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Studies of Residuals Management in Industry

Blair T. Bower, Resources for the Future

Introduction and History

For more than ten years Resources for the Future (RFF) has been studying residuals generation and management in industry. The roots of these efforts lie in the original concern of RFF with problems relating to water quantity, and with the corresponding problem of estimating industrial water demand. Hence, the first efforts focused on water intake and water utilization within the individual industrial plant, rather than on the residuals stemming from production activities.

There were two basic reasons why RFF became involved in these detailed industry water studies. First, in 1960 industrial water withdrawals comprised the largest type of water use in the United States, excluding water power. Since that time industrial water withdrawals have become even more predominant quantitatively, as industrial output has continued to increase in magnitude and complexity. Both water withdrawals for, and liquid residuals from, industrial operations have major impacts on the economics, technology, and institutional arrangements for water resources planning and management, including water quality management. Second, past estimates of future industrial water use, traditionally termed "needs" or "requirements," had been done on a very rudimentary and naive basis. This became particularly apparent in the studies under the aegis of the Senate Select Committee on Water Resources.

Traditionally estimates of future industrial water use were based on

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Note: I am much indebted to my colleague, Clifford S. Russell, for many helpful comments on the original version of this paper.

historical data on gallons per employee, gallons per unit of raw product processed, gallons per unit of final product output, and even gallons per acre of "type" of industrial activity, i.e., light manufacturing. The basic data used were aggregate data, i.e., across a given industry, based on nationwide mail questionnaire surveys, such as those of the Bureau of the Census. Thus, regional differences in industrial water utilization patterns were very often obliterated. In general, all estimates by planning agencies—both public and private—failed to consider changes in technology relating not only to production processes but also to raw material inputs and product mix. The efforts also failed to consider the price of water at both intake and outlet, as price affected industrial water utilization through the many substitution possibilities available in industrial water utilization systems and between such systems and other factor inputs. For these reasons RFF undertook to develop more rational bases for estimating future industrial water demands, where demand refers to economic demand. The Cootner-Löf study of the steam electric generation industry is the major example of published work from this first period of research.[1]

The next industry studies continued the concern with water, but the focus was broadened to include not only questions of water intake and inplant water utilization, but also liquid residuals generation, modification, disposal, and discharge. The liquid residuals and water quality parameters of concern were biochemical oxygen demand (BOD) and suspended solids (SS). The Löf-Kneese study of the beet sugar industry is the primary product of this period of research.[2] Even though the beet sugar industry is simple, in terms of process technology, and hence of the residuals generated, much was learned in the study about methodology, and the study generated information which has been widely used.

The study of residuals management in the New York region for the Regional Plan Association, although not directly a research project of RFF, provided the stimulus for a further expansion of the framework of the RFF industry studies.[3] This study made clear the basic technologic, physical, and economic interrelationships among the two basic types of

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[1] P. H. Cootner and G. O. G. Löf, *Water Demand for Steam Electric Generation: An Economic Projection Model* (Washington, D.C.: Resources for the Future, 1966).

[2] G. O. G. Löf and A. V. Kneese, *The Economics of Water Utilization in the Beet Sugar Industry* (Washington, D.C.: Resources for the Future, 1968).

[3] B. T. Bower, et al., *Waste Management: Generation and Disposal of Solid, Liquid and Gaseous Wastes in the New York Region*, A Report of the Second Regional Plan (New York: Regional Plan Association, 1968).

residuals—materials and energy, and the three states of the former—liquid, gaseous, and solid. The result was that subsequent RFF industry studies focused simultaneously on the management of all residuals generated in the industrial plant. Water was still of concern as a factor input, and in terms of various types of possible trade-offs, both among components of the total water utilization and residuals management subsystems and between those subsystems and the production process. Current studies of petroleum refining,[4] pulp and paper manufacture,[5] and the coal electric energy industry[6] are examples of this expanded focus.

The presently conceived objectives of the industry studies have evolved over the years. They are:

1. to determine the factors which influence residuals generation in an industry and to determine the quantitative responses, to the extent possible, to variations in those factors;
2. to determine the range of options available in an industry to respond to increasingly stringent constraints placed upon the discharge of residuals to the environment, i.e., constraints on the use of common property resources as inputs to production processes;
3. to determine the proportion of total production costs represented by net residuals management costs taking all impacts on costs into consideration, under increasingly stringent constraints on residuals discharges and in relation to different sets of factor input costs, such as fuel and raw materials, production variables, technology of production, and product output specifications;
4. to develop models of production-residuals generation for different industries for use in analyses of regional residuals management; and
5. to determine the extent to which the physical, technological, and economic interrelationships among the types and states of residuals require that all residuals be considered simultaneously in order to determine the optimal residuals management strategy for an industrial plant.

All except the last are discussed to some degree herein.

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[4] C. S. Russell, *Residuals Management in Industry: A Case Study of Petroleum Refining* (Baltimore: Johns Hopkins Press, 1973).

[5] B. T. Bower, G. O. G. Löf, and W. M. Hearon, "Residuals Management in the Pulp and Paper Industry," *Natural Resources Journal* 11: 4 (1972): 605–623.

[6] J. K. Delson, R. J. Frankel, and B. T. Bower, "Residuals Management in the Coal Electric Energy Industry," Resources for the Future, unpublished.

Conceptual Frameworks and Analytical Methods

Various conceptual-analytical frameworks could be utilized in studying residuals management in industry. The following describes both the evolution and the essence of the approach adopted.

A production process—manufacturing, mining, logging, agriculture—operates on one or more raw materials via physical, chemical, and biological transformations by use of capital equipment and inputs of human and nonhuman energy to produce one or more desired outputs. However, no production process can be designed for 100 per cent conversion of inputs into desired outputs.[7] Thus there are material and energy outflows in addition to the desired outputs of products and/or energy.[8] The former are termed "nonproduct outputs" of the production process. They consist of: (1) nonproduct materials *formed* in the production process; (2) raw materials not transformed in the production process, such as catalysts; and (3) nonused or nondesired energy outputs from the production process.

It is assumed that the objective of the firm undertaking the production process is, at least loosely, to maximize the present value of net profits in relation to prices of inputs and outputs and subject to whatever constraints are relevant. Even if there are no constraints on the use of common property resources, i.e., atmosphere, biosphere, water bodies, it is economically necessary in many cases to recover and reuse substantial portions of the nonproduct outputs, both material and energy. Although the discussion immediately below is couched in terms of materials, it is equally relevant to energy flows.

The extent to which materials recovery is practiced at any point in time at a particular industrial plant is a function of the relative costs of recovered materials versus new (makeup) materials, the latter usually being purchased in the market or from another section of the plant at a price which may or may not be close to the open market price. The costs of recovery are a function of the technology of the production process

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[7] Almost always, if not always, several processes and operations are involved in transforming the inputs into the outputs. For convenience the *set* of such activities is referred to as a production process. For a useful classification of production processes see R. U. Ayres, "A Materials-Process-Product Model," *Environmental Quality Analysis: Theory and Methodology in the Social Sciences,* A. V. Kneese and B. T. Bower, editors (Baltimore: Johns Hopkins Press, 1968), pp. 35–67.

[8] In the production processes of energy generation and heating, the desired outputs are electric energy and heat energy, respectively.

and the technology of materials recovery. Trade-offs are possible between the design of the production process to reduce the formation of nonproduct materials and the extent of utilization of materials recovery technology. In effect, the plant optimizes the *combination* of the production process *plus* the materials recovery system, in the absence of constraints on residuals discharges. (When constraints of one type or another are imposed on residuals discharges, the "total system" is optimized—production process, materials and energy recovery, residuals management measures, as is discussed below.)

Although essential in terms of describing the "ground rules" for studies of residuals management in industry, the above provides no operational framework. A first attempt to become operational was based on a formulation adapted from studies of industrial water utilization.[9] Thus, residuals generation in the absence of constraints on residuals discharges is expressed in terms of the primary variables as follows:

$R_{git} = f\,(RM, PP, PO)$, where
R_{git} = quantity of residual i generated per unit time, t;
RM = type of, and hence characteristics of, raw materials;
PP = technology of production process, including technology of materials and energy recovery and technology of by-product production; and
PO = product output specifications.

There are other variables which affect residuals generation, and may be of major importance in specific cases, particularly in the short run.[10] Examples are operating rate, i.e., output per unit time, the cost of in-plant water recirculation, and the physical layout of the plant—which in turn affects other variables such as the cost of water recirculation.

Residuals *discharge*, i.e., into the various environmental media, is then a function of the same factors plus the effluent controls imposed on the plant and the technology of residuals modification. Thus:

$R_{dit} = f\,(RM, PP, PO, EG, TR)$, where
R_{dit} = quantity of residual i discharged per unit time, t;
RM, PP, PO are the same as above;

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[9] B. T. Bower, "The Economics of Industrial Water Utilization," *Water Research*, A. V. Kneese and S. C. Smith, editors (Baltimore: Johns Hopkins Press, 1966), pp. 143–173.

[10] Bower, "Industrial Water Utilization," p. 153.

EC = controls imposed on discharge of liquid, gaseous, solid, and energy residuals (heat and noise), i.e., standards, charges; and

TR = technology of residuals modification.

However, these formulations are inadequate, particularly in failing to make explicit the role of: (1) prices of factor inputs, i.e., chemicals, electric energy, and heat; and (2) exogenous variables such as tax policies, import quotas, postal rates, technological changes in other production processes which utilize the outputs of the production process under consideration, and the factors which influence final demand in terms of the characteristics of final products, i.e., Madison Avenue, internal R & D for product development, sales departments. Russell has proposed an excellent conceptual model which includes such factors; it is shown in figure 1.[11] As Russell states, even though this is only a qualitative framework, it serves two useful purposes:

> First, it focuses attention separately on the influences outside the firm which indirectly and those which directly affect residuals generation patterns. And second, it emphasizes that within the production process itself other inputs can frequently be substituted for primary residuals generation. That is, it illustrates the fundamental sense in which it is misleading to assume that analyses based on fixed coefficients (such as pounds of BOD generated per unit of output) are conceptually valid.[12]

Basically this is the conceptual framework for the ongoing RFF studies of residuals management in industry.

Given a conceptual framework, several procedures have been used to make it quantitative, in terms of (1) method of analysis, (2) focus of study, and (3) source of information. With respect to the first, simulation and linear programming have been used, and simulation-linear programming combinations could have been used. The individual plant and the total system, i.e., set of spatially separate component activities, to produce a specified output, are the two foci which have been used. The following list shows the combinations of analytical method-focus used in the industry studies thus far:

Beet sugar: Plant—Simulation
Pulp and paper: Plant—Simulation

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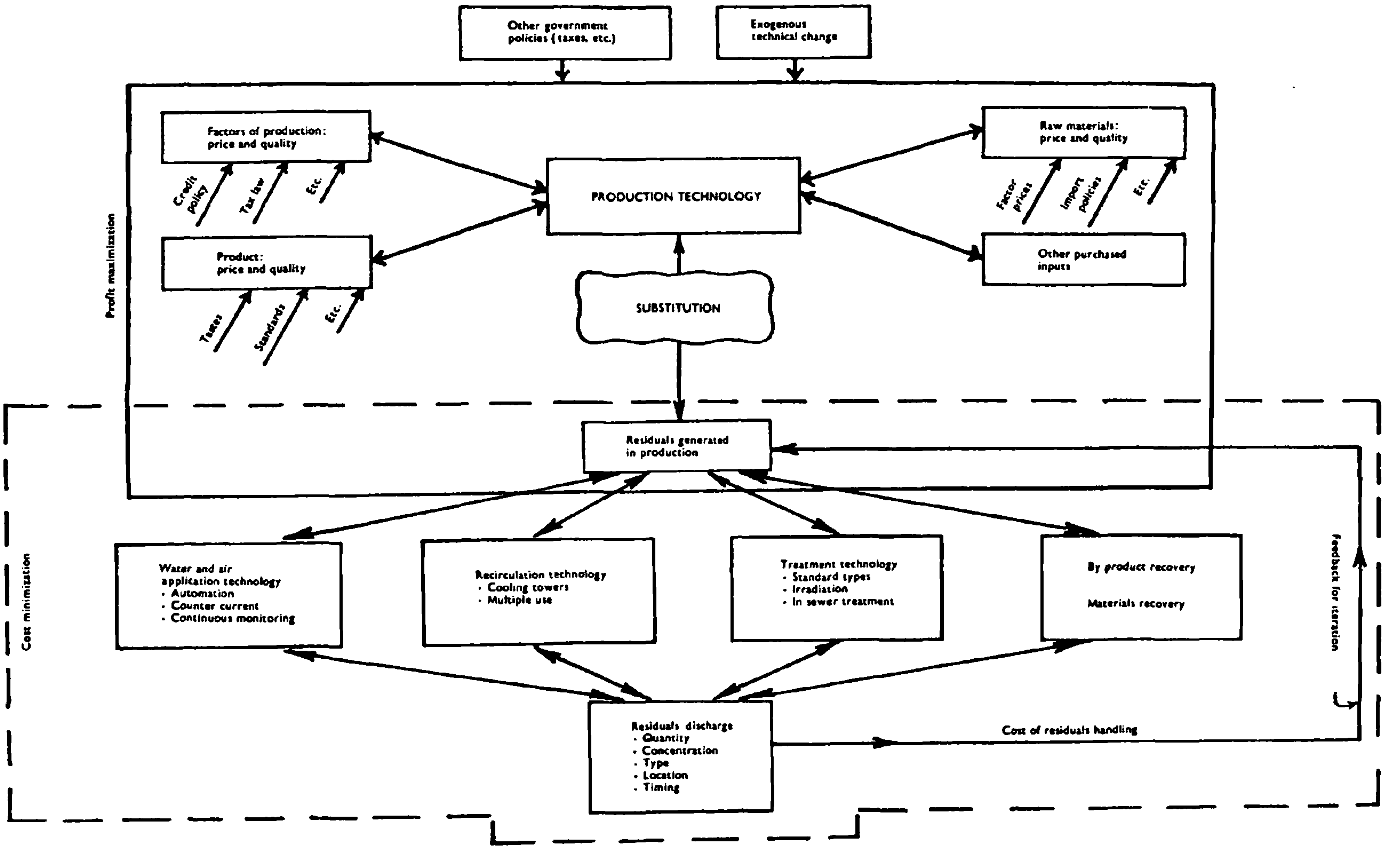
[11] C. S. Russell, "Models for Investigation of Industrial Response to Residuals Management Actions," *Swedish Journal of Economics* 73: 1 (1972): 136–138.

