# AN ADVANCED LINEAR PROGRAMMING REFINERY MODEL

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A Dissertation

Presented to

the Graduate Faculty of the College of Business Administration

University of Houston

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In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy

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by
Frank A. Taylor, III
December, 1978

## ACKNOWLEDGEMENTS

Several individuals other than myself contributed significantly to this paper. Dr. Russell Thompson provided guidance and encouragement as the head of my dissertation committee, and also provided material support.

The other members of my dissertation committee, Dr. F.D. Singleton and Dr. Lynn R. Lamotte, contributed their time and expertise in reviewing the paper, and offered many interesting suggestions and observations.

Credit is due Mr. John Stone for his very valuable help and suggestions on the computer related aspects of the paper, and for informing me that my demand curves for capital and water were upside down. Several representatives of the Pullman-Kellog Company gave helpful technical assistance in modeling refinery units, particularly with regard to the update options for older units. They are Warren Schreiner, E. L. Whittington, and J. R. Murphy.

The typing of the paper was handled initially by Ms. Niami Hanson and in the final stages by Ms. Patsy Anderson. I would like to express my appreciation and thanks to all these people.

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## ABSTRACT

In this dissertation a linear programming model of the petroleum refining industry is developed which reflects the age structure of the refining industry. This has been done by creating three classifications for refinery units: old, intermediate, and new, and assigning all refinery capacity to one of the classifications using a rough approximation method. Also modeled are investment opportunities available to refiners, including both investments in new units and investments in the updating of older units.

Two major purposes are served by this "vintaging" of petroleum refinery units and representation of investment opportunities. First, refinery product costs may be estimated more accurately, and the sensitivity of these costs to federal and/or state policies may be more reliably determined. Second, curves representing the derived demand for capital in the petroleum refining industry may be constructed by parametric analysis. The model, therefore, represents a tool for studying the interactions of policies affecting environmental, energy, and capital parameters.

In this paper the model has been used for several purposes. First, the effect of upward sloping crude oil supply curves on refinery product prices was examined.

This analysis was undertaken because it seems possible that there may be some breaks in the pricing solidarity of the oil exporting nations. Piecewise approximations of constant elasticity crude oil supply curves provided a means of studying this contingency. The effect of varying supply elasticities on capital demand within the petroleum refining industry was also studied.

Attention has also been given to the interactions of capital application, long run costs, and short run costs in the refining industry. By appropriately adjusting constraints on capital and unit capacities one may use the model to show the effect of capital application on long run and short run costs. It is demonstrated how these interactions can be used to study the dynamic aspects of policy analysis.

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# CHAPTER 1

# INTRODUCTION

Formulation of intelligent public policies toward energy producing and intensively energy consuming sectors of the economy would ideally require a simultaneous evaluation of the primary effect of government actions on each individual industry as well as induced effects. Induced effects may be defined as the impact a government policy has on a given industry through the policy's effect on the suppliers or the customers of that industry. Such ideal and comprehensive evaluations have not been made in the past and are unlikely in the future, but improvements in the present decision making processes are certainly possible. In this paper an attempt is made to develop such an improvement.

## Previous Work

An attractive approach to the comprehensive problems with which public policy must contend involves the use of large linear programming models. Comprehensive linear programming models have been developed which represent the iron and steel industry (7), the petroleum refining industry, and the petrochemical industry (8). Thompson *et al*. have developed a comprehensive set of process models of energy and water intensive industries including petroleum refining, petrochemicals, chlorine-caustic soda, synthetic rubber, electric power generation, ammonia-nitrogeneous fertilizers, and inorganic chemicals (4,38,39).

The initial impetus for the development of such models was a desire to improve upon the predictive capacity of the square Leontief inter-industry flow model (1). Although the Leontief model was itself a considerable improvement over predictions based on monetary aggregates such as GNP, it was deficient in dealing with the phenomenon of substitutibility and complementarity. Linear programming models can allow both for the possibility that a single item can be produced by more than one process or that a single process can produce more than one item. Later, it was discovered that the ability of L.P. models to choose optimal sets of vectors to satisfy a set of constraints was useful in predicting industry response to such stimuli as environmental regulation and energy policy. Additional benefits were the projection of the cost of a given policy and the shadow price estimate of the effect of a given policy on the cost of individual products.

No industry lends itself to the advantages of linear programming analysis more than the petroleum refining industry. Almost all of the individual refinery units produce not one but several products, some of which are similar or identical to the products produced in other units.

Thus complementarity and substitutability are pervasive. Dozens of different unit designs can be used to meet a given purpose. This unit flexibility along with scores of different possible feedstocks and refining configurations produces a large number of possible strategies to simultaneously meet environmental restrictions, satisfy demand requirements, and fulfill national energy policies. This situation can be approximated by LP models with a large number of processing vectors.

Accordingly, several linear programming refining models have appeared in the published literature, and no doubt many more are proprietary. One of the first refinery LP models was constructed by Manne (2) and was "addressed to the problem of estimating output capabilities for an entire economy." This model was concerned primarily with studying the interactive effects of various operating vectors in meeting some specified slate of final demands. Little emphasis was placed on utility consumption or residuals.

A later model which was aimed at the "simultaneous consideration of air, water, and land (solid) problems" was formulated by Russell (3). This model contains process vectors in which residuals and utilities are broken out explicitly. The model was used to trace the effects of effluent changes on the emission levels of various specific pollutants, and to measure, through shadow prices, the cost of emission reduction. An expanded and improved version of the Russell model was developed by Thompson, Calloway, and Schwartz (See Figure 1). This model was used initially in conjunction with other process models developed by Thompson *et al.*, to improve upon the analysis of the Russell model. Later, this group of process models was used in a feedback loop which also contained a demand model for important final and intermediate industrial products, and a supply model for basic energy raw materials. Figure 2 shows the steps required to reach a partial equilibrium solution using these models. The modeling system was used to measure the simultaneous effects of prospective environmental and energy policies, and projected availabilities of energy raw materials. Specifically, the models have been used to a) estimate production costs, b) determine least cost process configurations and c) estimate capital requirements for the industries modeled. A schematic of the way this system correlates various policy and other considerations is given in Figure 3.

Separate refinery modeling work has been carried out by Bonner and Moore Associates Inc. (5). Their Refineries Petrochemical Modeling System (RPMS) is set up to generate representative refinery processing vectors for any region in the U.S. or for the nation as a whole. The system also features a detailed representation of crude oil types. A schematic of the RPMS system is given in Figure 4. RPMS data has been used extensively by the FEA in its Project

