estimated in the national accounts framework, it is possible to get at them in a marginal sense. Indeed, estimates of this sort are needed to determine when, where, and how pollution should be controlled.

This line of investigation requires the use of some sort of model to portray the effects that would result from the institution of different types of control measures. Several models designed to aid in the analysis of these problems were examined, among them the national I-O model and the Russell-Spofford model, which is a linear programming model that can go some distance toward optimizing while taking into account process options available, transport of pollutants, exposures of receptors, damages suffered or avoided, and also prediction of changes in some aspects of the environments involved.

We then examined briefly some of the data and information needed to apply these models (or any model) to the design of pollution control schemes. Comprehensive information on materials flows is essential, and it must be linked with location. A serious problem in the implementation of a materials balance accounting system which we have only pointed out is that of classification. On the one hand, great detail is needed because of the specific effects and sources of many pollutants, but the same degree of detail cannot be carried into all parts of the accounting system. Detail is most important for the flows from economic units to the environment.

The need for a large body of information on alternative processes bearing on pollution reduction was emphasized. This is required for three areas: industrial processes, handling and processing of final consumer effluents, and alteration of environmental states.

Finally, pollution control can come close to its target only if usable estimates of effects on receptors are available. These should be expressed in money terms if possible. The need for information of this kind in a form useful to the design of pollution control measures is pressing.

In sum, progress in measuring the benefits and costs from environmental pollution will depend on the efforts of a very large group of people with diverse skills. The problem is rendered complex not only by the physical and biological aspects of the systems involved but also because pollution problems generally are location-specific. An emission that has no adverse effects in one area may be a great danger in another.

We have been able only to allude to the pressing need for estimates of damages suffered from various levels of pollutants in the environment. The desirability of expressing these damages in monetary form, if possible, has been emphasized, although many effects of environmental pollution are psychic. This does not mean that they cannot be related to sums of money, but in many cases this will be very difficult.

The fact that many features of the environment which do not lend themselves very readily to quantitative description may nevertheless be of great importance to many persons greatly complicates the task of comprehensive estimation of benefits and costs from environmental pollution.

COMMENT

WILLIAM VICKREY, Columbia University

I find myself in such close general agreement with what Herfindahl and Kneese present in their paper that I hope I may be forgiven for taking this opportunity to make a few remarks prompted primarily by some of the preceding papers.

Mancur Olson's characterization of governments as generally inefficient has, I think, to be considered in the light of the fact that the activities involved are of a type which, when they are carried on by private enterprise, are to varying degrees carried on by a monopoly, and that these monopolies themselves are often considered to be less efficient than their competitive counterparts. There is a considerable body of opinion, for example, holding that the pricing policies, at least, of publicly owned electric power distribution systems have been more conducive to efficiency than those of privately owned systems. In the case of telephone service, again, many major innovations, among them the combination hand set, direct distance dialing, and free emergency calls from public telephones, were common practice in publicly operated services considerably before they were general in private systems. And while some claims have been made that the quality of service offered tended to be higher in private systems, it is at least arguable that this quality of service might well have been excessive in consideration of its greater cost, motivated by the closer association of private telephone managements with business and higher-income consumers whose preferences for a higher grade of service, even at a higher cost, may have been given rather more weight than might be considered appropriate on an over-all basis. In the field of pricing, especially, public enterprise seems to have been more daring than private monopoly: witness the off-peak passenger fare schemes of the Canadian National Railways, the promotional electricity rates of the Tennessee Valley Authority, and the low prices offered by many public telephone systems for very brief long-distance calls. It is at least dangerous to attempt to judge performance of public enterprise by the financial standards used in the competitive areas of the economy. To the extent that the New Jersey Turnpike is a financial success, for example, it is an economic failure in that such success necessarily entails an impaired performance in relieving congestion on U.S. 1.