[12] Russell, "Models for Investigation," p. 138.

Figure 1

A Proposed Model of Industrial Residuals Generation and Discharge



Source: C. S. Russell, "Models for Investigation of Industrial Response to Residuals Management Actions," *Swedish Journal of Economics* Vol. 73, No. 1 (1972): 137.

Petroleum refining: Plant—LP
Steel:[13] Plant—LP
Steel scrap:[14] Plant—LP
Coal-electric energy: Total system—Simulation

The different foci of the industry studies merit emphasis. All of the studies except that of the coal-electric energy can be characterized as micromodels. Thus, the study of petroleum refining analyzed a single petroleum refinery, taking the alternative types of crude oil inputs as given and not associating those inputs with any of the residuals problems involved in providing those inputs, i.e., in the activities of exploration, drilling, transport to the refinery via tanker or pipeline.[15] In contrast, the total system focus of the coal-electric energy industry study involved consideration of residuals generation and management throughout the entire system from coal in the ground to energy produced at the high side of the busbar, not just the power plant itself. The latter focus, while computationally more difficult, enables explicit analysis of interactions and trade-offs among the different spatially separated components, thereby providing a larger range of options for residuals management.

One or more of three sources of information and procedures were used in the studies. For the beet sugar study, the information was obtained by a questionnaire survey of all the plants in the industry. This 100 per cent response could not have been obtained without the full cooperation of the industry. The analysis of the data was then made by RFF staff. A second procedure, used for the petroleum refining and steel industries, was for RFF staff to plumb available literature in order to construct LP models, resorting to specific experts in the industry for detailed information and answers to questions when necessary. The third procedure, used for the pulp and paper study, was to combine RFF staff capability with outside consultant expertise in the technology of the industry to develop materials balance and flow diagrams for the various processes in the industry, information not available anywhere in the published—or even in unpublished—literature.

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[13] W. J. Vaughan and C. S. Russell, "A Linear Programming Model of Residuals Management for Integrated Iron and Steel Production," *Journal of Environmental Economics and Management* (July 1974).

[14] J. W. Sawyer, *Automotive Scrap Recycling* (Baltimore: Johns Hopkins Press, 1974).

[15] Theoretically, the price of crude petroleum input should reflect the costs of managing the residuals problems in these activities, but it is highly doubtful if this is the case at present.

Some Difficulties Facing Industry Studies

Although relatively few benefits are likely to be derived from presenting a complete listing and discussion of the difficulties facing the researcher undertaking a study of residuals management in industry, some discussion of at least a few difficulties is warranted. The difficulties relate to the availability of data and to the interpretation of whatever data are available.

First, data typically are available on only some of the various residuals of interest, because few plants measure regularly even all of the major residuals. Further, most of the data published consist of residuals discharges, which discharges are the result of some combination of residuals generation and residuals modification after generation. Such data preclude any analysis—statistical or otherwise—of the effects of the variables identified previously.

Even where data on residuals generation are available, they rarely are published in relation to the variables which have determined that generation. Rather, the data are published in terms of, for example, pounds of BOD per ton of paper for the total integrated paper mill, or perhaps an integrated kraft paper mill, or pounds of BOD per barrel of crude petroleum charge to a "petroleum refinery," not by individual operations. In fact, there are many combinations of type(s) of raw material used, production operations, and detailed product output specifications for a single 4-digit SIC category, such as paper mills. Typically in a single integrated paper mill there are: multiple cellulose-containing raw materials used—logs, chips, wood products residues, sometimes waste paper; multiple pulping processes—sulfate, mechanical, perhaps sulfite, with both batch and continuous digesters; multiple product outputs—dozens of types of paper and/or paper products. Even for a mill producing only linerboard, typically a dozen or more weights (grades) of board are produced.

Second, and closely related to the first, is that an adequate industry study requires the calculation of almost complete materials, electric energy, and heat balances for the production processes involved. Such materials and energy balances are rarely available, even in unpublished form. The "almost complete" stems from two caveats. One, some energy and materials quantities representing less than 1 or 2 per cent of the total energy or materials involved can usually be neglected, except where even the small amount can have substantial adverse effects when discharged, as in the case of toxic or malodorous materials. Two, heat, water vapor, and carbon dioxide discharged to the atmosphere can be ignored, at least in the short run. Thus, keeping track of these residuals is not necessary, other than for insuring consistency in the total materials and energy balances. It should be emphasized that the determination of all of the residuals associated with producing a given product requires determining the amount of purchased energy or fuel required, over and beyond the energy generated within the plant. This is simply to say that, in producing a ton of paper, SO_2 is SO_2, whether it is generated at the paper mill or in the fossil-fuel power plant of the utility serving the area and the paper mill. Similarly, the materials and energy used in residuals modification in response to effluent controls must be included in the analysis.

A third data problem is a lack of data on costs of factor inputs, process units, and residuals modification measures—both capital and operation/maintenance, where relevant. For example, depending on the bookkeeping "policy" of the company's financial officer, wood products residues obtained from another company mill and shipped to the company's paper mill in the same region for use as input in paper production, may be priced at the going market price for such raw material in the region, or at zero (excluding transport costs). The "cost" of chemical inputs to pulping depend on whether the source is a captive chemical plant at the paper mill or the open market, and the bookkeeping policy. This becomes particularly important in evaluating residuals management costs where nonproduct material outputs are the same as the chemical inputs, as is discussed in some detail below.

Many costs are site specific, or at least significantly affected by site factors. Site topography, access to water, energy or fuel costs, raw material availability, et al., affect plant design and costs, and hence total production costs. For a single company producing the same product by the same process in two different paper mills, the ratio of raw wood costs between the mills can be as much as two to one. In absolute terms, the difference is several times greater per ton of paper output than total residuals management costs per ton. Published data on capital costs of some residuals management facilities show ranges of ten to one for the identical type of facility for the same volume throughput and residuals loading. Published data on basic production costs are often misleading because they rarely relate to a totally new plant, but rather to some component thereof. Usually there is a mix of technologies in a given plant, because of the multiplicity of processes involved in producing the output and the changes which have been made in different process units at different points in time.

A fourth difficulty is the short-run variability in residuals generation. To what extent such variation affects, or is reflected in, published data on residuals is not known. Only rarely are ranges of residuals published; even more rare is a frequency distribution of residuals discharge or generation per ton.

A given production process—such as the manufacture of paper—is normally designed in the engineering sense to produce a range of types of outputs, i.e., grades of paper, with one particular grade likely to be dominant in terms of proportion of total output. Maximum production efficiency in the physical sense is achieved when producing this grade. But once in operation several variables affect residuals generation from day to day, and seasonally, such as the quality of incoming logs and/or chips, the sharpness of the saws in the wood preparation operation, and demand for different product outputs. Pressure for increased daily output can result in "pushing" certain components of the production process, such as digesters, beyond design capacity, thereby resulting in larger than "normal" residuals generation per ton. Variation in BOD residuals generation per ton of almost two to one has been recorded within a single month for a given linerboard mill.

Similar short-run variations occur in other industries.[16] One illustration, from the canning industry, is shown in figure 2. The daily variation in pounds of BOD generated per ton of tomatoes processed results primarily from variation in the quantity and quality of incoming raw material, but also because of daily variations in product output mix.

A fifth problem is that of determining what the particular production process to produce a specified product with a given basic technology would be in the absence of pollution controls. Such information is *essential* for determining both residuals generation and costs attributable solely to residuals management. Most existing manufacturing installations have varying amounts of residuals modification facilities, which have been added over the years in response to various pressures for effluent control. Neither the production process itself nor the residuals modification measures would likely be identical for the given plant, if a new plant were going to be constructed at the same site with today's constraints and prices. The available data typically do not differentiate between basic production costs and residuals management costs.

The problem is illustrated in figure 3, which shows an hypothetical

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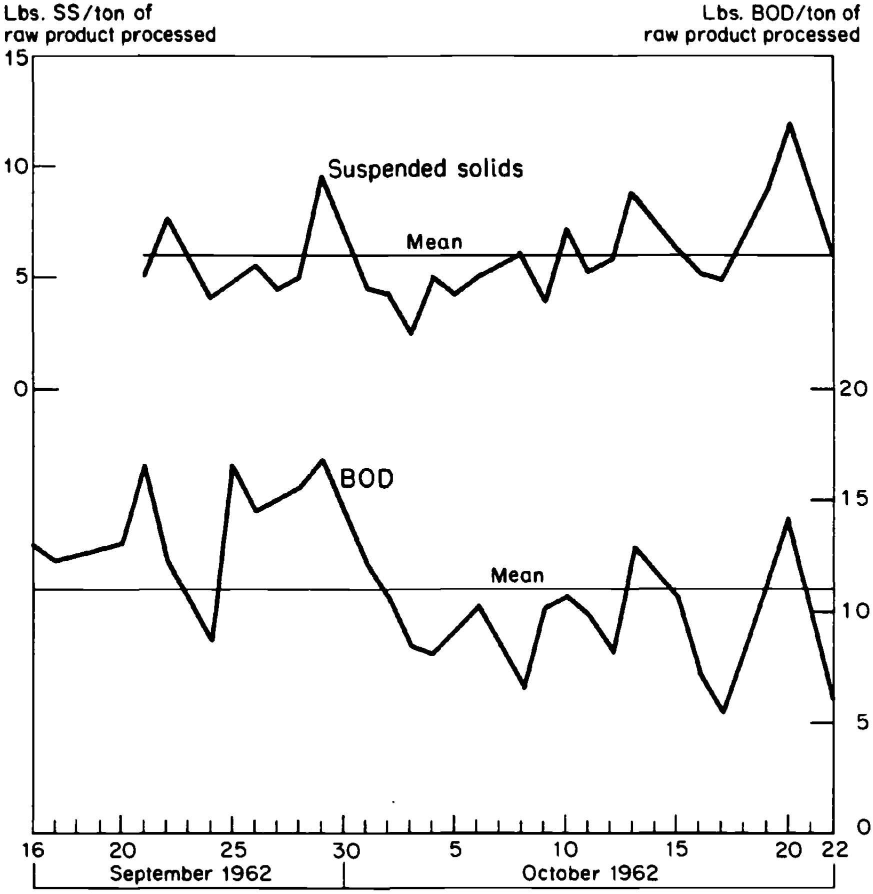
[16] It should be noted that short-run variations in residuals generation also occur as a result of accidental spills and breakdowns.

Figure 2

Daily Variation in Residuals Generation During Processing of Tomatoes



relationship between degree of modification of nonproduct material outputs and net annual cost, for cases—relatively numerous it should be noted—in which these outputs have a positive value. In terms of profit maximization for the individual plant, materials recovery is undertaken to the level where the marginal benefits from materials recovery equal the marginal costs of recovery.[17] This level defines "residuals generation,"

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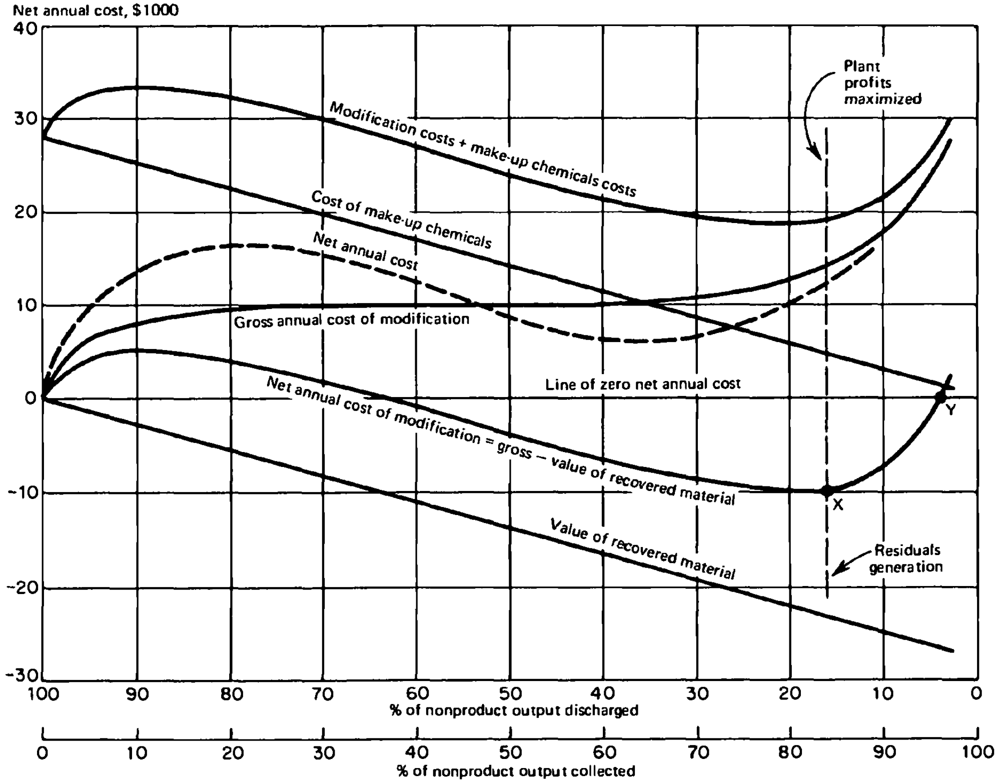
[17] The same is true for by-product production. The degree to which such production would be undertaken in the absence of environmental quality controls is a func-

Figure 3

Hypothetical Cost Curve for Modification of Nonproduct Material Which can be Used In-plant



Source: Löf, Hearon, and Bower, "Residuals Management."

and is designated by X in figure 3. The range in materials recovery from zero to this level is termed economic materials recovery. Thus, the quantity of this particular material residual generated equals the quantity of *nonproduct output* material minus the quantity of economically recovered materials.[18]

In reality the net annual cost of modification curve is likely to be much flatter in the vicinity of the maximum profit level than as shown, as is illustrated subsequently in figure 6. The factors affecting the shape of the curve include the cost of makeup chemicals, chemical recovery costs—including capital facilities, energy, and other operating costs, effects on other residuals and residuals modification measures, and effects on other factor inputs.

