Towards an Improved Procedure for Estimating Industrial-Pollutant Emissions

by

Georgios Ioannis Kassinis
AB and BS
Cornell University
(1990)

Submitted to the Department of
Urban Studies and Planning in Partial Fulfillment of
the Requirements for the
Degree of

MASTER IN CITY PLANNING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 1992

Signature of Author______________________________
Department of Urban Studies and Planning
May 13, 1992

Certified by__________________________ 5/13/92
Dr. Jesse C. Ribot
Thesis Supervisor

Accepted by______________________________
Professor Ralph Gakenheimer
Chair, MCP Committee

Towards an Improved Procedure for Estimating Industrial-Pollutant Emissions

by

Georgios Ioannis Kassinis

Submitted to the Department of Urban Studies and Planning
on May 13, 1992 in partial fulfillment of the requirements for
the degree of Master in City Planning

ABSTRACT

Procedures that were devised in the 1960s and 1970s for projecting pollution-emission levels are not adequate--being too crude and hence inaccurate. As environmental problems mount, it is imperative that analysts be able to project emission levels with reasonable accuracy. In this study, we introduce, develop, and apply a method for projecting pollution emissions by a given industry. In contrast to previous applications of the input-output framework to account for pollution generation and abatement, we conduct our analysis at the microlevel--that of an individual industry and its component parts.

Input-output analysis provides the theoretical basis from which the procedure evolves. However, industrial/activity-complex analysis, an offspring and extension of input-output analysis itself, has inspired the analytical framework we use to describe and simulate the operation of an industrial activity. In this study, the method is applied to the case of the petroleum-refining industry

Using the framework proposed in this thesis, analysts can estimate the changes in the pollutants generated by an industry as a function of process configurations, alternative technologies, and different raw-material and fuel inputs. Based on the information generated by the method, environmental policy makers can see where interventions could be made in order to induce industries to meet specified environmental quality levels. In addition, the framework allows direct comparison among process configurations, alternative technologies, and different levels of abatement. Finally, it allows analysts to calculate and assess the extent of any interpollutant tradeoffs that would result from changes in processes, inputs, and abatement activities.

The analytical framework is designed to be flexible and dynamic, in that it allows for constant modification and expansion. Policy makers--

even those who do not possess technical backgrounds--can easily use it to generate different operation and associated pollution-generation scenarios. The information generated by the proposed procedure can be used in conjunction with and/or as an input into cost-estimation analyses. In combination with an economic analysis, this framework can facilitate identification of least-cost combinations of inputs, processes, and abatement measures that satisfy a given level of environmental quality.

Thesis Supervisor: Dr. Jesse C. Ribot
Title: Visiting Lecturer

Acknowledgements

First and foremost, I would like to thank Professor Walter Isard of Cornell University for his advice and generous assistance in shaping scattered ideas into a comprehensive piece of work. I have been fortunate to benefit from his advice while a student both at Cornell and at MIT. I would like to thank Professor Sid Saltzman of Cornell University for first introducing me to the world of research in the social sciences as an undergraduate at Cornell. At MIT, my thesis supervisor Dr. Jesse Ribot provided constant support, encouragement, and constructive criticism throughout the long months of thesis preparation and writing. I am thankful for that. I would like to thank Professor Karen R. Polenske for her detailed comments and advice.

I would like to express my gratitude to the A. C. Leventis Foundation of Paris, France, for their generous financial support without which writing this thesis would not have been possible.

Last but not least, I would like to thank my parents--to whom this thesis is dedicated--my brother, my sisters, and Elizabeth for their love, support, and encouragement.

Table of Contents

List of Tables

Chapter 1

Introduction

Procedures that were devised in the 1960s and 1970s for projecting pollution-emission levels are not adequate--being too crude and hence inaccurate. As environmental problems mount, it is imperative that analysts be able to project emission levels with reasonable accuracy. In this study, we introduce, develop, and apply an input-output/industrial-complex method for projecting the pollution emissions of a given industry. In contrast to previous applications of the input-output framework to account for pollution generation and abatement at the economy-wide level (among others, Daly, 1968; Ayres and Kneese, 1969; Leontief, 1970), we conduct our analysis at the microlevel--that of an individual industry and its component parts.

Input-output analysis provides the theoretical basis from which the procedure evolves. However, industrial/activity-complex analysis, an offspring and extension of input-output analysis itself (Isard, Schooler, and Vietorisz, 1959; Isard, 1960), has inspired the analytical framework we use to describe and simulate the operation of an industrial activity in its various forms.

Purpose

As public awareness increases and public scrutiny of environmental policy heightens, decision makers are increasingly pressed to show that the policies aimed at ensuring a specified level of environmental quality are both economically and socially efficient (the latter referring to questions of social welfare approximated by such indicators as public health). Toward such an end, they must be able to identify, target, and control those individual processes or combinations of processes within each industry that entail the least cost per unit of effluent reduction and whose control meets the specified level of environmental quality.

Using the analytical framework proposed in this thesis, analysts can estimate the changes in the pollutants generated by an industry as a function of process configurations, alternative technologies, and different raw-material and fuel inputs. Based on the information generated by the method, environmental policy makers can see where interventions could be made in order to induce industries to meet specified environmental quality levels (which are implicitly or explicitly stated in all approaches to pollution control); that is, which changes in processes, technologies, and inputs should be introduced and adopted in order to ensure the desired level of environmental quality. In addition, they can use the framework to make direct comparisons among process configurations, alternative technologies, and different levels of abatement. Finally, analysts can use it to calculate, observe, and assess the extent of any tradeoffs in terms of pollution generated (i.e., increases in the emissions of pollutant A coupled with decreases in the emissions of pollutant B) that would result from changes in processes, inputs, and abatement activities.

By focusing attention on each individual pollution-generating process and the variables involved with its operation, analysts can utilize the framework to identify the least-cost opportunities to reduce pollution. Although analysts cannot simultaneously optimize all of the activities and variables involved, they can do so for each of them individually. At the same time, however, an integrated and complete picture of the entire industrial complex's operation is necessary since the operation of the individual activities is largely determined by the product slate produced by the entire system. In other words, analysts must look at each process in context. We do so in this study by constructing a series of prototypes that describe alternative modes of operation and abatement for an industry.

Further, analysts can use the method to complement the measurement of pollution by mechanical means, which is currently rarely conducted on an individual-process basis. Therefore, although it is not a substitute for actual measurements, the proposed pollution-estimation method has the advantage of providing more detailed information on the processes and inputs that contribute to pollution generation. Analysts and industry engineers can therefore use it to pinpoint the areas that should be targeted for control, to help control pollution by facilities already in existence, and to guide the selection of processes and systems for future facilities still in the planning stages.

The information on operation and pollution generation fed into the proposed procedure must be as comprehensive and inclusive as possible. Many of the operational parameters and variables that influence the pollution generated have to be incorporated into the analysis as well. Hence, the information requirements of a framework such as the one proposed are indeed significant. Our research reveals, however, that sufficient information exists that may enable analysts to construct such analytical frameworks and estimate the pollution emissions of a large number of industries. One of the most important sources of information, in fact, is the industries themselves.

As will become apparent, the framework is designed to be flexible and dynamic, in that it allows for constant modification and expansion. Policy makers--even those who do not possess technical backgrounds--can easily use it to generate different operation and associated pollution-generation scenarios. Analysts can expand the framework to incorporate even more detailed forms of analysis and information. The information generated by the proposed procedure can ideally be used in conjunction with and/or as an input into cost-estimation analyses. In combination with an economic analysis, this framework can facilitate identification of least-cost combinations of inputs, processes, and abatement measures that satisfy a given level of environmental quality.

Background

Before proceeding with the present study, we briefly introduce the predominant approaches to environmental policy and pollution control. We emphasize that a detailed discussion or evaluation of each individual approach or a comparison of two or more of these approaches is beyond the scope of this study. This overview will then set the stage for us to present the proposed pollution-estimation procedure. It is through the use of this procedure that we seek to feed more accurate and detailed information--on industrial pollution-control options and associated costs (both economic and noneconomic)--into the policy-making process. We believe that our procedure can serve as the informational basis for cost-estimation and optimization analyses that can eventually determine an optimal combination of processes, inputs, and abatement activities that satisfies a specified level of environmental quality.

In environmental policy, there are two main schools of thought on the problem of pollution control: the advocates of direct control and those who favor the economic approach. For those who advocate direct control, the strategy is direct imposition of regulations on polluters, usually emission process and product standards. On the other hand, the economic approach is based on the incentive concept. The advocates of the economic approach--which has been gaining in acceptance since the 1970s --seek to remedy the drawbacks of the former approach by providing flexibility and motivation, while enabling some objective to be achieved at the least possible cost to the community (Friedlaender, 1978; OECD, 1980; Baumol and Oates, 1979 and 1988; Fisher, 1981; Crandall, 1983; Tietenberg, 1988; Nordhaus, 1989). Basically, the polluter is expected to respond to an economic signal as opposed to the imposition of regulatory constraints. It should be noted that these are, in fact, the two extreme positions. In practice, the economic and regulatory instruments are often combined. The resulting environmental policies are therefore amalgams of many approaches rather than a clearcut adoption of a single one (OECD, 1980: 7; Baumol and Oates, 1988: 159-176; Tietenberg, 1988: 306-332; Crandall, 1983: 58-80).

Within the economic approach, effluent charges (sometimes called Pigouvian fees or taxes[1]) are designed to induce the polluter to reduce emissions to a targeted level where the unit rate of charge is equal to the marginal cost of treatment. Beyond this level, it is cheaper for the polluter to pay the charge than to continue abatement. In contrast, a system of marketable (that is transferable) emission permits, also an economic approach to environmental policy, is one in which the regulatory authority effectively determines the aggregate quantity of emissions, but leaves the allocation of these emissions among sources to market forces. To implement such a system, the environmental authority would issue permits for waste discharges such that, in the aggregate, total discharges

---

[1] Named after the British economist Arthur Pigou who was one of the first to suggest that an appropriate "price," in this case a tax, be placed on polluting activities so as to internalize the social (external) costs of pollution (Baumol and Oates, 1988: 1). Pigou (1877-1959), an economist at Cambridge University, suggested such taxes in his influential book <u>The Economics of Welfare</u> (Varian, 1987: 554).

would be at the level that equates marginal abatement costs and marginal social damage. Trading of these permits among sources would then, in theory, establish the market-clearing price. Such a permit system is very different from the direct-control approach to permits or licenses. Under a system of direct controls, the environmental authority specifies for each source an allowable level of emissions. The emissions quota assigned to a particular source is not tradeable so that there is no market in emission permits (Baumol and Oates, 1988: 58-59).

As an actual policy tool, effluent charges and marketable emission permits have in the past been viewed as "an academic curiosity with no practical implications" (Friedlaender, 1978: 1). Instead, specific emission standards have been set for stationary sources to ensure that ambient air-quality standards are met. The control of air pollution has, therefore, taken the form of government regulation instead of the "invisible hand of the pricing system to ensure that private and social costs coincide with respect to air pollution" (Friedlaender, 1978). According to its proponents, the use of predetermined standards as an instrument of environmental policy is preferable given the significant information requirements of the alternative approaches (Baumol and Oates, 1988: 160). For example, the proper level of a Pigouvian tax upon the activities of the generator of an externality (pollution) should theoretically be equal to the marginal net damage produced by that activity (Baumol and Oates, 1988).

Analysts usually find it very difficult, or even impossible, to obtain a reasonable estimate of the money value of this marginal damage. The number of activities involved and the number of persons affected by them is so great that, on this score alone, the task becomes enormous. Analysts have equal difficulty in determining the marginal benefits resulting from the imposition of pollution-control measures. For example, they find it as difficult to quantify the benefit accruing to a society in the form of improved public health due to a five percent decrease in pollution as to determine the societal costs inflicted by pollution in the first place. At the same time, however, we emphasize that an enormous amount of information is necessary to achieve anything that can even pretend to approximate optimality by means of centralized calculation. Hence, information requirements and bottlenecks hamper the standards approach as well (Baumol and Oates, 1988: 160-161).

As stated above, our aim in the present study is clearly not to determine what is or ought to be the best policy but rather to contribute to the informational requirements of the environmental policy process as a whole.[2] Although we use, by necessity, theoretical tools that assume an 'ideal' set of conditions, we conduct the analysis primarily within a less-than-ideal setting.

---

[2] In "Using Mathematical Programming Models for Cost-Effective Management of Air Quality," R. J. Anderson (1982) provides a very interesting mathematical treatment of the question of cost-effective air-quality management. His model is applied to all three approaches to environmental pollution control--emissions standards, charges, marketable permits--and depending on the underlying assumptions, he generates different results with respect to which set of policies is cost-effective.

The Method Revisited

No system of charges or emission standards can operate optimally unless accurate information is available regarding actual emissions. This information must also be easily accessible, reasonable in cost, and comprehensible in nature. Measuring the level of ambient pollution is an extremely delicate operation subject to a number of uncertainties. There are equally substantial difficulties in measuring emissions themselves. Technicians and analysts can take manual measurements, but this method is difficult and costly, especially if carried out over a long period and if the emissions fluctuate widely. Essentially, then, the quality and cost of information on industrial-pollution emissions obstruct the optimal operation of either a system of charges or a system of emission standards.

Analysts can overcome these difficulties by evaluating emissions indirectly by means of emission factors (OECD, 1980: 54). Each polluting activity can be characterized by the average amount of pollutant produced --expressed in terms of a specific unit of input or output as a function of the activity in question (EPA, 1985). These emission factors can be corrected by treatment coefficients that take into account the abatement measures actually carried out by the plants concerned.[3] Our procedure

---

[3] The emission factors in question are based on engineering analyses of the processes involved. In addition to their correction by treatment coefficients, industry engineers can improve their accuracy by taking into account the age and level of maintenance of the industrial process under consideration. However accurate on a case-by-case basis, the factors describing the pollutant emissions of a process across industries of the same type suffer from the 'ills' of aggregating a large number of activities which, although theoretically identical, are, in reality, different.

utilizes such emission factors, which are obtained mainly from engineering sources, in order to calculate pollutant emissions both for individual subprocesses as well as for an industry as a whole.

Our review of the relevant literature indicates that methods strictly relying on a single discipline are not sufficient to deal with the multifaceted problems of industrial pollution and abatement (Isard et al., 1972; Isard, 1974; Fronza and Melli, 1982; Braat and van Lierop, 1987; Zannetti, 1990). Neither engineers nor economists, for example, can solve these problems alone. They can rely, though, upon a comprehensive yet detailed method--such as the one we propose in this study--to estimate and compare the effects on emission levels of different fuels, raw-material inputs, process configurations, technologies, and levels and types of abatement. Implied also is their ability to use the method to calculate these emissions. Analysts can evaluate alternative pollution-generation scenarios comparatively and assess the resulting tradeoffs in terms of differential pollution emissions. Furthermore, the procedure generates results that are simple enough in form so as to be easily employed by all environmental policy makers--those with scientific or technical backgrounds as well as those without.

As mentioned above, the method combines elements of input-output analysis and activity/industrial complex analysis with the dynamics of the industrial process to which it is applied. Through such a framework, analysts can trace the effects of pollution-control policies on both the level of pollution as well as the structure of the industry itself. They can simulate and compare any changes in technology, raw material and fuel inputs, or abatement processes. Given the resource and emission-level constraints imposed by the policy-making environment, the method can serve as the basis for formulating an optimal pollution-control policy. In the case of the emission-standards approach, for example, both regulators and industry analysts can use our method to simulate the operation of the industry under scrutiny and identify the least-cost operating and abatement scenario that meets the imposed standard.[4] In the case of the pollution-charges approach, our method can again be of importance in identifying an optimal level of pollution abatement--one that corresponds to a certain industrial-operation scenario. The planned tax or charge would then be based on that level.

We use the petroleum-refining industry as a case study in this thesis because it provides a challenging testing ground for the proposed procedure. As one of the most complex and diverse industries both in the United States and abroad (Gary and Handwerk, 1984), it provides us with an opportunity to test various levels of analysis in terms of processes and refinery prototypes as well as various inputs. We use its complexity to test the applicability and sufficiency of our formulations and data to the problems posed by a very complex industry.

---

[4] As mentioned above, the information generated by our method must be used in conjunction with a cost analysis in order to find the least-cost pollution-control operating scenario among the large number of scenarios generated by the method.

Thesis Format

This thesis consists of four chapters in addition to the introduction. Chapter 2 presents the theoretical foundations of the proposed technique and a formal statement of the proposed pollution-estimation procedure. We review the use of input-output techniques for modeling pollution generation and abatement and present an introduction to activity/industrial-complex analysis, incorporating many of its elements into the proposed framework.

Chapter 3 offers a brief review of the development and scope of the petroleum-refining industry both in the United States--which possesses the most complex petroleum-refining industry (Gary and Handwerk, 1984; Wijetilleke and Ody, 1984)--and in the rest of the world. We also include references to current and future trends in the industry and their demonstrated and potential effects on the pollutant mix it produces. Finally, we discuss processes generating direct pollutant emissions along with appropriate control technologies and other abatement measures.

Chapter 4 presents an application of the method to the petroleum-refining industry specifically. We first apply the method to the case of a 'hydroskimming' refinery--the simplest type of a refinery in operation today and one that is often found not only in the developing world but also in Western and Eastern Europe (Wijetilleke and Ody, 1984; D. P. Plummer, 1984). Subsequently, we apply the method to model the operation and estimate the air-pollutant emissions of a modern 'integrated' refinery. We demonstrate how the mix and quantities of pollutants emitted change with changes in refinery processing configurations (i.e., the cases of different refinery prototypes as well as processes within a prototype); how the air-pollutant mix changes when the fuel-input mix changes; and, how different levels of abatement activities influence the level of pollution eventually emitted. In all cases, any resulting tradeoffs in terms of simultaneous increases and decreases in the emission levels of two or more pollutants are identified.

Chapter 5 contains some general concluding comments. We briefly assess the role that the proposed methodology can play in the formulation of air-pollution control policy, especially as far as the estimation of the costs of pollution control is concerned. We also evaluate the flexibility and capacity of the method to generate information on air-pollution emissions, given a multitude of technological and economic constraints.

In the Appendix, we present a simulation of the U. S. petroleum-refining industry. More specifically, we use a cluster approach to model the refining industry of each of the four major Petroleum Administration for Defense (PAD) districts and to construct a representative refinery prototype for each region. We then simulate the operation of each refinery prototype and estimate its air-pollutant emissions, relying, again, on the proposed method. In taking the application a step further--beyond the theoretical treatment of 'textbook' refinery prototypes, their operation, and their pollution generation--our goal is to assess the sufficiency of both the proposed method versus the demands posed by a diverse group of existing refineries and the availability and quality of data on their operation.

Chapter 2

Theoretical Foundations of the Proposed Procedure

This chapter establishes the theoretical foundations of the proposed pollution-estimation procedure. Input-output analysis provides the theoretical basis from which the procedure evolves. However, industrial/activity-complex analysis[5], an offspring and extension of input-output analysis itself (Isard, Schooler, and Vietorisz, 1959; Isard and Schooler, 1959; Isard, 1960; 1972; 1974; 1975), has inspired the actual analytical framework we use to describe and simulate the operation of an industrial activity in its various forms. We begin with a reference to the applications of input-output analysis in environmental and pollution modeling. We then continue with a brief presentation of some of the fundamental aspects of industrial-complex analysis and its potential applications. In the final section, we formally outline the pollution-estimation procedure to be implemented in later chapters for the petroleum-refining industry.

Input-Output Analysis and Environmental Modeling

Input-output methodology and the Leontief framework itself have been used and extended by many researchers during the past twenty-five years to account for the environmental pollution generation and

---

[5] The terms "industrial-complex analysis" and "activity-complex analysis" will be used interchangeably throughout this and the following chapters.

abatement associated with interindustry activity (Miller and Blair, 1985: 236). Among others, Victor (1972), Pai (1979), and Miller and Blair (1985) provide detailed descriptions and critiques of the various proposed frameworks. Here, we outline some of the main features and shortcomings of the various environmental applications of the input-output framework.

One of the most important problems "... to be resolved in environmental models [using input-output analysis] is the appropriate unit of measurement of environmental (or ecological) quantities--for example, in monetary or physical units" (Miller and Blair, 1985: 236). In the alternatives we consider here, we see formulations using each convention. Analysts classify environmental input-output models into the following three categories: *generalized input-output models,* which are formed by augmenting the technical coefficients matrix with additional rows and columns to reflect pollution generation and abatement activities; *economic-ecologic models,* which result from extending the interindustry framework to include "ecosystem" sectors, where flows are recorded between economic and ecosystem sectors along the lines of an interregional input-output model; and finally, *commodity-by-industry models,* which express environmental factors as "commodities" in a commodity-by-industry input-output table (Miller and Blair, 1985).

Generalized Environmental Input-Output Models

In order to account for the pollution generation associated with interindustry activity, we can consider a matrix of pollution-output or direct-impact coefficients, $v = |v_{kj}|$. Each element of this matrix is the amount of pollutant type *k* generated per dollar's worth of industry *j*'s output. The level of pollution associated with a given vector of total outputs X can then be expressed as $v^* = vX$ where v^* is the vector of total pollution generated by industry *j*. By using the traditional Leontief model, $X = (I - A)^{-1} Y$, we can compute v^* as a function of final demand, that is, the total pollution of each type generated by the economy directly and indirectly in supporting that final demand: $v^* = [v(I - A)^{-1}] Y$. The bracketed quantity can be viewed as a matrix of total impact coefficients; that is, an element of this matrix is the total pollution impact generated per dollar's worth of final demand (Miller and Blair, 1985: 237).

Another way of accounting for pollution generation and abatement in a traditional Leontief model is to augment the technical coefficients matrix with a set of pollution-generation and/or abatement coefficients. In the case of pollution generation, the coefficients reflect the amount of a particular pollutant generated per dollar's worth of industry output. Similarly, the pollution-abatement coefficients reflect inputs to pollution-elimination activities.[6]

---

[6] Leontief first proposed this approach in 1970 in "Environmental Repercussions and the Economic Structure: An Input-Output Approach" that appeared in the Review of Economics and Statistics. The article also appears in Leontief's Input-Output Economics (1986).

Pai (1979: 26-48) presents an assessment of a series of what he terms "generalized environmental systems models." He states that with the exception of the Leontief model, all other models under consideration, namely those of Ayres and Kneese (1969), Cumberland (1966), Daly (1968), and Isard (1968), can be considered as environmental simulation models as opposed to formal policy-analysis models (Pai, 1979: 27).[7] Despite their "generic" similarity as input-output models, the two types of models, designed to model the economy-environment interaction, are operated with different objectives that result in different manipulation of the input-output framework (Pai, 1979).

Ayres and Kneese (1969) frame their two-sector economy-environment interaction model in general equilibrium terms. In theory, the underlying materials-balance principle ensures that all materials that enter and leave the economic system pass through these two sectors. The principal liability of the model is that it is virtually impossible to implement. They design the model's formal mathematical structure to trace residual flows in the economy and relate these to a general equilibrium model of resource allocation. Moreover, their particular formulation of the model implies a knowledge of all preference and

---

[7] As Pai indicates the difference between the two types of models stems from the way in which each model is used to simulate the interaction between economy and environment as well as the "degree of closure postulated in the relationship" (1979: 27). In complete system models, the relationship between the economy and the environment is treated as a closed one, while in a more policy-analysis oriented model focusing directly on the implications of particular policy interventions, the same degree of systems closure may not be implied.

production functions, including relations between residuals discharge and external costs as well as all possible factor and process substitutions--an almost impossible task (Victor, 1972: 25-35; Pai, 1979: 28-30).