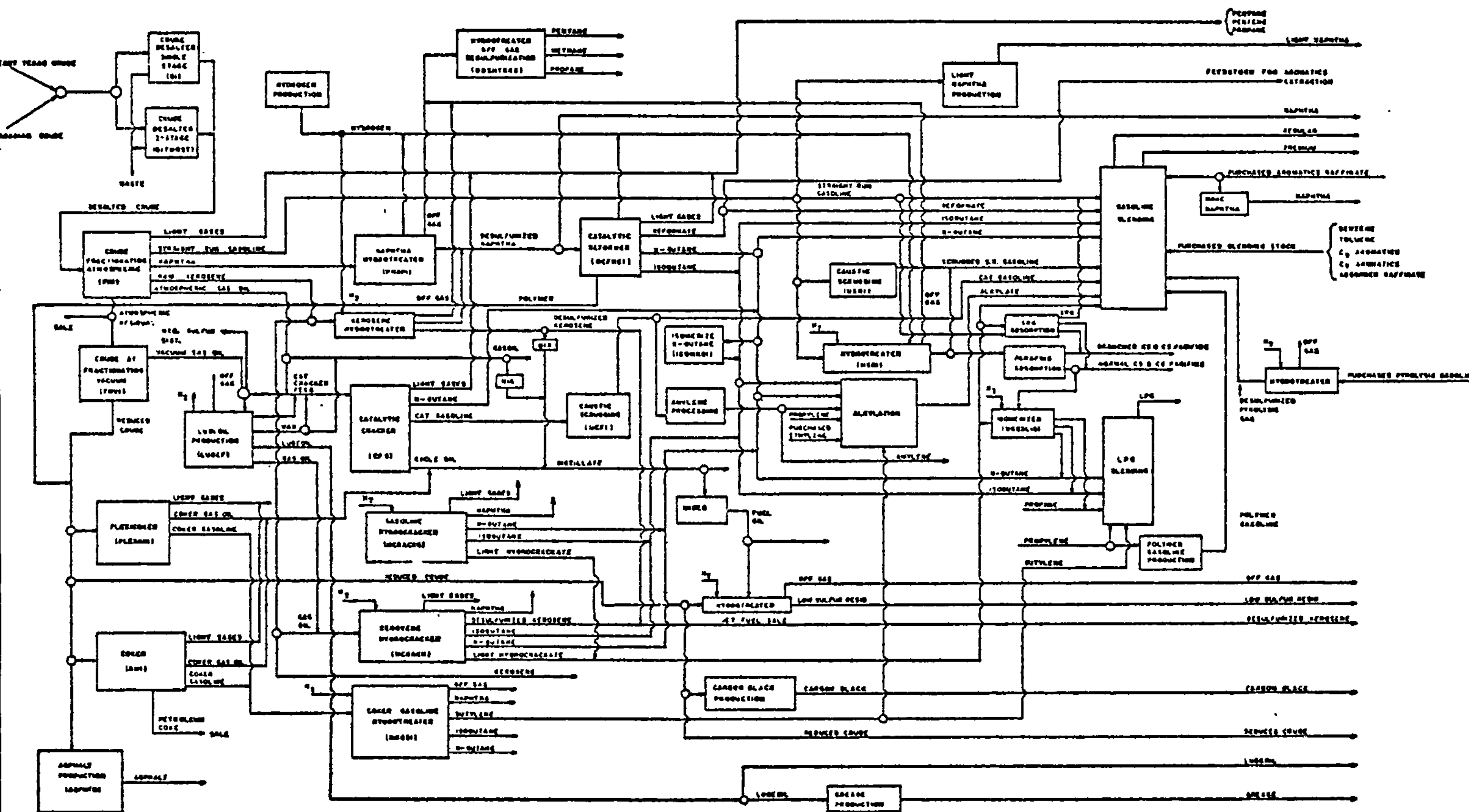

Figure 1
Taken from The Cost of Energy and a Clean Environment
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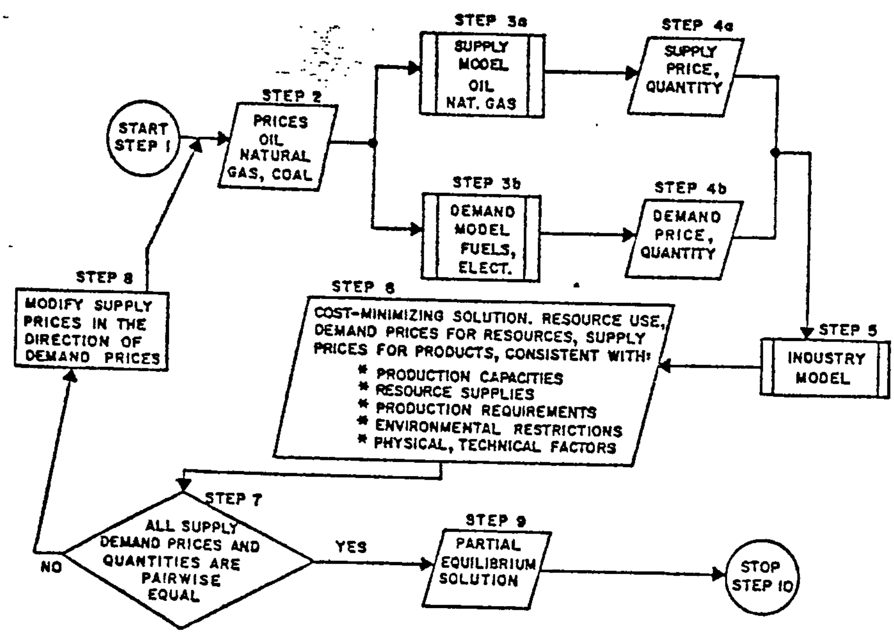


Figure 2
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Illustrative Diagram of Driving Issues' Affect on IIM