Thus, only by quite detailed analysis can the "residuals generation" level be determined, and hence the base from which the costs of residuals management *should* be measured. To illustrate, with respect to recovery furnaces in kraft mills, Kittle stated in 1966 that, ". . . in past years, precipitators were usually installed for the purpose of achieving about 90 per cent collection efficiency. Today few new precipitators are ordered having a designed collection efficiency of less than 97.5 per cent." [19] Because the statement referred to conditions prior to significant air pollution controls, it is clear that the 90 per cent collection efficiency installations were *not* for air pollution control but for chemical recovery, i.e., to minimize total production costs. Given the small increases in chemical costs and the *reduction* in chemical recovery costs at kraft mills since 1966, it is likely that in many locations much of the additional increment of particulate recovery would be economically justified even in the absence of effluent controls.

A final difficulty involves the application of the analyses to existing industrial operations rather than to new plants. In the main, the RFF industry studies have involved new plants to be built, i.e., a "grass roots" refinery or new paper mill, not plants already in existence.[20] However,

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tion of the profit maximization objective. Beyond that level, which corresponds to residuals generation, additional by-product production involves costs greater than returns, hence represents a net economic cost to the firm. However, it may still be the least-cost alternative for reducing residuals discharge.

[18] Minus, where relevant, the nonproduct output used in *economic* byproduct production. Economic by-product production is analogous to economic materials recovery.

[19] R. W. Kittle, "Current Status and Future Prospects—Pulp Mill Air Pollution Control," *Proceedings: The Third National Conference on Air Pollution*, PHS Publication 1649 (Washington, D.C.: Government Printing Office, 1967), pp. 232–235.

[20] The exception is the steel industry study.

much of what has been learned is valid for existing plants. This is demonstrated by the analysis of actual behavior in various cases, where many of the alternatives available to new plants to reduce residuals discharges have been used at existing plants, albeit at sometimes higher costs than would be the case for the same alternative at a new plant. Residuals management costs at existing plants are of course affected by existing conditions, particularly the physical layout of the plant and the existing technology of production. Focusing on new plants has the advantage of being able to make explicit the base conditions for the analysis, and has led to many insights which would not have otherwise been gained.

Results of Industry Studies

Having discussed the conceptual framework for, and some of the problems of, the industry studies, the next task is to illustrate the types of outputs and what has been learned from these studies. Basically the studies have illuminated in detail: (1) the major factors influencing residuals generation, particularly the interrelationships among type of raw material, nature of production process, and product output; (2) the major significance of final demand, in terms of the relatively large changes in residuals generation stemming from changes in product characteristics; and (3) the range of options available for responding to effluent controls, and the costs associated therewith.

Individual plant: residuals generation

Paper manufacture. The types and quantities of residuals generated in the production of a specific type of paper are a function primarily of the raw material(s) employed, the pulping process used, the extent of bleaching, and the characteristics desired in the paper product. All of these factors are of course interrelated. The desired brightness of the final product determines the amount of bleaching required, for a given raw material and pulping process. Similarly, the desired strength, or any other product characteristic, limits the combinations of type of raw material and pulping process which can be used.

More specificity is given to these statements by considering an integrated mill producing jumbo rolls of tissue paper, i.e., *excluding* the converting operation. Table 1 shows the residuals generated in producing one ton of tissue paper for different combinations of raw material, pulping, bleaching, and product brightness. Not shown are by-products, and normally innocuous nonproduct outputs of water, carbon dioxide, and nitrogen. The residuals generated in the combustion of purchased fuel necessarily used in generating process steam and electric energy are included. Because the output under consideration is tissue *paper,* rather than tissues, the converting operation is not considered, although residuals are generated in converting. To the extent that there are losses of paper in the converting operation, *more* than one ton of tissue paper is required to produce one ton of *tissues.* This of course implies that residuals generation is higher when expressed per ton of final-user product.

The effects of the major variables are readily apparent: for example, pulping process—Ti 3 (magnefite) vs. Ti 4 (kraft); brightness—Ti 31 (GEB 25) vs. Ti 4 (GEB 80); type of raw material—Ti 34 (waste paper) vs. Ti 31 (soft wood). For these comparisons, respectively, the magnefite process generates no reduced sulfur compounds and less than half the particulates, but almost 2.5 times the SO_2, compared with the sulfate process. Reducing the product brightness, and hence the extent of bleaching—all other specifications remaining the same—from 80 to 25, the brightness of unbleached kraft, cuts SO_2 in half, dissolved solids by over 85 per cent, and BOD by almost 80 per cent. Using No. 1 mixed waste paper as the raw material instead of softwood logs and kraft pulping, results in an increase of almost 50 per cent in SO_2, no reduced sulfur compounds, essentially no particulates, some increase in dissolved solids, and many times more suspended inorganic solids. For other types of waste paper the quantities would be different.

The data in table 1 are based on materials, energy, and heat balances for each of the steps in the production processes involved, and represent the sums of all of the individual residuals streams generated, after taking into consideration economic amounts of recirculation of water and heat. As noted previously, there is considerable variation among plants using the same process and producing the same product, and day-to-day in the same plant.

Steel production. Similar to the manufacture of paper, the types and quantities of residuals generated in the production of steel are a function of the raw materials used, the production process, and the product output specifications.[21] There are three basic types of furnaces for the production of steel: open hearth, basic oxygen (BOF), and electric arc. Each of these is physically capable of producing, but at different costs, three ge-

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[21] This section is based on the Vaughan-Russell study, cited in footnote 13. Vaughan made the specific computer runs and prepared the background material for this section.

TABLE 1

Residuals Generation in the Production of One Ton of Tissue (or Napkin) Paper

(pounds per ton)

	P.C. No. and Pulp Mix (Brightness 80–82 GEB)							
Residual	*Ti 1 (100% Ca/ CEH)*	*Ti 2 (100% NH_4/ CEH)*	*Ti 3 (100% Mg/ CEH)*	*Ti 4 (100% K/ CEHD)*	*Ti 5 (50% K/ CEHDED; 50% SG/Zn)*	*Ti 6 (50% Mg/ CEHH; 50% SG/Zn)*	*Ti 7 (50% K/ CEHD; 50% Mg/ CEH)*	*Ti 8 (75% K/ CEHDED; 25% WPN/ FIB)*
Cl_2	1.1	1.1	1.1	1.2	0.6	0.6	1.1	0.9
ClO_2	0	0	0	0.6	0.6	0	0.3	0.9
SO_2[1]	125/34.0	114/29.0	48.7/15.0	5.6/20.0	2.8/25.0	24.6/23.0	27.1/17.0	4.2/19.0
RS	0	0	0	25.5	12.8	0	12.7	19.1
Part.[1]	27.5/1.7	27.1/1.4	27.7/0.8	57.5/1.0	34.6/1.3	19.8/1.2	42.6/0.9	43.2/1.0
DIS[2]	127	130	108	263	159	96	185	244
DOS[2]	2970	2900	190	244	193	178	217	261
SS–O	113	112	109	113	97	100	111	139
SS–I	4.4	4.4	4.1	4.5	3.2	3.0	4.3	3.3
BOD_5	820	804	92	147	105	84	120	151
So–I	55.4	46.0	77.9	82.0	50.3	49.7	79.9	65.1
So–O	83.0	63.1	63.1	0	0	31.9	31.5	3.2

(*continued*)

TABLE 1 (*concluded*)

	P.C. No. and Pulp Mix (Brightness 70–72 GEB)					*P.C. No. and Pulp Mix (Brightness 25 GEB)*			
Residual	*Ti 21 (100% Mg/H)*	*Ti 22 (100% K/CEH)*	*Ti 23 (50% Mg/H; 50% Sg/Zn)*	*Ti 24 (60% K/CEHD; 40% WPM/FIB)*	*Ti 25 (35% K/CEHD; 65% WPN/FIB)*	*Ti 31 (100% K/O)*	*Ti 32 (50% Mg/O; 50% SG/O)*	*Ti 33 (35% K/O; 65% WPN/F)*	*Ti 34 (100% WPM)*
Cl_2	0	1.2	0	0.7	0.4	0	0	0	0
ClO_2	0	0	0	0.3	0.2	0	0	0	0
SO_2[1]	48.1/25.0	5.6/20.0	24.0/23.0	3.4/20.0	2.0/19.0	5.1/7.0	23.4/19.0	1.8/17.0	0/17.0
RS	0	25.4	0	15.3	8.9	23.2	0	8.1	0
Part.[1]	27.4/0.7	57.4/1.0	19.5/1.1	34.5/1.0	20.1/0.9	52.4/0.3	19.1/1.0	18.4/0.6	0/0.8
DIS[2]	103	263	74	235	192	22	17	15	21
DOS[2]	144	227	140	311	278	41	108	29	63
SS–O	108	113	94	145	178	107	93	105	92
SS–I	4.1	4.4	3.0	101	1.6	4.1	2.9	1.4	202
BOD_5	79	143	69	163	148	31	46	27	36
So–I	79.0	81.8	48.7	55.6	37.7	73.7	44.1	32.8	13.8
So–O	62.2	0	31.1	6.0	8.3	0	30.3	6.9	12.8

Note: Raw material is softwood logs, except where waste paper is used. Specifications other than brightness are 14 basis weight (single ply), low wet strength (25%). Output is as air-dry paper, equivalent to 1,880 pounds on a bone-dry basis. Abbreviations follow the table.

[1] 1 per cent sulfur fuel oil is assumed for the purchased fuel used to generate heating steam and electric energy for plant use. Right-hand figure in each column of these rows is the quantity generated associated with fuel combustion.

[2] The division of total dissolved solids into organic and inorganic portions is to an extent arbitrary. For example, a dissolved compound comprised of a metal and a wood ingredient or derivative might be considered organic, inorganic, or partially in each category. In the analysis represented by this table, most of the dissolved excess and wasted chemical agents are classified DIS; most of the dissolved organic fractions of wood or waste paper as DOS.

Abbreviations for Table 1

Ti = tissue paper
P.C. = production combination
Ca = calcium base sulfite pulping
NH_4 = ammonium base sulfite pulping
Mg = magnefite (sulfite) pulping
K = kraft (sulfate) pulping
SG = stone groundwood pulping
WPN = waste paper, No. 1 News (raw material)
WPM = waste paper, No. 1 Mixed (raw material)
CEH, CEHD, etc. = kraft or magnefite bleaching sequences, where C = chlorination; E = caustic extraction; H = hypochlorite bleaching; and D = chlorine dioxide bleaching
Zn = groundwood bleaching, zinc hydrosulfite
O = no bleaching
F = waste paper processing-defibering
FIB = waste paper processing-defibering, deinking and bleaching

Residuals—Gaseous

Cl_2 = chlorine
ClO_2 = chlorine dioxide
SO_2 = sulfur dioxide
RS = hydrogen sulfide and organic sulfides
Part. = particulates

Residuals—Liquid

DIS = dissolved inorganic solids
DOS = dissolved organic solids
SS–I = suspended inorganic solids
SS–O = suspended organic solids
BOD_5 = 5-day biochemical oxygen demand

Residuals—Solid

So–I = inorganic solids
So–O = organic solids

neric types of steel: drawing quality, commercial quality, and alloy, which are defined principally on the basis of the contents of alloy elements—copper, chromium, nickel, molybdenum, and tin. Drawing quality steel has a total alloy content ≤ 0.13 per cent; commercial quality ≤ 0.21 per cent. Alloy steel must have exactly 1.75 per cent of these elements, subject to a specified distribution among them.

The three principal steel furnace types are most fundamentally distinguished on the basis of their heat sources. In the BOF the heat required for melting any cold metal charged and for carrying forward the refining reactions is contained in the molten iron charged. For the open hearth, combustion of an outside fuel (oil, coke oven or natural gas, etc.) is the heat source. In the electric arc, as the name implies, electrical energy, transformed into heat by an arc, is used. This heat source distinction implies, in turn, technological upper limits on the percentage of cold metal (scrap) in the furnace charge and has, under historically prevailing relative costs for ore, scrap, electricity, coal and other fuels, produced a range of normal charging practices. For the BOF, the upper limit on cold metal input is 30 per cent of total metallic input in the absence of such refinements as natural gas lancing for scrap premelting. For the open hearth and electric arc, since the heat source is external, 100 per cent scrap may be charged, but historically, integrated mills (i.e., those with blast furnace capacity), have seldom gone below a 50 per cent hot metal charge in the open hearth.[22] The electric arc, on the other hand, is normally operated on a 100 per cent cold metal charge, though hot metal may be used.