Economic-Ecologic Environmental Input-Output Models (fully-integrated and limited models) and Commodity-by-Industry Models

In this category of models, analysts extend the notion of commodity-by-industry accounts to accommodate environmental activities in terms of ecological commodities (Miller and Blair, 1985: 252). These are defined as non-marketable quantities that are either inputs used or outputs discharged from a production process. Moreover, as an alternative to appending environmental intensity rows to the technical coefficients, analysts can account more specifically for environmental or ecosystem flows by creating an "ecosystem submatrix" that is linked to the interindustry economic flows matrix in the same manner that regions are interconnected in an interregional input-output model. Such a model is often called a fully integrated model (Miller and Blair, 1985: 53-69, 252).

As far as fully-integrated models are concerned, Daly (1968) and Isard et al. (1968) have developed similar procedures that incorporate environmental activities into an input-output framework. Both Daly and Isard employ flow matrices within and between both economic activities and environmental processes. Transactions are grouped into four basic submatrices; the diagonal submatrices depict flows within the economy and the ecosystem, and the off-diagonal submatrices depict flows between the economy and the ecosystem and vice versa (Miller and Blair, 1985: 252).

Daly attempts to integrate purely-economic relations, purely-environmental relations, and the relationship between the two sectors into one model. He employs a highly-aggregated industry-by-industry characterization of the economic submatrix and a classification of ecosystem processes, dividing the model into human and non-human sectors. He describes interactions within the human sector as economic, with only commodities being produced and exchanged. The flows from the economic/human sector to the environmental/non-human sector are called externalities; opposite flows are termed 'free' goods. Critics of the model focus on the valuation system on which the accounting system must be constructed (Pai, 1979: 32; Victor, 1972: 37-41). Table 2.1 presents Daly's input-output model which is divided into four quadrants. Quadrant 2 is a simple three-sector, closed, economic input-output table. Quadrant 4 is an extension of the input-output formulation to ecological or non-human processes. Quadrants 1 and 3 provide the links between the economic and ecological quadrants 2 and 4. In quadrant 1, the ecological commodities produced by the economy are tabulated according to their source and destination. These commodities are included in what are normally defined as externalities. Quadrant 3 shows the 'free' goods that enter the economic sectors from the environment (Victor, 1972: 39-40).

Table 2.1

The Daly Input-Output Environmental Model

	INPUT TO										
OUTPUT FROM	Agri-culture (1)	Industry (2)	Households (Final Consumption) (3)	Animal (4)	Plant (5)	Bacteria (6)	Atmo-sphere (7)	Hydro-sphere (8)	Litho-sphere (9)	Sink (Final Consumption) (10)	TOTAL
	QUADRANT (2)			QUADRANT (1)							
1. Agriculture	...	q12	...	...	...	...	q17	...	...	...	Q1
2. Industry	q21	(q22)	q23	...	...	...	q27	...	...	...	Q2
3. Households (primary services)	...	q32	...	...	...	...	q37	...	...	...	Q3
	QUADRANT (3)			QUADRANT (4)							
4. Animal	...	...	...	...	...	...	q47	...	...	...	
5. Plant	...	...	...	...	...	...	q57	...	...	...	
6. Bacteria	...	...	...	...	...	...	q67	...	...	...	
7. Atmosphere	q71	q72	q73	q74	q75	q76	(q77)	q78	q79	q7, 10	Q7
8. Hydrosphere	...	...	...	...	...	...	q87	...	...	...	
9. Lithosphere	...	...	...	...	...	...	q97	...	...	...	
10. Sun (primary services)	...	...	...	...	...	...	q10,7	...	...	...	

Source: Peter A. Victor, Pollution: Economy and Environment. London: Allen & Unwin, 1972: 38.

Isard refines this basic paradigm by recognizing that secondary production of ecologic outputs--for example pollution generation--is incompatible with the assumption of one-product industries inherent in traditional Leontief models. Instead, Isard adopts the commodity-by-industry accounting scheme rather than a traditional industry-by-industry framework.[8] The former permits an accounting of multiple commodities, economic and ecologic, produced by a single industry--a factor crucial to our analysis as well since the activities described produce a variety of products--either 'goods' or 'bads' (Pai, 1979; Miller and Blair, 1985).

The four basic submatrices comprising Isard's input-output model (Table 2.2) include: Quadrant 1, which shows the inputs and outputs of the economy that enter into the environmental sector; Quadrant 2, the interindustry table, with columns representing industries and rows the commodities associated with those industries as outputs and resources; Quadrant 3, which presents the inputs and outputs of ecologic commodities to economic activities; and Quadrant 4, which represents the ecological system, where the ecological commodities of the rows enter the ecologic process of the columns as inputs and/or outputs (Victor, 1972: 44-47; Pai, 1979: 35).

The technical coefficients in Isard's model are estimated directly from

---

[8] A critical implication of the industry-by-industry accounts is that each industry must produce only one output and each output can only be produced by one industry. In other words, joint products are not allowed in the standard input-output system. On the other hand, the problem at hand is such that each industry produces at least two categories of products: a commodity output and a waste product.

Table 2.2
Isard's Economic-Ecologic Input-Output Model

	ECONOMIC ACTIVITIES						ECOLOGIC PROCESSES			
	Agri-culture	Textile		Petroleum refining		Sport fishing		Plankton production	Herring production	Cod production
Wheat										
Cloth										
ECONOMIC COMMODITIES			ECONOMIC SYSTEM: INTERSECTOR COEFFICIENTS 2				ECOLOGIC PROCESSES: THEIR INPUT AND OUTPUT COEFFICIENTS RE: ECONOMIC COMMODITIES 1			
Crude Oil				-						
Water intake				-						
Alkalinity				+						
ECOLOGIC COMMODITIES			3 ECONOMIC SECTORS: ... THEIR INPUT AND OUTPUT COEFFICIENTS RE: ECOLOGIC COMMODITIES				4 ECOLOGIC SYSTEM: INTERPROCESS COEFFICIENTS			
Plankton								+	-	
Herring									+	-
Cod										+

Source: Peter A. Victor, Pollution: Economy and Environment. London: Allen & Unwin, 1972: 42-43.

technical data. However, as Miller and Blair point out, since the model was never fully implemented, the adequacy of available data for such an estimation is very difficult to judge. In addition, the availability of data for the ecosystem submatrix appears to be the most troublesome point: they are virtually non-existent and impossible to specify (see critique by Victor, 1972: 41-47; Pai, 1979; and Miller and Blair, 1985: 253).

As far as limited economic-ecologic input-output models are concerned, Victor's framework (1972) limits the scope of Isard's fully-integrated economic-ecologic model to account only for flows of ecological commodities from the environment into the economy and of the waste products from the economy into the environment. By limiting the scope of the analysis, the data are generally available and the model can be implemented with little difficulty (Miller and Blair, 1985: 253). The basic accounting framework is a conventional commodity-by-industry table augmented with additional rows of ecological inputs and columns of ecological outputs.

Industrial-Complex Analysis

Unlike the aforementioned applications of the input-output technique in which analysts look at pollution generation and abatement at the economy-wide and industrial-sector level, we propose looking at pollution generation at the microlevel. That is, we simulate the operation of an industrial activity with the individual processes, inputs, and outputs interacting in a dynamic framework that generates a variety of alternative operation, pollution-generation, and abatement scenarios. In addition to the Leontief framework, industrial-complex analysis provides some of the analytic tools most relevant for our methodology. We do not attempt to provide a complete analysis of the inception, structure, and application of activity complex analysis. This task is beyond the scope and the needs posed by our study. We focus, however, on those of its characteristics that inspired some of the thinking in our procedure and present a rough picture of what we can achieve with activity complex analysis itself in its original form.

Definition of an Industrial Complex

Proposed and developed in the mid-1950s by Isard, Schooler, and Vietorisz, industrial-complex analysis was first applied to a study of the economy of Puerto Rico. That study attempted to examine questions of, among other things, industrial location and comparative cost for a variety of industries under consideration. According to Isard, the procedure is "a synthesis of comparative-cost and input-output analyses" (Isard, 1975: 467).

Isard et al. (1960: 324) define an industrial complex as "a set of activities occurring at a given location and belonging to a group (subsystem) of activities which are subject to important production, marketing, or other interrelations." In the extreme, the set of activities may reduce to a single activity, which for convenience of exposition is still defined as a complex. For example, one reference group of activities may comprise the successive stages in the manufacture of an end product or a class of end products. Isard stresses the locational interdependence of activities within any particular complex. Another type of complex may derive from the joint production of two or more commodities from a single class of raw materials. Finally, a complex may involve two or more basic raw materials and processes and two or more intermediate products--which may or may not enter into the production of intermediates. All of them may combine to form two or more end products. In turn, these intermediates can be used to manufacture other intermediates, which can be transformed into final-stage intermediates and ultimately into end products (Isard et al., 1960).

Determination of Structures of Specific Complexes

Once meaningful complexes are broadly sketched, the analyst must define the details of these structures. An industrial complex is, generally speaking, composed of more than one activity. Therefore, the internal interrelations, that is, the interactivity linkages, must be explicitly expressed in quantitative terms. It is at this point that the concept of the interindustry matrix of input-output is introduced and becomes basic to the analysis. However, as we will demonstrate at a later point, the concept of an interindustry matrix can be extended to a concept of an interactivity matrix. The latter concept permits some important variations in production coefficients (i.e., nonlinearities) and introduces a number of alternative processes in order to allow for process substitution in the linear programming sense (Isard et al., 1960: 328)--a very important feature for our pollution-estimation procedure as well.

Isard et al. illustrate the procedure with reference to the study of the Puerto Rican economy. First, they construct a table (Isard et al., 1960: 328-333) showing the amounts of various inputs and outputs associated with operating each individual or combined productive process (activity)--that may be encountered in a specific selected complex--at a 'unit level.'[9] Table 2.3 presents a synopsis of the Isard interactivity table. It should be noted that the inputs and outputs listed in this table are expressed in physical terms rather than in the monetary units used in input-output analysis. The data are largely obtained from engineering sources. In addition, although in input-output analysis each sector has a single output, in activity complex analysis each sector (or activity or process) is allowed multiple outputs--a very important feature when modeling pollution-generating activities. Finally, another distinction of complex analysis from input-output analysis is that in the former, alternative processes are permitted and can be listed in the columns of the interactivity table being constructed. All alternative process or activity technologies can be considered in the analysis. Only one of those processes, though, is used when a specific complex or prototype is constructed (Isard et al., 1960: 328-331; Isard et al., 1972: 40-41). This

---

[9] The determination of the 'unit level' for any activity is arbitrary. An analyst usually defines it at a scale so as to facilitate computation and understanding of the problem (Isard et al., 1960: 328).

Table 2.3

The Puerto Rico Study
Annual Inputs and Outputs for Selected Oil-Refinery, Petrochemical, and Synthetic-Fiber Activities

	Oil Refinery Prototype 1	Oil Refinery Prototype 4	Ethylene Separation Prototype 4	Ethylene Glycol (oxidation)	Ammonia from Hydrogen	Ammonia from Methane	Nilon Filament
	(1) . . .	. . . (4) . . .	. . . (10) . . .	. . . (22) . . .	. . . (31) . . .	. . . (32) . . .	. . . (73) . .
1. Crude Oil MM bbl.	-9.428	-9.428					
2. Gasoline, str. -run MM bbl.	+2.074	+1.300					
3. Gasoline, cracked MM bbl.	+1.484	+2.226					
4. Gasoline, reformed MM bbl.		+1.486					
. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .
11. Heavy residual MM bbl.	+0.943						
12. Coke and carbon 10xMM bbl.		+4.033					
13. L. P. G. 10xMM bbl.	+6.860	+15.050	+0.508				
14. Hydrogen MM lb.	+0.950	+8.900			-2.000		
15. Methane MM lb.	+12.780	+34.860				-5.500	
. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .
22. Pure ethylene MM lb.			+16.100	-8.300			
23. Pure ethane MM lb			+30.190				
24. Steam MMM lb.	-0.801	-1.402	-0.148	-0.103		-0.023	-0.555
25. Power MM kwhr	-2.511	-3.999	-0.194	-0.800	-4.640	-5.600	-16.000
. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .	. . . .
Nylon Filament MM lb							+10.000

Source: Walter Isard et al., Methods of Regional Analysis: an Introduction to Regional Science. Cambridge, MA: The MIT Press, 1960: 329-330.

characteristic is featured in our analytical framework as well. In addition to the alternative processes and technologies included, the interactivity table incorporates and allows variable factor proportions and product mixes, as well as process substitution--another important characteristic useful for our analysis.

The columns of the table in question are numbered, and each represents one activity. The rows of the table are also numbered, and here each represents a commodity. When the commodity is used in a process as an input, this is so indicated by a minus sign; when it is yielded as an output, this is so indicated by a plus sign (Isard et al., 1960: 329).

Some of the columns of the table in question may deal with activities that produce just one output. In addition, the table does not list all the inputs and outputs encountered in all activities noted. In the case of the Isard framework, a complete list would be necessary only if the analyst had to construct complete profit and cost estimates. Therefore, how expansive or how inclusive the table is depends on the specific requirements of the research effort at hand. In Isard's table, a list is given for only those inputs and outputs whose amounts vary in direct proportion with the scale of the productive activity; for example, those that double when output doubles. Inputs such as labor and capital services are thus excluded. These inputs are part of the interactivity matrix, but they must be considered individually at a later stage, since they generally vary nonlinearly with the scale of operation (Isard et al., 1960: 331).

Summary of Industrial-Complex Analysis

As we briefly mentioned, industrial complex analysis, in its original form, "is concerned with regional patterns of incidence and growth of groups of industrial activities" (Isard et al., 1960: 348). These interrelations can be analyzed through a modern Weberian framework. In such a framework, an analyst looks at locational interdependence using an interactivity matrix--i.e., an interindustry matrix with alternative processes and with added data that permit adjustments for certain non-linearities and scale economies (Isard, 1960). Several forms of locational interdependence as well as questions of cost differentials among regions can be analyzed. The results obtained from such analyses can be used by analysts to obtain industrial projections and understand patterns of industrial location. Presumably, industrial-complex analysis can be a useful technique. Analysts can use it to identify and evaluate profitable scenarios and activity combinations that cannot be accurately assessed either by industry-by-industry comparative cost studies or by strictly linear interindustry techniques. In one sense, the industrial-complex approach can be viewed as a "hybrid" approach that can be used to isolate and evaluate the interplay of key variables among groups of highly-interrelated activities (Isard et al., 1960: 350).

Yet, as Isard himself points out, there are limits to the use of the industrial-complex approach in understanding and projecting an interregional system of industrial locations. It should not be employed where the production and marketing interrelations among activities of a reference group are relatively insignificant. Further, its effectiveness may be severely restricted in situations in which some of the activity interrelations result in economies that are largely nonquantifiable. Analysts cannot use it to look as deeply into a specific industry as they can do with an individual comparative study. In addition, when analyzing systems of activity, analysts cannot achieve the breadth of the typical regional and interregional input-output technique and other promising techniques of a general equilibrium orientation. However, the real merit of the industrial-complex approach is not that it is a substitute for relevant regional techniques. Rather, it is a complement to these techniques (Isard et al., 1960: 350).

Clearly, the relevance of activity-complex analysis to our study and our procedure lies in the analytical framework we can utilize, rather than its past uses. As we pointed out, we use many of the features of the interactivity framework employed in activity-complex analysis. This becomes evident in the final section of this chapter as well as in the following chapters in which our analysis is applied to the case of the petroleum-refining industry.

Formal Statement of the Pollution-Estimation Procedure

Based on this background of the applications and extensions of input-output analysis--both in the area of environmental analysis as well as in modeling industrial-activity operations--we present the procedure used in this study to estimate the pollution emissions of a petroleum-refining complex. Potentially, and depending on the availability of adequate data, we can apply this procedure to calculate estimates of pollution outputs of other industrial activities as well.

Consider industry (economic production sector) j. It encompasses processes $j_\alpha, j_\beta, \ldots, j_\rho$. An input or output of each commodity $j_{\mu g}$ (j = 1, ..., n and g = 1, 2, 3, ..., m) per unit level of output is associated with each process j_μ ($\mu = \alpha, \beta, \gamma, \ldots, \rho$) which we record in an appropriate matrix. Along the rows we list in order, the commodities from 1 to m. Along the columns we list the processes $j_\alpha, j_\beta, \ldots, j_\rho$ relevant for each industry j. Then, we construct the typical input-output table as an activity-analysis table, putting into each cell the appropriate coefficient $\alpha_{j\mu g}$ which is negative when it represents an input of commodity g per unit level of operation of process μ and positive when an output. The partition of the matrix consisting of rows $\lambda+1$ to ξ can be designated the pollution coefficient matrix and can be represented by

$$z = [\, z_{j\mu v} \,].$$

The $z_{j\mu v}$ coefficients are essentially the $\alpha_{j\mu g}$ coefficients describing the output of a pollutant type v ($v = \lambda + 1, \ldots, \xi$) per unit level of operation of a pollution-producing process μ. The interactivity matrix described above can be represented by

$$
I = \begin{bmatrix}
\alpha_{j\alpha 1} & \alpha_{j\beta 1} & \alpha_{j\gamma 1} & \alpha_{j\rho 1} \\
\alpha_{j\alpha, \lambda+1} & \alpha_{j\beta, \lambda+1} & \alpha_{j\gamma, \lambda+1} & \alpha_{j\rho, \lambda+1} \\
\cdot & \cdot & \cdot & \cdot \\
\cdot & \cdot & \cdot & \cdot \\
\alpha_{j\alpha m} & \alpha_{j\beta m} & \alpha_{j\gamma m} & \alpha_{j\rho m}
\end{bmatrix}
$$

For certain industries, this detail will not be sufficient. In many industries requiring heat as input (in the form of steam produced by process heaters, etc.) the output of pollutants as well as other commodities depends not only on the type of fuel (say natural gas, coal, fuel oil) used, but also on the source and consequently the composition of each type of fuel. Hence, we need to disaggregate each heat-producing process into subprocesses, each characterized by both type and source of fuel used as an input. We must then develop a submatrix for each such process, and at the same time disaggregate each of the relevant rows. Therefore, we disaggregate the energy-input row into as many rows as there are fuel inputs, that are distinguished by both type and source, to be considered for use or actually consumed (for example, different types of residual fuel oil with different sulfur contents). In order to derive pollutants per unit level of a given process, we then weight the pollutant outputs and inputs per unit level of each of the relevant subprocesses. We base the weights on the fractional mix of the subprocesses comprising the process in question.

In addition, the outputs of pollutants and other commodities and associated inputs depend on which source of each raw material is used as an input--for example, there are great differences in pollutants generated when crude oils from different geographic sources are refined (differences in composition--such as Sulfur content-- as well as in API[10] gravities, among other things). We must then subdivide each process into subprocesses, characterized not only by both type and source of fuel input, but also by source of each raw material input. We must also disaggregate each row that corresponds to a raw material. Hence, if there are, for example, ten different kinds of fuel inputs (each characterized by both a fuel type and source) and five sources of each of two basic raw materials (each source distinct in impurity content), we must consider theoretically at least 250 subprocesses. In practice, however, analysts need only consider the main subprocesses, or they can aggregate the subprocesses into a reasonable number of prototypes, given limited research resources, similar to what they do in input-output analyses when they aggregate a large number of unique individual economic activities (firms) into a smaller, more inclusive, set of economic sectors. Having derived pollutant emissions (and other outputs as well as inputs) for each process, the analyst may need to weight each process by the fractional magnitude that its output constitutes of the industry's total, or by some other key magnitude.

Finally, we consider the one or more pollution-abatement processes associated with the production operations of an industry. There may, of

---

[10] American Petroleum Institute (API).

course, be abatement activities in a region that pertain to a community as a whole, such as municipal waste treatment. However, we do not consider these here since we are only concerned with projecting pollution emissions by an industry itself. An abatement process essentially takes in as inputs the pollution emissions from other processes within the industry. It then turns out other products like sulfur (a good) as well as the portion of pollution emissions that is not successfully treated. It is also possible that other pollutants (bads) of the same or different type are produced . On net, the output of a pollutant is equal to the gross input less the amount successfully treated. On the other hand, we can also consider the substitution of 'cleaner' fuels for 'dirtier' ones or the adoption of more efficient and environmentally-sound technologies as abatement activities.

Theoretically, then, if we know the level of operation of each production process in the industry, that is, the $X_{j\mu}$ ($\mu = a, b, \ldots, \rho$), which when summed over all final product processes yields the total level of the industry, namely X_j ($j = 1, 2, 3, \ldots, n$), plus the level of each abatement process used by the industry ($X_{j,\rho}, X_{j,\rho-1}, X_{j,\rho-2}, \ldots$), we can determine the level of emissions of each pollutant by using:

$$P_{vj} = \sum \alpha_{vj\mu} \cdot X_{j\mu} \text{ for } v = \lambda + 1, \ldots, \xi.$$

This completes the discussion of the relevant theoretical background on which subsequent applications are based. The pollution-estimation framework we presented--unlike any other application of input-output analysis to account for pollution generation and abatement--enables analysts to engage in an in-depth examination of the pollution-generation and abatement aspects of an individual industry. In addition, the framework, which incorporates alternative technologies, different types and qualities of raw-material inputs and fuels, as well as different types and levels of abatement, allows analysts to construct and directly compare different prototypes based on their pollution outputs.

We believe that the detailed simulation of an industry's operation--covering the entire spectrum of inputs, processes, and abatement activities--is important since it can supply analysts with specific information on the dynamics of the composition of the pollution output. By using the proposed framework, analysts can trace the changes in the pollution output and the associated tradeoffs--in terms of differential pollution emissions--that result from different process configurations, raw-material inputs, fuels, and degrees of abatement. Furthermore, analysts can use the framework and the information it generates--when an industrial activity is simulated--as the basis for a cost-estimation/comparative-cost study that identifies the least-cost combination of variables (be it inputs, processes, and abatement measures) that meet a specified environmental-quality objective.

We apply, directly or indirectly, many of the concepts presented in this chapter in Chapter 4 and the Appendix in the two sets of applications pertaining to the petroleum-refining industry. We also demonstrate the ability of the framework to allow for extensive modifications and expansion. In Chapter 3, we provide the conceptual and informational background on the petroleum-refining industry that we need in order to apply the proposed procedure in the following chapter.

Chapter 3

An Overview of the Petroleum-Refining Industry

This chapter provides the conceptual and informational background on the petroleum refining industry. It therefore serves as reference for the technical aspects of subsequent discussions. We explain and define the many technical terms employed in a glossary at the end of this thesis.

The Industry's Importance and Evolution

The oil-refining industry is a critical link in the energy circuit. It transforms crude oil into transport fuels (gasoline, jet fuel, and diesel), residual fuel oil (widely used as a fuel in industry and the electric power sector), and other products, such as kerosene, used in developing countries for lighting and cooking. The industry is itself a heavy consumer of petroleum fuel in its own processes, and its facilities are capital intensive and frequently highly sophisticated.

In the early days of the evolution of the petroleum industry, up to about 1925, a few single products were made: petrol, kerosine, fuel oil, lubricants and wax. Straight distillation processes were adequate to produce them, occasionally followed by simple chemical treatments of the mixing and settling type to make them marketable. Today, petroleum is the source of hundreds of products, ranging from gases, to volatile liquids, to bitumen, and solid waxes. It is also the source of the hydrocarbon feedstocks for the vast petrochemical industry that has grown up since the Second World War. Moreover, besides distillation, there are now several other separation processes; and there are a variety of conversion processes that alter the chemical nature of the material and give considerable control over the quality and output of products for sale, making these less dependent upon the nature of the crude oil (Plummer, 1984: 329).