There is, to be sure, a "succession problem" that is more severe in government, especially where political parties alternate frequently in power, than in private industry. Private management tends to be judged rather critically in terms of the future prospects of the firm as viewed, at the time the management leaves office, by fairly sophisticated investors. This judgment tends to be reflected fairly conspicuously in the quoted prices of the shares of the company. Government administrations are under a much greater temptation to resolve current issues in an atmosphere of *après moi le déluge* by planting time bombs under the desks of their successors, for example, in the form of labor dispute settlements by which government officials, in collusion with the older and more influential members of the labor unions, provide for large benefits in the form of liberal pension provisions which will constitute substantial windfalls to the older union members, while meaning relatively little in terms of discounted present value to the younger union members and which will constitute a relatively small immediate burden on the public budget, especially if the benefits are unvested or unfunded or both. If bonds can be floated for the financing of non-self-liquidating public works, and sometimes even for current operating expenses that can be capitalized by relabeling as capital improvements what should properly be called maintenance or replacement, there is a grave temptation for incumbents to try to claim the credit for such expenditures, while leaving to their successors the onus of levying the taxes. In extreme cases the resulting policy of "billions for construction, but not one cent for operations" can lead to serious inefficiency, as happened, for example, with the New York Transit Authority, where this general tendency was reinforced, for the period 1951 to 1967, by a legislative mandate that required fares to be raised to cover operating expenses but not capital charges. When to this is added the temptation to favor the construction of enduring monuments to which commemorative plaques and names can be attached, the cumulative bias can be substantial.

I find I am intrigued by Olson's discussion of measurement possibilities in the field of broadcasting. Some aspects of the quantity of the product consumed are measured, at considerable expense, by the Nielson and other ratings, and the price, in terms of involuntary attention to commercials, can be expressed in terms of the ratio of programming to commercial time. As Olson indicates, this is a very high price indeed, the high price being a reflection of the fact that broadcast advertising is intrusive in a way that the classified ads, or even the display ads, in printed media are not. While the price thus exacted is subject to some degree of downward pressure from vague threats of license withdrawal by the FCC, and there is some degree of competition among stations and networks, "price" competition in terms of reducing the proportion of advertising seems to be minimal, with the result tending toward the shared monopoly solution of maximizing total "revenue," interpreted as prices times quantity, or in this case, the aggregate amount of man-hours spent by the the audience listening to or watching commercials. While there may be a modicum of information conveyed in this way, it seems to be far outweighed by misinformation, contained especially in advertisements for drugs of various kinds ranging from caffeine and aspirin to alcohol, the nicotine complex, and narcotics ("sleeping pills") (and then we wonder why we have a drug problem!).

There are interesting ramifications in Olson's suggestion for investigating the more directly monetary aspects of relating demand to a money measure by picking out a sample who would be required to pay a cash price for the reception of each program. It is worth noting that he deems it necessary that those picked out for the sample be compensated by some form of lump sum payment, in contrast to the procedure of drafting men for military service according to their dates of birth without any compensations. It may be hoped that arrangements would be made for appropriately reduced payments if the listener turns the program off in disgust halfway through. It is interesting to consider the application of this technique in another context, that of attempting to evaluate the benefits from an increased frequency of bus service. For example, in a small town the optimal long-run fare for a bus service may well be clearly zero, but whether a 10-minute or a 20-minute service should be operated may be less obvious. One could, experimentally, operate a 10-minute service with alternate buses designated "red" and "green" and similarly alternate bus stops designated "red" and "green." Then a suitable sample, say those who cannot show evidence that they were not born on the day of some month corresponding to the current dates would be required to pay an extra fare for boarding a bus of a color not corresponding to the stop they board at. By varying the extra fare and observing how many wait for the succeeding bus rather than pay the extra fare, the value of the more frequent service can be estimated.