These differences have important implications for residuals generation and management. The electric arc process is free of the problems associated with by-product recovery, treatment and disposal of residuals generated in coke oven operations, specifically BOD, oil, phenols, cyanides, and sulfur. On the other hand, the cold metallic charge to the electric arc can result in a very high level of particulate generation per ton of molten steel when the charge contains a significant portion of No. 2 steel scrap bundles—the proportion depending on the type of steel being produced. In addition, the electric arc furnace requires much more electric energy per ton of steel produced, with the consequent generation of larger quantities of gaseous residuals in the associated energy generation than for the open hearth and basic oxygen furnaces.

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[22] Open hearths are sometimes used in "cold-melt" shops with a 100 per cent cold metal charge, but these operations are not part of integrated mills. This practice is relatively rare.

Table 2 shows the pounds of residuals generated per ton of semifinished steel shapes—blooms, billets, and slabs, for a daily output of 2,000 tons, for the three types of furnaces and the three types of steels. The quantities would vary slightly with different mixes of shapes. (Note that any loss in fabrication, i.e., converting, if done at the steel mill, is not included, similar to the analysis of paper manufacture.) In addition to the assumptions indicated in the table, it is assumed that only 66 per cent of the ammonia produced per ton of coal charged to the coke ovens is contained in the coke oven gas, the remainder being contained in a raw ammonia liquor. Ammonia and phenol recovery from coke plant liquid residuals streams is possible, but will be undertaken only if the market prices of the ammonium sulphate and sodium phenolate by-products are sufficient to cover the costs associated with their production. The prices assumed for the analysis reflected in table 2 result in no recovery being undertaken. Finally, some of the slag generated in the OH and BOF steel furnaces could be recycled, depending on the relative costs of processing and disposal and on steel content. No recycling is assumed economically justified in this analysis.

The most pronounced effect of process and product variables on residuals generation is with respect to particulates. For a given type of steel, the BOF results in more than twice as many particulates per ton as the OH and EA furnaces. It should be emphasized however, that the scrap prices assumed resulted in a 50 per cent hot metal/50 per cent scrap charge to the OH furnace. Some higher level of absolute scarp prices would induce a 70 per cent hot metal/30 per cent scrap charge, thereby resulting in substantially higher generation of particulates, and of all other residuals as well, stemming from the corresponding increase in ancillary operations, i.e., coke ovens, blast furnaces.

Comparing the different types of steel for the same steel making process shows that again particulates are most affected. For all three furnace types, generation of particulates increases for the sequence of drawing quality, commercial quality, and alloy steel production. But the increase is significantly different among the furnace types, the relative quantities for the three types being, respectively: 1.0/1.55/1.87 for the open hearth; 1.0/1.04/1.11 for the basic oxygen furnace; and 1.0/1.20/4.26 for the electric arc. The increase in particulate generation reflects the fact that more No. 2 bundles of steel scrap can be used per ton of output, moving from drawing quality steel to alloy steel, because of increasingly higher total alloy content permitted. No. 2 bundles have higher dirt and organic matter, as well as alloy, content compared to other scraps; hence the higher particulate generation per ton as their use increases. The relatively smaller

TABLE 2

Residuals Generation in the Production of Three Types of Semifinished Steel Shapes, 2,000 Tons Per Day Output

(pounds per ton except heat)

	Drawing Quality Steel			*Commercial Quality Steel*			*Alloy Steel*		
Residual	*OH*[a]	*BOF*[b]	*EA*[c]	*OH*	*BOF*	*EA*	*OH*	*BOF*	*EA*
				Gaseous					
Particulates[d]	20.9/1.4	55.3/2.1	9.5/13.3	33.1/1.5	57.6/2.1	14.6/12.7	40.0/3.3	61.4/4.4	84.4/12.7
SO_2[d]	7.9/2.3	11.7/3.4	0/22.0	8.1/2.4	11.8/3.4	0/21.0	8.1/2.6	11.7/3.4	0/21.0
				Liquid					
BOD_5	1.76	2.62	0	1.75	2.63	0	2.62	1.76	0
Oil	0.21	0.31	0	0.21	0.31	0	0.31	0.21	0
Phenols	0.51	0.77	0	0.52	0.77	0	0.77	0.52	0
Ammonia	1.17	1.74	0	1.20	1.75	0	1.74	1.20	0
SS[e]	0.10	0.14	0	0.10	0.14	0	0.14	0.10	0
Sulfur	0.19	0.28	0	0.19	0.28	0	0.28	0.20	0
Heat, 10^6 BTU	1.01	1.54	0.08	0.79	1.57	0.08	1.47	1.00	0.08
				Solids					
Slag	457.2	683.2	235.9	460.3	686.3	53.2	691.5	448.3	48.9
Solids OTS[f]	0.8	1.2	19.7	0.8	1.2	53.4	1.2	0.8	53.4

Assumptions: Raw material for ironmaking: iron ore—high iron (65 per cent Fe), low sulfur (0.6 per cent S), fines; coal—predominantly low sulfur (0.6 per cent S); charge to OH is 50 per cent hot metal/50 per cent scrap; to BOF is 70 per cent hot metal/30 per cent scrap. The OH charge reflects the low absolute level of scrap price assumed, i.e., relative price of scrap/hot metal = 0.59.

Particulate removal facilities assumed in place only at the sinter strand and the blast furnace, operating at removal efficiencies of 90 per cent and 99.2 per cent, respectively. This level of removal is justified in the absence of environmental controls, because of the value of the recovered gas as fuel.

3 per cent sulfur coal is assumed for use in energy generation.

[a] Open hearth furnace.

[b] Basic oxygen furnace.

[c] Electric arc furnace.

[d] Right hand figure in each column is the quantity associated with energy generation.

[e] Suspended solids.

[f] Solids other than slag, i.e., unrecycled mill scale, bottom ash, unburned forerunnings.

increase in particulate generation for the BOF reflects the technological constraint on the quantity of scrap which can be used in that type of furnace.

Individual plant: response to effluent controls

Petroleum refining. The response to effluent controls is first illustrated by the analysis of a 150,000 barrels per day (crude charge) "grass roots" refinery with the sizes of process units and magnitudes of product outputs shown in table 3.[23] For this refinery, the residuals generated and discharged under conditions of no effluent controls—other than those reflected by existing standard American Petroleum Institute oil-water separators and sour-water scrubbers—are shown in table 4. Given this refinery and the specified conditions, what will be the response to an effluent charge, such as that imposed on oxygen demanding organics, expressed as BOD_5?

The response is shown in figure 4. Discharges of BOD, sulfide, phenols, and ammonia decrease rapidly over the range of charges from 1 cent to 7 cents per pound. At the latter level of effluent charge on BOD, almost 70 per cent of the BOD generation, i.e., the load after the oil-water separators and sour-water scrubbers, has been reduced. Note that, simultaneously, the following reductions have occurred in other liquid residuals: phenols, about 82 per cent; ammonia, about 48 per cent; sulfide, about 74 per cent. Reduction of oil is very slight; of heat not at all. No further reduction occurs until the effluent charge is between 14 and 15 cents per pound, when BOD reduction reaches about 80 per cent. As the charge increases between 15 and 25 cents per pound, the BOD reduction increases to about 95 per cent at the latter figure.

It is important to emphasize that reduction in discharge of BOD results in the generation of secondary residuals, particularly "solids" formed in the standard activated sludge process for modifying BOD, i.e., at an assumed rate of 0.75 pounds of dry sludge solids per pound of BOD removed.[24]

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[23] The material in this section is based on Russell, *Residuals Management in Industry*, especially Chap. VI.

[24] Sulfur released as hydrogen sulfide or SO_2 and vaporized hydrocarbons are quantitatively insignificant. Some BOD removal at each level is accounted for by recirculation, e.g., effluent from secondary treatment to desalter water makeup. In these cases sludge generation depends on the steady state concentrations attained in the streams involved. This complication is ignored, and it is assumed that no increment to sludge generation results from such recirculation alternatives.

TABLE 3

Process Units and Product Outputs
150,000 Barrels Per Day Petroleum Refinery

	Process Units Per Barrel of Crude Charged (barrels)
Desalting	1.00
Atmospheric distillation	1.00
Coking	.133
Hydrotreating	.139
Reforming	.139
Catalytic cracking	.466
Alkylation	.076
Sweetening	.393
	Product Outputs (quantity per day)
Products sold	
Refinery gas	2.944×10^6 lbs.
Kerosene/diesel oil	15,760 barrels
Distillate fuel oil	17,400 barrels
Low sulfur	8,880 B
Medium sulfur	8,230 B
High sulfur	290 B
Polymer	660 barrels
Premium gasoline[a]	35,100 barrels
Regular gasoline[b]	51,150 barrels
Residual fuel oil	3,000 barrels
Straight run gasoline sold as petrochemical feed	16,360 barrels
Recovered sulfur	40.0 long tons
Products used internally	
Hydrogen (burned)	100,250 lbs.
Sweet coke (burned)	1,180,000 lbs.
Sour coke (burned)	260,000 lbs.
Coke burned in catalyst regeneration	1,540,000 lbs.

Note: Crude charged: 111,000 barrels East Texas (low sulfur) plus 39,000 barrels Arabian Mix (high sulfur) totals 150,000 barrels per day.

[a] Octave $\geq$ 100; tetraethyl lead content $\leq$ 2.5 cc/gal.

[b] Octave $\geq$ 94; tetraethyl lead content $\leq$ 2.5 cc/gal.

TABLE 4

Residuals Generation Per Barrel in a 150,000 Barrels Per Day Petroleum Refinery

Residual	*Generation (lbs. per barrel)*
	Gaseous
Particulates	0.423
SO_2	1.429
	Liquid
BOD_5	0.060
Oil	0.047
Phenols	0.032
Ammonia	0.021
Sulfide	0.003
Heat (10^6 BTU)	0.300

Assumptions—

Cost of water withdrawals: cooling, \$.015/1000 gallons; desalter, \$.025/1000 gallons; process steam, \$.15/1000 gallons.

Cost of purchased fresh heat: 2.0% sulfur, \$.477/10^6 BTU; 1.0% sulfur, \$.593/10^6 BTU; 0.5% sulfur, \$.661/10^6 BTU.

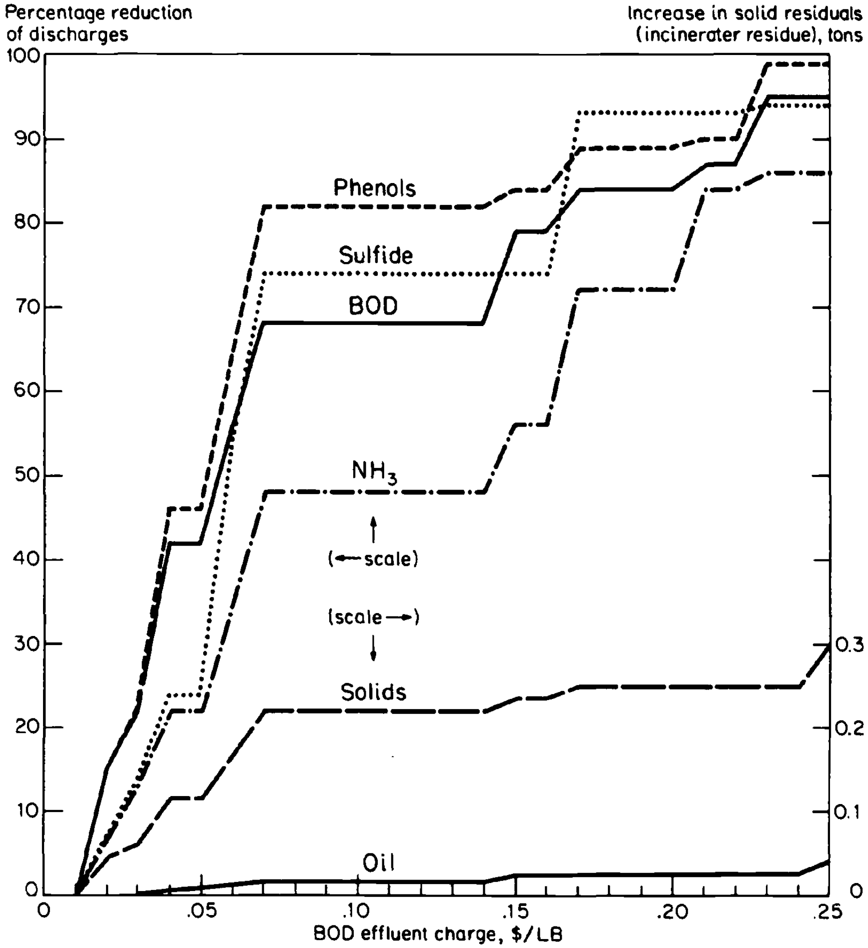
Price of recovered sulfur: \$20/long ton.

At the 7 cents per pound of BOD effluent charge, the dry weight of sludge generated is 4,020 pounds per day, in the form of a dilute sludge, i.e., 5 per cent solids. Thus the total weight of raw sludge generated represents about 80,400 pounds, or 40.2 tons per day. At the 15 cents and 25 cents per pound charge levels, the weights of raw sludge generated are 45.4 and 52.9 tons per day, respectively. Disposal of this sludge requires thickening and incineration. Assuming the cost of thickening and incineration is about \$2.00 per ton of raw sludge, sludge handling increases the costs of BOD reduction by \$80 per day, \$91 per day, and \$106 per day, at charge levels of 7 cents, 15 cents, and 25 cents, respectively. In addition, the generation of particulates is increased by 1.2 per cent, 1.3 per cent, and 1.6 per cent at the corresponding three charge levels. The increase in solids, i.e., incinerator residues, is shown on figure 4.