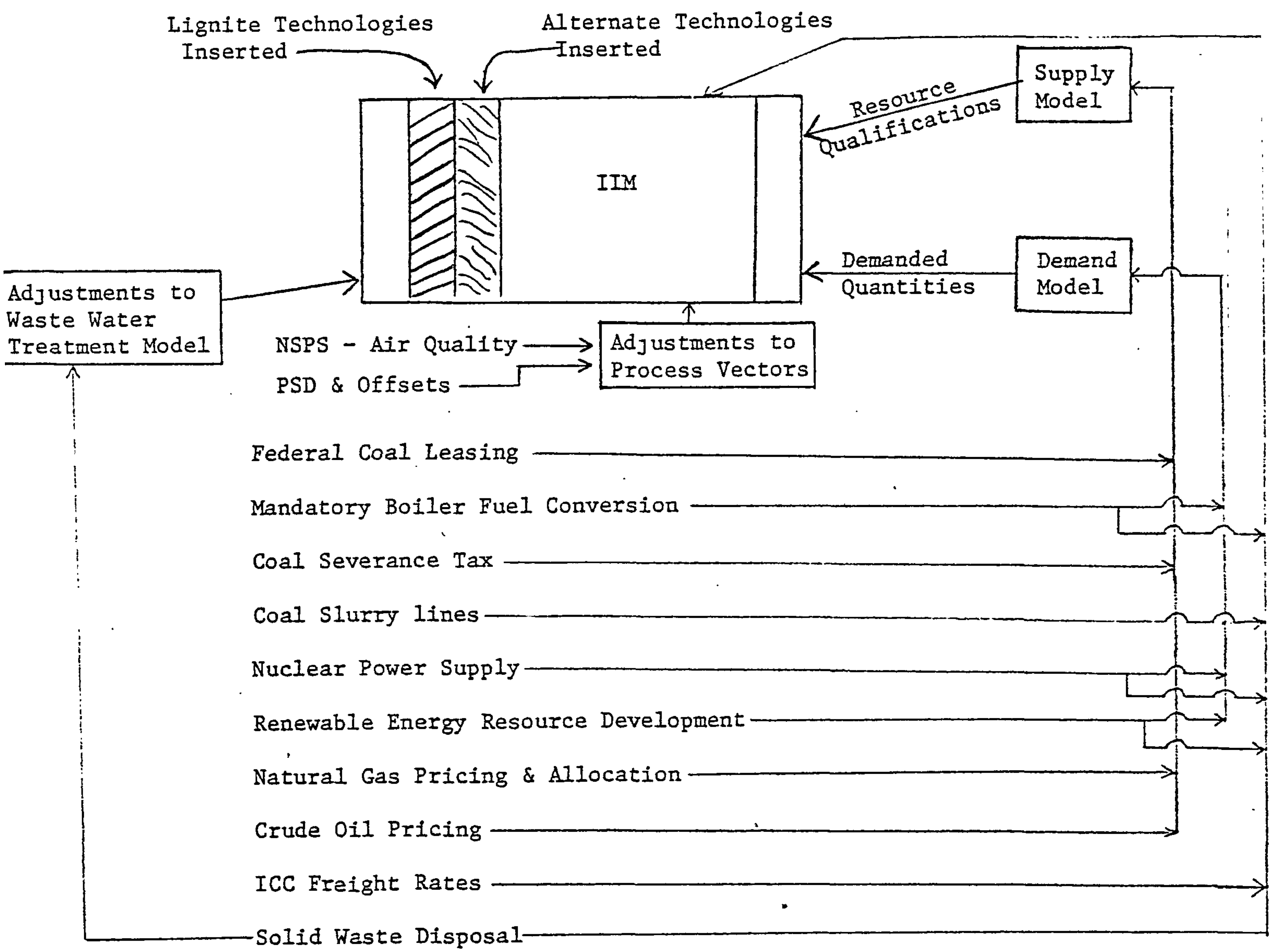



Figure 3

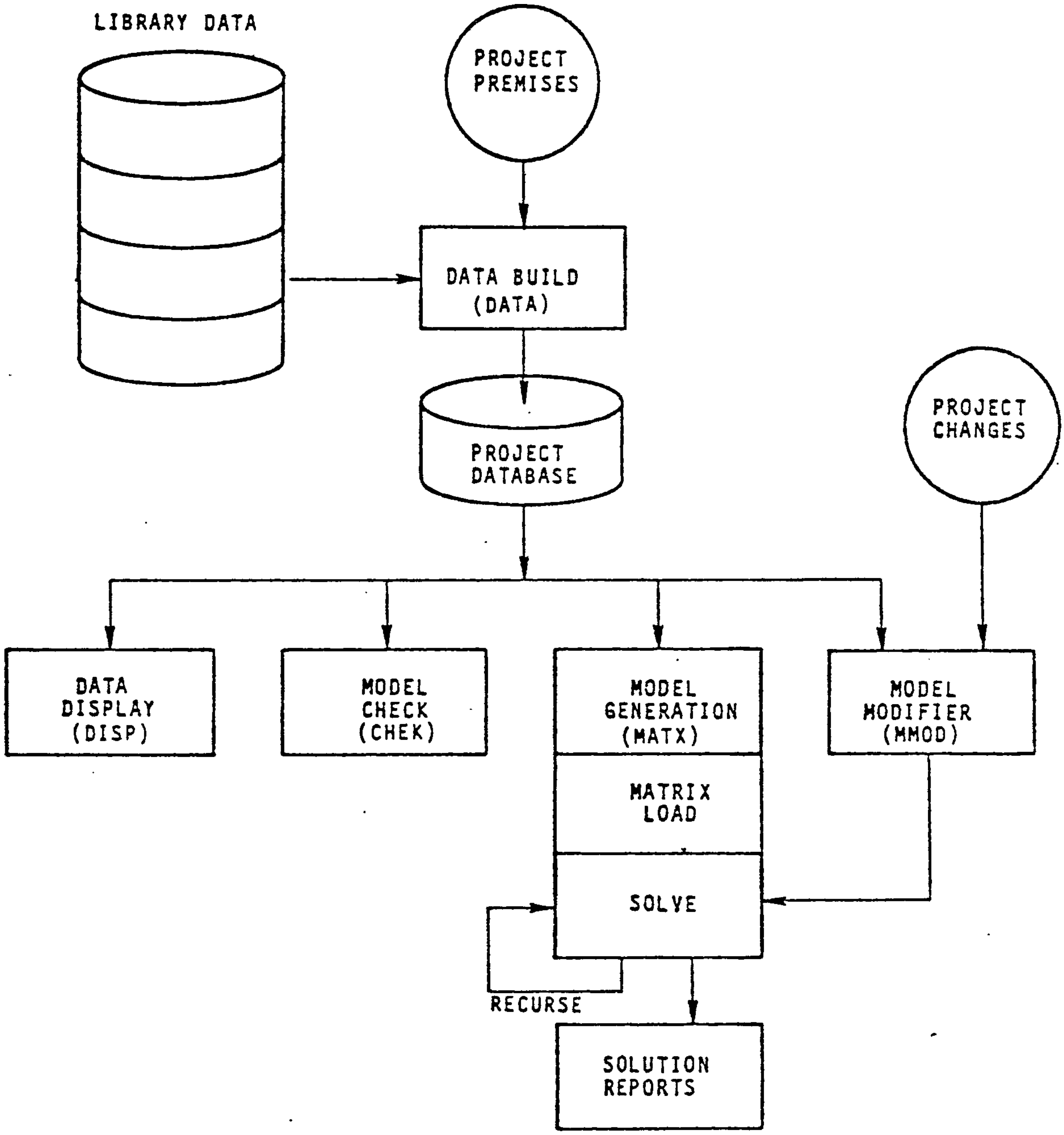



Figure 4

Taken from Banner & Moore Marketing Literature

Independence Evaluation System (PIES). The RPMS generated refinery model is shown in relation to other PIES components in Figure 5.

The PIES refinery model has been used extensively in government projections and studies such as the 1976 National Energy Outlook (6) and was used extensively in formulating the Carter Administration's National Energy Plan. The RPMS system continues to play an important role in PIES analyses and in other government policy evaluation projects.

The Thompson models have been developed under the auspices of The National Science Foundation, the University of Houston Energy Institute, the Texas Energy Advisory Council, and the Federal Energy Administration.

The work done so far by the Thompson group has been reviewed by leading technicians in industry government and education. The modeling work has been documented in three monographs: The Cost of Clean Water (31), The Cost of Electricity (32) and The Cost of Energy and a Clean Environment (4). Important uses have been made of the modeling capability by the Texas State Government, the Federal Government, and Wharton Forecasting Association, Inc. Additional uses of the models are being developed at the Electric Power Research Institute, the International Institute for Applied Systems Analysis, the Institute of Meteorology and Water Management in Warsaw, Poland and

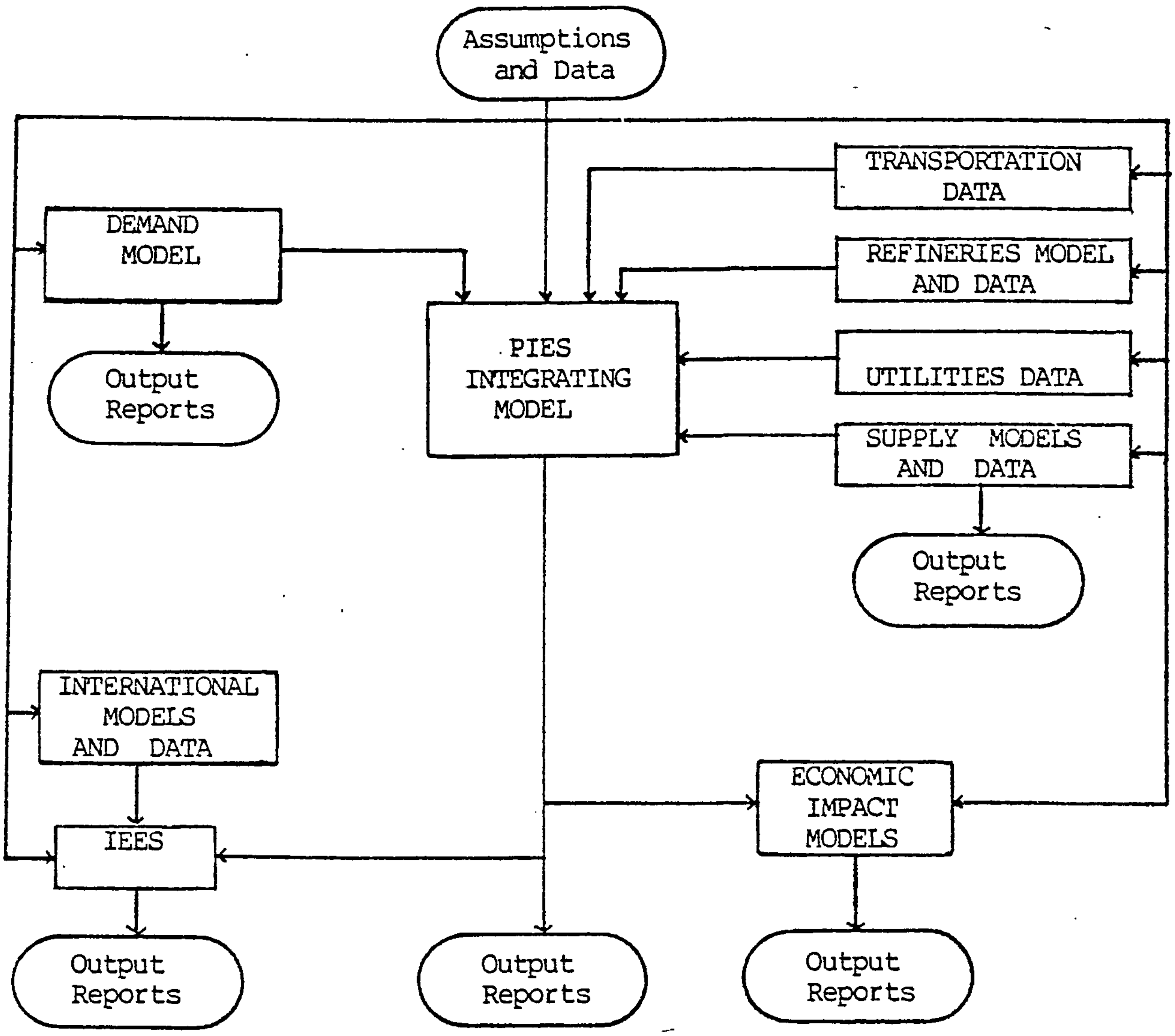



Figure 5

Taken from FEA/N/115 Page 6

Brookhaven National Laboratories.