Crude-oil refining is the art of choosing the crude oils (so far as choice may exist) and of using the flexibility of the refinery processes so as to make the mix of products with the best financial return for the expenditure. This is not a fixed goal, however. Prices of crude oils and the required quantities, quality, and proportions of the different products vary with market demand. With the passage of time, there is also persistent demand for higher quality products. Refinery operations must constantly be studied to facilitate adaptation to changing needs. It takes from two to four years to design and build a new unit in a refinery, whether the process itself is new or established. Consequently, the decision to adopt a new process or build more of existing types of units must be taken in anticipation of market requirements and trends (EPA, 1976; Plummer, 1984; Gary and Handwerk, 1984).

Following the second oil shock, all of the main fuel categories (gasoline, middle distillates, and residual fuel oil) showed some decline in world demand (Plummer, 1984; Wijetilleke and Ody, 1984). The proportionate decline, however, was far greater for residual fuel oil than for distillate products. These changes in demand gave rise to supply-demand imbalances, particularly in countries with only primary distillation facilities, where the yield of different grades of petroleum fuels is limited to the same proportions as found in the crude oils processed.[11]

To eliminate or reduce these imbalances, refineries require additional secondary-processing facilities to enable them to convert surplus residual fuel oil to distillate products. A majority of the refineries in operation today were planned during the post-World War II period, but prior to the oil crises of the 1970s (Plummer, 1984; Wijetilleke and Ody, 1984). Except for the U. S. industry, and a few refineries in industrialized countries with secondary-processing facilities, most refineries were of austere design and consisted only of primary distillation and product quality upgrading facilities. These facilities, by the very nature of their design, produced principally fuel oil, which was then the dominant fuel consumed. The changes in consumption patterns and the likely continuation of these trends indicate a need for a restructuring of the refining industry to increase its yield of distillates (Wijetilleke and Ody, 1984). Indeed, last year's observed worldwide increases in downstream processing capabilities--especially in the United States, Western Europe, and in the

---

[11] The yield of residual fuel oil from crude oil distillation ranges from 30 to 55 percent of total production for most crude oils currently processed, whereas, in the majority of countries, demand for residual fuel oil has declined to a range of 15 to 35 percent of total consumption of all fuel. Conversely, the production of total distillate petroleum products is below demand, with the output from simple distillation between 44 and 67 percent compared to a demand which ranges from 50 to 70 percent of total fuel requirements (Wijetilleke and Ody, 1984).

Asia-Pacific region[12]--were consistent with similar trends observed throughout the 1980s (Oil and Gas Journal, December 23, 1991: 34).

The U. S. Refining Industry

A discussion of world petroleum refining would not be complete without a review of the U. S. refining industry, which is by far the largest and technologically most sophisticated.[13] Although the U. S. refining industry grew primarily to serve the domestic market, its potential to supply large quantities of distillates with relatively low incremental investments makes it of potentially increasing importance in the world oil market. U. S. refineries are more complex than those of Rotterdam and Singapore--two of the most significant refining complexes in the world[14] --and yield a much higher proportion of distillates. However, both refining centers are planning and implementing schemes for upgrading

---

[12] In the United States, a major portion of the increases in question was concentrated in the state of Texas. On the other hand, in the Asia/Pacific region, Singapore refineries are pioneering in upgrading their processing facilities (Oil and Gas Journal, December 23, 1991: 34-35).

[13] According to the American Petroleum Institute (January 1992), the estimated world-wide crude-oil refining capacity by area (in thousands of barrels per day) was: United States 15,559 (20.8%); other Western Hemisphere 9,436 (12.6%); Middle East 5,021 (6.7%); Africa 2,872 (3.8%); Asia and Australasia 12,603 (16.9%); Western Europe 14,224 (19.1%); and former USSR/Eastern Europe 14,927 (20%).

[14] In 1990, Singapore's share of world crude-oil refining capacity was 1.4%--4.2% higher than in 1989. Given the size of Singapore, the magnitude of its refining industry is indeed enormous. On the other hand, Rotterdam, Europe's most important oil-trading center, occupies a similar position in terms of its petroleum refineries. The Netherlands as a whole (including Netherlands Antilles) possessed 2.3% of the world's crude-oil refining capacity. Again, the size of the Netherlands and the centrality of Rotterdam within its refining industry add to the importance of the aforementioned figure (BP Statistical Review of World Energy, June 1991: 14).

their facilities. Indeed, the Asia/Pacific petroleum-refining industry is the fastest growing in the world both in terms of capacity and sophistication (Oil and Gas Journal, December 23, 1991: 35; Wijetilleke and Ody, 1984).

The U. S. petroleum-refining industry has undergone tremendous expansion and change since the 1950s. Enormous increases in the size of process units, new catalytic processes, shifting product demands, and new sources of petroleum from tar sands and oil shales have made present-day technology and the economics of petroleum refining a very complex and sophisticated science (Gary and Handwerk, 1984: iii).

The quality of crude oils processed by U. S. refineries is expected to worsen gradually in the future, while the demand for heavy fuel oil is expected to continue to decrease (Gary and Handwerk, 1984: 1). This will require refineries to process the entire barrel of crude rather than just the material boiling below 1050°F. Sulfur restrictions on fuels (coke and heavy fuel oils) are affecting bottom-of-the-barrel processing as well (Gary and Handwerk, 1984). These factors will require extensive refinery additions and modernization, and the shift in market demand between gasoline and distillates for transportation fuels will challenge catalyst suppliers and refinery engineers to develop innovative solutions to these problems.

The environmental impacts of fuel preparation and consumption will probably require that a significant shift take place in product distribution--i. e., less gasoline and more distillate fuel in terms of percent of crude (Oil and Gas Journal, December 16, 1991: 39-46). This will have a major effect on refinery processing operations and will place a burden on refinery construction along with producing the need to provide increased capacity for high-sulfur and heavier crude oils (Tahmassebi, 1991: 20-23; Energy Information Administration, 1991: 88-89). In fact, in order to meet current environmental regulations for new refineries, in terms of product specifications and refinery emissions, refineries must incur extra costs, which are frequently considered to be in the range of 10 to 15 percent of total investment (Gary and Handwerk, 1984: 223-224). It should be noted, however, that since the end of World War II, petroleum refineries have made efforts to minimize discharge of wastes into the environment. This voluntary control of emissions was done on the basis of safety, fuel economy, and the economic advantages of good maintenance (Gary and Handwerk, 1984: 223).

Overview of Refining Operations

Petroleum-refinery operations range from the receipt and storage of crude oil at the refinery to petroleum handling and refining operations and finally to the storage and shipping of the finished refined products from the refinery. A refinery's processing scheme is largely determined by the composition of the crude-oil feedstock and the chosen slate of petroleum products. The arrangement of these processes will vary among refineries and few, if any, employ all of the same processes (Sittig, 1978: 1-3, 22-25; Speight, 1980; EPA, 1985: 9.1-1). Table 3.1 summarizes the general refinery processes and their associated operations.

The first phase in petroleum-refining operations is the separation of crude oil into its major components using three petroleum separation processes: (1) atmospheric distillation, (2) vacuum distillation, and (3) gas processing. Crude oil consists of a mixture of hydrocarbon compounds including paraffinic, naphthenic, and aromatic hydrocarbons plus small amounts of impurities including sulfur, nitrogen, oxygen, and metals. Refinery separation processes separate these crude-oil constituents into common-boiling-point fractions (Gary and Handwerk, 1984: 2-4).

The second phase consists of various conversion processes that produce high-octane gasoline, jet-fuel, and diesel fuel as well as other light fractions through the conversion of such components as residual oils, fuel oils, and light ends. Cracking, coking, and visbreaking processes are used to break large molecules into smaller petroleum molecules. Polymerization and alkylation processes are used to combine small petroleum molecules into larger ones. Isomerization and reforming processes are applied to rearrange the structure of petroleum molecules to produce higher-value molecules of a similar molecular size (Gary and Handwerk, 1984; Speight, 1980; EPA, 1985).

The third phase involves treating processes that stabilize and upgrade petroleum products by separating them from less desirable products and by removing objectionable elements. Undesirable elements, such as sulfur, nitrogen, and oxygen are removed by hydrodesulfurization, hydrotreating,

Table 3.1

Categories of General Refinery Processes and Associated Operations

Separation	Petroleum Conversion	Petroleum Treating
Atmospheric Distillation Vacuum Distillation Gas Processing	Cracking (thermal and catalytic) Reforming Alkylation Polymerization Isomerization Coking Visbreaking	Hydrodesulfurization Hydrotreating Chemical Sweetening Acid-Gas Removal Deasphalting

Feedstock and Product Handling	Auxiliary Facilities
Storage Blending Loading Unloading	Boilers Wastewater Treatment Hydrogen Production Sulfur Recovery Plant Cooling Towers Blowdown System Compressor Engines

Source: U. S. Environmental Protection Agency, Compilation of Air Pollutant Emission Factors. 4th Edition. Volume 1. Research Triangle Park, NC: Office of Air Quality Planning and Standards, 1985.

chemical sweetening, and acid gas removal. Treating processes employed primarily for the separation of petroleum products include such processes as desalting and deasphalting. Desalting is used to remove salt, minerals, grit, and water from crude oil feed stocks prior to refining. Asphalt blowing is used for polymerizing and stabilizing asphalt to improve its weathering characteristics (Gary and Handwerk, 1985; Speight, 1980; EPA, 1985: 9. 1-11).

Refinery Products

Although the average consumer tends to think of petroleum products as consisting of a few items, such as motor gasoline, jet fuel, kerosine, a survey conducted by the American Petroleum Institute (API) of the petroleum refineries and petrochemical plants revealed over 2,000 products made to individual specifications (cited by Gary and Handwerk, 1984: 6). Table 3.2 shows the number of individual products in 17 classes.

In general, the products that dictate refinery design are relatively few in number, and the basic refinery processes are based on the large-quantity products, such as gasoline, jet fuel, and diesel fuel. Storage and waste-disposal are expensive, and it is necessary to sell or use all of the items produced from crude oil even if some of the materials, such as heavy fuel oil, must be sold at prices less than the cost of crude oil. Economic balances are required to determine whether certain crude fractions should be sold as is (i. e., straight-run) or further processed to produce products

Table 3.2

Products Made by the U. S. Petroleum Industry

Product Class	Number of Different of Different Products in Class
Fuel gas	1
Liquefied gases	13
Gasolines	40
Motor	19
Aviation	9
Other	12
Jet Fuels	5
Kerosines	10
Distillates (diesel fuels and light fuel oils)	27
Residual fuel oils	16
Lubricating oils	1156
White oils	100
Rust preventives	65
Transformer and cable oils	12
Greases	271
Waxes	113
Asphalts	209
Cokes	4
Carbon Blacks	5
Chemicals, solvents, misc.	300
TOTAL	2347

Source: James H. Gary and Glenn E. Handwerk.
Petroleum Refining: Technology and Economics.
2nd Edition. New York: Marcel Dekker, 1984: 6.

having greater value (Sittig, 1978; Plummer, 1984; Gary and Handwerk, 1984).

Process-Emission Sources and Control Technology

In this section, we describe refining processes that are significant air-pollutant contributors. We discuss process-flow schemes, emission characteristics, and emission control technology for each process. Tables 3.3 and 3.4 summarize information on individual process emissions. In a following section, we briefly discuss wastewater and solid-waste issues.

Vacuum Distillation

Topped crude withdrawn from the bottom of the atmospheric distillation column is composed of high-boiling-point hydrocarbons. When distilled at atmospheric pressures, the crude oil decomposes and polymerizes to foul equipment. To separate topped crude into components, it must be distilled at very low pressure and in a steam atmosphere. In the vacuum distillation unit, topped crude is heated and then flashed into a multi-tray vacuum distillation column where the topped crude is separated into common-boiling-point fractions by vaporization and condensation. Standard petroleum fractions withdrawn from the vacuum distillation column include lube distillates, vacuum oil, asphalt stocks, and residual oils (Gary and Handwerk, 1984: 43-45; EPA, 1985: 9. 1-4).

Table 3.3
Major Pollutants Emitted by Petroleum Refineries and Refining Processes that are Direct Air-Pollutant Contributors

Particulates	Sulfur Oxides	Carbon Monoxide
Fluid Catalytic Cracking	Fluid Catalytic Cracking	Fluid Catalytic Cracking
Moving-bed CC	Moving-bed CC	Moving-bed CC
Fluid Coking	Fluid Coking	Fluid Coking
Delayed Coking	Delayed Coking	Delayed Coking
Boilers	Compressor Engines	Compressor Engines
	Blowdown Systems	Blowdown Systems
	Claus Plant	
	Stretford Unit	
	Boilers	
Hydrocarbons	**Nitrogen Oxides**	**Aldehydes**
Fluid Catalytic Cracking	Fluid Catalytic Cracking	Fluid Catalytic Cracking
Moving-bed CC	Moving-bed CC	Moving-bed CC
Fluid Coking	Fluid Coking	Fluid Coking
Delayed Coking	Delayed Coking	Delayed Coking
Compressor Engines	Compressor Engines	Compressor Engines
Blowdown Systems	Boilers	
Claus Plant	Blowdown Systems	
Stretford Unit		
Boilers		
Vacuum Distillation		
	Ammonia	
	Fluid Catalytic Cracking	
	Moving-bed CC	
	Fluid Coking	
	Delayed Coking	
	Compressor Engines	

Source: U. S. Environmental Protection Agency, Compilation of Air Pollutant Emission Factors. 4th Edition. Volume 1. Research Triangle Park, NC: Office of Air Quality Planning and Standards, 1985.

Table 3.4
Air-Pollutant Emissions by Refining Process

	Partic. (1)	SOx (2)	CO (3)	HC's (4)	NOx (5)	Aldeh. (6)	Ammonia (7)
Vacuum Distillation							
Uncontrolled lb/1000 bbl vacuum feed	Neg	Neg	Neg	50	Neg	Neg	Neg
Controlled	Neg	Neg	Neg	Neg	Neg	Neg	Neg
Fluid Catalytic Cracking							
Uncontrolled lb/1000 bbl fresh feed	242	493	13,700	220	71	19	54
Electrostatic Precipitator and CO boiler lb/1000 bbl fresh feed	45	493	Neg	Neg	71	Neg	Neg
Moving-bed Catalytic Cracking lb/1000 bbl fresh feed	17	60	3,800	87	5	12	6
Fluid Coking Units							
Uncontrolled lb/1000 bbl fresh feed	523	NA	NA	NA	NA	NA	NA
Electrostatic Precipitator and CO boiler lb/1000 bbl fresh feed	6.85	NA	Neg	Neg	NA	Neg	Neg
Delayed Coking Units	NA	NA	NA	NA	NA	NA	NA
Industrial Boilers and Process Heaters Residual Fuel Oil, Natural Gas, and LPGs Combustion.	See Tables 4.1, 4.2, and 4.3 for combustion emissions						
Compressor Engines							
Reciprocating Engines lb/1000 cubic feet gas burned	Neg	2 S*	0.43	1.40	3.40	0.10	0.20
Gas Turbines lb/1000 cubic feet gas burned	Neg	2 S*	0.12	0.02	0.30	NA	NA

Table 3.4 cont'd

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Blowdown Systems Uncontrolled lb/1000 bbl refinery feed	Neg	Neg	Neg	580	Neg	Neg	Neg
Vapor Recovery System lb/1000 bbl refinery feed	Neg	26.90	4.30	0.80	18.90	Neg	Neg

* S = Sulfur content of the fuel used.

Source: U. S. Environmental Protection Agency,
Compilation of Air Pollutant Emission Factors.
4th Edition. Volume 1. Research Triangle Park, NC: Office of Air Quality
Planning and Standards, 1985.

The major sources of atmospheric emissions from the vacuum-distillation column are associated with the steam ejectors or vacuum pumps. A major portion of the vapors withdrawn from the column by the ejectors or pumps are recovered in condensers. There are approximately 50 pounds (23 kg) of noncondensable hydrocarbons per 1000 barrels of topped crude processed in the vacuum-distillation column. A second source of atmospheric emissions from vacuum-distillation columns is combustion products from the process heater. Process-heater requirements for the vacuum-distillation column are approximately 37,000 British thermal units (Btu) per barrel of topped crude processed in the vacuum column (EPA, 1985: 9.1-4). We discuss process-heater emissions and their control as well as fugitive-emission sources later in this section.

Control technology applicable to the noncondensable emissions vented from the vacuum ejectors or pumps include venting into blowdown systems or fuel-gas systems, and incineration in furnaces or waste-heat boilers. These control techniques are generally greater than 99 percent efficient in the control of hydrocarbon emissions, but they also contribute to the emission of combustion products (EPA, 1985; Sittig, 1978; Jones, 1973).

Catalytic Cracking

Catalytic cracking, using heat, pressure, and catalysts, converts heavy oils into lighter products with product distributions favoring the more valuable gasoline and distillate blending components. Feedstocks are usually gas oils from atmospheric distillation, vacuum distillation, coking, and deasphalting processes. All of the catalytic cracking processes in use today can be classified as either fluidized-bed or moving-bed units (EPA, 1985: 9. 1-4; Gary and Handwerk, 1984: 99).[15]

Fluidized-bed Catalytic Cracking (FCC). The FCC process uses a catalyst in the form of very fine particles that act as a fluid when aerated with a vapor. Fresh feed is preheated in a process heater and introduced into the bottom of a vertical transfer line or riser with a hot regenerated catalyst. The hot catalyst vaporizes the feed bringing both to the desired reaction temperature (EPA, 1985; Gary and Handwerk, 1984: 100).

Moving-bed Catalytic Cracking (TCC).[16] In the TCC process, catalyst beads flow by gravity into the top of the reactor where they contact a mixed-phase hydrocarbon feed. Cracking reactions take place as the catalyst and hydrocarbons move concurrently downward through the reactor to a zone where the catalyst is separated from the vapors. The gaseous reaction products flow out of the reactor to the fractionation section of the unit. The operating temperatures of the reactor and regenerator in the TCC process are comparable to those in the FCC process (EPA, 1985: 9. 1-5).

Air emissions from catalytic-cracking processes include combustion

---

[15] There are very few moving-bed (or Thermafor Catalytic Cracking or TCC) units in operation today, and the FCC unit has taken over the field (Gary and Handwerk, 1984: 99).

[16] Thermafor Catalytic Cracking.

products from process heaters and flue gas from catalyst regeneration. Emissions from the catalyst regenerator include hydrocarbons, oxides of sulfur, ammonia, aldehydes, oxides of nitrogen, cyanides, carbon monoxide, and particulates. The particulate emissions from FCC units are much greater than those from TCC units because of the higher catalyst-circulation rates used (EPA, 1985: 9.1-5).

FCC particulate emissions are controlled by cyclones and/or electrostatic precipitators. Particulate-control efficiencies are as high as 80 to 85 percent. Carbon-monoxide-wasteheat boilers reduce the carbon-monoxide and hydrocarbon emissions from FCC units to negligible levels. TCC catalyst regeneration produces similar pollutants to FCC units but in much smaller quantities. The particulate emissions from a TCC unit are incinerated to negligible levels by passing the flue gases through a process-heater fire-box or smoke-plume burner. In some installations, sulfur oxides are removed by passing the regenerator flue gases through a water or caustic scrubber (Sittig, 1978: 76-89; EPA, 1985; Oil and Gas Journal, 1991).

Thermal Cracking

Thermal-cracking processes include visbreaking and coking, which break heavy-oil molecules by exposing them to high temperatures (Gary and Handwerk, 1984: 54-55; EPA, 1985: 9. 1-5).

Visbreaking. Topped (distilled) crude or vacuum residuals are heated and thermally cracked in the visbreaker to reduce the viscosity of the charge. The cracked products are quenched with gas oil and flashed into a fractionator. A heavy distillate recovered from the fractionator liquid can be used as a fuel-oil blending component or used as catalytic cracking feed (EPA, 1985; Sittig, 1978: 67-70).

Coking. Coking is a thermal-cracking process used to convert low value residual fuel oil to higher value gas oil and petroleum coke. Vacuum residuals and thermal tars are cracked in the coking process at high temperature and low pressure. Products are petroleum coke, gas oils, and lighter petroleum stocks. Delayed coking is the most widely used process today, but fluid coking is expected to become an important process in the future (Gary and Handwerk, 1984: 55-56; EPA, 1985; Sittig, 1978: 70-73).

Analysts are unclear as to what emissions are released and where they are released (EPA, 1985; Sittig, 1978; Jones, 1973; Burklin et al., 1977). Air emissions from thermal-cracking processes include coke dust from decoking operations, combustion gases from the visbreaking and coking process heaters, and fugitive emissions. We discuss emissions from process heaters later. Fugitive emissions from miscellaneous leaks are significant because of the high temperatures involved, and are dependent upon equipment type and configuration, operating conditions, and general maintenance practices. Particulate emissions from delayed-coking operation, associated with removing the coke from the coke drum and subsequent handling and storage operations, can be very significant.

Hydrocarbon emissions are also associated with cooling and venting the coke drum prior to coke removal; however, comprehensive data for delayed-coking emissions are not included in the literature (EPA, 1985: 9.1-8; Burklin et al., 1977; Sittig, 1978).

Particulate-emission control is accomplished in the decoking operation by wetting down the coke. Generally, there is no control of hydrocarbon emissions from delayed coking. However, some facilities are now collecting coke drum emissions in an enclosed system and routing them to a refinery flare (EPA, 1985: 9.1-8).

Utilities Plant

The utilities plant supplies the steam necessary for the refinery. Although the steam can be used to generate electricity by throttling through a turbine, it is primarily used for heating and separating hydrocarbon streams. When used for heating, the steam usually heats the petroleum indirectly in heat exchangers and returns to the boiler. In direct-conduct operations, the steam can serve as a stripping medium or a process fluid. Steam may also be used in vacuum ejectors to produce a vacuum (EPA, 1985: 9. 1-8). We discuss emissions from boilers and applicable emission-control technology in other sections.

Sulfur-Recovery Plant

Sulfur-recovery plants are used in petroleum refineries to convert hydrogen sulfide (H_2S), separated from refinery-gas streams, into the more disposable by-product, elemental sulfur. To comply with environmental factors, at least 98 percent of the sulfur must be removed from the hydrogen-sulfide-rich gases. A Claus sulfur unit followed by a Stretford absorption unit reduces the hydrogen-sulfide content of the exit gases to less than five parts per million (ppm) (EPA, 1985: 5.18; Gary and Handwerk, 1984: 214-223). We present data on emissions from sulfur-recovery plants in the next chapter.

Blowdown Systems

Most refining-processing units and equipment subject to planned or unplanned hydrocarbon discharges are manifolded into a collection unit, called the blowdown system. The blowdown system provides for the safe disposal of hydrocarbons (vapor and liquid) discharged from pressure-relief devices. It can thus be considered as an abatement activity. By using a series of flash drums and condensers arranged in decreasing pressure, the blowdown is separated into vapor and liquid cuts. The separated liquid is recycled into the refinery. The gaseous cuts can either be smokelessly flared or recycled (EPA, 1985: 9.1-8).

Uncontrolled blowdown emissions consist primarily of hydrocarbons. The emission rate in a blowdown system is a function of the amount of equipment manifolded into the system, the frequency of equipment discharges, and the blowdown-system controls (EPA, 1985: 9.1-8). Emissions from the blowdown system can be effectively controlled by combustion of the noncondensables in a flare. To obtain complete combustion (as required by most states in the United States), steam is injected in the combustion zone of the flare to provide turbulence and to inspirate air. Steam injection also reduces emissions of nitrogen oxides by lowering the flame temperature (EPA, 1985: 9.1-8).

Process Heaters

Process heaters (furnaces) are used extensively in refineries to supply the heat necessary to raise the temperature of feed materials to reaction or distillation level. The fuel burned may be refinery gas, natural gas, residual fuel oils, or combinations, depending on the economics, operating conditions, and emissions requirements. Process heaters may also use carbon-monoxide-rich regenerator flue gas as fuel (EPA, 1985; Sittig, 1978; Jones, 1973).