Translating these BOD reductions into cost impacts on the refinery is illustrated in figure 5, in terms of the increase in daily cost (capital plus

Figure 4

*Response to BOD Effluent Charge,
150,000 Barrels Per Day Petroleum Refinery*

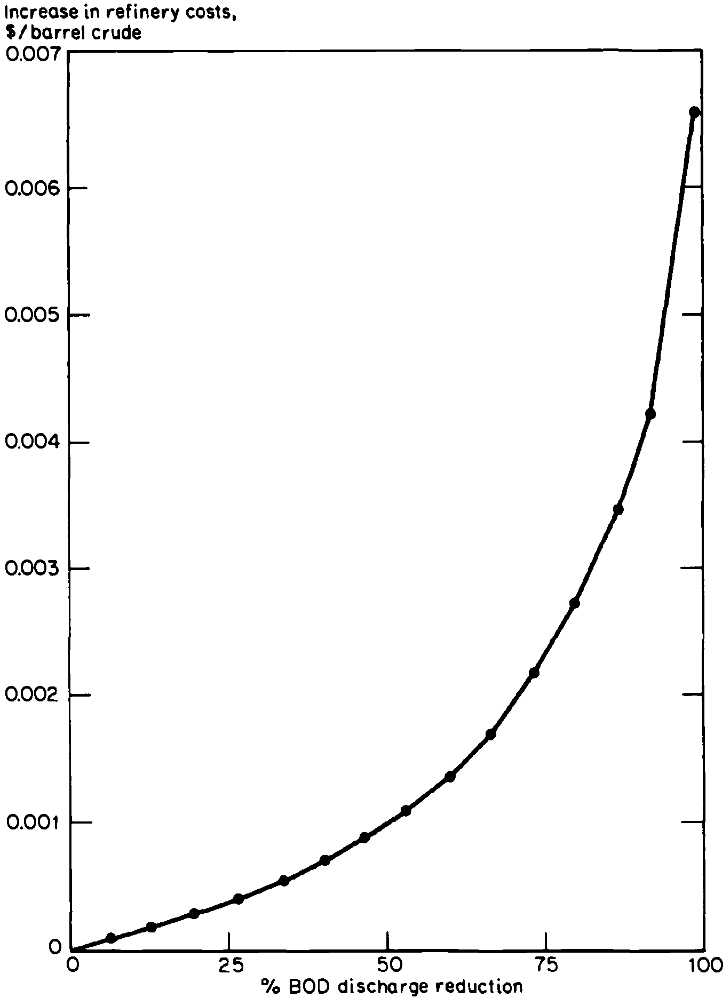


operating) per barrel as the degree of BOD reduction increases. It is clear that the total cost of reducing BOD discharge is small relative to daily refinery costs, for example, 75 per cent BOD reduction costs only about $0.002 per barrel of crude processed or about 0.045 per cent of daily costs. For 100 per cent reduction the cost would be about 3.5 times as much.

Figure 5

Total Cost of BOD Discharge Reduction, 150,000 Barrels Per Day

(including disposal of sludge)



The costs are of the same order of magnitude for phenols, sulfide, and ammonia.

Although the preceding discussion of the impacts of effluent charges on a grassroots petroleum refinery is only partial, it serves to illustrate clearly the method of analysis and the useful results which can be obtained. A complete discussion is of course available in the previously cited book by Russell.

Paper manufacture. Regardless of how the effluent controls are expressed, any study of industrial response to such controls requires analysis of the options, and their costs, associated with each of the major residuals streams in an industrial plant. This will be illustrated by considering P.C. Ti 4 (see table 1) for an integrated kraft mill producing 500 tons per day of tissue paper. To produce 500 tons per day of paper requires a pulping capacity of about 580 tons per day. Other units of the production process are sized as necessary to enable production of the specified output.

Table 5 shows the five significant sources of particulate generation for the mill. It is assumed that most of the particulates normally recovered from the lime kiln stack and recovery furnace stack are being recycled to the chemical system and that the quantities shown in the table are those in excess of the economically recoverable amounts, represented by point *X* in figure 3.

TABLE 5

Main Sources of Particulate Generation in an Integrated Kraft Paper Mill

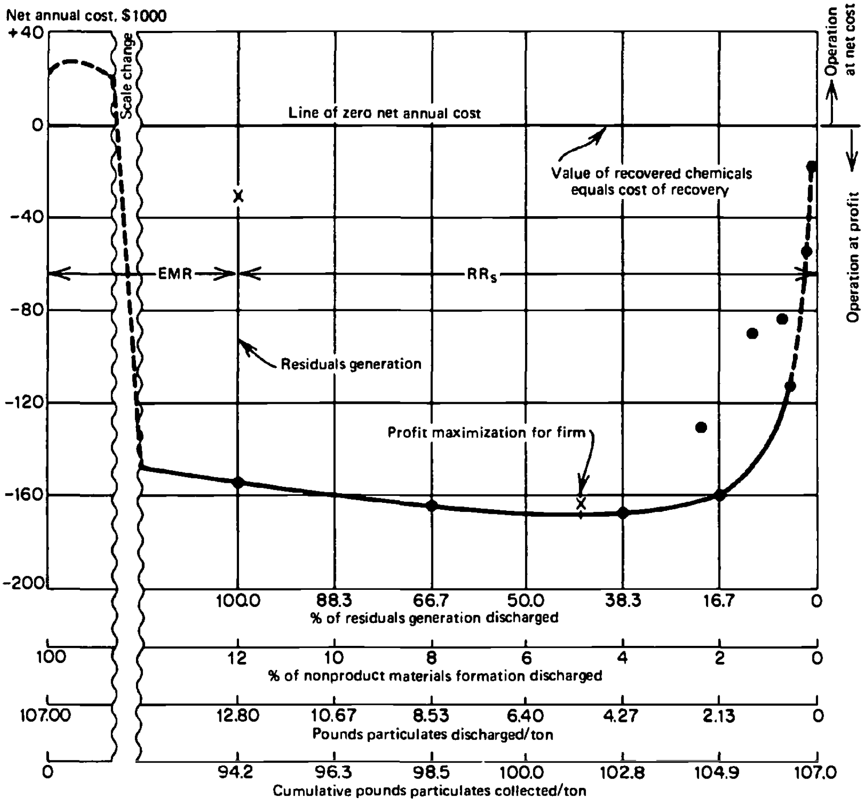
Source	*Pounds of Particulates Generated Per Ton of Paper*
Recovery furnace stack	5.0
Lime kiln stack	11.7
Combination bark-fuel boiler stack	27.6
Slaker vent	0.7*
Smelt dissolving tank vent	1.2
Fuel-fired boiler stack	1.0
Total	47.2

* Estimated.

Figure 6 shows the net annual cost for different degrees of modification

Figure 6

Net Annual Cost of Recovery Furnace Particulate Modification: Integrated Kraft Mill Producing 500 Tons Per Day of Tissue Paper



Source: Bower, Löf, Hearon, "Residuals Management."

of the nonproduct particulate materials formed in the flue gases from the recovery furnace, the first entry in the preceding list.[25] The points shown above the curve represent alternative measures for the same degree of particulate modification, but with higher costs. Up to the level of modification designated by *X*, particulate modification represents economic

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[25] G. O. G. Löf, W. M. Hearon, and B. T. Bower, "Residuals Management in Pulp and Paper Manufacture," *Forest Products and the Environment*, AIChE Symposium Series Vol. 69, No. 133 (Dec. 1973): 141–149.

materials recovery (EMR), i.e., measures which would be undertaken in the absence of effluent controls because of the value of the recovered chemicals.[26] From level X to 100 per cent removal, if that were possible—particulate modification represents residuals modification with partially offsetting benefits from the value of recovered materials. In this case the residuals modification-materials recovery technology involves end-of-pipe measures, such as electrostatic precipitators and wet scrubbers.

Similar relationships were developed for each of the particulate streams indicated in table 5. These were combined to develop the least cost of various degrees of particulate modification, as shown in table 6. Analysis of wet methods for modifying gaseous residuals indicated that the incremental costs associated with having to modify the secondary liquid residuals from wet scrubbers were higher than "dry" gaseous residuals modification measures for all streams.

Similar analyses were made for the various nonproduct liquid streams. Two major differences between the gaseous and liquid residuals merit mention. One is that few options exist for liquid residuals modification measures which result in any returns. The other is that minimum cost liquid residuals modification measures often involve combining various streams of the same residual for simultaneous (joint) modification. Rarely is it economical to combine several streams of the same gaseous residual generated at different locations in the plant.

In order to demonstrate the impact of increasingly stringent effluent controls imposed simultaneously on the major residuals, four sets of discharge standards were developed, involving the major residuals of concern. These sets are shown in table 7. Level III represents standards which are currently in effect in various states. Note that these standards are framed in terms of permitted discharges per ton of output. Standards

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[26] Note the difference in the totals of particulates generated between table 1 and table 5. The reason is that the data available at the time the flow diagrams and materials balances were made, for table 1, indicated 12 per cent discharge as the profit maximizing point. Additional information obtained subsequently provided a better basis for the analysis and showed that at present the profit maximizing level of discharge for a new plant would be about 5 per cent. As can be seen, the curve is relatively flat between about 12 per cent and about 2 per cent. It does not take much of a change in factor input costs to shift the profit maximizing level in this range by several per cent. This demonstrates the difficulty in determining, from available data, the quantity of residuals which would be generated in a "grass roots" plant in the absence of environmental controls.

It should be emphasized that the costs of particulate removal should be interpreted as illustrative. For example, variation in gas flow rates, particle sizes, equipment costs, amortization schedules, and other factors may result in substantial differences from plant to plant for the same process and product.

TABLE 6

Net Annual Cost of Particulate Modification, Integrated Kraft Mill Producing 500 Tons Per Day of Bleached Tissue Paper

	No Modification		*"Low" Modification*		*"Medium" Modification*		*"High" Modification*	
	Lbs. Part. Per Ton	*Annual Net Cost in Dollars*	*Lbs. Part. Per Ton*	*Annual Net Cost in Dollars*	*Lbs. Part. Per Ton*	*Annual Net Cost in Dollars*	*Lbs. Part. Per Ton*	*Annual Net Cost in Dollars*
Particulate discharge	47.2		30		8		4	
Particulate removal:								
Bark boiler stack	0	0	17.2	8,940	25.9	14,300	26.0	19,500
Lime kiln stack	0	0	0	0	10.3	17,000	11.6	32,900
Recovery furnace stack	0	0	0	0	2.5	5,000	3.9	32,400
Lime slaker vent	0	0	0	0	0.5	750	0.6	2,390
Smelt tank vent	0	0	0	0	0	0	1.0	10,560
Fuel boiler stack	0	0	0	0	0	0	0	0
Total removal	0	0	17.2	8,940	39.2	37,050	43.2	97,750
Cost of solids disposal		0		3,150		4,540		4,560
Cost of liquid residual disposal		0		0		0		0
Total net annual cost of particulate control		0		$12,090		$41,590		$102,310

Notes:

1. Costs are in 1970 dollars and are based on estimates of operating labor, maintenance labor and supplies, power and material requirements, 12.5 per cent annual charge on estimated capital investment, and are credited with chemical recoveries at typical market prices. Operation 350 days per year was assumed.

2. The gas streams to be treated and the extent of particulate removal from a stream were selected so as to obtain the lowest cost of removing the required quantity of particulates, regardless of particulate composition.

3. Cost of solids disposal includes only the solids resulting from removal of particulates not recycled to the process, and excludes disposal costs for other solid residuals. It is based on a nominal $2 per ton hauling and landfill cost.

4. None of the particulate removal processes used results in generation of a liquid residual.

TABLE 7

Specification of Increasingly Stringent Residuals Discharge Standards

(pounds per ton)

Residual	*Level 0*	*I*	*II*	*III*	*IV*
SO_2	No Control[1]	50	35	20	10
Particulates	No Control	30	8	4	2
Reduced sulfur compounds	No Control	10	2	0.5	0.2
Suspended solids	No Control	50	20	10	5
BOD_5	No Control	60	35	20	10

Note: Standards apply to total mill operation, i.e., from all sources.

[1] No restrictions on discharges; reflects basic production costs.

so expressed ignore the size of a plant, and hence implicitly the assimilative capacity of the environment of the plant, but they represent the approach which the federal government has adopted, i.e., "standard effluent levels."

The residuals management costs to meet levels I, II, and III are shown in table 8, in terms of dollars per ton, for an integrated kraft mill producing 500 tons per day of tissue paper (P.C. Ti 4).[27] The much higher costs for liquid residuals modification than for gaseous residuals modification reflect the substantial value of materials recovered from gaseous residuals streams, comparable alternatives not existing for the liquid residuals streams. Also shown in table 8, for comparison, are the residuals management costs per ton for a paper mill of the same output capacity but producing *unbleached* tissue paper (P.C. Ti 31). The impact of changing just one product specification is very significant, residuals management costs for Ti 31 being about 15 per cent, 24 per cent, and 21 per cent of those of Ti 4 for levels I, II, and III, respectively.

Implications for future behavior and technological change can be drawn from this type of detailed analysis of residuals management in an industry, implications which could not be obtained by any other approach, i.e., statistical analysis (even if data were available, which they

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[27] These levels correspond to "low," "medium," and "high" residuals modification in table 6.