The Need

In the past the Integrated Industry Model, as developed by Thompson et al., has been used to evaluate complex public policy problems and provide insight on the sensitivity of the economy to various disturbances. Previous modeling work has indicated the importance of capital-related costs to overall industrial costs and illustrated the significance of these costs to public and private policy makers. Accordingly, a considerably more detailed analysis of these costs is justified, particularly with respect to the more important capital intensive industries.

The petroleum refining industry is an excellent candidate for such a detailed analysis for several reasons. First, its importance as one of the vital components of the U.S. industrial complex is obvious. Second, it is quite capital intensive, with approximatley 75% of all refinery costs exclusive of feedstocks being capital related. Third, it is an industry in which technological change has been relatively rapid. This history of innovation createsboth a need and an opportunity for constant investment in new capital and adaptations of older equipment. Additional factors giving impetus to technological change in petroleum refining have been the change in the "mix" of products demanded by the public, a change in raw material quality, and imposition of environmental restrictions. Relatively higher demands for transportation fluids and petrochemical feedstocks and the use of relatively heavier, high sulfur crude inputs have dictated heavy capital investment in such units as catalytic crackers, hydrocrackers, and reformers. Environmental restrictions on lead in gasoline and sulfur emissions to the atmosphere have mandated installation of increased reformer and hydrotreater capacity. Major technological innovations occurring in cat cracker design and in reformer design and catalyst performance have created significant investment opportunities both in new equipment installations and in upgrading of older equipment.

These factors have created a need to carefully analyze the probable capital investment strategies of the petroleum refining industry. Multiple investment strategies arise from the opportunities to invest in different functional types of new units, different unit designs within a functional type, and upgrade opportunities for old equipment. Investment profiles and timing can be optimized to meet different future demand/regulatory scenarios within the constraints imposed by the available investment opportunities.

# CHAPTER 2

## DEFICIENCIES IN EXISTING MODELS

Models which attempt to provide insight into technological and economic phenomenon and thus influence policy decisions must examine in detail all the significant inputs and outputs of the entity which the model tries to represent. For models which attempt a representation of the petroleum refining industry, significant inputs are capital, labor, and crude oil, while significant outputs include gasoline, light gases, middle distillates and heavy fuel oils. Products which are less important in terms of volume are greases, lube oil, and petroleum coke. Residuals and certain specialty products used in refineries must also be considered in any detailed representation.

The models currently in existence which attempt to analyze the petroleum refining industry are predominantly linear programming models (see previous work) and they possess different degrees of detail in different areas. The Bonner and Moore RPMS System has a great deal of detail in crude oil representation with 26 North American crude oils, 10 Middle Eastern, 7 African, and 12 "other" crude oil types. The University of Houston refinery model has very detailed representations of process energy systems with a large number of possible combination of boilers, fuel types, scrubbers, and turbines.

Existing refinery technology is usually represented in LP process models in one of two ways. The first way is to base the technical coefficients of production vectors on new technology. This is tantamount to assuming that all the equipment in the industry being studied is new. A second technique is to represent existing technology by an "average" vector which represents the weighted average inputs and outputs of all processing units. In both cases, vectors representing existing units are usually accompanied by capacity constraints to prevent the model algorithm from formulating an unrealistic solution based on more processing capacity than exists in the period of study. Additional vectors representing new construction allow the expansion of any type of processing capacity by accepting a penalty in capital cost.

Both of the above methods are deficient in accurately representing technological options, and capital investment opportunities available to petroleum refineries. If all new existing technology is assumed, then total refinery production costs cannot be accurately estimated, nor can unit substitution options be exercised. In industry, it is a common practice to construct a new process unit to expand capacity or to simultaneously expand capacity and replace an old unit. The latter option cannot be portrayed accurately either by a model which assumes all new existing capacity or one which assumes average technology.

Capital investment options in current refinery models are generally restricted to investment in new units of some type of refining capacity. However, in addition to unit substitution options, a refinery possesses unit update options. And, in the past, these update options have absorbed a significant fraction of total refinery investment. Old equipment can be modified to increase its effectiveness at its present function or in some cases converted to some different function. A catalytic cracker, for example, can be modified to riser cracking and/or advanced catalyst regeneration with significantly less capital than would be required to construct a new catalytic cracker (see Chapter 4). Such a capital investment option cannot be represented by modeling formats which do not recognize the heterogeneity of existing refinery units.

If all significant capital investment opportunities are not specified in the LP model, then the derived set of LP solutions will not accurately represent the production possibility frontier of the refining industry. However, none of the models currently in use seem to have a detailed representation of the capital equipment currently being used in refineries or the full range of capital investment opportunities available within the industry.

Such a deficiency leads to a number of potentially significant problems. First, without complete representation of existing refinery units refinery costs may be either overstated or understated. If only new technology is represented in the model then overall refining costs will be understated and marginal costs may be substantially understated. This is true because economies of scale, more efficient catalysts, and better equipment designs make new units cheaper to run than older units. Thus, older units set the marginal cost of production. If weighted average technologies are represented in the model then refining costs may be overstated. In some circumstances it may be optimal to retrofit an old unit or to shut down an old unit and build a new one. Denied such opportunities, the model using weighted average vectors may not reach a true optimum solution.

A second problem arises if the analyst wishes to study the derived demand for capital within the refining industry. Newer units typically have a better product profile for a given feedstock than older units. Newer reformers turn a higher percentage of their naptha feed into high quality gasoline blending stock. Newer cat crackers make more of the lighter than desirable hydrocarbon liquids than older cat crackers. Thus, a model which includes representation of new refinery units only will, in general, demand less capital than would the actual industry with its mix of older and new units.

Aside from the question of product profiles, the absence of a whole set of investment opportunities may shift or distort the capital demand curve derived by the model. Unless old and intermediate units along with their update options are represented in the model, a whole set of investment opportunities available to industry will not be available to the model. This may shift and/or distort the capital demand curve.

A final problem associated with lack of a comprehensive representation of capital equipment involves residuals. Newer units typically have lower air and water borne emissions than older units and this may lead to distortion in the estimated environmental costs of a given policy. The absence of older units would tend both to understate the present amount of emissions and to understate the costs of cleanup.

## Vintaging

Classifying refinery units by age creates the opportunity to deal with the problems of policy analysis outlined above. By roughly dividing existing refinery units into age categories (or vintaging) the following is accomplished:

1) A more accurate representation of existing refinery plant equipment is obtained, along with a more accurate idea of current capabilities and potential problems.

2) More accurate estimates of marginal costs are

obtained.

3) More accurate estimates of total costs are obtained.

4) Derived demand for capital and other input factors can be more accurately traced.

5) More accurate estimates of residuals cost and output may be obtained.

6) By constraining capital availability appropriately, one may introduce a dynamic dimension into policy analysis. Thus, the model can be used to estimate not only the costs of a given policy, but also the time required for implementation.

7) Investment opportunities involving updating of existing equipment can be represented.

## Objectives

The objectives of this work are two-fold. The first is to develop an improved linear programming refinery model, starting with the existing refinery model initially developed under NSF RANN contract GI 34459, to soundly estimate the economic demands for capital and the marginal costs of producing refinery end products.

The second objective involves application of the improved model. The sensitivity of the refining industry to upward sloping supply curves for crude oil will be examined. Specifically, the derived demand for capital and water in the industry will be analyzed under differering assumptions about the price elasticity of crude oil supply. Also examined will be the effect of different elasticities on the marginal prices of important refinery end products. A final application will be a demonstration of how a vintaged model may be used to simulate the interactions of long run cost curves, short run cost curves and capital application. This will also be done under assumptions of specified crude oil supply elasticity.

The analysis of upward sloping supply curves for crude oil was chosen for two reasons. First, upward sloping supply curves seem a reasonable possibility that has been overlooked by most analysts. Pricing policy disputes within OPEC itself have become sufficiently sharp to appear in the public press. Such disputes have the potential to break the united front that OPEC has presented to the consuming nations. In addition, nonOPEC nations are supplying a larger percentage of the world's oil (see Figure 6 below) and this increases the chances of nonuniform pricing policies among the producer nations.

Therefore, under the reasonable assumption that domestic crude oil supplies are not likely to be sufficient for some time (if ever), an upward sloping supply situation could result from a new set of pricing policies adopted by OPEC or from policy disputes within OPEC or the entry of significant new supplies into the world oil market.