All the criteria pollutants are emitted from process heaters. The quantity of these emissions is a function of the type of fuel burned, the nature of the contaminants in the fuel, and the heat duty of the furnace.[17] Sulfur oxides can be controlled by fuel desulfurization or fuel-gas treatment. Carbon monoxide and hydrocarbons can be limited by increased combustion efficiency. Currently, four general techniques or modifications for the control of nitrogen oxides are being investigated: combustion modification, fuel modification, furnace design, and flue-gas

---

[17] In Chapter 4, we present tables of detailed emission factors for different fuels used in process heaters.

treatment. Several of these techniques are presently being applied to large utility boilers, but their applicability to process heaters has not been established (EPA, 1985: 9.1-9).

Compressor Engines

Many older refineries run high-pressure compressors with reciprocating and gas-turbine engines fired with natural gas. Natural gas has traditionally been a cheap, abundant source of energy. Examples of refining units operating at high pressure include hydrodesulfurization, isomerization, reforming and hydrocracking. Internal combustion engines are less reliable and harder to maintain than steam engines or electric motors. For this reason and because of increasing natural gas costs, very few such units have been installed in the last few years (EPA, 1985: 9.1-9).

The major source of emissions from compressor engines is combustion products in the exhaust gas. These emissions include carbon monoxide, hydrocarbons, nitrogen oxides, aldehydes, and ammonia. Sulfur oxides may also be present, depending on the sulfur content of the natural gas. All these emissions are significantly higher in the exhaust from reciprocating engines than from turbine engines. The major emission-control technique applied to compressor engines is carburator adjustment similar to that applied on automobiles (EPA, 1985; Burklin et al., 1977).

Asphalt Blowing

The asphalt-blowing process polymerizes asphaltic residual oils by oxidation (heated air is involved), increasing their melting temperature and hardness to achieve an increased resistance to weathering. The reaction involved is exothermic, and steam is sometimes needed for temperature control.

Air emissions from asphalt blowing are primarily hydrocarbon vapors vented with the blowing air. The quantities of emissions are small because of the prior removal of volatile hydrocarbons in the distillation units. However, the emissions may contain hazardous polynuclear organics. Emissions are 60 pounds per ton of asphalt produced. These emissions can be controlled to negligible levels by vapor scrubbing, incineration or both (EPA, 1985: 9.1-11).

Fugitive Emissions

Fugitive-emission sources are generally defined as volatile-organic-compound (VOC) emission sources not associated with a specific process but scattered throughout the refinery. Fugitive emission sources include valves of all types, flanges, storage facilities, process drains, cooling towers, and oil/water separators. Fugitive VOC emissions are attributable to the evaporation of leaked or spilled petroleum liquids and gases. Normally, refineries can control fugitive emissions by minimizing leaks and spills through equipment changes, procedure changes, and improved monitoring and maintenance practices (EPA, 1985: 9.1-10 to 9.1-12). EPA (1985: 9.1-10 and 9.1-13) provides detailed information on both controlled and uncontrolled fugitive emissions for most emission sources. For the purpose of our analysis, however, an average figure of 45,000 pounds of VOC emissions per day (based on the operation of a 330,000 barrels-per-calendar-day (BPCD) refinery) is adequate.[18]

Overview of Solid/Liquid Wastes and their Treatment

The wide variety of process sequences coupled with the wide variety of products produced by the petroleum-refining industry leads to a complex set of wastes of varying composition and characteristics. Typical wastes generated include a variety of sludges (oil-water separator, air flotation, biological, etc.), tank bottoms, and filter clays to name just a few. Estimates of the amounts of wastes generated range from 0.63 million tons to 2.2 million tons annually (Burton and Ravishankar, 1989: 12). Waste-treatment methods are usually broken down into physical, thermal, chemical, and biological processes. A wide range of technologies are available in each of these waste-treatment categories. Burton and Ravishankar (1989) provide a detailed discussion of these technologies. Such a discussion, however, is beyond the scope of this study--whose focus

---

[18] As we indicated, detailed information on fugitive emissions for most emission sources is available (EPA, 1985). However, these emissions are attributed to thousands of individual pieces of equipment throughout the refinery. Including all of them in a refinery simulation would be extremely difficult. Moreover, since fugitive emissions are a function of refinery maintenance and product handling, their consideration for policy purposes is not vital to our analysis.

is air-pollutant emissions.

This concludes the brief discussion of petroleum refining operations and the pollutant-emission problems associated with each major refining process. Drawing upon the information outlined above as well as the information summarized in the accompanying tables, we illustrate, in Chapter 4, the pollution-estimation procedure presented in Chapter 2.

Chapter 4

Application of the Pollution-Estimation Method

In this chapter, we apply the general method for industry emission projection, that we conceptually developed in Chapter 2, to the case of the petroleum-refining industry--a complex industry for pollution analysis. The application requires the use of all the procedures discussed in Chapter 2--namely, multiprocess analysis, fuel-type and source analysis, raw-material-type and source analysis, prototype analysis and abatement-process analysis. We employ the activity-complex-analysis methodology and input-output concepts to organize and use the data and information related to pollution generation in a comprehensive way.

Despite the various simplifications introduced to make the task more manageable given the resource and time constraints of this study, we should reiterate that the illustration of the procedure remains a fairly elaborate and cumbersome task, given the complexity of the industry involved; however, the petroleum-refining industry is one of the most complex and difficult industries to simulate.[19] Nevertheless, individuals with limited technical background can easily understand the outcome of the analysis and use it in pollution-control-related policy making. This will become evident when the illustration is completed.

---

[19] That is, the application of the method to other industries promises not to be as complicated.

Refinery-Prototype Specification and Analysis

Within an industry, many processes may need to be considered both in terms of different technologies as well as different sources of fuels and raw materials. To avoid excessive research costs in terms of time and effort, as well as money, we consider prototypes. Because there are a number of prototypes that we could consider for the petroleum-refining industry, we begin with an analysis of the various possible refinery prototypes.[20]

Although no two refineries are exactly alike, petroleum refineries may be classified in general groups according to either the general purpose of the refinery (i. e., portion of the product slate emphasized) or any specialty processing associated with the refinery, such as lube-oil or petrochemical processing. Topping, fuel oil, and gasoline refineries each produce a different yield structure and consequently utilize significantly different processing sequences. Refineries producing lube oils or petrochemicals employ special process streams. Sittig (1978) classifies refineries into five basic categories: topping, fuel-oil, gasoline, lube-oil, and petrochemical refineries.

Another categorization has been used in a comprehensive report to the National Commission on Water Quality by Engineering-Science, Inc. as well as by EPA (Gordian Associates, 1974; Engineering-Science, 1975; Sittig, 1978). Their purpose was to develop a subcategorization strategy to

---

[20] To illustrate our general procedure and develop the data for prototypes, we need consider only two.

group together refineries with common pollution-abatement problems from both technical and economic standpoints. This would permit the development of representative model refineries for each subcategory, so that costs, materials, and labor for various levels of wastewater-abatement performance could be estimated for a single plant. This information could then be extrapolated across the entire subcategory. From our analysis of the subcategorization of the petroleum-refining industry, we concluded that, due to the *add-on* nature of refinery processes, it would be possible for a refinery to produce almost any product mix. In other words, a strict subcategorization in which certain plants all produce a certain product mix exclusive of that in another subcategory is essentially impossible.

The U. S. Environmental Protection Agency (EPA) has found it convenient to categorize the various petroleum refineries into five groups, given below, based on raw-waste-load (RWL), product-mix, refinery-process, and wastewater-generation characteristics. This classification system which includes five divisions, is based on the components of a classification system proposed by the American Petroleum Institute (API) in the mid-1960s (cited by Sittig, 1978: 23).

Subcategory 1 (Topping Refinery): This includes topping (distillation) and catalytic reforming whether or not the facility includes any other process in addition to topping and catalytic processes. This subcategory is not applicable to facilities that include thermal processes (coking, visbreaking, etc.) or catalytic cracking.

Subcategory 2 (Cracking Refinery): This includes topping and cracking, whether or not the facility includes any processes in addition to topping and cracking, unless specified in one of the subcategories listed below.

Subcategory 3 (Petrochemical Refinery): This includes topping, cracking, and petrochemical operations, whether or not the facility includes any process in addition to topping, cracking, and petrochemical operations, except lube-oil manufacturing processes.

Subcategory 4 (Lube Refinery): Topping, cracking, and lube-oil manufacturing processes, whether or not the facility includes any process in addition to topping, cracking, and lube-oil manufacturing processes, except petrochemical operations.

Subcategory 5 (Integrated Refinery): Topping, cracking, lube-oil manufacturing processes, and petrochemical operations, whether or not the facility includes any process in addition to topping, cracking, lube-oil manufacturing processes, and petrochemical operations.

Although Plummer (1984) does not strictly categorize refineries, he offers a similar, but rather more flexible, approach which allows us to construct a classification scheme based, again, on the processes operated in the refinery complex examined. More specifically, he considers a 'hydroskimming' refinery[21] as his base-case refinery and builds upon that by adding more elaborate treatment and conversion processes.[22] We

---

[21] EPA's Topping Refinery.

[22] More specifically, Plummer points out that this base-case refinery would consist of a crude-oil distilling unit, a gasoline-sweetening unit, and a catalytic reformer. In

should emphasize that a large refinery complex (or any refinery complex in that matter) is perpetually under modification to accommodate new crude oils or new products or new qualities to satisfy "incessant market changes" (Plummer, 1984: 333). We should keep in mind throughout the course of this discussion that we are dealing with an extremely dynamic, ever-changing system.

Drawing on the above as well as on the extensive literature on petroleum-refining operations, we choose first to consider and examine two refinery prototypes: a base-case 'hydroskimming' or 'topping' refinery and an 'integrated' refinery, covering, in this respect, the entire spectrum of refinery-operation complexity.[23] Other cases or prototypes will structurally be upgrades of the 'hydroskimming' refinery prototype or sub-cases of the integrated one.

Fuel-Type and Source Analysis

We now consider and analyze the fuels that a refinery complex consumes in order to satisfy its energy needs. A wide variety of fuels, of different quality and composition, is used by petroleum refineries.[24] The

---

addition, it would employ a desulfurization unit. As the need develops to produce specialty products such as bitumens, lubes, and waxes and to increase the yield of premium products, such as motor gasoline, above that obtainable from crude, many more units will be added. A large and complex refinery would therefore employ some or all of the following processes: vacuum distillation, catalytic cracking, hydrocracking, solvent and lube-oil extraction, a dewaxing plant, an alkylation unit, an aromatics-extraction unit, lubricating-oil refining plants, and a coking plant

[23] Strictly as far as processes employed are concerned.

[24] Refinery fuels include: natural gas, residual and distillate fuel oil, LPGs,

fuel mix consumed by any refinery is unique in quality and composition since refineries use a significant amount of fuels they produce internally--either as intermediate or final products. As it becomes evident when we calculate the pollutant-emissions produced by a refinery, the fuel mix as well as the fuel quality and chemical composition play a crucial role in determining the pollutant mix produced.[25]

Tables 4.1, 4.2, and 4.3 examine more closely the emissions associated with the combustion of fuels such as natural gas, fuel oil, and liquefied petroleum gases (LPGs) respectively. In Table 4.1, we indicate that the sulfur-dioxide emission factor is based on an average sulfur content of the natural gas combusted. In addition, we note that the improper operation and maintenance of a natural-gas-burning industrial boiler results in significant increases in the levels of carbon-monoxide emissions. In Table 4.2, we present emission factors for the combustion of residual and distillate fuel oils in industrial boilers. We indicate that sulfur-dioxide and sulfur-trioxide emissions, for both types of fuel oil, are a function of the oils' sulfur content. Moreover, for residual-fuel-oil combustion, nitrogen-oxide emissions are a function of the fuel's nitrogen content. Finally, we show how particulate emissions vary as a function of grade and sulfur content of residual fuel oil. In Table 4.3, we summarize

---

petroleum coke, and still/refinery gas. The corresponding gross heating values are: 1,050 Btu per cubic foot; 15,300 Btu per gallon; 142,700 Btu per gallon; 96,100 Btu per gallon; 169,600 Btu per gallon; and 1,200 Btu per cubic foot respectively.

[25] In Chapter 3, we presented the significant contribution of fuel-consuming auxiliary facilities/power systems to direct pollutant-emissions production.

Table 4. 1

Uncontrolled Emissions for Natural Gas Combustion
(in lbs per million cubic feet)

	Particulates	Sulfur Dioxide	Nitrogen Oxides	Carbon Monoxide	Volatile Organic Compounds
Furnace Type					
Industrial Boiler	3	0.6*	140	35**	2.9

Notes:
* Based on an average sulfur content of natural gas of 2 kg/10^6 ft^3.
** May increase 10 to 100 times with improper operation or maintenance.

Source: U. S. Environmental Protection Agency,
Compilation of Air Pollutant Emission Factors.
4th Edition. Volume I. Research Triangle Park, North Carolina:
Office of Air Quality Planning and Standards, 1985.

Table 4. 2

Uncontrolled Emissions for Fuel Oil Combustion
(in lbs per one thousand gallons)

Boiler Type and Type of Fuel Oil	Particu- lates	Sulfur Dioxide	Sulfur Trioxide	Carbon Monoxide	Nitrogen Oxides	Volatile Organic Compounds
Industrial Boilers						
Residual Oil	*	157S	2S	5	55**	0.64
Distillate Oil	2	142S	2S	5	20	0.126

Notes:
* Particulate emission factors for residual oil combustion are on average a function of fuel-oil grade and Sulfur content:
Grade 6 oil: [10(S) + 3] lb/1000 gal where S is the weight percent of sulfur in the oil. This relationship is based on 81 individual tests (the correlation coefficient is 0.65).
Grade 5 oil: 10 lb/1000 gal
Grade 4 oil: 7 lb/1000 gal

** Nitrogen emissions from residual oil combustion in industrial boilers are strongly related to fuel nitrogen content, estimated more accurately by the relationship:

[lb NOx/1000 gal = 22 + 400 (N)^2],

where N is the weight percent of nitrogen in the oil. For residual oils having high (> 5 weight %) nitrogen content, the emission factor is [120 lb NOx/1000 gal].

Source: U. S. Environmental Protection Agency, Compilation of Air Pollutant Emission Factors. 4th Edition. Volume I. Research Triangle Park, North Carolina: Office of Air Quality Planning and Standards, 1985.

Table 4. 3
Emission Factors for Liquefied Petroleum Gas (LPG) Combustion
(in lbs per one thousand gallons of fuel)

Furnace Type and Fuel	Particulates	Sulfur Dioxide	Nitrogen Oxides	Carbon Monoxide	Volatile Organic Compounds
Industrial Furnace					
Butane	0.285	0.09S	13.2	3.3	0.27
Propane	0.265	0.09S	12.4	3.1	0.26

Notes:
* S is the weight percent of Sulfur in the fuel.

Source: U. S. Environmental Protection Agency,
Compilation of Air Pollutant Emission Factors.
4th Edition. Volume I. Research Triangle Park, North Carolina:
Office of Air Quality Planning and Standards, 1985.

emission factors for LPG combustion. This gas is usually 95 percent propane. However, it can be any one of several specified mixtures of propane and butane (Gary and Handwerk, 1984: 300). Again, we indicate that sulfur-dioxide emissions are a function of the fuel's sulfur content.

Raw-Material (crude oil) Type and Source Analysis

The basic raw material for refineries is petroleum or crude oil, even though in some areas synthetic crude oils from other sources--such as tar sands--are included in the refinery feedstocks. The term petroleum or crude oil covers a wide assortment of materials consisting of mixtures of hydrocarbons and other compounds. The chemical compositions of crude oils are surprisingly uniform even though their physical characteristics vary widely. Small differences in composition, then, can greatly affect the physical properties and the processing required to produce a desired set of products. The elementary composition of crude oil by weight percent (% by weight) usually falls within the following ranges (Speight, 1980: 49; Gary and Handwerk, 1984: 16):

Carbon 83.0 - 87.0
Hydrogen 10.0 - 14.0
Nitrogen 0.1 - 2.0
Oxygen 0.05 - 1.5
Sulfur 0.05 - 6.0

Petroleum chemists have made many attempts to classify petroleum into certain types. However, no successful universal method of classification has evolved yet. The original methods of classification arose because of commercial interest in various types of petroleum and were a means of providing refinery operators with a rough guide to processing conditions. Crude oils have therefore been classified by *compound type,* based on a *correlation index,* by *density,* by *carbon distribution,* and finally based on a parameter called *viscosity-gravity constant* (Speight, 1984: 40-47). In the United States, crude oils are classified as paraffin base, napthene base, asphalt base, or mixed base. There are also some crude oils in the Far East which have up to 80 percent aromatic content, and these are known as aromatic-base oils (Gary and Handwerk, 1984).

Crude oil is very complex and except for its low-boiling components, refiners do not attempt to analyze for the pure components contained in it. Sulfur content is the one petroleum property most pertinent to our analysis.[26] Along with API gravity, sulfur content is the property that has had the greatest influence on the value of crude oil, although nitrogen and metals content are increasing in importance. The sulfur content is expressed as percent sulfur by weight and varies from less than 0.1 percent to greater than 5 percent (see above). Crudes with greater than 0.5 percent sulfur generally require more extensive processing than those with lower sulfur content. Although the term 'sour' crude initially referred to those crudes containing dissolved hydrogen sulfide independent of total sulfur content, it has come to mean any crude oil with a sulfur content high enough to require special processing. There is no sharp dividing line

---

[26] Other very useful properties include: API Gravity, Pour Point, Carbon Residue, Salt Content, and Distillation Range (Gary and Handwerk, 1984: 17-19).

between sour and sweet crudes, but 0.5 percent sulfur content is frequently used as the criterion (Gary and Handwerk, 1984: 17-18). Table 4.4 presents information on some characteristics of various crudes.

Along with process configuration, the crude slate imposes limitations on the product mix that a refinery can produce. In the extreme, a change in crude type can downgrade refinery capacity and hence product output. Similarly, a refinery designed to run on sweet crude may be incapable of processing sour crude. There are two reasons for this: first, the sour crude is more corrosive and the metallurgy of the crude unit may not be adequate; and, second, the higher-sulfur crude produces more pollutants (H_2S, SO_2, etc.) which the refinery may be incapable of removing without major alterations and additions of abatement activities (Gary and Handwerk, 1984).

Two other factors make description of crude slates more difficult. First, crude production and properties for a given oil field vary with time and location in the field. For example, as crude production declines in an oil field, the gravity of the crude tends to increase. This tends to make the crude less valuable to a refinery because processing is more difficult and the yield of light products per barrel decreases. Forecasting of crude production is extremely hard; yet to design new refineries and make intelligent alterations to existing refineries (including expensive abatement processes), engineers must have adequate information on the origin, quality, and composition of the crude slate (Gary and Handwerk, 1984). Table 4.5 provides information on the fractional mix of crude-oil

Table 4.4
Specific Gravity and Average Sulfur Content of Selected Crude Oils

Origin	Sulfur Content	Specific Gravity
Canada	4.54	0.85
Indonesia	0.15	0.85
Iran	1.40	0.86
Iraq	2.93	0.85
Kuwait	2.45	0.87
Mexico	4.05	0.88
Nigeria	0.66	0.86
USSR	0.20	0.86
United Kingdom	0.66	0.86
United States*	0.60	0.85
Venezuela**	5.70	0.90

Notes:

* Sulfur-content tends to vary at different points in time even in the case of crudes pumped from the same oil field. Moreover, the variability observed in a country of the size of the United States is enormous. For example, compare East-Texas crude's sulfur content (0.55% by wt) with that of West-Texas crude (2% by wt).

** In addition, Speight reports sulfur-content figures for crude oils from West Venezuela (2.2% by wt) and East Venezuela (0.55% by wt). The variation in sulfur content within a country is indicative of the complexities involved with describing and using the variability a crude's characteristics in a modeling exercise such as this one.

Source: James G. Speight, The Chemistry and Technology of Petroleum. New York: Marcel Dekker, 1980; James H. Gary and Glenn Handwerk, Petroleum Refining: Technology and Economics. 2nd Edition. New York: Marcel Dekker, 1984; Energy Information Administration, Petroleum Supply Annual. Volumes 1 and 2. Washington, DC: U. S. Government Printing Office, 1991.

Table 4.5
Mix (in fractions) of Crude-Oil Input for U. S. Refineries, by Source of Crude, 1989.

Source of Crude	Mix of Crude-Oil Input
United States	0.655
Saudi Arabia	0.073
Mexico	0.054
Canada	0.055
Nigeria	0.049
Venezuela	0.035
Iraq	0.028
United Kingdom	0.020
Angola	0.016
Indonesia	0.015

Source: Energy Information Administration, Petroleum Supply Annual. Volumes 1 and 2. Washington, DC: U. S. Government Printing Office, 1990.

inputs for U. S. refineries, by source of crude, in 1989.

Pollution Estimation for Prototypes I and II

Using a format similar to that of input-output and activity complex analysis, we list a number of refining processes at the head of columns of Table 4.6 (Prototype I) and Table 4.7 (Prototype II). These processes correspond to the $j_\alpha, j_\beta, \ldots, j_\rho$ discussed in Chapter 2. We sometimes disaggregate the column headings to describe alternative technologies, different levels of operation, and different pollution-control measures and efficiencies.

We then list commodities, either inputs or outputs, that are involved in these processes, i. e., the $g = 1, \ldots, p$ of Chapter 2, and indicated as the first subscript in the coefficients $\alpha_{gr\mu}$ (where $r = 1, \ldots, n$, refers to the prototype involved). In performing this task, we follow Gary and Handwerk (1984). In the first row, we list the raw material crude oil. Then, in descending order, we list two intermediate products, desalted crude and topped crude. Following are a series of inputs, such as power, fuel, steam, process and cooling water, and then a series of fuels, such as natural gas, still gas, and fuel oil. We finally include a series of air-pollutant outputs ranging from particulates to aldehydes and ammonia.

We should note that in Tables 4.6 and 4.7, we do not purport to list inputs and outputs for all refinery products. This is beyond the scope of this study. We merely list the inputs and those pollutant outputs that are necessary for demonstrating the use of the proposed procedure. The

Table 4.6

Interactivity Table for Refinery Prototype I
(Basis: 100,000 BPCD of Alaska-North-Slope Crude Oil)

	Desalter (1)	Atmospheric Distillation (2)	Vacuum Distillation (3)	Hydro-treater (4)	Catalytic Reforming (5)
1. Crude Oil	-1	0	0	0	0
2. Desalted Crude	1	-1	0	0	0
3. Topped Crude	0	0.561	-1	0	0
4. Power	-0.12	-0.5	-0.196	-1.995	-3.008
5. Fuel	0	-0.07	-0.039	-0.099	-0.3
6. Steam	0	-6	-8.99	-5.986	-30.04
7. Process water	-1.253	0	0	0	0
8. Cooling water	-3.989	-6.005	-60.004	-299.97	-599.971
9. Natural Gas	0	0	0	0	0
10. Still/Refinery Gas	0	0	0	0	0
11. Residual Fuel Oil	0	0	0	0	0
12. Particulates	0	0	0	0	0
13. Sulfur Dioxide	0	0	0	0	0
14. Sulfur Trioxide	0	0	0	0	0
15. Carbon Monoxide	0	0	0	0	0
16. Carbon Dioxide	0	0	0	0	0
17. Hydrocarbons	0	0	0.05*	0	0
18. Nitrogen Oxides	0	0	0	0	0
19. VOCs	0	0	0	0	0
20. Aldehydes	0	0	0	0	0
21. Ammonia	0	0	0	0	0

Notes:
* This factor represents uncontrolled emissions. When the emissions are controlled, the factor is approximately equal to zero.
**We assume that no. 4 residual fuel oil with 1% Sulfur by weight.