Of course, any evaluation of this kind has a cost in that during the evaluation the members of the sample, at least, will not be making optimal use of the service being provided. Moreover, to the extent that the individuals concerned are aware that the results of the measurement will be used to determine whether or not they will get the improved bus service, they may be tempted to bias their behavior according to whether or not they individually prefer the better service, together with whatever share of the added tax burden they expect to have to bear in order to finance it. This bias, moreover, will be the greater the smaller the sample. This can, perhaps, be considered an instance of what might be termed the Acton-Heisenberg principle: "Every use of a measure for a socially important purpose corrupts the measurement, and the worse the measure to begin with or the more important the use, the greater the corruption."

Turning to the Herfindahl-Kneese paper, my chief concern is with the concept that in the long run it is appropriate as a first approximation to assume that environmental services are constant, and that hence a correct welfare concept requires that outlays to control pollution or defend against its presence are not to be considered a part of the final product. While this is a convenient convention that at least reduces a part of the bias inherent in treating as final product outlays that merely preserve the status quo, it introduces an awkward distinction between the accounting procedure deemed appropriate for long-term purposes and that obviously required to account for the impact of short-run variations in antipollution efforts, not related to variations in pollution-producing activity. But although some such convention does represent a compromise, albeit arbitrary, between considering that environment has improved and that it has deteriorated, it does not in principle solve the problem inherent in this appraisal. Impact on the environment is only one of the many aspects of the problem of dividing the product of government activity between final product and intermediate product. If air pollution is a negative, final by-product of industry, to the extent that it is not controlled, do we not also have to consider jails as a negative, final by-product of the government's production of security? It is difficult enough to determine whether even over past history the environment has improved or worsened, considering, for example the impact of DDT on malaria on the one hand and on the peregrine falcon on the other, or the increased pollution of streams vis-à-vis the reduced incidence of typhoid fever on the other; determining what is currently happening, on balance, to the environment, or what environmental trend might be considered optimal is even harder. We have already for a long time been guilty of ignoring the fact that much government output is intermediate product on any reasonable definition. Perhaps in the course of trying to deal with the problem of environmental change we can be brought to face the entire problem of the welfare impact of the government sector more realistically, even at the expense of some accuracy of computation.

In any case it seems a natural extension of the idea of incorporating environmental impacts in an input-output model, whether in terms of economic values or materials balances, that the dynamic aspects not be overlooked, and that distinctions be made between the treatment accorded short-lived pollution, such as that of streams, and of sulphur and nitrogen compounds in the air, and that accorded long-term and in some cases irreversible changes such as the dispersion of heavy metals, the accumulation of carbon dioxide in the atmosphere, or the extinction of species or the introduction of new predators.

Finally, it is perhaps worthwhile pointing out that while when considered in isolation the control of pollution at the household level through effluent charges may appear to involve disproportionately high costs, if such control is considered in conjunction with other costs, such as, in the case of the automobile, congestion and accident costs, the prospects may be considerably brighter. Indeed, if a system of congestion charges were to be instituted, the superposition of charges reflecting marginal pollution costs would be a fairly simple matter, involving chiefly a periodic rating of the individual automobiles, following which charges could be imposed that would take into account such factors as the time and place at which the vehicles are operated, and even, if desired, weather conditions. Such charges would have a salutary role to play especially during periods of transition from more to less pollution-prone vehicles, providing an equitable sharing of the burden between those using the new and those retaining the old vehicles, as well as providing appropriate incentives for the relegation of the pollution-prone vehicles to types of use where the pollution produced would have less impact. The required mechanism consists merely of some optical or electronic identifier device on each vehicle which will enable it to be identified each time it passes scanning stations located along various screen lines. From the records thus generated and the recorded characteristics of the car, the appropriate charge could be computed and billed to the owner, and would represent the contribution that operation of the vehicle makes to congestion costs, pollution costs, and possibly accident hazard. A cost of assessing and collecting the charge which might be considered excessive for one of these elements separately may become a relatively minor drawback when applied to all three purposes at once.