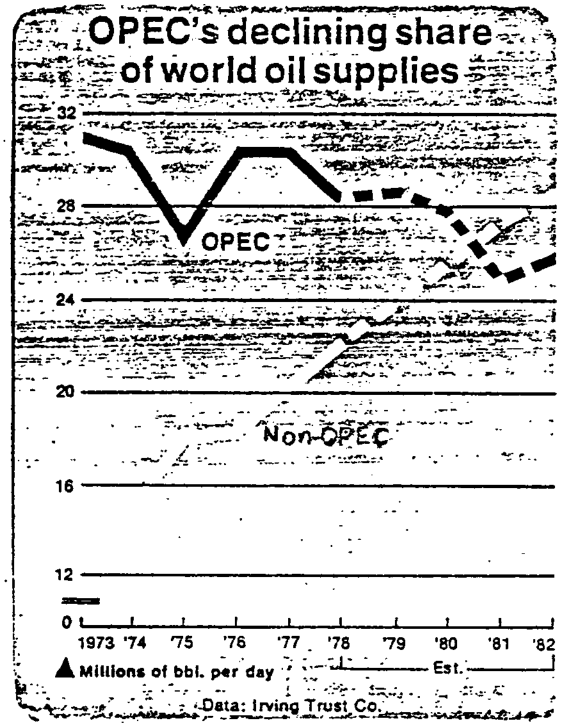



Figure 6

Taken from Business Week, June 12, 1978

A second reason for choosing to analyze upward sloping supply curves is to increase the sensitivity of the analysis of the derived demand for capital. Capital investment decisions are made using marginal prices for raw materials as guidelines. Therefore, since capital is to a certain extent a substitute for crude oil in producing some refinery products, it is possible that the slope of the crude oil supply curve may be as important a determinant of capital demand as the price of capital itself. To fully exercise the extended investment options in the new model it is desirable to vary the slope of the crude oil supply curve.

The operational objective of the analysis will be to determine the impact of alternative supply scenarios on the price/quantity relationships for important refinery end products and factor inputs.

The improvements are addressed to the deficiencies encountered in existing models discussed in an earlier section. Improvements include a more detailed representation of the age distribution of refinery units and a representation of some important investment opportunities other than installation of new units.

It is hoped that additional analytical detail will result in:

1) improved estimates of the cost of compliance with any given set of energy/environmental policies;

2) more realistic appraisals of the equipment configuration which would become optimal under any given set of policies;

3) meaningful estimates of the industry's economic demands for capital;

4) sound estimates of the economic supplies of important refinery end products; and

5) a capability to add a dynamic dimension to policy analysis.

# CHAPTER 3

## REFINERY UNIT DESCRIPTION

Some minimal knowledge of the way a refinery operates is a necessity in understanding how a refinery model works. Therefore, this section describes the basic refinery units along with their inputs and outputs. A flow chart of how the units relate to each other is provided in Figure 3.

Desalters - Removal of salt is the first step in the refining process for almost all types of crude oils. Crude oil must be desalted to avoid corrosion and fouling of equipment. Also, some metals, which cause deactivation of some of the catalysts used in downstream units, are partially removed by the desalter.

Desalting is carried out by mixing the crude oil intimately with water. The salts in the oil dissolve in the water and are carried away in the aqueous stream. As a result of the intimate mixing, oil/water emulsions form in the desalter, which must be broken with chemicals and/or high potential electric fields The water emerging from these emulsions contains not only the salt but also significant quantities of phenols, sulfides, and B.O.D. (9) and thus a significant source of refinery water pollution.

The desalting process is quite efficient with up to

90% of the salt being removed in a single stage desalter. Additional salt can be removed by a second stage if a two stage desalter is deemed necessary. Two stage units also require less water and thus represent a lower emissions alternative to single stage units.

Atmospheric Distillation - The atmospheric distillation unit is usually the first major unit that the crude oil stream encounters in the refinery. Atmospheric distillation units separate the crude barrel into different portions depending on boiling point. These crude "fractions" may then be sent to other refinery units for additional processing. Boiling ranges for typical crude oil fractions in order of ascending boiling point are:

| Fraction | Boiling Range (ASTM°F) |
|---|---|
| butanes and lighter | 90 - 220 |
| light straight run gasoline (LSR) | 180 - 400 |
| kerosine | 330 - 400 |
| light gas oil (LGO) | 420 - 640 |
| atmospheric gas oil | 550 - 830 |
| feed to vacuum distillation | 750+ |

Each of these products is drawn out of a distillation tower as a side stream, with five to eight trays separating each product. Thus the tower usually contains from 30 to 50 trays in all. As the table above indicates, some overlap exists in the boiling ranges of the various fractions. This gives the refiner a certain degree of freedom in choosing the exact temperature at which he wishes to make the separation. By altering the temperature range of a given fraction, the refiner can change both the amount and the properties of that fraction. For example, it is possible, by increasing the temperature at which the S.R.G. cut is taken, to obtain a larger amount of somewhat less volative S.R.G.

The type of crude oil being processed strongly affects the amount and properties of each of the petroleum fractions. The Bureau of Mines' Routine Distillation Method gives fractions in crude in percentages distilled at fixed temperatures. This test shows that even when two crude samples are from the same general area, they can differ substantially in properties. Analysis of several different California crudes by this method showed that total gasoline and naphtha varied from 33.5% to 17.9% of the incoming crude (11).

Vacuum Distillation - The vacuum distillation unit processes the heaviest fraction coming out of the atmospheric unit, and further separates that fraction. The separation could not be carried out in the atmospheric unit, since at atmospheric pressure, excessively high temperatures would be required. With the lower temperatures required in the vacuum unit, separation of the heavier fractions can be accomplished without excessive thermal cracking, and the product loss and equipment fouling problems that accompany such cracking.

Pressure inside a vacuum distillation unit is kept very low: around 25 to 40 mm Hg. The effective pressure of the hydrocarbon stream being processed is still lower, since steam is injected into the distillation unit's inlet to lower the partial pressure of the hydrocarbon component. The steam also helps minimize coke formation.

The steam is used in fairly substantial amounts (12) and, of course, comes into intimate contact with hydrocarbons. This produces a certain amount of contaminated water. The vacuum is maintained by steam ejectors and this steam is also contaminated with hydrocarbon wastes. If the ejectors exhaust into barometric condensers a great deal more water may be contaminated.

Coking - Coking is essentially a severe thermal cracking process by which the refinery minimizes its production of residual fuel oils. By cracking such stocks as the residuals from the vacuum distillation unit, and cat cracker slurry oil, the refinery is able to increase the amounts of light gases and middle distillates that it obtains from a barrel of crude. Refinery coke (carbon) is a by-product of this process. This coke is used in the steel and aluminum industries. Additional benefits arise from the fact that a large portion of the metals originally in the crude oil are captured in refinery coke.

Two major coking processes exist: delayed coking and fluid coking. Delayed coking involves heating the incoming feed as high as 950°F in a specially designed heater. Fluid velocities are kept high in this heater to avoid coke formation in the heater tubes. Steam may also be injected into the heater tubes along with the hydrocarbon stream to suppress coke formation still further. Insulated surge drums are placed at the heater's outlet to slow the hydrocarbon stream and give the coke time to form. As the coke forms it settles to the bottom of the insulated drum. Usually, the surge vessels are installed in pairs so that while one is being emptied of coke the other is in service. Delayed coking units are discussed in the literature (13,14).

The fluid coking process is truly continuous, involving no cycling of surge drums as in the delayed coking process (15). It is a heat balanced process since a portion of the total coke make is burned to provide all process heating requirements. In the reactor, coke is formed and removed continuously from a fluidized bed of coke particles. Liquid products leave the reaction zone through cyclones and enter a distillation tower. The high boiling distillates that emerge from the tower are recycled to the reactor while lighter liquids are sent to other refinery processing units or are blended.

Hydrotreating - Catalytic hydrotreating has two essential purposes: First, it stabilizes petroleum products by saturating compounds such as olefins or diolefins which may polymerize to form gums or other materials. Second, hydrotreating removes objectionable compounds such as sulfur, nitrogen and some metals. In recent years environmental regulations have required considerable additional investment in hydrotreating facilities to remove these materials.