TABLE 8

Net Residuals Management Costs Per Ton of Output, Integrated Kraft Mill Producing 500 Tons Per Day of Tissue Paper

	Level of Discharge Standards		
Costs	*I*	*II*	*III*
P.C. Ti 4: Unbleached Tissue Paper			
Gaseous residuals modification, $/ton	0.16	0.59	1.66
Liquid residuals modification, $/ton	3.07	4.09	6.76
Solid residuals disposal, $/ton	0.38	0.38	0.38
Total, $/ton	3.61	5.06	8.80
P.C. Ti 31: Unbleached Tissue Paper			
Gaseous residuals modification, $/ton	0.12	0.46	0.83
Liquid residulas modification, $/ton	0.10	0.40	0.72
Solid residuals disposal, $/ton	0.33	0.33	0.33
Total, $/ton	0.55	1.19	1.88

Note: Costs are in 1970 dollars and are based on estimates of operating labor, maintenance labor and supplies, power and material requirements, 12.5 per cent annual charge on estimated capital investment, and are credited with chemical recoveries at typical market prices. Operation 350 days per year was assumed.

The costs of any secondary solid residuals generated in liquid and gaseous residuals modification, i.e., sludge, are included in the liquid and gaseous residuals modification costs.

are not). For example, the fact that liquid residuals management costs are so large relative to gaseous residuals management costs suggests the logical direction of plant responses and research and development efforts. In fact this is what has occurred in the industry. To reduce the former costs, paper mill water systems have been tightened and in-plant water recirculation has been increased, thereby reducing the hydraulic load on liquid residuals modification systems, and hence costs. Additional effort is being expended to develop "dry" paper-making processes. Because the effluents from bleaching by traditional methods of bleaching represent the major source of liquid residuals and of liquid residuals management costs, as the comparison of Ti 31 with Ti 4 shows clearly, research continues on new methods of bleaching, such as oxygen bleaching, to eliminate or drastically reduce the bleaching residuals that are expensive to modify. In addition, research is underway on new methods of (wet) pulping, which would result in fewer and/or more easily modified liquid residuals from pulping. The other logical response, indicated clearly by the above analysis, namely, changing product brightness to eliminate the need for bleaching—and minimize total resource use—has been given little consideration.

Total system: residuals generation and response to effluent controls

Coal-electric energy industry. Up to this point the focus has been on the individual industrial plant. In this section the analysis shifts to a focus on the total system, i.e., several spatially separate activities necessary to produce a given output. The study of the coal-electric energy industry illustrates this approach. Instead of analyzing a power plant as the "residuals-environmental quality management system," as has traditionally been done, the activities involved from mining the coal in the ground through energy delivered at the load-center substation are included. The four elements of this system, shown in figure 7, are: coal mining; coal preparation; coal or energy transport, the latter being relevant when energy is generated at the mine; and energy generation via coal combustion. Coal preparation generally takes place at or very near the mine. Also shown in figure 7 are the major residuals streams generated throughout the system.

The problem is formulated as follows: assuming a given energy demand at the load-center substation, determine the minimum cost system of coal production, processing, transport, coal use in the power plant, energy transport, and residuals handling activities which will meet specified and comparable quality levels with respect to all environmental media, air, water, land, *throughout* the system.[28] Trade-offs are possible among raw coal quality, degree of coal preparation, transport of coal or energy, combustion technology, and residuals handling technology at the mine-preparation plant and the power plant. For example, if an objective is to reduce the ambient concentration of sulfur dioxide in a specified region, there are several combinations of alternatives among the many elements of the system which can be utilized, such as high or low sulfur

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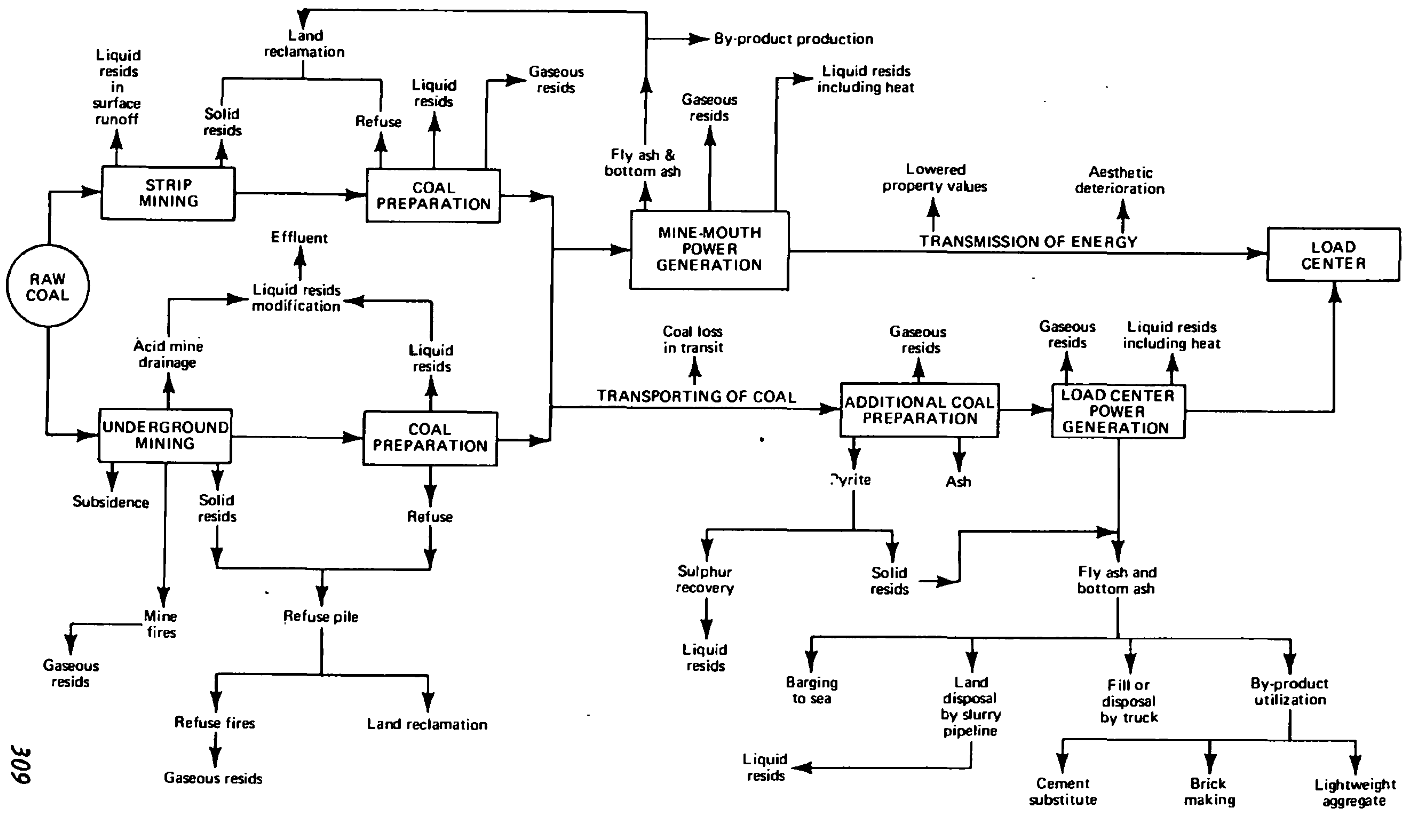
[28] The ambient environmental quality standards, and hence discharge standards, should rationally vary among the different spatially separated elements of the system, if there are differences in assimilative capacity and damages from discharges. Thus, the early development of mine-mouth plants assumed that location in relatively isolated, i.e., sparsely settled, areas would permit lower discharge standards. The current controversy with respect to power plants in the southwest suggests that this was not an optimal policy. Hence, essentially the same standards have been assumed throughout the system.

Figure 7

Alternative Residuals Generation and Modification in the Use of Coal to Produce Electric Energy



coal, different levels of coal preparation, various methods of coal or energy transport, and various measures for removal of sulfur dioxide in the stack of the generating plant. Thus, at least a partial alternative to removal of residuals in the stack gas is to increase the degree of coal preparation for the removal of sulfur (and ash). However, it is important to emphasize that there are residuals from the coal preparation process itself which must be handled in a satisfactory fashion to preclude adverse environmental quality impacts. Further, since coal preparation inevitably means that some of the heat value in each ton of mined coal is thrown away, more coal will have to be mined to provide the same heat input to the generating plant to meet the specified energy output. This may increase the residuals problem with respect to coal mining. Nevertheless, by expanding the scope of the system the possibility of finding a more efficient set of measures for handling residuals is likely to be increased compared to a focus limited solely to the power plant.

The major residuals generated in the coal-electric energy system are:

(1) acid mine drainage from underground mining;
(2) overburden from strip mining;
(3) suspended solids in coal preparation plant wash water;
(4) particulates from air-flow cleaners and thermal driers at coal preparation plants;
(5) particulates in power plant gaseous emission;
(6) sulfur oxides in power plant gaseous emission;
(7) water-borne heat from power plant.

Various strategies, singly or in combination, are possible for reducing discharges of these different residuals to the various environmental media. Some of these are indicated in table 9, along with their impacts on each of the elements of the coal-electric energy system and on the related residuals streams. The interrelationships among the various residuals with respect to strategy are indicated. For example, increasing the degree of coal preparation in order to remove some portion of the ash and sulfur from the fuel input to the power plant reduces the residuals generated at the power plant, but increases the residuals generated in coal mining (because more hydrocarbons are discarded, thereby requiring more coal to be mined for the same energy output) and in coal preparation. Modifying power plant flue gas and use of cooling towers to reduce thermal discharges to water courses are both energy-intensive measures, thus requiring more coal to be mined to produce the same net energy output and hence generating more residuals in coal mining and preparation.

TABLE 9

Impacts of Strategies for Improving Ambient Environmental Quality in the Utilization of Coal to Produce Electric Energy

Strategy	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Impacts on system										
Quantity of coal mined	0[1]	0	0	0	−[1]	+[1]	−	+	0	+
Quantity of raw mine drainage	−	0	0	0	−	+	−	+	0	+
Quantity of refuse at mine	0	+	+	+	−	+	−	+	0	+
Quantity of coal transported	0	0	0	0	−	−	−	+	0	+
Quantity of solid residuals at power plant	0	0	0	0	−	−	−	+	0	+
Impacts on residuals										
Useful land	+	0	0	0	+	−	+	−	0	−
Acid and iron effluent	0	−	0	0	−	+	−	+	0	+
Suspended solids discharged from preparation plant	0	0	−	0	−	+	−	+	0	+
Particulate discharged from preparation plant	0	0	0	−	−	+	−	+	0	+
Particulate and sulfur oxides discharged from power plant	0	0	0	0	−	−	−	−	0	+
Heat discharged from power plant to water courses	0	0	0	0	−	0	0	+	0	−
Suspended solids discharged from power plant to water courses	0	0	0	0	−	−	−	+	−	+
Solid residuals from power plant	0	0	0	0	−	−	−	+	+	+

Strategies:

1. Grade and replant land
2. Treat acid mine drainage
3. Treat waste water from preparation plant
4. Collect particulates from preparation plant
5. Increase generator efficiency
6. Use more coal preparation
7. Use higher quality *raw* coal
8. Treat power plant flue gas
9. Treat suspended solids from power plant
10. Use cooling towers

[1] 0 = no change; − = less; + = more; all + changes represent negative impacts except for land, i.e., increasing quanity of coal mined *increases* amount of acid and iron effluent, a negative impact.

A strategy to reduce the discharge of one residual may add to the costs of handling another residual or generate additional residuals which result in other environmental quality problems. Removing sulfur in power plant flue gas increases the resistivity of the fly ash, thereby making electrostatic precipitation less efficient.[29] The use of cooling towers to reduce thermal discharges into water courses involves a transfer of the residual heat from a liquid discharge to a gaseous discharge. This emission from a cooling tower may result in such undesirable environmental effects as local fogging and icing, cloud formation, and increased precipitation.[30] In turn, various alternatives are available for modifying these secondary effects, such as by superheating the plume or by using finned heat exchangers.[31] Any such further modification adds to the residuals modification costs.

The impact on energy cost of effluent controls imposed on various residuals throughout the coal-electric energy system was assessed by positing three levels of control on effluents. The characteristics of these three levels for the two cases investigated, mine-mouth power plant and load center power plant, are listed in table 10.

Level I basically reflects no modification of nonproduct outputs except what would be done in the absence of effluent controls, i.e., economic materials recovery, plus what additional control was being done in the early 1960's before the major push for improving air quality began. Level II approximates current (1972–73) standards; Level III reflects a still larger reduction in discharges.

The least-cost combination of activities throughout the system to meet these control levels was determined. The results for the three levels are shown in table 11, in terms of the cost of energy and the quantities of residuals discharged into the environment.

The relative costs, compared with Level I, are shown in table 12. These cost increases are distributed approximately as follows for the mine-mouth plant: from Level I to Level II—about one-third to coal mining and preparation; about two-thirds to power plant for higher

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[29] A shift from 2 per cent sulfur coal to 1 per cent sulfur coal reduces collection efficiency of electrostatic precipitators from 99 per cent to 98 per cent. See W. J. Cahill, Jr., and R. G. Ransdell, Jr., "Low Sulfur Coal Cuts Precipitator Efficiency," *Electrical World* 168, 20 (1967): 111–112.

[30] See E. Aynsley, "Cooling Tower Effects: Studies Abound," *Electrical World* 173, 19 (1970): 42–43.

[31] H. Veldhuizen and J. Ledbetter, "Cooling Tower Fog: Control and Abatement," *Journal Air Pollution Control Association* 21, 1 (1971): 21–24.