Source: U. S. Environmental Protection Agency, Compilation of Air Pollutant Emission Factors. 4th Edition. Volume 1. Research Triangle Park, NC: Office of Air Quality Planning and Standards, 1985; James H. Gary and Glenn E. Handwerk, Petroleum Refining: Technology and Economics. 2nd Edition. New York: Marcel Dekker, 1984.

Table 4.6 cont'd

	Process Heater			Blowdown Systems Vapor Recovery (9)
	Natural Gas (6)	Still Gas (7)	Residual Fuel Oil (8)	
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	-1	0	0	0
10	0	-1	0	0
11	0	0	-1	0
12	3	3.5	7**	0
13	0.6	0.8	157	0.0269
14	0	0	2	0
15	35	37	5	0.0043
16	0	0	0	0
17	0	0	0	0.0008
18	140	150	55	0.0189
19	5.8	6.5	1.28	0
20	0	0	0	0
21	0	0	0	0

Table 4.7

Interactivity Table for Refinery Prototutpe II
(Basis: 100,000 BPCD of Alaska-North-Slope Crude Oil)

	Desalter (1)	Atmospheric Distillation (2)	Vacuum Distillation (3)	Coking	
				Fluid	
				Uncontrolled (4)	Electrostatic Precipitator (5)
1. Crude Oil	-1	0	0	0	0
2. Desalted Crude	1	-1	0	0	0
3. Topped Crude	0	0.561	-1	0	0
4. Power	-0.12	-0.5	-0.196	-2.104	2.104
5. Fuel	0	-0.07	-0.039	-0.16	-0.16
6. Steam	0	-6	-8.99	-26.263	-26.263
7. Process Water	-1.253	0	0	0	0
8. Cooling water	-3.989	-6.005	-60.004	-100	-100
9. Natural Gas	0	0	0	0	0
10. Still/Refinery Gas	0	0	0	0	0
11. Residual Fuel Oil	0	0	0	0	0
12. LPGs	0	0	0	0	0
13. Petroleum Coke	0	0	0	0	0
14. Particulates	0	0	0	0.523	0.00685
15. Sulfur Dioxide	0	0	0	NA	NA
16. Sulfur Trioxide	0	0	0	NA	NA
17. Carbon Monoxide	0	0	0	NA	0
18. Carbon Dioxide	0	0	0	NA	0
19. Hydrocarbons	0	0	0.05*	NA	0
20. Nitrogen Oxides	0	0	0	NA	NA
21. VOCs	0	0	0	NA	NA
22. Aldehydes	0	0	0	NA	0
23. Ammonia	0	0	0	NA	0
24. Hydrogen Sulfide	0	0	0	NA	NA
25. Elemental Sulfur	0	0	0	0	0
26. Carbon Dioxide	0	0	0	0	0
27. Hydrogen Sulfide	0	0	0	0	0

* Emissions are negligible when controlled.

Source: U. S. EPA, <u>Compilation of Air Pollutant Emission Factors.</u>
Research Triangle Park, NC: Office of Air Quality Planning and Standards, 1985.

Table 4.7 cont'd

	Coking Delayed	Hydrotreater	Catalytic Reforming	Catalytic Cracking			Alkylation	Hydrocracker
				FCC		Moving Bed		
				Uncontrolled	Electrostatic Precipitator			
	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	2.104	-1.995	-3.008	-6.006	-6.006	-6.006	-3.753	-14.471
5	-0.16	-0.099	-0.3	-0.1	-0.1	-0.1	-1.039	-0.275
6	-26.263	-5.986	-30.04	0	0	0	-10.938	-93.987
7	0	0	0	0	0	0	0	0
8	-100	-299.973	-599.971	-499.318	-499.318	-499.318	-3706.2	-563.07
9	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0
14	NA	0	0	0.242	0.045	0.017	0	0
15	0.136	0	0	0.493	0.493	0.06	0	0
16	NA	0	0	0	0	0	0	0
17	NA	0	0	13.7	0	3.8	0	0
18	NA	0	0	0	0	0	0	0
19	NA	0	0	0.22	0	0.087	0	0
20	NA	0	0	0.071	0.071	0.005	0	0
21	NA	0	0	0	0	0	0	0
22	NA	0	0	0.019	0	0.012	0	0
23	NA	0	0	0.054	0	0.006	0	0
24	2.556	0.764	0.552	0	0	0	0	5.883
25	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0

Table 4.7 cont'd

	Hydro-gen Pro-duction (14)	Gas Plant (15)	Amine Trea-ter (16)	Claus Plant							
				Number of Catalytic Stages and Control Efficiency							
				2-Uncontroll.		3-Uncontroll.		4-Uncontroll.		Controlled	
				92 (17)	95 (18)	95 (19)	97.5 (20)	96 (21)	99 (22)	99 (23)	99.9 (24)
1	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0
4	-781.25	-3425	-0.01	-23.1	-23.095	-23.1	-23.095	-23.095	-23.1	-23.1	-23.1
5	-237.19	-172.4	-0.001	0	0	0	0	0	0	0	0
6	0	0	0	6374.1	6374.13	6374	6374.13	6374.13	6374	6374	6374
7	-5287.5	0	0	-814.8	-814.78	-815	-814.781	-814.781	-815	-815	-815
8	-343125	-1E+06	-4.399	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	348	211	211	167	167	124	40	4
16	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	285.45	285.45	285	285.45	285.45	285.5	285.5	285.5
19	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	260.51	260.508	261	260.508	260.508	260.5	260.5	260.5
25	0	0	0	1	1	1	1	1	1	1	1
26	0	0	0	-285.5	-285.45	-285	-285.45	-285.45	-285	-285	-285
27	0	0	0	-2597	-2596.8	-2597	-2596.77	-2596.77	-2597	-2597	-2597

Table 4.7 cont'd

	Stretford Unit (25)	Process Heater					Compressor Engines		Blowdown Systems	
		Nat. Gas (27)	Still Gas (28)	Res. Fuel Oil (29)	LPGs (30)	Petroleum Coke (31)	Reciprocating (32)	Gas Turbines (33)	Uncontrolled (34)	Vapor Recovery System/ Flaring (35)
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0
4	-2187.5	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0
8	-13500	0	0	0	0	0	0	0	0	0
9	0	-1	0	0	0	0	0	0	0	0
10	0	0	-1	0	0	0	-1	-1	0	0
11	0	0	0	-1	0	0	0	0	0	0
12	0	0	0	0	-1	0	0	0	0	0
13	0	0	0	0	0	-1	0	0	0	0
14	0	3	3.5	7**	0.55	NA	0	0	0	0
15	0	0.6	0.8	157	0.99	NA	.002S	.002S	0	0.0269
16	0	0	0	2	0	NA	0	0	0	0
17	0	35	37	5	2.2	NA	0.00043	0.00012	0	0.0043
18	2575	0	0	0	0	NA	0	0	0	0
19	0	0	0	0	0	NA	0.0014	0.00002	0.58	0.0008
20	0	140	150	55	12.8	NA	0.0034	0.0003	0	0.0189
21	0	5.8	6.5	1.28	0.53	NA	0	0	0	0
22	0	0	0	0	0	NA	0.0001	NA	0	0
23	0	0	0	0	0	NA	0.0002	NA	0	0
24	0	0	0	0	0	NA	0	0	0	0
25	1	0	0	0	0	NA	0	0	0	0
26	-2575	0	0	0	0	NA	0	0	0	0
27	-2350	0	0	0	0	NA	0	0	0	0

tables, however, can be easily expanded to include additional rows of inputs and outputs associated with the listed processes if additional information needs to be generated. This flexibility and expandability is one of the main advantages of the proposed framework since it can be very easily updated and enriched given the specific needs of a user or the availability of additional or more accurate information.

Pollution Estimation for Prototype I

As mentioned above, we first apply the proposed procedure to estimate the emissions of a base-case refinery, termed Prototype I, similar to the 'hydroskimming' and 'topping' refineries described at the beginning of the chapter. The basic processes operated in this prototype are:

1. Crude desalting
2. Atmospheric distillation
3. Vacuum distillation
4. Gas recovery and sweetening
5. Desulfurization
6. Catalytic reforming
7. Hydrotreating
8. Gasoline blending
9. Auxiliary facilities (process heaters, blowdown systems, steam and cooling water systems)

Although we emphasize processes with direct emissions, we present most of the major processes employed so that the estimation of the fuel requirements for the prototype in question is more accurate. The operation of this prototype does not include refinery-wide abatement processes (like Claus or Stretford units).[27] We incorporate them in the description of an integrated refinery complex in the following section.

Selected input-output data for unit levels of process operation are given in Table 4.6.[28] Following Gary and Handwerk's analysis, we assume a level of operations of 100,000 barrels of crude oil per calendar day (BPCD).[29] Based on EPA (1976 and 1985), Sittig (1979), Speight (1980), and Gary and Handwerk (1984), the table also includes the amount of pollutants emitted by each process per unit level of operation (termed emission factors by EPA).

For simplicity, we assume that the refinery's process heaters consume three types of fuel with the following fractional mix: natural gas: 0.10; residual fuel oil (no. 4): 0.30; refinery/still gas: 0.60 (Scenario A); therefore, the interactivity table describing the prototype's operation will present three different entries for the fuel system disaggregating in that way the operation of the process heater system by fuel type (see the three column entries--(6), (7), and (8)--for the process-heater operation in Table 4.6).

The total fuel requirement of Prototype I is approximately 27,097 x 10^6

---

[27] Blowdown systems, however, represent an abatement activity designed to control Volatile Organic Compound (VOC) emissions.

[28] A unit level of operation can be defined arbitrarily for each process so that our calculations can be simplified. Where necessary and where it is not obvious by the information provided, we will indicate the unit levels operation of the processes examined.

[29] This is the amount of crude oil throughput that a refinery can process in one calendar day when operated at full capacity. We also assume that the 100,000 barrels of petroleum are Alaska-North-Slope crude. Refineries usually process a mix of different crudes.

Btu/day. Given the above fractional fuel mix and assuming a 100 percent conversion efficiency[30], natural gas contributes 2,710 x 10^6 Btu which corresponds to 2.581 x 10^6 cubic feet of natural gas, still/refinery gas contributes 16,258 x 10^6 Btu/day corresponding to 13.548 x 10^6 cubic feet of still gas, and residual fuel oil 8,129 x 10^6 Btu/day corresponding to 54,087 gallons of residual fuel oil.[31]

Based on the above and the Gary-and-Handwerk calibration results, the level of operations for the processes outlined above[32] (with the exception of the gas plant and the desulfurization and gasoline-blending units which are not involved in the pollution estimation) is depicted by the activity-level vector shown as Column 1 in Table 4.8.

---

[30] The assumption, although clearly unrealistic, serves the purpose of illustrating the procedure. The efficiencies of utility boilers and refinery heaters, however, vary widely, depending on the type of equipment, its age and maintenance as well as on a multitude of other factors. A single measure of fuel conversion efficiency is therefore almost impossible to reach.

[31] The estimation of the fuel requirements is based on the fuel and steam requirements of the following processes as described in Gary and Handwerk's analysis (see page 289 for a summary of utility requirements) as well as those of a gas plant: desalting, atmospheric and vacuum distillation, catalytic reforming, and hydrotreating. We assume that the total fuel requirements for steam generation are 1,200 Btu/lb of steam (Gary and Handwerk, 1984: 264).

[32] We assume the level of operations for process heaters burning gaseous fuels to be one million cubic feet of gaseous fuel. In the case of liquid fuels, we assume the level of operation to be one thousand gallons of fuel. We will maintain these assumptions throughout this thesis. Figures in activity-level vectors should be interpreted accordingly.

Table 4.8

Activity-Level Vectors for Prototype I

Scenarios A, B, and C

Activity	Scenario A	Scenario B	Scenario C
Desalter	100,000	100,000	100,000
Atm. Distill.	100,000	100,000	100,000
Vac. Distill.	56,060	56,060	56,060
Hydrotreater	18,040	18,040	18,040
Cat. reform.	24,930	24,930	24,930
NG Heater	2.581	2.581	10.323
SG Heater	13.548	13.548	11.290
FO Heater	54.087	54.087	18.029
Blowdown	100,000	100,000	100,000

Multiplying the (11 x 9) matrix of pollution coefficients (that is, Table 4.9 of pollution coefficients for Prototype I)[33] with the (9x1) activity-level vector for Scenario A, yields a (11x1) vector representing the pollution emissions of this version of Prototype I (Column 1 of Table 4.11 and Table 4.12).

Recall that pollutant emissions vary with type and source of fuel, as do the inputs and other outputs of a process or a prototype. We can illustrate this point with reference to Prototype I (Scenario B). All other things being equal, we change the variable 'sulfur content' that enters into the equation that determines the SOx emissions of the residual fuel oil

---

[33] This pollution-coefficients table is a partition of the matrix describing the operation of Prototype I (Table 4.6). See also Chapter 2.

Table 4.9

Pollution-Coefficients Table for Refinery Prototype I

Scenarios A and C

	Desalter (1)	Atm. Distill. (2)	Vacuum Distill. (3)	Hydro-treater (4)	Cat. Reform. (5)	Process Heater Nat. Gas (6)	Process Heater Still Gas (7)	Process Heater Fuel Oil (8)	Blowdown System Vapor Recovery (9)
1. Particulates	0	0	0	0	0	3	3.5	7	0
2. Sulfur Dioxide	0	0	0	0	0	0.6	0.8	157	0.0269
3. Sulfur Trioxide	0	0	0	0	0	0	0	2	0
4. Carbon Monoxide	0	0	0	0	0	35	37	5	0.0043
5. Carbon Dioxide	0	0	0	0	0	0	0	0	0
6. Hydrocarbons	0	0	0.05	0	0	0	0	0	0.0008
7. Nitrogen Oxides	0	0	0	0	0	140	150	55	0.0189
8. VOCs	0	0	0	0	0	5.8	6.5	1.28	0
9. Aldehydes	0	0	0	0	0	0	0	0	0
10. Ammonia	0	0	0	0	0	0	0	0	0
11. Hydrogen Sulfide	0	0	0	0.764	0.552	0	0	0	0

Source: U. S. Environmental Protection Agency, Compilation of Air Pollutant Emission Factors. 4th Edition. Volume I. Research Triangle Park, NC: Office of Air Quality Planning and Standards, 1985.

Table 4.10

Pollution-Coefficients Table for Refinery Prototype I

Scenario B

	Desalter (1)	Atm. Distill. (2)	Vacuum Distill. (3)	Hydro-treater (4)	Cat. Reform. (5)	Process Heater			Blowdown Syst. Vapor Recovery (9)
						Nat. Gas (6)	Still Gas (7)	Fuel Oil (8)	
1. Particulates	0	0	0	0	0	3	3.5	7	0
2. Sulfur Dioxide	0	0	0	0	0	0.6	0.8	314	0.0269
3. Sulfur Trioxide	0	0	0	0	0	0	0	4	0
4. Carbon Monoxide	0	0	0	0	0	35	37	5	0.0043
5. Carbon Dioxide	0	0	0	0	0	0	0	0	0
6. Hydrocarbons	0	0	0.05	0	0	0	0	0	0.0008
7. Nitrogen Oxides	0	0	0	0	0	140	150	55	0.0189
8. VOCs	0	0	0	0	0	5.8	6.5	1.28	0
9. Aldehydes	0	0	0	0	0	0	0	0	0
10. Ammonia	0	0	0	0	0	0	0	0	0
11. Hydrogen Sulfide	0	0	0	0.764	0.552	0	0	0	0

Source: U. S. Environmental Protection Agency, Compilation of Air Pollutant Emission Factors. 4th Edition. Volume I. Research Triangle Park, NC: Office of Air Quality Planning and Standards, 1985.

Table 4.11

Refinery Prototype I

Pollution-Output Vectors for Scenarios A, B, and C

	Scenario A	Scenario B	Scenario C
1. Particulates	433.77	433.77	196.69
2. Sulfur Dioxide	11194	19686	5535.78
3. Sulfur Trioxide	108.17	216.35	36.06
4. Carbon Monoxide	1292.00	1292.00	1299.20
5. Carbon Dioxide	0	0	0
6. Hydrocarbons	2883	2883	2883
7. Nitrogen Oxides	7258.30	7258.30	6020.30
8. VOCs	172.26	172.26	156.34
9. Aldehydes	0	0	0
10. Ammonia	0	0	0
11. Hydrogen Sulfide	27544	27544	27544

Source: Author's calculations.

Table 4.12

Refinery Prototype I
Pollution Output for Scenarios A, B, and C
(pounds per barrel crude-oil input)

	Scenario A	Scenario B	Scenario C
1. Particulates	0.0043	0.0043	0.0020
2. Sulfur Dioxide	0.1119	0.1969	0.0553
3. Sulfur Trioxide	0.0011	0.0022	0.0004
4. Carbon Monoxide	0.0129	0.0129	0.0130
5. Carbon Dioxide	0	0	0
6. Hydrocarbons	0.0288	0.0288	0.0288
7. Nitrogen Oxides	0.0726	0.0726	0.0602
8. VOCs	0.0017	0.0017	0.0016
9. Aldehydes	0	0	0
10. Ammonia	0	0	0
11. Hydrogen Sulfide	0.2754	0.2754	0.2754

from 1 percent to 2 percent (see Table 4.2 above for more information on the pollutant emissions associated with the combustion of residual fuel oil). This results in a different coefficient entering the cell representing unit-level emissions associated with the combustion of fuel oil in a process/refinery heater. Given that the activity-level vector remains unchanged (see Columns 1 and 2 of Table 4.8), we follow the same procedure as in Scenario A to obtain the new pollution vector. Tables 4.11 and 4.12 (Column 2) describe the resulting pollution-output vector. A simple comparison between Columns 1 and 2, in both Table 4.11 and Table 4.121, reveals a substantial increase in the levels of both sulfur dioxide and sulfur trioxide generated.

Now if we change the fuel fractional mix to natural gas = 0.40, still gas = 0.50, and residual fuel oil = 0.10 (Scenario C), all other things being equal (as in Scenario A), the activity-level vector changes as Column 3 of Table 4.8 shows. A simple comparison between Columns 1 and 2 (Scenarios A and B with the same fuel mix) and Column 3 shows the changes in the process-heater entries for the three fuels as a result of the change in the prototype's fuel fractional mix. Again, the resulting pollutant-output vector changes as Tables 4.11 and 4.12 (Column 3) indicate. Here, we point out an apparent interpollutant tradeoff concerning the level of pollution generated by the three operating scenarios of Prototype I. We observe that the emissions of particulates, sulfur oxides, and nitrogen oxides for Scenario C decrease in comparison to both Scenarios A and B. At the same time, the emissions of carbon monoxide are slightly higher.

Given the number of different fuels, fuel qualities, and fuel fractional mixes possible, we can generate a large number of combinations of fuel mixes and estimate, through this analytical framework, their impact on the resulting pollutant-output vector.[34] Fairly simple modifications of the coefficients in the interactivity Table 4.6 (and its associated pollution-coefficient matrices, Tables 4.9 and 4.10) for Prototype I and the activity-level vectors of Table 4.8, enable us to trace the changes affected on the pollutant-output vector and observe the resulting tradeoffs. We believe that, although we have varied only one of the parameters affecting pollution generation--namely fuel input--and made only a limited number of the possible modifications, we were able to demonstrate the ability of the method to generate information based on different sets of variables. In the case of the integrated refinery to be examined next, we vary all the parameters influencing the pollution mix and illustrate how the framework can accommodate and respond to the changes in question. Here, we simply sought to illustrate the use of the procedure.

We note that the analysis and calibration results employed are based on 100,000 barrels of Alaska-North-Slope crude oil. If another source of crude is utilized, then, the level of operation of the various activities involved will change accordingly; consequently, the pollution output will also change. Given the different composition of the various crudes as well

---

[34] Our focus in this prototype's variations has been on the fuels involved partly because the refining processes considered here do not generate direct pollution emissions.

as their different gravities (see Table 4.4 for characteristics of crudes of different origin), process and equipment modifications will be necessitated. Although an elaborate discussion of the technical aspects of this issue is clearly beyond the scope of this study, we will revisit it when we apply this analytical framework to the case of the U. S. petroleum-refining industry in the Appendix.

Pollution Estimation for Prototype II

Although the illustration of the use of the pollution-estimation procedure in the case of Prototype I revealed some of the complexities as well as the infinite number of variations that can be examined when analyzing a complex industrial process through the proposed framework, we must expand the example and demonstrate the method for the case of an integrated refinery.

Drawing upon Gary and Handwerk's analysis as well as that of Sittig (1978), and Plummer (1984), we re-introduce an 'integrated' refinery as one that includes the entire gamut of refinery separation, conversion, and treatment processes as well as a variety of abatement activities. This application brings together all aspects of analysis introduced in Chapter 2 and reiterated at the beginning of this chapter. Based on the literature definition of an integrated refinery (Sittig, 1978; EPA, 1985; Plummer, 1984; Gary and Handwerk, 1984; Leffler, 1979), as well as our own assessment and analysis, the integrated refinery we examine--designated Prototype II--

includes the following processes and abatement activities in addition to the processes described under Prototype I:[35]

1. Coking
2. Catalytic cracking
3. Alkylation
4. Hydrocracking
5. Hydrogen production
6. Gas plant
7. Amine treater
8. Claus Plant
9. Stretford unit
10. Auxiliary facilities (process/refinery heaters, steam system, cooling water system, blowdown systems, and compressor engines).

In examining this prototype, we introduce another dimension of analysis, namely, the inclusion of alternative technologies and different levels of abatement in the analytical framework. In the case of coking, for example, we examine three sets of alternative sets of technologies designed to perform essentially the same task although at different degrees of efficiency and with different abatement measures attached to them (or no abatement at all): uncontrolled fluid coking (no abatement), fluid coking with an electrostatic precipitator, and delayed coking (see Columns 4, 5, 6 of Table 4.7). As we show in the application to follow, different pollution coefficients are associated with the operation of the three alternative coking processes. We can modify our framework--describing the matrix of input-output coefficients for Prototype II--as well as the appropriate activity-level vectors to incorporate these different cases and obtain three different sets of pollutant-output vectors, all other things

---

[35] We note that petroleum refining is an essentially additive process.

being equal. This is also true for the case of catalytic cracking, which also involves three different kinds of processes with different requirements and emissions: moving-bed catalytic cracking, uncontrolled fluid catalytic cracking, and fluid catalytic cracking with an electrostatic precipitator (see Columns 9, 10, and 11 of Table 4.7). In this section, we demonstrate the flexibility of the framework in adopting and incorporating changes in its coefficients and its ability to accommodate different process configurations.

In the case of Prototype II, we incorporate the use of the entire spectrum of fuels used to power a refinery complex. The interactivity Table 4.7 includes column entries for process/refinery heaters using these fuels. This level of detail enables us--as in the case of Prototype I--to demonstrate the effects of different fuel fractional mixes on the refinery's pollution mix. In the interactivity Table 4.7 describing the operation of Prototype II, we also include variations of processes that may not be used together in one refinery (processes that may be substitutes--such as the various coking and cracking operations we mentioned above). Activity-complex analysis and interactivity tables allow us to list those processes in the same tabular framework (unlike input-output tables). They are presented so that we can demonstrate the estimation of the pollution mix produced by variations (in terms of processes involved) of an integrated refinery. In each case, the interactivity matrix corresponding to each refinery variation (or scenario) is different (all derived from Table 4.7). We present each one separately (as Tables 4.14, 4.15, and 4.16), along with its corresponding activity-level vector (summarized in Table 4.13)--as was the case when we examined fuel-type and quality variations in the case of Prototype I.