A wide variety of petroleum products are hydrotreated ranging from motor gasoline to heavy residual fuel oils. Although processes differ somewhat depending on the product being hydrotreated and the process licensor, they are all fundamentally similar. (For descriptions of specific processes, see (17) and (18)). Fresh feed is mixed with makeup hydrogen and a hydrogen rich recycle gas and charged to a reactor section. The reactor consists of a vessel containing a fixed bed of a catalyst such as cobalt, molybdenum, or vanadium oxide. After passing over the catalyst bed at temperatures high enough to achieve processing objectives but low enough to avoid excessive feed cracking, the hydrocarbon stream enters a separation vessel. Here, hydrogen gas is flashed off of the liquid stream along with light hydrocarbon gases and hydrogen sulfide.

Product profile depends primarily on the hydrocarbon stream being treated, and the main product is always a desulfurized and stabilized version of the incoming feed. However, some cracking takes place in the hydrotreating reaction, and even in the case of heavy fuel oils, some light constituents will be produced. This makes a fractionator for liquids necessary. Also, it is, of course, necessary to provide equipment for the separation of hydrogen sulfide gas.

Hydrocracking - Hydrocracking is a highly flexible process which can be used in applications as diverse as upgrading heavy residue into lighter oils or changing napthas into liquefied petroleum gases. The process can either change heavier portions of the crude barrel into lighter fuel oils or increase the yield of motor fuel. Hydrocrackers and cat crackers can work in tandem in a refinery, with cat crackers processing the more easily cracked atmospheric and vacuum gas oils, while the hydrocracker operates on the more refractory coker distillates and cycle oils. In the design stage hydrocracking is especially flexible and can even be used to convert lignite into gasoline. Hydrocracking also achieves the objectives of stabilizing, desulfurizing, and denitrifying hydrocarbon feedstocks.

Two basic types of hydrocracking process exist: fixed bed and moving bed. Most installed units employ the fixed bed technology. (Descriptions of individual processes may be found in 19 and 20). Fixed bed units may employ one or two stages in the reaction section. The hydrocracking catalyst is a molecular sieve catalyst impregnated with a rare earth metal. With fixed bed technology, the catalyst gradually loses its activity as the reaction takes place until, finally, it must be regenerated. Moving bed processes allow continuous removal and regeneration of catalyst or addition of fresh catalyst. Thus, over the life of a run, moving bed processes can maintain better product profiles and, also, the runs can be longer.

The extent to which a given refinery can make use of a hydrocracking process depends on its feedstock and its required product profile. Hydrocracking is used most extensively in California where heavy feedstocks are processed and gasoline demands are high. Other factors affecting the hydrocracking process are hydrogen availability and competition for hydrogen use. It is important to the refiner to maintain a balance between the hydrogen available from refineries and other sources and uses of hydrogen. Environmental constraints currently mandate a large degree of hydrotreating which compete with hydrocracking for available hydrogen.

Alkylation - Alkylation involves the addition of low molecular weight olefins to isoparaffins to form higher molecular weight isoparaffins. This reaction, which is essentially the reverse of cracking, is carried out to produce a high octane blending stock for motor fuels. Most of the product obtained can be made to fall into the

88 - 94 motor octane number range (21).

Two catalysts are used commercially for the alkylation process, and the choice of catalyst dictates the choice of alkylation process to the refiner. The catalyst used are sulfuric acid and hydroflouric acid and each has at least one licensed process built around it.

In the HF alkylation process licensed by Phillips Petroleum (22) fresh liquid feed composed of olefins and isobutanes is charged to a specially designed combination reactor settler. In the reactor section the hydrocarbon feed is mixed initimately with concentrated HF. The hydrocarbons and the acid are then allowed to separate into distinct phases in the settler. The hydrocarbon phase is drawn off, and a fractionator separates it into alkylate, propane, and recycle isobutane. Additional processing steps may be required to separate normal butane from the alkylate.

A description of a sulfuric acid based alkylation process may be found in ref. (23). The processing steps of a sulfuric acid based alkylation technology are essentially the same as those found on HF. Differences between the two processes are primarily operating differences, royalty and licensing cost differences, and to some extent product profile differences. The advantages and disadvantages of both processes are examined in ref. (24).

Catalytic Reforming - The catalytic reforming process rearranges the structure of hydrocarbon atoms into forms which give better performance as motor gasoline. The reformer's main function is to reduce the amounts of paraffins, olefins, and napthenes in the feedstock and increase the amounts of higher octane aromatic compounds. A typical analysis for reformer feedstocks and products is given below (25).

| Component | Feed | Product (Volume %) |
|---|---|---|
| Paraffins | 45-55 | 30-50 |
| Olefins | 0-2 | 0 |
| Napthenes | 30-40 | 5-10 |
| Aromatics | 5-10 | 45-60 |

The increased aromatics content of the product stream gives a gasoline blending stock that can have a research octane number of 102 or higher with no lead additives. The reformer also produces several valuable by-products, the most important of which is hydrogen. Hydrogen production is increasingly important in refining operations, since hydrogen is used to remove sulfur, and nitrogen compounds found in crude oil, and to upgrade heavy hydrocarbon fractions to more valuable middle distillates. A former product profile is given below (28).

Product Yields

| | |
|---|---|
| Hydrogen scf/bbl. feed | 1530 |
| $C_1$ - $C_3$ scf/bbl. feed | 195 |
| $C_5$ + Reformate, Liquid Vol. % | 79.1 |

Feedstocks for the reformer can come from several sources: 1) a cut from the crude distillation tower (virgin naptha), 2) a portion of the product stream from the catalytic cracker, and 3) a portion of the product stream from the hydrocracker. The refiner has the option of taking wide or narrow "cuts" from each of these potential feedstock streams for reformer feedstock.

The primary processing problem in catalytic reforming is formation of coke on the catalyst. Coke formation is favored by the same reactor conditions that favor maximum aromatization and hydrogen production, and coke deactivates the reformer catalyst. Therefore, a trade-off exists between the amount of reformate producted and its quality. If severe reactor conditions are maintained, a reformate with a very high octane number will be obtained, but yields will be lower. Less severe conditions will produce a larger amount of lower octane reformate.

The importance of the coke formation problem is emphasized by the fact that reformers are classified according to how the coke deactivated catalyst is regenerated. There are three major reformer types: semi-regenerative, cyclic, and continuous. Several variations of each of the major types are offered by major licensors. In semi-regenerative operations, the reactor is simply taken out of service periodically and the coke is burned off of the catalyst. Cyclic units have several reactors, which can be taken out of service one by one without shutting down the rest of the operation. Thus, the normal mode of operation for a cyclic reformer is to have one reactor out of service for catalyst regeneration, while the other reactors are on stream. The third reformer type employs special equipment to continuously withdraw small amounts of catalyst for regeneration.

The three reformer types vary in capital investment required, and in gasoline production efficiency. The continuous reformer features an ability to achieve the highest possible octane numbers and yields of the three types. This is possible because the continuous catalyst regeneration capability allows the refiner to run the reformer at very severe conditions. Coke forms on the catalyst rapidly under such conditions, but is removed as quickly as it forms. Cyclic reformers cannot be run under conditions as severe as continuous reformers, and the semiregenerative units are even less capable of tolerating extremes. Therefore, product yield/quality profiles are best with continuous, and worse with semiregenerative operations, with cyclic operations falling in between those two. As one might expect, the capital requirements of reformers are proportional to their operating efficiency. Continuous reformers are most costly, followed by cyclic units, and semiregenerative reformers are the least expensive of the three.

Catalytic Crackers - Catalytic cracking is one of the more widely used processes for converting heavy oil fractions into lighter, more valuable fractions, such as gasoline and light gases. The catalytic cracker is composed of two basic parts: the reactor and the regenerator.

In the reactor, catalyst is intimately mixed with the incoming hydrocarbon stream and the larger hydrocarbon molecules are "cracked" into smaller molecules. In the cracking process coke is deposited on the catalyst, causing it to gradually lose its effectiveness. This makes the regeneration step necessary.

In the regenerator, controlled amounts of air are used to burn away the coke covering the catalyst without heating the catalyst so hot that it loses its activity. The regenerated catalyst is then returned to the reactor via a catalyst "riser." Thus the catalyst moves continuously back and forth between the reactor and the regenerator.

Catalytic Cracker Classifications - In addition to the obvious classifications based on age and size, catalytic crackers can be subdivided into technical classifications. All cat crackers now in operation can be defined as either moving bed (29) or fluidized bed units (30,31). At least one variation of each basic type is on the market.