TABLE 10

Characterization of Environmental Quality Control Levels: Coal-Electric Energy System With Mine-Mouth Power Plant and Coal-Electric Energy System With Load-Center Power Plant

Phase of Production	*Environmental Control Level*		
	Minimal–I	*Moderately High*–II	*High*[1]–III
	Coal-Electric Energy System With Mine-Mouth Power Plant		
Coal mining[2] (strip mining)	No grading; minimal erosion control	Grading; high degree of erosion control	Grading; high degree of erosion control; reclamation
Coal preparation	No control	Closed circuit water system; scrubbers for particulate control	Closed circuit water system; scrubbers and air recirculation for particulate control
Power plant	Relatively low efficiency particulate control; no SO_2, NO_x, thermal controls	High efficiency particulate control; limestone scrubbing for SO_2 control, high stack + flue gas reheat for NO_x; natural draft wet type cooling towers	Very high efficiency removal of particulates, SO_2, NO_x, i.e., by two scrubbers in tandem or scrubber plus wet-type electrostatic precipitator; dry-type cooling towers
Energy transport[3]	Standard lattice-type transmission towers throughout; no underground line	About 10 per cent longer route; about 45 per cent tubular pole-type transmission towers; no underground line	100 per cent tubular pole-type transmission towers; 10 per cent of line underground
	Coal-Electric Energy System With Load-Center Power Plant		
Coal mining[4] (underground)	No control	Prevention of contact between ground water and oxidized pyritic material	Prevention plus neutralization of acidic mine drainage, if formed
Coal preparation	Same as for mine-mouth plant	Same as for mine-mouth plant	Same as for mine-mouth plant
Coal transport	Negligible residuals generated	Negligible residuals generated	Negligible residuals generated
Power plant	Same as for mine-mouth plant except for moderate efficiency particulate control plus somewhat higher stack than at mine-mouth plant	Same as for mine-mouth plant	Same as for mine-mouth plant
Energy transport[3]	Standard lattice-type transmission towers throughout	About 10 per cent longer route; 100 per cent tubular pole-type transmission towers	100 per cent of line underground

Note: See page 315 for notes to table 10.

TABLE 11

Residuals Management Costs and Residuals Discharges for Three Levels of Environmental Quality

(coal-electric energy system)

	Case I: Mine-Mouth Plant,[1] *High-Impurity Seam, Area-Strip Mine*			*Case II: Load-Center Plant,*[2] *Low-Impurity Seam, Deep Mine*		
Environmental Quality Design Level	I	II	III	I	II	III
Price of power (mills/kwh):						
At busbar	6.00	7.05	8.57	6.94	7.92	9.37
At load-center substation	7.64	9.00	11.78	7.17	8.20	9.98
Residuals Flow to Environment (annual basis, except for transmission)						
Acres of disturbed land/Acres of reclaimed land	$\left[\frac{980}{0}\right]$	$\left[\frac{1040}{1040}\right]$	$\left[\frac{1250}{1250}\right]$	rs	rs	rs
Gross increase in mine drainage:						
Million gallons	rs	rs	rs	110	80	90
Tons of sulfuric acid	rs	rs	rs	360	180	0
Preparation plant water (1 to 8% solids), million gallons	0	0	0	0	0	0
Preparation plant refuse, tons	0	1,600,000	2,600,000	0	0	300,000
Preparation plant air-borne dust, tons	0	4,400	900	0	0	700
Power-plant stack emissions, tons:						
Particulates	140,000	900	100	25,000	700	100
Sulfur oxides (sulfur content)	200,000	29,000	15,000	28,000	7,500	3,500
Nitrogen oxides (nitrogen content)	10,000	8,000	2,000	10,000	8,000	2,000
Power-plant solid waste, tons	1,000,000	950,000	800,000	300,000	450,000	300,000
Thermal discharge to watercourse, billion BTU	6,000	0	0	6,000	0	0
Water consumption (extra evaporation), million gallons	7,500	5,000	0	7,500	5,000	0
Transmission-line towers:						
Lattice type	4,000	2,500	0	120	0	0
Tubular poles	0	2,000	4,000	0	150	0
Underground circuit-miles/Total circuit-miles	$\left[\frac{0}{800}\right]$	$\left[\frac{0}{880}\right]$	$\left[\frac{80}{800}\right]$	$\left[\frac{0}{25}\right]$	$\left[\frac{0}{28}\right]$	$\left[\frac{25}{25}\right]$

Notes for Table 10

[1] Reflects the limit of available or nearly available technology. TVA implies that relatively high removals of NO_x could be achieved by some combination of facilities involving only incremental development beyond present technology. See Tennessee Valley Authority, *Sulfur Oxide Removal From Power Plant Stack-Gas-Use of Limestone Wet-Scrubbing Process* (Springfield, Virginia: National Technical Information Service, 1969) p. 60.

[2] High sulfur and high ash contents coal seam.

[3] To load center substation.

[4] Low sulfur and low ash contents coal, deep seam.

Notes for Table 11

Note: Residuals management costs are based on 1968 prices; 8 per cent rate of return on power plant investment, 10 per cent on coal mining/preparation investment.

Power plant consists of two 800-MW units; other elements of system are sized to provide the requisite input to the power plant.

rs indicates not relevant.

[1] Four-year construction period, with annual outlays of 10 per cent, 40 per cent, 40 per cent, and 10 per cent; half of draft and flue gas equipment replaced after 15 years; insurance and local taxes at 1 per cent of plant investment; 30-day supply of coal; heat rates 9,010, 9,300, 9,690 BTU/net kw, for levels I, II, and III, respectively, reflecting the increased energy required for residuals modification.

[2] Five-year construction period, with annual outlays of 5 per cent, 20 per cent, 50 per cent, 20 per cent, and 5 per cent; half of draft and flue-gas equipment replaced after 15 years; insurance and local taxes at 3 per cent of plant investment; 60-day supply of coal; heat rates 8,850, 9,175, 9,565 BTU/net kw, for Levels I, II, and III, respectively.

TABLE 12

Relative Costs of Energy

Type of Cost	*Environmental Quality Control Level* I	II	III
Mine-Mouth Plant[1]			
Without transmission cost	1.00	1.18	1.43
With transmission cost	1.00	1.18	1.54
Load-Center Plant[2]			
Without transmission cost	1.00	1.14	1.35
With transmission cost	1.00	1.14	1.39

[1] Area-strip mine, high impurity coal seam.

[2] Deep underground mine, low impurity coal seam.

level of gaseous residuals modification and the shift from once-through cooling to a wet cooling tower; from Level II to Level III—primarily to power plant, where over 90 per cent is attributable to the shift to a dry cooling tower, and secondarily to the more expensive design of the transmission lines. Less than 5 per cent of the increased cost is attributable to the higher level of modification of the gaseous residuals. For the load center plant: from Level I to Level II—virtually all of the increase to the power plant, attributable to the higher level of gaseous residuals modification and to the shift to a wet cooling tower; from Level II to Level III—as with the mine-mouth plant, primarily to the power plant and transmission.

Concluding Observations

The foregoing discussion has illustrated several basic findings from a program of research on residuals management in industry. These findings can be summarized as follows.

First, there are many factors, exogenous to the plant, the company, and even to the particular industry, which affect residuals generation in industry. For some of these factors the linkage is long, but the effects are substantial. Although this may appear obvious to some, prior to such industry studies the linkages have not been traced nor spelled out quantitatively.

Second, there are many factors, endogenous to the plant, which affect residuals generation in industry. There is, of course, overlapping between the exogenous and endogenous factors, for example, with respect to the stimuli of technological change in production processes. In order to predict behavior, this overlapping must be unraveled, which can only be done by detailed microanalysis.

Third, there is a multiplicity of possible responses by plant management to constraints imposed on the discharge of residuals to the various environmental media, whatever the nature of those constraints. These options include changing raw materials, production process, even product output specifications, plus materials recovery, by-product production, and conventional residuals modification.

Fourth, management policies for a single type of residual, i.e., gaseous, liquid, solid, thermal, have often overlooked the effects on the generation of secondary and tertiary residuals and on the additional inputs required for reduction in the discharge of primary residuals, especially energy. The industry studies described herein enable explicit consideration of the physical magnitude and economic costs of these effects.

What remains is to indicate the various uses of these studies (models). At least three major uses should be mentioned. One use is that of determining the possible responses of an industry to constraints, of whatever type, placed on the discharge of residuals to the environment. This includes both the increases in costs as the contraints become more stringent and the *net* effect on total production costs under constraints, for a given product output mix. The results show that up to relatively high levels of reduction in residuals discharge, per unit of product or per unit of raw product processed, the proportion of total production costs represented by residuals management costs is only a few per cent. However, as "zero discharge" of liquid and gaseous residuals is approached, residuals management costs become a substantial proportion of total production costs.[32] Both economies of scale and multi-product outputs reduce the per unit costs of residuals management.

A second use is the corollary one of estimating the effects of variables, such as technological change and public policies, on future residuals discharges from industry.[33] Because of the many variables affecting residuals generation, this use requires analyses of possible changes over time in critical variables such as production process, product mix, tax policies, depletion allowances, secondary materials recovery technology, and costs of inputs (heat, energy, chemicals).

Both of these uses are directly relevant to current discussions of "pollution control" policies and their effects, for example, by the Council on Environmental Quality (CEQ), Environmental Protection Agency (EPA), and the U.S. Congress.[34] Each of the CEQ annual reports has included estimates of the impacts of pollution control on industry production costs. The 1972 Water Pollution Control Act Amendments included a

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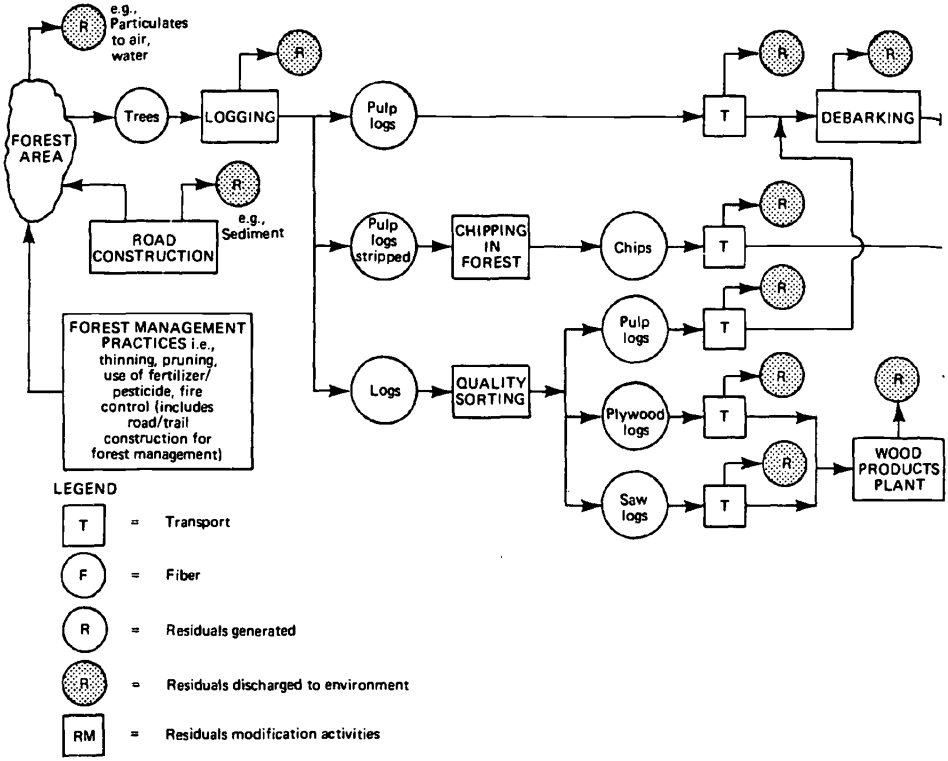
[32] "Zero discharge" of all residuals is of course impossible, even neglecting the residuals normally considered innocuous, i.e., CO_2, water vapor, heat to the atmosphere, and dissolved solids. The inevitable consequence of a zero discharge policy for liquid and gaseous residuals is an increase in the quantity of solid residuals requiring disposal.

[33] For such an application see C. W. Howe, et al., *Future Water Demands—The Impacts of Technological Change, Public Policies, and Changing Market Conditions on the Water Use Patterns of Selected Sectors of the U.S. Economy: 1970–1990* (Washington, D.C.: Resources for the Future, 1971), pp. 44–69.

[34] For example, see *The Economic Impact of Pollution Control, A Summary of Recent Studies, Prepared for the CEQ, Department of Commerce, and EPA* (Washington, D.C.: U.S. Government Printing Office, 1972).