In the following paragraphs, we examine four variations of the integrated-refinery case. Scenario A involves the use of a fuel mix consisting of 20 percent natural gas, 40 percent still gas, 30 percent fuel oil, and 10 percent LPGs. The activities operated are desalting, atmospheric and vacuum distillation, delayed coking, hydrotreating, catalytic reforming, moving-bed catalytic cracking, alkylation, hydrocracking, hydrogen production, gas plant, amine treater, Claus plant (2 catalytic stages/uncontrolled), process heaters with the four fuels mentioned above, reciprocating compressor engines, and blowdown systems (vapor-recovery system and flaring). The activity-level vector depicting the operation of Scenario A is shown as Column 1 in Table 4.13.

Table 4.13
Activity-Level Vectors for Prototype II
Scenarios A, B, C, and D

Scenario A	Scenario B	Scenario C	Scenario D
100,000	100,000	100,000	100,000
100,000	100,000	100,000	100,000
56,060	56,060	56,060	100,000
23,760	23,760	23,760	23,760
18,040	18,040	18,040	18,040
24,930	24,930	24,930	24,930
32,300	32,300	32,300	32,300
7,460	7,460	7,460	7,460
16,930	16,930	16,930	16,930
25.6	25.6	25.6	25.6

Table 4.13 cont'd

36.2	36.2	36.2	36.2
815,040	815,040	815,040	815,040
86.6	86.6	86.6	86.6
9.6	9.6	9.6	9.6
10.7	26.9	10.7	10.7
9.4	8.2	9.4	18.8
112.575	37.525	112.575	112.575
58.689	29.344	58.689	58.689
9.4	8.2	9.4	100,000
100,000	100,000	100,000	

The entries in the above four activity-level vectors correspond to the activities listed, in the same order, at the heads of the columns of the pollution-coefficient tables associated with each vector.

The pollution-coefficient matrix corresponding to Scenario A is obtained from Table 4.7 when the above activities (also listed in Table 4.14) are operated. By multiplying the (11x20) pollution-coefficient matrix, Table 4.14, with the (20x1) activity-level vector for Scenario A, we obtain the (11x1) pollution-output vector presented as Column 1 in Tables 4.17 and 4.18.

The second version of Prototype II under consideration (Scenario B) employs the same activities as Scenario A; however, a different fuel mix is employed: 50 percent natural gas, 35 percent still gas, 10 percent fuel oil, and 5 percent LPGs. The pollution-coefficient matrix is the same as that in Scenario A (Table 4.14); however, the new activity-level vector is shown as

Table 4.14
Pollution Coefficients Table for Prototype II
Scenarios A and B

	Desalter (1)	Atm. Distill. (2)	Vacuum Distill. (3)	Delayed Coking (6)	Hydro-treater (7)	Catalytic Reforming (8)	Moving Bed Catalytic Cracking (11)	Alky-lation (12)	Hydro-cracker (13)	Hydrogen Production (14)
1. Particulates	0	0	0	0	0	0	0.017	0	0	0
2. Sulfur Dioxide	0	0	0	0.136	0	0	0.06	0	0	0
3. Sulfur Trioxide	0	0	0	0	0	0	0	0	0	0
4. Carbon Monoxide	0	0	0	0	0	0	3.8	0	0	0
5. Carbon Dioxide	0	0	0	0	0	0	0	0	0	0
6. Hydrocarbons	0	0	0.05	0	0	0	0.087	0	0	0
7. Nitrogen Oxides	0	0	0	0	0	0	0.005	0	0	0
8. VOCs	0	0	0	0	0	0	0	0	0	0
9. Aldehydes	0	0	0	0	0	0	0.012	0	0	0
10. Ammonia	0	0	0	0	0	0	0.006	0	0	0
11. Hydrogen Sulfide	0	0	0	0	0	0	0	0	0	0

Source: U. S. Environmental Protection Agency, Compilation of Air Pollutant Emission Factors. 4th Edition. Volume 1. Research Triangle Park, NC: Office of Air Quality Planning and Standards, 1985; James H. Gary and Glenn E. Handwerk, Petroleum Refining: Technology and Economics. 2nd Edition. New York: Marcel Dekker, 1984.

Table 4.14 cont'd

	Gas Plant (15)	Amine Treater (16)	Claus Plant 2-stage Uncontrolled 92 (17)	Stretford Unit (25)	Process Heater				Reciprocating Compressor Engines (32)	Blowdown System Vapor Recovery and Flaring System (35)
					Natural Gas (27)	Still Gas (28)	Residual Fuel Oil (29)	LPGs (30)		
1	0	0	0	0	3	3.5	7	0.55	0	0
2	0	0	348	0	0.6	0.8	157	0.09	2	0.0269
3	0	0	0	0	0	0	2	0	0	0
4	0	0	0	0	35	37	5	2.2	0.43	0.0043
5	0	0	285.45	2575	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	1.4	0.0008
7	0	0	0	0	140	150	55	12.8	3.4	0.0189
8	0	0	0	0	5.8	6.5	1.28	0.53	0	0
9	0	0	0	0	0	0	0	0	0.1	0
10	0	0	0	0	0	0	0	0	0.2	0
11	0	0	260.508	0	0	0	0	0	0	0

Column 2 in Table 4.13. The changes in the vector due to the modified fuel mix can be observed when Columns 1 and 2 of Table 4.13 are compared. The resulting pollution-output vector is shown as Column 2 in Tables 4.17 and 4.18. The wide variation in the emissions of some of the pollutants is demonstrated by a simple comparison of the first two columns of the tables in question. The use of a larger amount of 'cleaner' fuels such as natural gas and a smaller amount of fuel oil translate into lower emissions of particulates, sulfur oxides, and nitrogen oxides. However, the emissions of carbon monoxide are higher in Scenario B than in Scenario A.

The third case involving Prototype II (Scenario C), explores another aspect of the proposed framework, namely, the use of alternative process technologies. More specifically, fluid catalytic cracking with an electrostatic precipitator replaces moving-bed catalytic cracking. Keeping the fuel mix the same as in Scenario A of Prototype II and the rest of the processes unchanged, we multiply the modified pollution-coefficient matrix, Table 4.15, with the activity-level vector shown as Column 3 in Table 4.13 to obtain the pollution-output vector presented as Column 3 in Tables 4.17 and 4.18. The tradeoffs in terms of simultaneous decreases and increases in the emission levels of different pollutants are dramatically demonstrated when we compare the first three columns of Tables 4.17 and 4.18. Although its emissions of particulates, sulfur dioxide, and nitrogen oxides are higher than those of either Scenario A or B, Scenario C

Table 4.15
Pollution Coefficients Table for Prototype II
Scenario C

	Desalter (1)	Atm. Distill. (2)	Vacuum Distill. (3)	Delayed Coking (6)	Hydro-treater (7)	Catalytic Reforming (8)	FCC Electrostatic Precipitator (10)	Alky-lation (12)	Hydro-cracker (13)	Hydrogen Production (14)
1. Particulates	0	0	0	0	0	0	0.045	0	0	0
2. Sulfur Dioxide	0	0	0	0.136	0	0	0.493	0	0	0
3. Sulfur Trioxide	0	0	0	0	0	0	0	0	0	0
4. Carbon Monoxide	0	0	0	0	0	0	0	0	0	0
5. Carbon Dioxide	0	0	0	0	0	0	0	0	0	0
6. Hydrocarbons	0	0	0.05	0	0	0	0	0	0	0
7. Nitrogen Oxides	0	0	0	0	0	0	0.071	0	0	0
8. VOCs	0	0	0	0	0	0	0	0	0	0
9. Aldehydes	0	0	0	0	0	0	0	0	0	0
10. Ammonia	0	0	0	0	0	0	0	0	0	0
11. Hydrogen Sulfide	0	0	0	0	0	0	0	0	0	0

Source: U. S. Environmental Protection Agency, Compilation of Air Pollutant Emission Factors. 4th Edition. Volume 1. Research Triangle Park, NC: Office of Air Quality Planning and Standards, 1985; James H. Gary and Glenn E. Handwerk, Petroleum Refining: Technology and Economics. 2nd Edition. New York: Marcel Dekker, 1984.

Table 4.15 cont'd

	Gas Plant (15)	Amine Treater (16)	Claus Plant 2-stage Uncontrolled 92 (17)	Stretford Unit (25)	Process Heater				Recipro-cating Compressor Engines (32)	Blowdown System Vapor Recovery and Flaring System (35)
					Natural Gas (27)	Still Gas (28)	Residual Fuel Oil (29)	LPGs (30)		
1	0	0	0	0	3	3.5	7	0.55	0	0
2	0	0	348	0	0.6	0.8	157	0.09	2	0.0269
3	0	0	0	0	0	0	2	0	0	0
4	0	0	0	0	35	37	5	2.2	0.43	0.0043
5	0	0	285.45	2575	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	1.4	0.0008
7	0	0	0	0	140	150	55	12.8	3.4	0.0189
8	0	0	0	0	5.8	6.5	1.28	0.53	0	0
9	0	0	0	0	0	0	0	0	0.1	0
10	0	0	0	0	0	0	0	0	0.2	0
11	0	0	260.508	0	0	0	0	0	0	0

produces much lower amounts of carbon monoxide, hydrocarbons, aldehydes, and ammonia. Therefore, the choice among scenarios based solely on lower pollutant emissions is difficult since there is no easy way for aggregating the emissions of different pollutants. However, we can clearly choose between different process configurations as well as fuel mixes when we seek a lower level of emissions for a specific pollutant. We will return to this issue when we discuss the potential policy-making implications of the proposed procedure in the last chapter.

Finally, we examine a fourth version of Prototype II (Scenario D) in which all the major abatement activities are operated at their maximum. Thus, this refinery employs controlled vacuum distillation, fluid coking/electrostatic precipitator, fluid catalytic cracking/electrostatic precipitator, a Claus plant with controlled emissions, a Stretford unit, as well as a vapor-recovery system and flaring.[36] It should be noted that this version of Prototype II does not employ compressor engines--a feature of many older refineries and a significant pollutant contributor. Multiplying the modified pollution-coefficient matrix, Table 4.16, with the activity-level vector shown as Column 4 in Table 4.13, we obtain the pollution-output vector recorded as Column 4 in Tables 4.17 and 4.18. Again, we observe the resulting interpollutant tradeoffs in terms of simultaneous increases and decreases in the emission levels of different pollutants.

---

[36] The rest of the processes employed are the same as in the previous cases examined. These processes include: desalting, atmospheric distillation, hydrotreating, catalytic reforming, alkylation, hydrocracking, hydrogen production, gas plant, and amine treater.

Table 4.16

Pollution Coefficients Table for Prototype II

Scenario D

	Desalter (1)	Atm. Distill. (2)	Vacuum Distill. (3)	Fluid Coking Electrostatic Precipitator (5)	Hydro-treater (7)	Catalytic Reforming (8)	FCC Electrostatic Precipitator (10)	Alky-lation (12)	Hydro-cracker (13)
1. Particulates	0	0	0	0.00685	0	0	0.045	0	0
2. Sulfur Dioxide	0	0	0	0	0	0	0.493	0	0
3. Sulfur Trioxide	0	0	0	0	0	0	0	0	0
4. Carbon Monoxide	0	0	0	0	0	0	0	0	0
5. Carbon Dioxide	0	0	0	0	0	0	0	0	0
6. Hydrocarbons	0	0	0	0	0	0	0	0	0
7. Nitrogen Oxides	0	0	0	0	0	0	0.071	0	0
8. VOCs	0	0	0	0	0	0	0	0	0
9. Aldehydes	0	0	0	0	0	0	0	0	0
10. Ammonia	0	0	0	0	0	0	0	0	0
11. Hydrogen Sulfide	0	0	0	0	0	0	0	0	0

Source: U. S. Environmental Protection Agency, Compilation of Air Pollutant Emission Factors. 4th Edition. Volume 1. Research Triangle Park, NC: Office of Air Quality Planning and Standards, 1985; James H. Gary and Glenn E. Handwerk, Petroleum Refining: Technology and Economics. 2nd Edition. New York: Marcel Dekker, 1984.

Table 4.16 cont'd

	Hydrogen Production (14)	Gas Plant (15)	Amine Treater (16)	Claus Plant Controlled 99.9 (24)	Stretford Unit (25)	Process Heater				Blowdown System Vapor Recovery and Flaring System (35)
						Natural Gas (27)	Still Gas (28)	Residual Fuel Oil (29)	LPGs (30)	
1	0	0	0	0	0	3	3.5	7	0.55	0
2	0	0	0	4	0	0.6	0.8	157	0.09	0.0269
3	0	0	0	0	0	0	0	2	0	0
4	0	0	0	0	0	35	37	5	2.2	0.0043
5	0	0	0	285.45	2575	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0.0008
7	0	0	0	0	0	140	150	55	12.8	0.0189
8	0	0	0	0	0	5.8	6.5	1.28	0.53	0
9	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0
11	0	0	0	260.508	0	0	0	0	0	0

Table 4.17

Refinery Prototype II

Pollution Output Vectors for Scenarios A, B, C, and D

(in lbs)

	Scenario A	Scenario B	Scenario C	Scenario D
1. Particulates	1434.53	937.28	2338.9	2534.6
2. Sulfur Dioxide	55761.28	43955.77	69747	36714
3. Sulfur Trioxide	225.15	75.05	225.15	225.15
4. Carbon Monoxide	124589.8	124670.1	1849.8	2193.6
5. Carbon Dioxide	49439.97	49439.97	49440	49440
6. Hydrocarbons	5706.26	5704.62	2896.2	80
7. Nitrogen Oxides	11940.31	9512.82	14072	15450
8. VOCs	298.61	272.82	298.61	359.71
9. Aldehydes	388.54	388.42	0.94	0
10. Ammonia	195.68	195.44	1.88	0
11. Hydrogen Sulfide	22559.99	22559.99	22559.99	22559.99

Source: Author's calculations.

Table 4.18

Refinery Prototype II
Pollution Output for Scenarios A, B, C, and D
(pounds per barrel crude-oil input)

	Scenario A	Scenario B	Scenario C	Scenario D
1. Particulates	0.0143	0.0094	0.0234	0.0253
2. Sulfur Dioxide	0.5576	0.4396	0.6975	0.3671
3. Sulfur Trioxide	0.0023	0.0008	0.0023	0.0023
4. Carbon Monoxide	1.2459	1.2467	0.0185	0.0219
5. Carbon Dioxide	0.4944	0.4944	0.4944	0.4944
6. Hydrocarbons	0.0571	0.0570	0.0290	0.0008
7. Nitrogen Oxides	0.1194	0.0951	0.1407	0.1545
8. VOCs	0.0030	0.0027	0.0030	0.0036
9. Aldehydes	0.0039	0.0039	0	0
10. Ammonia	0.0020	0.0020	0	0
11. Hydrogen Sulfide	0.2256	0.2256	0.2256	0.2256

Source: Author's calculations.

Through detailed applications of the proposed procedure, we were able to demonstrate that it can actually be used to perform an elaborate simulation of a complex industry such as the petroleum-refining industry and estimate the amounts of pollutants it produces. We used the analytical framework to construct several variations of two basic refinery prototypes involving a variety of process configurations, fuel inputs, and types and levels of abatement. We then traced the effects of the changes in the variables in question on the amounts of pollutants produced by the petroleum refinery. After calculating the pollution emissions for each operating scenario, we were able to compare the different emission levels and identify any tradeoffs in terms of simultaneous increases and decreases in the amounts of different pollutants generated.

Admittedly, the information and data requirements for such a scheme are significant. However, the required information, although not always found in comprehensive reports or literature reviews, does exist in available literature--both published and unpublished (industry technical reports, memoranda, surveys etc.). The quality of available data, however, is not always as high as desired because of outdated and incomplete sets of data, etc. This sometimes requires assumptions as well as extrapolations based on parallel textbook cases found in the literature. The proposed framework thus serves another task--that of organizing available data in a comprehensive way so that they can be more easily manipulated and interpreted. Most importantly, however, analysts can use the detailed information generated by this framework as the basis for analyses that seek to identify a least-cost combination of inputs, processes, and abatement activities that meets a desired level of environmental quality. We demonstrated in detail how the different operation and abatement scenarios--that analysts may consider--can be constructed and how the pollution they generate can be calculated. The flexibility, expandability, and dynamic character of the framework in accommodating changes in the variables and coefficients involved was demonstrated throughout this chapter.

In the next chapter, we focus on the potential uses of the proposed procedure in environmental policy making. We examine how the procedure can be used in conjunction with other types of analyses and discuss the difficulties involved with the application of such a detailed framework for projecting industrial-pollutant emissions.

Chapter 5

Policy Relevance and Concluding Remarks

Accurate information is essential for effective pollution-control policy. It is important for environmental policy makers to be aware of the dynamics of pollution generation not just on the aggregate level but also at the microlevel--that of the individual industrial process. In this study, we presented and applied a framework to organize and analyze the variables that are directly or indirectly involved in industrial-pollution generation. At the same time, we presented these variables, be it fuels, individual processes or raw materials, in such a way so that they can be combined to form prototypes that yield different pollution outputs. The framework has, by design, a dynamic and flexible character in that we can simultaneously examine and compare alternative technologies and abatement measures--with respect to the pollutants they generate and control. This is also true for the case of fuel inputs and raw materials. Interpollutant tradeoffs in terms of simultaneous increases and decreases in the amounts of two or more pollutants generated, as a result of process or input changes, can also be traced through the framework. We illustrated in detail the ability of the framework to do so in Chapter 4.

Our intention has been to introduce a framework that can serve as a basis for comparing alternative pollution-generating scenarios involving an industry--both in terms of pollutant emissions as well as in terms of the costs associated with the adoption of one set of technologies or inputs versus another.[37] As we demonstrated in Chapter 4, analysts can incorporate abatement activities of different type and pollution-control efficiency into the analysis to provide an integrated representation of the operation of an industry from an environmental/pollution-control perspective. Procedures devised in the 1960s and 1970s for projecting pollution emission levels through the use of input-output methodology are not adequate to provide the informational basis for industrial-pollution-control policies.

Environmental policy makers can use the comprehensive nature of the proposed procedure and its ability to generate alternative pollution-generation and abatement scenarios, combined with available cost data for each component involved, to enhance the effectiveness of environmental policy-making. Using this technique, they can identify the least-cost solutions that an industry can adopt--in terms of combinations of processes, inputs, and abatement activities--to meet a specified level of environmental quality. In this way, they can ensure a more cost-effective application of potential policy measures and a more efficient use of the resources allocated for pollution control.

As indicated above, we did not intend this study to fill the lacuna in

---

[37] A comparative-cost study involving various levels of pollution outputs and alternative process configurations, abatement levels, raw material inputs, and fuels is beyond the scope of this study. However, this can be easily done on the basis of the information generated by our framework and relevant cost data for the variables involved.

cost estimates with new estimates of actual costs for controlling pollution from various sources; nor did we want to suggest which process configuration or abatement level is the desired or optimal one under any circumstances. Rather, our goal is to present a comprehensive framework to organize information and data on the various aspects of an industrial operation and to allow for the construction of various hypothetical operating scenarios to estimate the pollution outputs generated by each one of them. Because each industry is broken down into its individual processes and inputs, in their various types and combinations, the contribution of each process to the overall pollution output can be calculated. In addition, we can observe the different pollutant emissions of alternative technologies, as was demonstrated in the application of the method in previous chapters. Finally, as shown in Chapter 4, we can assess the pollution-output variations and interpollutant tradeoffs resulting from the use of different fuel types and fuel mixes.

We concede that the data and information requirements of our proposed framework are significant. However, our research reveals that sufficient information exists that may enable analysts to construct such analytical frameworks and estimate the pollution emissions of a large number of industries.[38] In using the information and data available, though, analysts should be aware of the biases and limitations inherent in

---

[38] See, for example, E. P. A.'s AP-42 multipliers that provide information on pollution generation by approximately 150 industries. Pollutant-emissions data are given for all major processes that contribute to the pollution output of each industry examined.

them (Crandall, 1983: 34-44).

We emphasize that this method is essentially a modeling exercise. By nature "models are primarily instruments for research and understanding" (Braat and van Lierop, 1987: 17); and by definition, models are not copies but rather simplified versions of a part of reality. Although the simplification may be its greatest drawback, it is what makes a model useful because it offers a comprehensible version of a problem situation. Further, aggregation--as in the case of constructing a prototype, however inclusive that may be--leads to a condensation of information and hence to a loss of detailed insight. Aggregation, however, enhances the understanding of complex phenomena--such as industrial pollution generation--by structuring the data so as to focus attention on their important general features. Moreover, an aggregation analysis often exhibits results that are not in agreement with behavioral relationships specified at a disaggregate level (Braat and van Lierop, 1987: 31). We believe that through the proposed procedure we achieve a constructive combination of both levels of analysis although the latter is clearly emphasized. We do not claim, however, that the procedure is free of all the disadvantages associated with either level of analysis.

After re-capping the various attributes of the proposed framework, we briefly revisit the question of how the proposed method fits into the overall environmental-policy framework. Combined with the discussion of approaches to pollution control and environmental policy presented in Chapter 1 and the theoretical background and applications presented in

Chapters 2 and 4, we use this final discussion to add the last dimension to the analysis presented in this thesis.

Environmental or pollution-control policies are the outcome of a long and often tedious decision-making process in which the benefits of pollution control are balanced against the costs. The cost information needed to select pollution-control policies depends upon the objectives and methods of the decision-making process itself. Policy makers often suggest that a pollutant must be controlled to the maximum extent that is technologically feasible or that the best available technology (BAT) be applied to its control (Crandall, 1983: 60).[39] If this requirement were interpreted literally, it would mean that an existing pollution-control device--even if extremely expensive--must be used. Given the resource scarcity every society faces, this proposition is obviously flawed since resources would have to be redirected from other socially equally desirable activities. In a society that must satisfy its needs from limited resources, the crucial decisions that policy makers must make concern the allocation of these resources among many competing needs. It is thus imperative that the information on which individual allocations are based is as comprehensive and inclusive as possible. This definitely applies to the case of pollution-control-related resource allocations as well.

For most pollutants, control is not an all-or-nothing matter. Often,

---

[39] If the 'best available technology' is interpreted to mean 'cheapest' or more 'efficient' (in terms of cost per unit of pollution reduction), policy makers have to obviously address the question of tradeoffs between different abatement measures and the level of environmental quality they can achieve.

industries can incorporate technologies that provide different levels of control for a single pollutant. The Claus sulfur-recovery plant discussed in Chapter 4 serves as an example of this. In addition, the choice of different input mixes (fuels and raw materials) can also result in differential levels of pollution reduction while maintaining a constant product slate. The selection of the proper degree of control necessitates that analysts compare the costs of different levels of pollution abatement. Therefore, they must calculate the marginal costs of different levels of pollution control based on information on the various production scenarios of an industry on which the pollution-control measures are to be applied. The analytical framework we developed presents such an overall picture of an industry that is considered for pollution control.

The formal definition of an "efficient" degree of pollution control is one in which the marginal cost of abatement is equal to its marginal benefits. Textbooks on environmental economics demonstrate this principle in detail (Baumol and Oates, 1988; Tietenberg, 1988). The marginal costs (MC) of pollution control are shown as an increasing function of the degree of abatement. This functional form assumes that the first pollution-control measures may be relatively inexpensive, but once the inexpensive technologies have been exhausted, further abatement at high levels of pollution control will be more expensive per unit of abatement. In turn, the marginal benefit (MB) of abatement curve is depicted as a decreasing function of the degree of abatement. Thus, the downward-sloping marginal-benefit curve reflects great benefits from abatement at high pollution concentrations and declining benefits as the environment becomes less and less polluted. The intersection point of the marginal cost and marginal benefit curves depicts the optimal level of control. Clearly then, the selection of this efficient degree of abatement requires the estimation of an aggregate marginal abatement cost curve like the one described above. To do so for an industry, analysts require detailed informational inputs on, among other things, its operation and pollution generation. The proposed framework has the demonstrated ability to satisfy such requirements.