The moving bed type uses catalyst beads about 1/8 to 1/4 inch in diameter. These beads fall from the top of the reactor in the form of an annular curtain surrounding the hydrocarbon feed. The catalyst and the feed move concurrently through the reactor and are separated at the bottom. After the accumulated coke is burned off the catalyst, the regenerated catalyst is carried to the top of the reactor by a stream of air to start the cycle again.

The fluidized bed catalytic cracker uses catalyst in the form of small particles which can be supported on a stream of upward sweeping gas. The catalyst is transported from the regenerator to the reactor and maintained in a fluidized condition by the hydrocarbon feed stream. Catalyst in continuously withdrawn from the reactor and sent to the regenerator.

Catalytic crackers can also be classified as heat balance or nonheat balance units. Since the cracking reaction in endothermic and regenerative process is exothermic, opportunities exist to use the heat of the regeneration step in the reaction step. Units which do this are heat balance units. Other units might recover the heat of regeneration in the form of steam and receive a steam credit.

Water born residuals from catalytic cracking arise from the substantial amounts of heat that must be removed from the regeneration step, and from several points at which water is injected into the hydrocarbon stream. Air pollution may be created by noxious gases from the burning of the coke on the catalyst.

At the point at which the catalyst is separated from the hydrocarbon stream, stripping stream and/or purge steam is required to efficiently achieve the separation. Also, sealing steam may be required at the point at which the catalyst is introduced into the feed stream. Most of the steam condenses later in the catalytic cracker fractionator and contains B.O.D., C.O.D., Phenol, sulfides and other contaminants.

Two sources (29) and (32) indicate that the total amount of steam used in older units is about 5% by weight of total feed (fresh feed plus recycle). In newer units, steam requirements are decreased by as much as 50% (32). Revamp units fall somewhere in between these extremes with a "best guess" figure of about 20% less than the older units.

# CHAPTER 4

# MODEL DEVELOPMENT

The model represents nine basic petroleum refining operations: atmospheric distillation, vacuum distillation, coking, reforming, isomerization, alkylation, catalytic cracking, hydrocracking, and hydrotreating. These units are represented in the model by column vectors whose activity levels are constrained by right hand side values representing product demand requirements and existing capacities of given refinery units. The model processes two basic types of crude oil: one representing a high sulfur Arabian crude, and the other representing a lower sulfur East Texas crude.

The new version of the model is improved in the sense that it is more flexible, allows for more operating and investment options, and more closely resembles the actual state of the industry than the previous model version. In particular, two new features have been added to the revised version of the petroleum refinery model. First, the model has been "vintaged" to reflect the age structure of the refining industry. Second, vectors have been included to allow upgrading of some existing facilities as well as investment in new refinery units.

Vintaging-general

The new version of the model is built around the concept of three basic types of refinery units: old units, intermediate units, and new units. Old units are defined as those which existed before 1957, intermediate units are defined as those built between 1957 and 1967, and new units are those built after 1967. The time period used are arbitrary and do not reflect any technical factors such as active construction periods or innovation timing. Old refineries are assumed to be small (35,000 bbl/day), intermediate refineries are assumed to be medium sized (100,000 bbl/day), and new refineries are assumed to be large (200,000 bbl/day). These assumptions about size/age relationship are usually but not always true. Individual refinery units are also assumed to generally follow this age/size pattern. The total existing capacity for each type of unit is divided among these three categories by an approximation method. This method is based on the fact that retirement of refinery equipment has taken place at a slow rate in the past. Using a one percent per year retirement rate, comparisons of published figures for refinery unit capacities in 1957, 1967, and 1976 were used to distribute total capacity into the three categories. This distribution was checked for reasonableness against data for announced refinery unit additions over the past twenty years.

Within the old, intermediate, and new categories, capacities are further divided among updated and nonupdated equipment for those refinery units for which update opportunities exist. Capacities are divided among different update verions by very rough approximations based on "best guess" estimates from construction industry sources. In terms of the relative reliabilities of the capacity estimates used in this study, the estimates for total existing unit capacity are very accurate, the breakdown among old, intermediate, and new units is less accurate, and the breakdown among the different update options within a given unit/age category is least accurate.

For vintaging purposes refinery units can be broken into 4 categories:

1) units which have experienced major technological design changes over the past twenty years, with prospects for significant retrofit opportunities on old units;

2) units which have undergone major change but lack significant retrofit opportunities;

3) units which have experienced only evolutionary changes in the past twenty years; and

4) units which are too new to allow for significant vintaging.

The nine units addressed in this study are divided among these categories as follows:

Category 1 - cat crackers and reformers

Category 2 - cokers

Category 3 - distillation units, desalters, hydrotreaters, alkylation units, and isomerization units

Category 4- hydrocrackers

The general modeling strategy followed was to assemble column vectors representing old, intermediate, and new units for each type of refinery activity.

Where significant update options exist, vectors have been included to represent both the update opportunity for unconverted equipment and equipment that has already been updated. For example, old cat crackers can be converted to riser cracking, and vectors have been added to the model to represent the different output profiles for these updated units. The vectors representing existing cat crackers which could be converted to riser cracking differ from those vectors representing units already converted in that the former contain a capital change for the cost of conversion while the latter do not.

This convention also differentiates between existing new units and added capacity. Capital related costs such as depreciation and return on investment are included in vectors for added capacity but not in vectors for existing capacity. Such costs are considered "sunk" for existing units and no longer relevant to the optimization. Accordingly, objective function values in the columns for existing units reflect only operating costs such as maintenance, labor, etc.

The modeling strategy outlined above resulted in the pattern of vectors for low recycle catalytic crackers shown in Figure 7. All vectors representing existing equipment contain entries to reflect the inputs and outputs of operating cat crackers. These vectors do not contain a capital row entry since the capital required to build these units is considered a sunk cost. The update and new build vectors contain a capital row entry to reflect the capital cost of making the indicate conversion. These vectors essentially perform the function of relaxing the right hand side constraints (K) on the vectors representing existing equipment. This is accomplished by consuming the amount of capital necessary to make a unit addition or conversion. Note that the update vectors "consume" intermediate or old capacity (as well as capital), while relaxing the constraints on converted capacity. The estimated total amount of existing cat cracker capacity is divided among seven categories: old, intermediate, new, old converted to riser cracking (update 1), old converted to riser cracking and advanced catalyst regeneration (update 2), converted intermediate (update 1) and converted intermediate (update 2). All vectors for existing units have entries in the appropriate capacity row to indicate that all of these activities consume some form of existing catalytic cracker capacity.

Catalytic crackers present the most complex modeling task since two significant update options are available. This results in the replacement of one catalytic cracking

## Figure 7

### SCHEMATIC OF CAT CRACKER VINTAGING

| | OPERATION ACTIVITIES EXISTING PLANTS CAPITAL COSTS SUNK | | | | | | | CONSTRUCTION ACTIVITIES NEW BUILDS & UPDATES REQ. CAPITAL INVESTMENT | | | | | RIGHT HAND SIDE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | UNCONVERTED | | | UPDATE 1 | | UPDATE 2 | | UPDATE 1 | | UPDATE 2 | | NEW | |
| | OLD | INT. | NEW | OLD | INT. | OLD | INT. | OLD | INT. | OLD | INT. | PLANT | |
| Operating Cost | 0.32 | 0.25 | 0.23 | 0.47 | 0.31 | 0.44 | 0.29 | | | | | | |
| Capital Investment | | | | | | | | 0.919 | 0.357 | 0.907 | 0.359 | 1.39 | |
| Capacity Constraints | | | | | | | | | | | | | |
| Old plants | 1 | | | | | | | 1 | | 1 | | | $\leq K_1$ |
| Int. plants | | 1 | | | | | | | 1 | | 1 | | $\leq K_2$ |
| New plants | | | 1 | | | | | | | | | -1 | $\leq K_3$ |
| Old Update 1 | | | | 1 | | | | -1.05 | | | | | $\leq K_4$ |
| Int. Update 1 | | | | | 1 | | | | -1.05 | | | | $\leq K_5$ |
| Old Update 2 | | | | | | 1 | | | | -1.12 | | | $\leq K_6$ |
| Int. Update 2 | | | | | | | 1 | | | | -1.12 | | $\leq K_7$ |
| Material Balances | | | | | | | | | | | | | |
| CC feed | -1 | -1 | -1 | -1 | -1 | -1 | -1 | | | | | | |
| Cat gasoline | 0.545 | 0.545 | 0.638 | 0.586 | 0.586 | 0.595 | 0.595 | | | | | | |
| Cycle stock | 0.32 | 0.32 | 0.25 | 0.304 | 0.304 | 0.299 | 0.299 | | | | | | |
| By-products | + | + | + | + | + | + | + | | | | | | |
| Utilities | +/- | +/- | +/- | +/- | +/- | +/- | +/- | | | | | | |
| Residuals | + | + | + | + | + | + | + | | | | | | |

vector in the old model with seven vectors in the new version. Other refinery units are less complex, but the general treatment is the same.