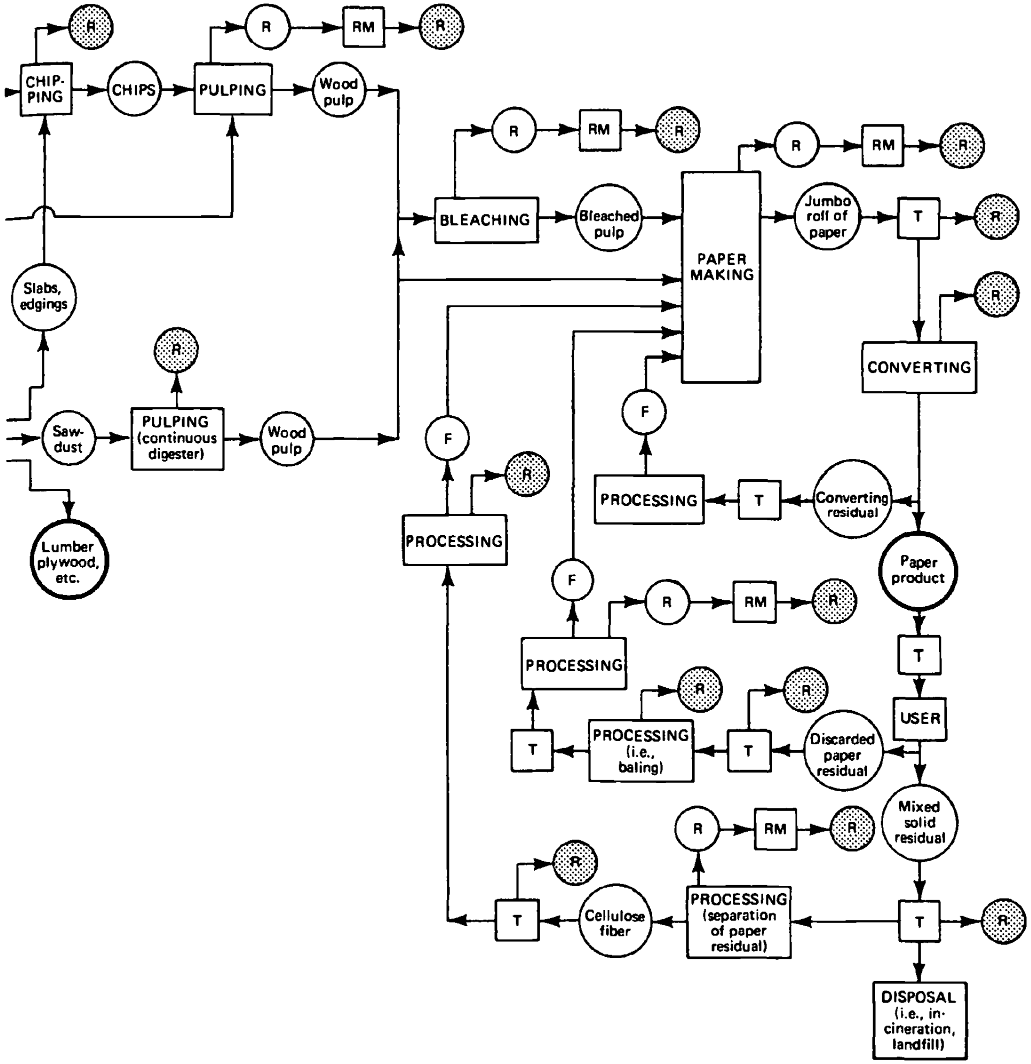
Figure 8

Components of Systems for Producing a Specified Paper Product



Notes:

1. Not all activities nor all sources of residuals generation are shown.
2. Only major residuals modification activities are shown.
3. Inputs into activities, i.e., electric energy, fuel, chemicals are not shown.
4. Only road construction component of transport on forest lands, which is a function primarily of logging, is shown.
5. The diagram is not meant to imply that there is only one forest area, wood products plant, paper mill, et al, involved in producing the final product.


R
R
RM
R
CHIP-PING
CHIPS
PULPING
Wood pulp
R
RM
R
R
RM
R
BLEACHING
Bleached pulp
PAPER MAKING
Jumbo roll of paper
T
R
R
CONVERTING
Slabs, edgings
R
Saw-dust
PULPING (continuous digester)
Wood pulp
F
F
R
PROCESSING
T
Converting residual
Lumber plywood, etc.
PROCESSING
R
F
R
RM
R
Paper product
PROCESSING
T
R
R
USER
T
PROCESSING (i.e., baling)
T
Discarded paper residual
Mixed solid residual
R
RM
R
R
T
Cellulose fiber
PROCESSING (separation of paper residual)
T
R
DISPOSAL (i.e., incineration, landfill)

provision that studies of the cost impacts of the discharge controls specified in the Act be undertaken. In the development of discharge regulations, EPA is developing "standard effluent levels" for the major residuals-discharging industries. The approach discussed herein is directly relevant to this purpose, and in fact is being used therefor. In addition, the results of this micro approach to the analysis of industrial behavior enable predictions of: responses to effluent controls and the costs thereof, and the direction of technological change and research effort, because the analyses (and costs) are based on observed behavior at existing and newly built plants. The major difference between existing and "grass roots" plants involves the constraints imposed by the physical layout and location of the existing plant. These constraints may shift the sequence of options adopted at a plant or preclude certain options because of excessive costs. But the direction of response is the same for both existing and new plants.

The third use of industry studies is in connection with analyses of regional residuals-environmental quality management. This use has been discussed previously by Russell and is discussed in another paper for this conference.[35] Although the level of sophistication or degree of refinement of industry models for this use will of necessity be substantially less than in an individual industry study, the detailed study is essential for identifying the critical variables as a basis for developing the more simplified models to be components of a regional study.

One final point might be mentioned. In the last few years, as an element of the "environmental debate," there has been considerable discussion of the relative merits of alternative types of final products, for example, paper packaging versus plastic packaging, natural fibers versus man-made fibers. To enable rational discussion of this issue requires industry models which include the totality of processes and operations associated with a given product, from raw material extraction through use of the product and "disposal" after use, and the corresponding inputs and residuals generation-management-discharge. This focus is exemplified by the coal-electric energy industry study, and by figure 8, which shows alternative total systems associated with a given paper product. Perhaps the next important step in the analysis of residuals management in industry is to generate more studies of this type.

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[35] C. S. Russell, "Models for Investigation," pp. 154–156 and C. S. Russell, W. O. Spofford, Jr., and R. A. Kelly, "Operational Problems in Large Scale Residuals Management Models," *Economic Analysis of Environmental Problems* (New York: National Bureau of Economic Research, 1975).

COMMENT

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Even the most radical environmentalist wants to know the economic impact of more severe antipollution policies. The number of dollars of cost imposed on companies—and perhaps ultimately on consumers of products from these companies—would be a useful figure to have available, if only to anticipate which policies are likely to bring forth a strong political reaction from companies and consumers. The conservative environmentalist wants the same information: base line estimates of costs of various policy alternatives, to put against the "benefits" of carrying through on these alternatives.

The RFF studies of residuals management described by Bower promise estimates of the costs of various policy options in the sugar beet, paper, petroleum refining, electricity and steel industries. The question is whether these studies can deliver useful estimates. The question might be asked in terms of (1) whether the findings are good "predictors" of policy-derived costs likely to be incurred under present circumstances in these industries and (2) in the absence of present findings on the accuracy of predictions, whether the RFF methodology can likely be used to produce predictions in the future of changes in important aspects of corporate behavior from regulatory policy changes. There is reason to doubt the ability of the residuals model to deliver, because of both empirical and methodological problems.

Empirical validation of residuals management models has not begun, at least not in terms of showing accuracy in predicting the steel or petroleum industry-wide costs of new environmental standards. The RFF approach is to build a model of a new or "grass roots" firm along lines of an "input requirements" function where the effluent is the dependent variable or "required input." There is no mention in the Bower paper of comparisons between industry-wide effluent behavior with that of his "representative firm." Moreover, most of the data required for direct comparison are not available. This is because of the extreme specificity of the RFF descriptions of the "firm." These show the marginal costs of waste treatment per physical unit of waste removed in a typical 2,700 ton plant [as in G. O. G. Löf and A. V. Kneese, *The Economics of Water Utilization in the Beet Sugar Industry* (Washington, D.C.: Resources for the Future, 1968), figure 8, page 105]. Companies do not keep statistics on marginal costs, so it is not possible to validate Bower's sensitivity analyses of *costs at the margin* with respect to policy changes. In fact, many companies produce statistics to make such studies impossible. Most firms regularly provide detailed historical cost statistics which—being subject to joint product allocation, revaluation of earlier investments, and arbitrary attribution of "investor's costs"—lead to biased indicators of economic cost changes, as shown in T. R. Stauffer, "The Measure of Corporate Rates of Return: A Generalized Formulation," *The Bell Journal of Economics and Management Science* (Autumn 1971).

The Bower findings on electric power costs, as related to environmental quality standards, are a case in point. The RFF approach of "costing out" a new plant with accompanying mine, rail and storage capacity produces estimates of cost increases from going through three environmental quality levels—with an overall percentage increase in costs per kilowatt hour of only 14 per cent for meeting 1973 standards (Bower, table 11). These are changes in incremental costs in the newest 800 megawatt electric coal fired plant with all of the policy options freely available on location, transportation, and fuel source required to make the least-cost decision in the long run. The RFF "grass roots" firm costs have to be compared with the changes in industry-wide average costs of installed and new plants required to meet new environmental quality levels. These industry-wide changes on average may be many times greater than the RFF grass roots firm changes. In fact, a significant number of East Coast generating companies showed an inability to meet the standards at any cost below regulated prices (which are clearly twice incremental costs or more). They did so by electing to declare shortages at the winter peak *with standards.* Also, others have forecast that the increases in average prices per kilowatt of capacity consequent upon cost increases will be many times larger than those increases in marginal costs shown in Bower (see M. Roberts, "Who Will Pay for Cleaner Power," *Sierra Club Conference on Electric Power Policy,* Johnston, Vermont, January 14–15, 1972). Roberts finds "increase in rates" to be 20 per cent or greater for the cases most similar to the materials management model. See also, Phillip Sporn's article in *The Environment and Economic Growth,* Sam Schurr, editor (Washington, D.C.: Resources for the Future, 1972). The problem is not that the RFF description is inaccurate; rather, the RFF changes in costs with respect to effluent discharge cannot be assessed by measurement on the company level, and industry-wide average cost changes, or price changes from effluent regulation, do not measure the same thing.

The RFF methodology is more troublesome than the predictions. First, there is a problem involved in the motivation for the model. As Bower states at the outset of his paper, the purpose is to delineate important factors which determine the disposition of materials, and to find the cost effects of manipulating these factors to improve environmental quality. This would seem to imply that an initial step in delineating these factors would be to construct models that predict accurately *at the industry level* the behavior of *industry-wide costs and outputs* with respect to environment related factors. But the models which are actually built—or so it seems from the description—are of *brand new firms, not old industries.* The RFF firms do not represent the average state of technology in the industry at the present time, nor even that in firms likely to affect industry output as a result of cost changes brought on by new environmental rules (the largest half-dozen operating firms). The RFF representative firm is free to exercise many more options than would be available to firms already installed in the industry. As a result, the RFF model firm must represent the real firm in the very long run if there were no further technological progress.[1] Thus the difficulty with the method is whether or not the "grass roots" firm is really meant to be predictive of industry behavior.

There are problems with the working procedure as well. Some readers might express displeasure with the totally orthodox nature of the framework—that, underneath all of the new technical words such as "residuals management" there is the classical framework in economic theory of the profit-maximizing multi-product firm. In this RFF formulation, the only new element is that some products (effluents) have negative prices. Going beyond qualitative description, the modeling procedure is either a "simulation approach" or a "linear programming approach." There is a third approach which should have been offered—or at least should not have been ignored, given its wide use at the present time. This is the approach in "industrial organization studies" which calls on the usual models of the multi-product firm in economics, but with cost and demand conditions described at the market level within the framework of prevailing industry institutions. The studies are usually "comparative static," in that predictions are made as to changes of prices or outputs following from changes in government policies. The forecast is tested most often by regression equations with prices and quantities in "reduced forms" as

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[1] This statement is more or less descriptive of the particular RFF studies—perhaps least descriptive of the sugar beet study, and most of the paper study. Each RFF report is different from each other, because of variation presumably in opportunities to use information as well as because of variations in skills of authorship. But I have taken the view that there is good reason for Bower's report beyond the mere collection of papers from one institutional source—or that there is an RFF modeling "approach," and that Bower's description of that approach is accurate.

functions of the exogenous policy variables. The tests are usually carried out on market-wide industry pricing and production, where these are expressed in ordinary accounting data, and produce statistics of "average" industry-wide effects at the present time.

The procedures proposed in the residuals management approach are in contrast to industrial economics practice. "Simulation" approaches in effect come from the construction of equations expressing engineering or physical relations in the firm where the critical coefficients are posited by those doing an "engineering design" study. The "industrial organization" approach is to posit price, cost and production relations in the market and then fit regression equations to those relations. Both approaches then simulate policy by inserting values of the policy variables in the resulting model. The standard for the simulation model is that it obeys scientific laws, and in some cases that it "optimizes." The model cannot be "tested" against prevailing conditions in the same way that regression analysis replicates present behavior because there are usually significant departures from maximum technical limits and from economic optimization in each company. And there are objections to the simulation approach: the firm being simulated is irrelevant to assessment of industry-wide effects, and the procedure is highly subjective among analysts so that there is no way to tell whether or not it is being conducted "in the correct manner."

Thus the problem is that of a choice between an industrial economic model—roughly a statistical regression equation model of industry pricing practice—and a simulation model of the newest plant. The choice to me would be the former. The industrial economic approach works with variables of the greatest concern for public policy—prices, outputs, changes of product quality where quality is measured by demand. This approach has been widely used, and now with increasing accuracy, in assessments of public policy.[2] In fact, it does not strike me that the residuals management model is likely to survive the present RFF project, because it does not meet "demands" for research findings relevant to setting market or industry-wide standards for environmental quality.

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[2] The most recent example of the industrial economic approach in electricity, one of the RFF industries, is that of J. M. Griffin, "A Long-Term Forecasting Model of Electricity Demand and Fuel Requirements," Ph.D. dissertation, University of Houston, 1972. This regression equation model has a "demand block," "conversion block" and "fuel share block." The division of the fuel requirements among coal, oil and natural gas is made by equations in which price differentials and local sulfur emission controls are independent variables. In fact, the fitted equations show an 11 per cent contraction in 1970 coal demand in the United States as a result of the imposition of various regional controls. Simulations of future KWH production, prices, and fuel use are made on the basis of various assumed values of GNP, fuel prices, and pollution regulations.