Once an appropriate degree of control has been selected for a pollutant in an area, the burden of cleanup must be allocated among many sources. The economist's solution to the problem is that a given degree of environmental improvement must be achieved at the least possible cost (Friedlaender, 1978: 323; OECD, 1980; Baumol and Oates, 1988). If there are many sources, the least-costly means of reaching a given level of environmental quality will be achieved if each source reduces its emissions until the marginal cost of abatement is equal for all sources. Theoretically, then, when the objective is to minimize the cost of achieving a given total emission rate from a set of resources, the marginal cost of abatement at each source must be equalized. To do so requires either a policy or set of measures that will automatically equalize marginal costs--such as an effluent charge--or knowledge of the marginal abatement cost curve for each source so that the efficient degree of abatement can be specified (this is important both from the government/regulatory authority's as well as the industry's perspective) . Thus, in many cases analysts, both those at the government and industrial level, may find it desirable to know the marginal cost of abatement curve for individual sources, as well as the aggregate for all sources in an area. They can use a framework such as the one proposed herein as the basis for such cost estimates as illustrated both in Chapter 4 and in the Appendix for the case of the U. S. petroleum-refining industry.

Most attempts to determine costs of pollution control use one or both of two standard methodologies. The first methodology is the engineering or simulation method. In this, engineering estimates are used to determine the capital and operating cost of each component in a pollution-control system. Frequently, analysts produce these engineering estimates as a single cost-figure for a particular control device for a particular source. If the technology of abatement is well understood, they can generate equations to describe the pollution-control cost function. In such cases, they need only insert the parameters for a particular pollution source to calculate the cost of controlling that source under closely specified conditions.

The other method of pollution-control cost estimation is the statistical or econometric method (Friedlaender, 1978: 294-295). Here, an equation is developed relating total costs for a pollution source to a number of variables, including the degree of pollution control. Analysts collect accounting data from a number of existing sources, and they use regression analysis to fit the equation to the observed data. The estimated parameters of the equation will show the cost of pollution control as a function of whatever independent variables have been included (Fronza and Melli, 1982; Friedlaender, 1978).

Despite the fact that each of the above costing methodologies may have shortcomings, the engineering one proves pertinent to our analysis. In the engineering method, analysts are likely to determine the estimated cost for a particular source: a new plant with a certain technology and a given rate of product output. They may, however, have difficulties in generalizing such results to an industry that includes new and old firms using a variety of production technologies and having a wide range of output rates. Because they estimate the costs for a single plant, it is impossible to compare them with actual experience in an industry. Rarely are the cost functions flexible enough to allow analysts to consider the many factors that vary from one source to another and may have profound influence on costs of pollution control. At this stage, they may find that prototype analyses as well as the disaggregation of the various activities into their component parts are both important and relevant. Again, the relevance of the proposed framework becomes evident.

Finally, we refer to another potential advantage of a pollution-estimation method that utilizes a prototype/scenario approach as well as incorporates alternative technologies. When abatement policies are expected to have a significant influence on technological progress, analysts may find it most useful to develop a set of scenarios with different schedules of policy and the resulting associated costs. The scenario approach may be particularly important when analysts want to estimate the separate impact of capital and operating costs over time or to ascertain the portion of the industry that might be affected in a given period.

Where does all of this leave us? It is clear that when decisions have to be made, the data are frequently inadequate to perform the kinds of analyses that would lead to the best possible outcome. To a point, there is little that can be done about this. Frequently, the desired cost information will be developed only as a result of whatever policy is chosen. To postpone policy decisions until costs are available may in fact be to postpone policies forever. In addition, the total, average, and marginal costs of abatement are likely to vary tremendously among industrial-pollution sources, depending upon factors such as age and maintenance of equipment, plant size, and location. Analysts cannot relate scattered estimates of pollution abatement that do not provide details on these variables. Thus, such estimates are of little use. In many cases, however, analysts can compile tables and derive functions that indicate the range of variation according to a number of important parameters. Thus, they can estimate abatement costs for a variety of sources, although such calculations will be expensive.

Analysts can use the proposed procedure to incorporate a multitude of factors associated with or responsible for the operation and pollution output of a specific industry. The ability of analysts to use it to simulate operational scenarios of different size, process, and input composition and to provide them with a comprehensive framework which both generates and summarizes pollution-emission estimates was demonstrated in detail in this thesis. Furthermore, analysts can use it to compare industrial prototypes that employ alternative technologies--modern and older, more environmentally sound or more efficient. Coupled with cost figures for its individual components, this method can provide a solid basis for a comprehensive estimation of the costs of abatement activities. Ultimately, it enables policy makers and industries to find an optimal abatement strategy given the political, economic, and other constraints posed by the policy-making environment.

Appendix

The U. S. Petroleum-Refining Industry: An Application of the Pollution-Estimation Method

In this appendix, we present a simulation of the U. S. petroleum-refining industry. More specifically, we use a cluster approach to model the refining industry of each of the four major Petroleum Administration for Defense (PAD) districts and to construct a representative refinery prototype for each region. We then simulate the operation of each refinery prototype and estimate its air pollutant emissions relying, again, on the proposed method. In taking the application a step further--beyond the theoretical treatment of 'textbook' refinery prototypes, their operation, and their pollution generation--our goal is to assess the sufficiency of both the proposed method versus the demands posed by a diverse group of existing refineries and the availability and quality of data on their operation.

Overview of the Industry's Structure

The petroleum-refining industry is one of the most complex and technically sophisticated industries in the United States. In 1991, there were 202 refineries in operation ranging in size from about 400,000 barrels per calendar day (BPCD) to only a few hundred BPCD (Energy Information Administration, 1991). These refineries vary from fully-integrated, high-complexity plants, capable of producing a complete range of petroleum products and some petrochemicals (see Prototype II of Chapter 4), to very simple plants, capable of producing only a very small number of products (similar to Prototype I of Chapter 4). In addition, some refineries are modern and of recent construction, while others contain at least some process units constructed 40 or more years ago (Energy Information Administration, 1991; Oil and Gas Journal, December 1991). Refinery crude slates vary widely from refinery to refinery as do product mixes and, to some extent, product properties. Thus, each refinery is characterized by a unique capacity, processing configuration, and product distribution.

Despite this diversity of operations, there are logical regional groupings of major refineries with similar crude-supply patterns, processing configurations, and product outputs. Therefore, within a given refining district, called Petroleum Administration for Defense (PAD) district[40], there are similarities that allow us, again, to simulate the operation of the entire refining industry through the use of refining prototypes and then estimate their pollutant emissions. Drawing on an

---

[40] For the purpose of collecting statistics on the refining industry, the United States has been divided into five refining regions called Petroleum Administration for Defense (PAD) districts. This geographic aggregation of the 50 states and the District of Columbia was done in 1950. These districts were originally instituted for economic and geographic reasons as Petroleum Administration for War (PAW) districts in 1942. PAD I includes refineries located in the eastern seaboard states; PAD II includes mid-western refineries; PAD III includes refineries located in states bordering the Gulf of Mexico, New Mexico, and Arkansas; PAD IV includes refineries located in the Rocky Mountain states; and, PAD V includes refineries located along the west coast (EPA, 1976; Energy Information Administration, 1991).

earlier study of the U. S. refining industry (EPA, 1976), we construct four prototypes--each corresponding to a PAD district--to simulate the approximately 200 individual refineries and hence the U. S. refining industry. PAD district IV, with only four percent of the U. S. refinery total, is excluded from the simulation due to its very small size.[41] Process configuration was the major factor employed in selecting the refineries in a cluster from which a representative prototype was then constructed. Hence, these clusters are indicative of the types of refineries in the different PAD regions of the United States today, except for small (less than 30,000 BPCD) atypical plants.[42] We should note that process configuration also served as the basis for constructing the two prototypes discussed in Chapter 4.

Refinery Simulation

PAD district I was simulated by three refineries in the Philadelphia-New Jersey area with capacities ranging from 180,000 to 185,000 barrels per calendar day (BPCD). PAD II was simulated by five refineries located in

---

[41] PAD I with 9 percent, PAD II with 22 percent, PAD III with 45 percent, and PAD V with 20 percent are represented in the prototype analysis and simulation (Energy Information Administration, 1991).

[42] In addition to the typical refineries, there are a large number of small, non-integrated, essentially unique refineries in the United States. Their combined process capacity however is less that 10 percent of the total U. S. throughput. The plants range from those whose primary product is asphalt to those that are essentially topping refineries producing a very small number of products. Often, these refining configurations are designed to enable them to produce products for marketing in the immediate geographic area. These can be viewed as specialty refineries and are essentially incapable of simulation or easy description, except on a case-by-case basis.

Indiana, Ohio, and Illinois with capacities ranging from 130,000 to 360,000 BPCD. PAD III was simulated by ten refineries in Texas and Louisiana with capacities ranging from 220,000 to 460,000 BPCD. Finally, PAD V was simulated with five refineries located in the Southern California area with capacities ranging from 125,000 to 285,000 BPCD.

We used the annual refining surveys published in the Oil and Gas Journal as well as those in the Petroleum Supply Annual published by the Energy Information Administration as the basic reference sources for determining the cluster-model processing configurations and capacities, allowing simulation of the refineries examined. We also used the aforementioned sources to obtain data on the fuel mix used in the refineries of each PAD district during 1991. Table A.1 supplies these data. The fractional fuel mixes describing fuel consumption in each PAD district are assumed to be those consumed by the refinery prototypes we construct for each such district.

Summaries of Regional Refinery-Prototype Operations and Pollution Generation

Before estimating the pollutant emissions of each regional refinery prototype, we present the necessary information on their operation. This is obtained from the simulation of each area's refining industry as outlined above. We use these data to construct the refinery activity-level vectors, which along with the appropriate pollution-coefficient matrices

Table A.1

Major Fuels Consumed by U. S. Refineries by PAD District in 1990

(Thousand Barrels, Except Where Noted)

	PAD Districts					United States
Type of Fuel	I	II	III	IV	V	
1. Crude Oil	0	0	0	0	0	0
2. Distillate Fuel Oil	163	31	47	0	156	397
3. Residual Fuel Oil	3,844	3,304	1,176	839	1,482	10,645
4. LPGs	1,187	2,437	1,008	236	3,857	8,725
5. Natural Gas (million cubic feet)	31,119	86,881	441,868	12,706	100,709	673,283
6. Still/Refinery Gas	20,791	50,268	111,241	7,288	49,826	239,414
7. Petroleum Coke	10,695	17,810	35,729	2,406	13,574	80,214
TOTAL						

Source: Energy Information Administration,
Petroleum Supply Annual.
Volumes 1 and 2. Washington, DC: U. S. Government Printing Office, 1991.

Table A.1 cont'd

	Gross Heat Content (billion Btu) by PAD						Fractional Mix					
	I	II	III	IV	V	U. S.	I	II	III	IV	V	U. S.
1	0	0	0	0	0	0	0.000	0.000	0.000	0.000	0.000	0.000
2	978	186	282	0	936	2,382	0.006	0.001	0.000	0.000	0.003	0.001
3	24,217	20,815	7,409	5,286	9,337	67,064	0.148	0.067	0.009	0.116	0.032	0.040
4	4,748	9,748	4,032	944	15,428	34,900	0.029	0.032	0.005	0.021	0.054	0.021
5	32,675	91,225	463,961	13,341	105,744	706,947	0.200	0.295	0.538	0.294	0.368	0.424
6	24,949	60,322	133,489	8,746	59,791	287,297	0.153	0.195	0.155	0.193	0.208	0.172
7	75,935	126,451	253,676	17,083	96,375	569,519	0.464	0.410	0.294	0.376	0.335	0.341
TOTAL	163,502	308,747	862,849	45,399	287,612	1,668,109	1.000	1.000	1.000	1.000	1.000	1.000

for each prototype lead to the desired pollution-output vectors.

East-Coast Refinery Prototype (I)

The first prototype we examine is an East-Coast (PAD I) refining complex with a nominal capacity of 180,000 BPCD. The crude/raw-material input is made up of: 30,000 barrels of Tiajuana crude; 35,000 barrels of Nigerian crude; 90,000 barrels of Arabian light crude; and, 45,000 barrels of Algerian crude. The total heat requirement of the refinery, based on the processes it employs and their nominal capacities, is approximately 94,274 x 10^6 Btu per day. The fuel mix includes fuel oil (15 percent), LPGs (3 percent), natural gas (20 percent), still gas (15 percent), and petroleum coke (47 percent). Based on the above fractional mix, each fuel's heating value, and the total heat requirement, we calculate the quantity of each fuel consumed in the refinery's process heaters.[43] Thus, the fuel input includes: 17.957 x 10^6 cubic feet of natural gas; 11.784 x 10^6 cubic feet of still gas; 94,085 gallons of fuel oil; 29,430 gallons of LPGs; and 261,255 gallons of petroleum coke.

As an integrated refinery, the East-Coast refinery prototype employs most of the processes employed by Prototype II of Chapter 4. The processes and their nominal levels of operation are listed below[44]:

---

[43] It should be recalled the heating values for the five fuel types are: natural gas HV = 1,050 Btu/cubic foot; still gas HV = 1,200 Btu/cubic foot; fuel oil HV = 150,300 Btu/gallon; LPG HV = 96,100 Btu/gallon; petroleum coke HV = 169,600 Btu/gallon.

[44] The unit level of operation for all processes, except for the Claus plant and the Stretford unit, is one barrel of process feed. For the other two processes, the unit level of operation is one ton of elemental sulfur produced by them.

Desalter = 180,000 BPCD

Atmospheric Distillation = 180,000 BPCD

Vacuum Distillation = 70,000 BPCD

Hydrotreating = 47,330 BPCD

Catalytic Reforming = 41,700 BPCD

Fluid Catalytic Cracking = 68,000 BPCD

Alkylation = 14,000 BPCD

Hydrocracking = 21,000 BPCD

Claus Plant = 93.25 tons of Sulfur produced

Stretford Unit = 10.26 tons of Sulfur produced

Blowdown Systems = 180,000 BPCD

Given the above information, we set the activity-level vector describing the operation of the East-Coast refinery prototype. This is shown as Column 1 in Table A.2. Multiplying this activity-level vector with the appropriate pollution-coefficient matrix, Table A.3, yields the pollution-output vector shown as Column 1 in Tables A.4 and A.5. In Table A.3, we decided to include a column for the operation of a process heater using petroleum coke despite the fact that data for this fuel's combustion were not available. This is done since the fuel in question is an important contributor to the area's refinery fuel mix--as indicated in Table A.1. To facilitate calculations, then, we used as a proxy to petroleum-coke emissions, emissions resulting from the combustion of coke. The relevant coefficients can be corrected as petroleum-coke combustion emission factors become available.

Table A. 2

Activity-Level Vectors for Prototype I, II, III, and IV

Prototype I	Prototype II	Prototype III	Prototype IV
180,000	230,000	325,000	180,000
180,000	230,000	325,000	180,000
70,000	103,400	127,350	92,600
47,330	23,900	44,230	49,100
41,700	46,250	72,550	41,600
68,000	45,500	53,200	32,800
14,000	91,100	133,100	65,000
21,000	19,700	25,300	12,300
93.25	30,500	50,000	30,175
10.26	3 70.5	586.6	457.0
17.957	40.76	64.40	50.30
11.784	37.063	92.559	43.819
94.035	20.539	22.497	21.761
29.430	60.415	11.974	24.821
261.255	40.495	18.728	64.699
180,000	313.592	307.740	249.289
	230,000	325,000	180,000

Mid-West Refinery Prototype (II)

The second prototype is a Mid-West (PAD II) integrated refinery prototype with a nominal capacity of 230,000 BPCD. Its crude oil input includes 100,000 barrels of Arabian light crude (43 percent), 100,000 barrels of East Venezuelan light crude (43 percent), and 30,000 barrels of Nigerian crude (14 percent). The total heat requirement of the refinery, based on the processes it employs and their nominal capacities, is approximately 129,720 x 10^6 Btu per day. The fuel mix includes fuel oil (7 percent), LPGs (3 percent), natural gas (30 percent), still gas (19 percent), and petroleum coke (41 percent). Based on the above fractional mix, each fuel's heating value, and the refinery's total heat requirement, we calculate the quantity of each fuel consumed in the refinery's process heaters. Thus, the fuel input includes: 37.063 x 10^6 cubic feet of natural gas; 20.539 x 10^6 cubic feet of still gas; 60,415 gallons of fuel oil; 40,495 gallons of LPGs; and 313,592 gallons of petroleum coke.

In addition to the processes employed by the East-Coast refinery prototype, this refinery also employs delayed coking with a nominal level of operation of 23,900 BPCD. Therefore, the processes employed along with their nominal levels of operation are:

Desalter = 230,000 BPCD
Atmospheric Distillation = 230,000 BPCD
Vacuum Distillation = 103,400 BPCD
Delayed Coking = 23,900 BPCD
Hydrotreating = 46,250 BPCD
Catalytic Reforming = 45,500 BPCD
Fluid Catalytic Cracking = 91,100 BPCD
Alkylation = 19,700 BPCD
Hydrocracking = 30,500 BPCD
Claus Plant = 370.50 tons of Sulfur produced
Stretford Unit = 40.76 tons of Sulfur produced

Blowdown Systems = 230,000 BPCD

Given the above information, we set up the activity-level vector describing the operation of a Mid-West refinery prototype shown as Column 2 in Table A. 2. Again, we multiply the above activity-level vector with the appropriate pollution-coefficient matrix, Table A.6, to obtain the pollution-output vector shown as Column 2 in Tables A.4 and A.5. The same assumptions regarding the use of petroleum coke in one of the refinery's process heaters apply to this refinery prototype as in the case of the East-Coast refinery prototype.

Gulf-Coast Refinery Prototype (III)

The third prototype considered is a Gulf-Coast (PAD III) refining complex with a nominal capacity of 325,000 BPCD. The crude/raw material input is made up of 90,000 barrels of East Texas sweet crude and 235,000 barrels of Louisiana sweet crude. The total heat requirement of the refinery, based on the processes it employs and their nominal capacities, is approximately 179,975 x 10^6 Btu per day. The fuel mix includes fuel oil (1 percent), LPGs (1 percent), natural gas (54 percent), still gas (15 percent), and petroleum coke (29 percent). Based on the above fractional mix, each fuel's heating value, and the refinery's total heat requirement, we calculate the quantity of each fuel consumed in the refinery's process heaters. Thus, the fuel input includes: 92.559 x 10^6 cubic feet of natural gas; 22.497 x 10^6 cubic feet of still gas; 11,974 gallons of fuel oil; 18,728 gallons of LPGs; and 307,740 gallons of petroleum coke.

The processes employed and their nominal levels of operation are listed below:

Desalter = 325,000 BPCD
Atmospheric Distillation = 325,000 BPCD
Vacuum Distillation = 127,350 BPCD
Delayed Coking = 44,230 BPCD
Hydrotreating = 72,550 BPCD
Catalytic Reforming = 53,200 BPCD
Fluid Catalytic Cracking = 133,100 BPCD
Alkylation = 25,300 BPCD
Hydrocracking = 50,000 BPCD
Claus Plant = 585.6 tons of Sulfur produced
Stretford Unit = 64.4 tons of Sulfur produced
Blowdown Systems = 325,000 BPCD

Based on the above, we construct the activity-level vector describing the operation of the the Gulf-Coast refinery prototype which is shown as Column 3 in Table A.2. As in the previous two cases, we multiply the activity-level vector in question with its corresponding pollution-coefficient matrix, Table A.6, to obtain a pollution-output vector shown as Column 3 in Tables A.4 and A.5.

West-Coast Refinery Prototype (IV)

Finally, we consider a West-Coast (PAD V) integrated refinery. This fourth prototype has a nominal capacity of 180,000 BPCD. The crude/raw material input is made up of 70,000 barrels of California Wilmington crude; 22,000 barrels of California Ventura crude; and 78,000 barrels of Alaskan North Slope crude. The total heat requirement of the refinery, based on the processes it employs and their nominal capacities, is approximately 124,351 x 10^6 Btu per day. The fuel mix includes fuel oil (3 percent), LPGs (5 percent), natural gas (37 percent), still gas (21 percent), and petroleum coke (34 percent). Based on the above fractional mix, each fuel's heating value, and the refinery's total heat requirement, we calculate the quantity of each fuel consumed in the refinery's process heaters. Thus, the fuel input includes: 43.819 x 10^6 cubic feet of natural gas; 21.761 x 10^6 cubic feet of still gas; 24,821 gallons of fuel oil; 64,699 gallons of LPGs; and 249,289 gallons of petroleum coke.

The processes employed and their nominal levels of operation are listed below:

Desalter =180,000 BPCD
Atmospheric Distillation = 180,000 BPCD
Vacuum Distillation = 92,600 BPCD
Delayed Coking = 49,100 BPCD
Hydrotreating = 41,600 BPCD
Catalytic Reforming = 32,800 BPCD
Fluid Catalytic Cracking = 65,000 BPCD
Alkylation = 12,300 BPCD

Hydrocracking = 30,175 BPCD

Claus Plant = 457 tons of Sulfur produced

Stretford Unit = 50.3 tons of Sulfur produced

Blowdown Systems = 180,000 BPCD

Based on the above, we set up an activity-level vector describing the operation of the refinery prototype under consideration. This is shown as Column 4 in Table A.2. Following the same steps as in the three previous cases, we calculate the pollution-output vector associated with the operation of a West-Coast petroleum-refining complex. This is shown as Column 4 in Tables A.4 and A.5.

This concludes the application of the pollution-estimation procedure for the U. S. petroleum-refining industry. The representative nature of the refinery prototypes used enables us to calculate, if need be, an estimate of the total emissions produced by the U. S. refining industry in a given year since data on the operating capacities of refineries in the various petroleum-refining regions are widely available.

Table A.3
Pollution Coefficients for PAD I Refinery Prototype

	Desalter (1)	Atm. Distill. (2)	Vacuum Distill. (3)	Hydro-treater (7)	Cat. Reform. (8)	FCC Electr. Precip. (10)	Alky-lation (12)	Hydro-cracker (13)
1. Particulates	0	0	0	0	0	0.045	0	0
2. Sulfur Dioxide	0	0	0	0	0	0.493	0	0
3. Sulfur Trioxide	0	0	0	0	0	0	0	0
4. Carbon Monoxide	0	0	0	0	0	0	0	0
5. Carbon Dioxide	0	0	0	0	0	0	0	0
6. Hydrocarbons	0	0	0.05	0	0	0	0	0
7. Nitrogen Oxides	0	0	0	0	0	0.071	0	0
8. VOCs	0	0	0	0	0	0	0	0
9. Aldehydes	0	0	0	0	0	0	0	0
10. Ammonia	0	0	0	0	0	0	0	0
11. Hydrogen Sulfide	0	0	0	0	0	0	0	0

Notes:

a. We assume that Grade 4 fuel oil is used.

b. The average weight percent Sulfur content for PAD district I fuels is 1.

Source: U. S. Environmental Protection Agency,
Compilation of Air Pollutant Emission Factors.
4th Edition. Volume 1. Research Triangle Park, NC: Office of Air Quality Planning and Standards, 1985.

Table A.3 cont'd

	Claus Plant Controlled 99.9 (24)	Stretford Unit (25)	Process Heater Natural Gas (27)	Still Gas (28)	Residual Fuel Oil (a), (b) (29)	LPGs (b) (30)	Petroleum Coke (30a)	Blowdown Syst. Vapor Recovery System and and Flaring (35)
1	0	0	3	3.5	7	0.55	4.5	0
2	4	0	0.6	0.8	157	0.09	37.6	0.0269
3	0	0	0	0	2	0	0	0
4	0	0	35	37	5	2.2	42.7	0.0043
5	285.45	2575	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0.0008
7	0	0	140	150	55	12.8	63.1	0.0189
8	0	0	5.8	6.5	1.28	0.53	1.42	0
9	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0
11	260.508	0	0	0	0	0	0	0

Table A.4

The U. S. Petroleum-Refining Industry
Pollution-Output Vectors for Prototypes I, II, III, and IV
(in lbs)

	Prototype I	Prototype II	Prototype III	Prototype IV
1. Particulates	5005.54	6138.92	7824.86	4463.75
2. Sulfur Dioxide	63356.38	77340.00	96662.59	59141.59
3. Sulfur Trioxide	188.17	125.66	29.22	55.10
4. Carbon Monoxide	13529.26	16827.69	18711.02	14023.90
5. Carbon Dioxide	53037.71	210716.22	333275.00	259973.15
6. Hydrocarbons	3644.00	5354.00	6627.50	4774.00
7. Nitrogen Oxides	34548.15	42713.59	52242.09	35339.25
8. VOCs	687.76	892.56	1145.32	815.65
9. Aldehydes	0	0	0	0
10. Ammonia	0	0	0	0
11. Hydrogen Sulfide	24992.37	96518.21	152814.00	119052.16

Source: Author's calculations.

Table A.5

The U. S. Petroleum-Refining Industry
Pollution Output for Prototypes I, II, III, and IV
(pounds per barrel crude-oil input)

	Prototype I	Prototype II	Prototype III	Prototype IV
1. Particulates	0.0278	0.0267	0.0241	0.0248
2. Sulfur Dioxide	0.3520	0.3363	0.2974	0.3286
3. Sulfur Trioxide	0.0010	0.0005	0.0001	0.0003
4. Carbon Monoxide	0.0752	0.0732	0.0576	0.0779
5. Carbon Dioxide	0.2947	0.9162	1.0255	1.4443
6. Hydrocarbons	0.0202	0.0233	0.0204	0.0265
7. Nitrogen Oxides	0.1919	0.1857	0.1607	0.1963
8. VOCs	0.0038	0.0039	0.0035	0.0045
9. Aldehydes	0	0	0	0
10. Ammonia	0	0	0	0
11. Hydrogen Sulfide	0.1388	0.4196	0.4702	0.6614

Source: Author's calculations.

Table A.6

Pollution Coefficients for PAD II, III, and V Refinery Prototypes

	Desalter (1)	Atm. Distill. (2)	Vacuum Distill. (3)	Delayed Coking (6)	Hydro-treater (7)	Cat. Reform. (8)	FCC Electr. Precip. (10)	Alky-lation (12)
1. Particulates	0	0	0	0	0	0	0.045	0
2. Sulfur Dioxide	0	0	0	0.136	0	0	0.493	0
3. Sulfur Trioxide	0	0	0	0	0	0	0	0
4. Carbon Monoxide	0	0	0	0	0	0	0	0
5. Carbon Dioxide	0	0	0	0	0	0	0	0
6. Hydrocarbons	0	0	0.05	0	0	0	0	0
7. Nitrogen Oxides	0	0	0	0	0	0	0.071	0
8. VOCs	0	0	0	0	0	0	0	0
9. Aldehydes	0	0	0	0	0	0	0	0
10. Ammonia	0	0	0	0	0	0	0	0
11. Hydrogen Sulfide	0	0	0	0	0	0	0	0

Notes:

a. We assume that Grade 4 fuel oil is used.

b. The average weight percent Sulfur content of fuels by PAD district is: PAD II = 1.02, PAD III = 1.22, and PAD V = 1.11.

Source: U. S. Environmental Protection Agency,
Compilation of Air Pollutant Emission Factors.
4th Edition. Volume 1. Research Triangle Park, NC: Office of Air Quality Planning and Standards, 1985.

Table A.6 cont'd

	Hydro-cracker (13)	Claus Plant Controlled 99.9 (24)	Stretford Unit (25)	Process Heater					Blowdown Syst. Vapor Recovery System and and Flaring (35)
				Natural Gas (27)	Still Gas (28)	Residual Fuel Oil (a), (b) (29)	LPGs (b) (30)	Petroleum Coke (30a)	
1	0	0	0	3	3.5	7	0.55	4.5	0
2	0	4	0	0.6	0.8	157S	.09S	37.6	0.0269
3	0	0	0	0	0	2S	0	0	0
4	0	0	0	35	37	5	2.2	42.7	0.0043
5	0	285.45	2575	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0.0008
7	0	0	0	140	150	55	12.8	63.1	0.0189
8	0	0	0	5.8	6.5	1.28	0.53	1.42	0
9	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0
11	0	260.508	0	0	0	0	0	0	0

Glossary

ALKYLATION. A refinery polymerization process uniting olefins and isoparaffins; particularly , the reacting of butylene and isobutane using sulfuric or hydrofluoric acid as a catalyst to produce high-octane gasoline-blending components.

API GRAVITY. An arbitrary gravity scale defined as:

$$^{o}API = (141.5/\text{Specific gravity } 60\text{-}60 \text{ F}) - 131.5$$

This scale allows representation of the specific gravity of oils, which on the $60/60^{o}F$ scale varies only over a range of 0.776 by a scale which ranges from less than 0 (heavy residual oil) to 340 (methane).

AROMATICS. A class of hydrocarbons whose structure contains at least one unsaturated ring compound containing six carbon atoms. Benzene is the simplest hydrocarbon within this category. Toluene and xylene are other common aromatics. This class of hydrocarbons exhibits very high gasoline octane numbers.

BARREL. 42 gallons.

BARRELS PER CALENDAR DAY (BPCD). Average refinery flow rates based on operating 365 days per year.

BARRELS PER STREAM DAY (BPSD). Flow rates based on actual on-stream time of a unit or group of units. This notation equals barrels per calendar day divided by the service factor.

BEAVON/STRETFORD PROCESS. A sulfur removal process generally applied to Claus plant tail-gas streams. The process involves catalytic conversion of SO_x to H_2S prior to reduction to elemental sulfur.

BITUMEN. That portion of petroleum, asphalt, and tar products which will dissolve completely in carbon disulfide.

BLENDING. One of the final operations in refining, in which two or more different components are mixed together to obtain the desired range of properties in the final product.

BOTTOMS. In general, the higher-boiling residue which is removed from the bottom of a fractionating tower.

CATALYST. A substance that assists a chemical reaction to take place but which is not itself chemically changed as a result.

CLAUS PROCESS. A sulfur recovery process which employs thermal and catalytic conversion of SO_x and H_2S to elemental sulfur; widely employed for refining sulfur recovery.

COKING. A refinery process which converts heavy residual petroleum fractions (such as the bottoms product from vacuum distillation) into lighter products and petroleum coke. The petroleum coke yield typically represents about 25% of the feed.

CRACKING. The breaking down of higher molecular-weight hydrocarbons to lighter components by the application of heat. Cracking in the presence of a suitable catalyst produces an improvement in yield and quality over simple thermal cracking.

CUT. That portion of crude oil boiling within certain temperature limits.

DEWAXING. The removal of wax from lubricating oils, either by chilling and filtering, solvent extraction, or selective hydrocracking.

DISTILLATE FUEL. A class of petroleum products with boiling ranges between approximately 350 and 700°F which have been produced as an overhead (or distillate) stream in a refinery distillation process. The major products within this category are: aviation turbine fuel, kerosene, no. 2 fuel oil, and diesel fuel.

FLASHING. Distillation.

HYDROCRACKING. A refinery process which reacts heavy liquid petroleum fractions in the presence of a catalyst, in a hydrogen-rich environment.

ISOMERATE. The product of an isomerization process.

ISOMERIZATION. The rearrangement of straight-chain hydrocarbon molecules to form branched-chain products.

KEROSINE. A middle-distillate product composed of material of 300 to 550°F boiling range. The exact cut is determined by various specifications of the finished kerosine.

LIGHT ENDS. Hydrocarbon fractions in the butane and lighter boiling range.

LIQUEFIED PETROLEUM GAS (LPG). Liquefied light ends gases. This gas is usually 95% propane, the remainder being split between ethane and butane. It can be any one of several specified mixtures of propane and butane.

MIDDLE DISTILLATES. Atmospheric pipestill cuts boiling in the range of 300 to 700°F vaporization temperature. The exact cut is determined by the specifications of the product.

PIPESTILL. A heater or furnace containing tubes through which oil is pumped while being heated or vaporized. They are useful for thermal cracking and distillation operations.

POLYMERIZATION. The combination of two or more unsaturated molecules to form a molecule of higher molecular weight. Propylenes and butylenes are the primary feed material for refinery polymerization processes.

REDUCED CRUDE. A crude whose API gravity has been reduced by distillation of the lighter lower-boiling constituents.

REFORMATE. A reformed naphtha which is upgraded in octane by means of catalytic or thermal reforming.

REFORMING. The conversion of naphtha fractions to products of higher octane value.

STILL/REFINERY GAS. Any form or mixture of gases, including carbon monoxide, hydrogen, methane, and ethane, produced as byproducts in the conversion of crude oil. Still gas is used as a refinery fuel and a petrochemical feedstock.

SWEETENING. The removal or conversion to innocuous substances of sulfur compounds in a petroleum product by any number of processes.

TAIL GAS. Light gases (methane to propane and H_2) produced as byproducts of refinery processing.

Bibliography

American Petroleum Institute. Basic Petroleum Data Book. Petroleum Industry Statistics. Vol. xii, no. 1. Washington, DC: American Petroleum Institute, January 1992.

Amoco Corporation. Annual Report 1990. Chicago, Illinois: Amoco, 1991.

Anderson, R. J., Jr. "Using mathematical models for cost-effective management of air-quality." In Fronza, Giorgio and Piero Melli, eds. Mathematical Models for Planning and Controlling Air Quality. Proceedings of an October 1979 IIASA Workshop. Oxford: Pergamon Press, 1982: 59-74.

Ayres, Robert and Allen Kneese. "Production, Consumption, and Externalities." American Economic Review 59, no. 3 (June 1969): 282-297.

Ayres, Robert. Resources, Environment and Economics: Applications of the Materials/Energy Balance Principle. New York: Wiley Interscience, 1978.

Baumol, William J. and Wallace E. Oates. Economics, Environmental Policy, and the Quality of Life. Englewood Cliffs, New Jersey: Prentice-Hall, 1979.

Baumol, William J. and Wallace E. Oates. The Theory of Environmental Policy. Englewood Cliffs, New Jersey: Prentice-Hall, 1988.

Biswas, Asit K., T. N. Khoshoo, and Ashok Khosla, eds. Environmental Modelling for Developing Countries. London: Tycooly Publishing, 1990.

Borup, Brett M. and E. Joe Middlebrooks. Pollution Control for the Petrochemicals Industry. Chelsea, Michigan: Lewis Publishers, 1987.

Berker, Bill D. and Kenneth E. Anderson. Modern Petroleum: A Basic Primer. Second Edition. Tulsa, Oklahoma: PennWelll Publishing, 1981.

Braat, Leon C. and Wal F. J. van Lierop, eds. Economic-Ecological Modeling. Studies in Regional Science and Urban Economics. Volume 16. Amsterdam: North-Holland, 1987.

The British Petroleum Company. BP Statistical Review of World Energy. Cleveland, Ohio: BP America Inc., June 1991.

Burklin, C. E. et al. Revision of Emission Factors for Petroleum Refining. EPA-450/3-77-030. Research Triangle Park, North Carolina: U. S. Environmental Protection Agency, October 1977.

Burrows, Paul. The Economic Theory of Pollution Control. Cambridge, Massachusetts: The MIT Press, 1980.

Burton, Dudley J. and K. Ravishankar. Treatment of Hazardous Petrochemicals and Petroleum Wastes: Current, New and Emerging Technologies. Park Ridge, New Jersey: Noyes Publications, 1989.

Clark, William C. "Energy and Environment: Strategic Perspectives on Policy Design." In Jefferson W. Tester, David Wood, and Nancy A. Ferrari, eds. Energy and the Environment in the 21st Century. Cambridge, Massachusetts: The MIT Press, 1991: 63-78.

Crandall, Robert W. Controlling Industrial Pollution. The Economics and Politics of Clean Air. Studies in the Regulation of Economic Activity. Washington, DC: The Brookings Institution, 1983.

Cristofaro, Alex. "The Cost of Reducing Greenhouse Gas Emissions in the United States." Draft. U. S. Environmental Protection Agency, Office of Policy Analysis, Air and Energy Division. December 4, 1990.

Daly, Herman. "On Economics as a Life Science." Journal of Political Economy 76, no. 3 (May/June 1968): 392-406.

Department of International Economic and Social Affairs, Statistical Office of the United Nations. 1988 Energy Statistics Yearbook. New York: United Nations, 1990.

Division for Industrial Studies, Sectoral Studies Branch, United Nations Industrial Development Organization. The Petrochemical Industry in Developing Countries: Prospects and Strategies. Sectoral Studies Series No. 20, volume 1. New York: United Nations, 1985.

Energy Information Administration, Office of Oil and Gas, U. S. Department of Energy. Petroleum Supply Annual. Volumes 1 and 2. Washington, DC: U. S. Government Printing Office, 1990 and 1991.

Energy Information Administration, U. S. Department of Energy. International Energy Annual. Washington, DC: U. S. Government Printing Office, 1989.

Energy Information Administration, U. S. Department of Energy. Monthly Energy Review. Washington, DC: U. S. Government Printing Office, 1990-1991.

Engineering-Science, Inc. Water Pollution Abatement Technology: Petroleum Refining Industry, Costs & Capabilities. Reports PB-234, 080-01 and -02. Washington, DC: National Commission on Water Quality, June 1975.

Exxon Corporation. 1990 Annual Report. Irving, Texas: Exxon, 1991.

Al-Fathi, Saadalla A. and Bright E. Okogu. "Energy and the environment: a production permits approach for oil." OPEC Review. An energy and development forum. Vol. xiv, no. 3 (Autumn 1990): 345-360.

Fee, Derek. Oil & Gas Databook for Developing Countries With Special Reference to the ACP Countries. London: Graham & Trotman, 1985.

Fisher, Anthony C. Resource and Environmental Economics. New York: Cambridge University Press, 1981.

Friedlaender, Ann F., ed. Approaches to Controlling Air Pollution. Cambridge, Massachusetts: The MIT Press, 1978.

Fronza, Giorgio and Piero Melli, eds. Mathematical Models for Planning and Controlling Air Quality. Proceedings of an October 1979 IIASA Workshop. Oxford: Pergamon Press, 1982.

Gary, James H. and Glenn E. Handwerk. Petroleum Refining: Technology and Economics. Second Edition. New York: Marcel Dekker, 1984.

Gharani, Ali A. "Projected maximum world refiners' demand for crude oil during 4Q 1991 and 1Q 1992." OPEC bulletin. Vol. xxi, no. 10 (November/December 1991): 17-19.

Gordian Associates. Energy Conservation: the Data Base. The Potential for Energy Conservation in Nine Selected Industries. Volume 2: Petroleum Refining. Washington, DC: Federal Energy Administration, June 1974.

Gray, James E., W. Kenneth Davis, and Joseph W. Harned, eds. Energy Supply and Use in Developing Countries. A Fresh Look at Western (OECD) Interests and U. S. Policy Options. A Report by the Joint Working Group of the Atlantic Council of the United States and the Member Committee of the United States World Energy Conference. Lanham, Maryland: University Press of America, 1988.

Hobson, George D., ed. Modern Petroleum Technology. Part 1. Fifth Edition. New York: John Wiley, 1984.

International Energy Agency. World Energy Statistics and Balances. Paris: OECD, 1989.

International Energy Agency. Oil and Gas Information 1988-1990. Paris: Organization for Economic Cooperation and Development, 1991.

International Petroleum Encyclopedia. Tulsa, Oklahoma: PennWell Publishing Company, 1991.

Isard, Walter, Eugene W. Schooler, and Thomas Vietorisz. Industrial Complex Analysis and Regional Development. A Case Study of Refinery-Petrochemical-Synthetic Fiber Complexes and Puerto Rico. Cambridge, Massachusetts: The MIT Press, 1959.

Isard, Walter and Eugene Schooler. "Industrial Complex Analysis, Agglomeration Economies, and Regional Development." Journal of Regional Science I, (Spring 1959).

Isard Walter, et al. *Methods of Regional Analysis: an Introduction to Regional Science*. Cambridge, Massachusetts: The MIT Press, 1960.

Isard, Walter, et al. *Ecologic-Economic Analysis for Regional Development*. New York: The Free Press, 1972.

Isard, Walter. "Activity-Industrial Complex Analysis for Environmental Management." *Papers of the Regional Science Association*. Volume 33. Philadelphia, Pennsylvania: The Regional Science Association, 1974: 127-140.

Isard, Walter and Frank J. Cesario, eds. *Working Papers on the Use of Regional Science Techniques in Environmental Management*. Regional Science Dissertation and Monograph Series No. 3. Ithaca, New York: Center for Urban and Development Research, Cornell University, 1974.

Isard, Walter. *Introduction to Regional Science*. Englewood Cliffs, New Jersey: Prentice Hall, 1975.

Isard, Walter and Georgios I. Kassinis. "On a General Method for Projecting Pollution Emissions by Sector, Region and Nation." Working Paper. Ithaca, New York: Department of Economics, Cornell University, 1990.

Jenkins, Gilbert. "The opportunity for Middle Eastern and African export refineries to the year 2002." *OPEC Review. An energy and development forum*. Vol. xiv, no. 4 (Winter 1990): 493-512.

Jenkins, Gilbert. *Oil Economists' Handbook-1985*. London: Elsevier Applied Science Publishers, 1985.

Jones, Harold R. *Pollution Control in the Petroleum Industry*. Park Ridge, New Jersey: Noyes Data Corporation, 1973.

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

Kneese, Allen V. and Charles L. Schultze. *Pollution, Prices, and Public*

Policy. Washington, DC: The Brookings Institution, 1975.

Lee, Bryan. "Highlights of the Clean Air Act Amendments of 1990." Journal of the Air and Waste Management Association. Vol. 41, no. 1 (January 1991): 16-19.

Leffler, William L. Petroleum Refining for the Non-Technical Person. Tulsa, Oklahoma: PennWell Publishing Company, 1979.

Leontief, Wassily. Input-Output Economics. Second Edition. New York: Oxford University Press, 1986.

McKeough, Kay, Jose Escay, and Sompheap Sem. A Visual Overview of the World Oil Markets. The World Bank Industry and Energy Department Working Paper. Energy Series Paper No. 8. Washington, DC: The World Bank, July 1988.

Miller, Ronald E. and Peter D. Blair. Input-Output Analysis. Foundations and Extensions. Englewood Cliffs, New Jersey: Prentice-Hall, 1985.

Molle, Willem and Egbert Wever. Oil Refineries and Petrochemical Industries in Western Europe. Buoyant Past, Uncertain Future. Aldershot, England: Gower, 1984.

Muller, Frederic. Energy and Environment in Interregional Input-Output Models. Boston, Massachusetts: Martinus Nijhoff, 1979.

Munasinghe, Mohan and Robert J. Saunders, eds. Energy Issues in the Developing World. The World Bank Industry and Energy Department Working Paper. Energy Series Paper No. 1. Washington, DC: The World Bank, February 1988.

Nordhaus, William D. "The Economics of the Greenhouse Effect." Presented for discussion at the MIT Workshop on Energy and Environmental Modeling and Policy Analysis. July 31-August 1, 1989. Cambridge, Massachusetts: MIT Center for Energy Policy Research, 1989.

Oil and Gas Journal. "Middle East Report." Vol. 89, no. 48 (Week of

December 2, 1991): 37-53.

Oil and Gas Journal. "Hazardous Waste and Environmental Report." Vol. 89, no. 50 (Week of December 16, 1991): 39-46.

Oil and Gas Journal. "Worldwide Refining Report." Vol. 89, no. 51 (Week of December 23, 1991): 33-82.

Organization for Economic Cooperation and Development. Pollution Charges in Practice. Paris: OECD, 1980.

Organization for Economic Cooperation and Development. World Energy Outlook. Paris: OECD, 1982.

Organization for Economic Cooperation and Development. World Energy Statistics and Balances. Paris: OECD, 1989.

Organization for Economic Cooperation and Development and International Energy Agency. Quarterly Oil Statistics and Energy Balances. First Quarter 1991. Paris: OECD, 1991.

Organization of Petroleum Exporting Countries. OPEC Annual Statistical Bulletin. Vienna, Austria: OPEC, 1991.

Pai, Gregory G. Y. Environmental Pollution Control Policy: An Assessment of Regional Economic Impacts. Ph. D. Dissertation. Cambridge, Massachusetts: Massachusetts Institute of Technology, June 1979.

Plummer, D. P. "The Petroleum Refinery." In Hobson, George D., ed. Modern Petroleum Technology. Part 1. Fifth Edition. New York: John Wiley, 1984: 329-350.

Refining and Gas Processing. Worldwide Directory. Tulsa, Oklahoma: PennWell Publishing Company, 1990.

Richardson, Harry. Input-Output Analysis and Regional Economics. New York: John Wiley and Sons, 1972.

Rose, David J. Learning about Energy. New York: Plenum Press, 1986.

Schobert, Harold H. The Chemistry of Hydrocarbon Fuels. London: Butterworth, 1990.

Sittig, Marshall. Petroleum Refining Industry. Energy Saving and Environmental Control. Park Ridge, New Jersey: Noyes Data Corporation, 1978.

Speight, James G. The Chemistry and Technology of Petroleum. New York: Marcel Dekker, 1980.

Speight, James G., ed. Fuel Science and Technology Handbook. New York: Marcel Dekker, 1990.

Stevens, Paul, ed. Oil and Gas Dictionary. London: The Macmillan Press, 1988.

Tahmassebi, Cyrus H. "US environmental regulations and their impact on the refining industry." OPEC bulletin. Vol. xxi, no. 10 (November/December 1991): 20-23.

Texaco Inc. Annual Report 1989. White Plains, New York: Texaco, 1990.

Thabit, Sabeeh S. M. "The development and analysis of integrated energy generation and supply systems for industry." OPEC Review. An energy and development forum. Vol. xiv, no. 2 (Summer 1990): 145-170.

Tietenberg, Tom. Environmental and Natural Resource Economics. Second Edition. New York: HarperCollins Publishers, 1988.

U. S. Congress, Office of Technology Assessment. Energy in Developing Countries. Washington, DC: U. S. Government Printing Office, 1991.

U. S. Environmental Protection Agency, Office of Research and Development, Industrial Environmental Research Laboratory. Environmental Considerations of Selected Energy Conserving Manufacturing Process Options. Volume IV. Petroleum Refining Industry Report. Cincinnati, OH: Industrial Environmental Research Laboratory, 1976.

U. S. Environmental Protection Agency, Office of Air Quality Planning and Standards. Compilation of Air Pollutant Emission Factors. 4th Edition. Volume I: Stationary Point and Area Sources. Research Triangle Park, North Carolina: Office of Air Quality Planning and Standards, 1985.

U. S. A. Oil Industry Directory. 31st Edition. Tulsa, Oklahoma: PennWell Publishing Company, 1992.

Varian, Hal R. Intermediate Microeconomics. A Modern Approach. New York: W. W. Norton & Company, 1987.

Victor, Peter A. Pollution: Economy and the Environment. London: George Allen & Unwin, 1972.

Wijetilleke, Lakdasa and Anthony J. Ody. World Refinery Industry - Need for Restructuring. World Bank Technical Paper No. 32. Washington, DC: The World Bank, 1984.

Wirl, Franz and Elizabeth Szirucsek. "Energy modelling - a survey of related topics." OPEC Review. An energy and development forum. Vol. xiv, no. 3 (Autumn 1990): 361-378.

Zannetti, Paolo. Air Pollution Modeling. Theories, Computational Methods and Available Software. New York: Van Nostrand Reinhold, 1990.