Revisions of vectors for specific units

Three units have not been vintaged for various reasons; hydrotreaters, alkylation units, and isomerization units remain essentially as they were in the older version of the model. This has been done partly because these units have undergone only evolutionary change since 1957.

Although two different alkylation processes exist (one based on hydrofluoric acid and one based on sulfuric acid catalyzation), the processes are quite similar from the standpoint of an LP model. Both processes produce similar products ]33,34] and require, overall, about the same amount of capital per installed unit. Hydrofluoric acid processes may be more advantageous for small plants or for plants not close to a good supply of sulfuric acid. However, the main differences seem to be related to operational characteristics (operating flexibility, safety, agitation requirements, etc. (35) not readily captured by a linear model.

Another reason for not vintaging these activities is that they include several slightly different activities in the model (i.e., hydrotreating of distillate, residual fuel oil, straight run gasoline, etc.) which would imply a large increase in model complexity and size as a result of vintaging.

As an additional negative factor, the existing capacity of alklylation an isomerization units is quite small relative to that of other refinery units. These considerations together lead to the conclusion that vintaging would not add enough analytical power to the model to compensate for the increased size and complexity that the vintaging process would require.

Cokers - Coking units are treated differently than the other type units because of their different development over the past twenty years. Delayed coking units have been in existence for a longer time and have not undergone radical changes over that period. Recently, however, a totally new coking process (flex coking) has been developed [36,37] which converts approximately 98% of the incoming hydrocarbon stream to gaseous or liquid products with only a 2% purge stream of solids. This purge stream contains 99% of the heavy metals in the feed stream.

Neither the literature nor industry sources make any mention of the possibilities of converting old coking units to the new process. This could be simply a function of economics since the new units are considerably more expensive than conventional units, and major conversions are generally less justifiable, economically, than new investment. Whatever the reason, no such conversions have been announced, no data on possible conversions seems to exist, and, accordingly, the assumption has been made that delayed coking units will not be converted to flex coking units.

For model simplification it has been assumed that no flex coking exists in the base year. This is not true, but compared to delayed coking capacity flex coking capacity is very small. Thus, the coking function is represented in the model by a set of fully vintaged delayed coking units with no update options and by a flex coking option available as new investment.

Cat Crackers - Catalytic crackers, with two possible update options as well as vintaged units, presented the most complex problem in the refinery model revisions. The problem could have been even larger, since only one of the two major types of cat crackers was considered; fluid bed units were modeled since they have a dominant place in the industry, while moving bed units were left out to avoid unnecessary complexity.

The two update options considered for cat crackers are:

1) conversion to riser cracking, and

2) conversion to advanced catalyst regeneration systems.

These improvements are independent and can be carried out either separately or simultaneously. These conversions are very labor intensive, and their cost is not particularly sensitive to unit size. The conversions are, therefore, much more attractive for intermediate units (100,000 bbl/day refineries) than for old units (35,000 bbl/day refineries). Although conversions are allowed in the model for both old and intermediate units, it is anticipated that the model will opt for conversion of old units only under fairly severe stress.

Industry sources indicate that a substantial portion (75%) of eligible cat cracker capacity has already been converted to riser cracking. Approximately 50% has already been converted to advanced catalyst regeneration. These percentages are not taken from any detailed study but, rather, represent the "best guess" of knowledgeable representatives of the refinery construction industry.

The update options and existing improvements are represented in the model by four types of column vectors: update to riser cracking, update to riser cracking (existing), update to riser cracking and advanced catalyst regeneration, and update to riser cracking and advanced catalyst generation (existing). Old and intermediate cat cracker capacity is divided among these options as follows:

unconverted - 25%

converted to riser cracking - 25%

converted to riser cracking and advanced catalyst generation - 50%.

These percentages are also "best guess" figures.

<u>Distillation units and desalters</u> - These units are in the category for which no significant update options are modeled. Changes in distillation tower technology have been slow, with construction material changes, improved tray efficiencies, and size being the major differences between

old and new units. Desalter changes have occurred, but desalters involve such small amounts of capital that it is assumed that, rather than troubling to update an old unit, refiners will simply build a new one.

Five atmospheric distillation units are modeled, including old, intermediate, and new units processing East Texas Crude and intermediate and new units processing Arabian crude. This breakdown allows for slight unit differences in processing high sulfur and low sulfur crudes. No old units processing Arabian crude are included in the model since few pre-1957 units were designed to process the higher sulfur Arabian imports. Industry sources indicate that it is unlikely that a unit designed to process only low sulfur crude could be economically converted to high sulfur service (due to metallurgical constraints). It would be cheaper in most circumstances to build a new unit.

Although changes have taken place in distillation tower technology, it has been assumed that most improvements (improved trays, more efficient heat exchangers, etc.) have already taken place. Substitition of tube heat exchangers for barometric condensers has, for the most part, already been forced by environmental regulations. Vacuum distillation units are treated similarly to atmospheric units.

Desalter technology has changed in that both electrostatic and chemical techniques are now used to break the water/oil emulsions that typically emerge from a desalter. This improved technology can be applied to old single stage units as well as to the newer two stage units. Two stage units, requiring somewhat more capital, can cut water requirements of a desalter by 50%. Since a good percentage of refinery residuals emanate from desalters, this option reflects an important means of pollution control. Both two stage and single stage desalters are represented in the model, with no update options included.

Reformers - The catalytic reforming process will be a very significant one in the immediate future. Federal mandates which reduce the amount of lead allowed in gasoline, along with continued high demand for motor fuels, will force increased investment in reformer capacity. These investment decisions will have to be made soon to bring enough reformer capacity in line in time to meet the Federal deadlines on lead.

Update options for reformers revolve around the possibilities presented by the new bi-metallic catalysts (14). These catalysts are not as susceptible to deactivation by coke formation as the older platinum catalysts, and this presents the refiner with the opportunity to improve the octane number of his reformate, improve the yield of reformate, or both. The new catalysts can simply be inserted in the old reformers, or the old reformers can be modified to take maximum advantage of the properties of the new catalysts. Usually, a reformer modification is accompanied by an expansion of the unit's capacity.

Reformers present a serious problem in modeling because their design and operating flexibility, along with the different feedstocks they can process, give a degree of freedom to the refiner that is difficult to represent in a linear model. Two major variables alone (gasoline yield and octane number) form a curve which represents an infinite number of operating modes for any given reformer after all other variables have been fixed. The problem, therefore, is to judiciously choose a number of design/feedstock/operating mode combinations which will adequately represent the reforming process in a finite (and reasonable) number of vectors.

The model now includes 48 reforming activities. The major classifications are as follows:

| | |
|---|---|
| size/age | - small/old, intermediate/intermediate, large/new |
| operating mode | - high severity, low severity |
| feedstock | - Arabian, East Texas |
| design | - semiregenerative, cyclic, continuous |
| capital investment | - old update (preexisting and new), intermediate update (preexisting and new), and new build |

It is assumed that 50% of all old and intermediate reformer capacity has already been updated. These update figures are also "best guess" figures. Cyclic and continuous processes are considered new build activities.

Hydrocrackers - Although hydrocracking (or destructive distillation with hydrogen) has been in existence for a long time, it has not been used extensively until relatively recently. Developed commercially by I. G. Farben Industries in 1927, the hydrocracking process has only come into its own since large quantities of by-product hydrogen have become available (from reformers). More recently, environmental restrictions on sulfur and metals in hydrocarbon products have caused some shifting of this by-product hydrogen away from hydrocrackers and towards hydrotreating processes.

There are two basic types of hydrocrackers: fixed bed and moving bed. The fixed bed type is dominant in the industry and this is the type modeled. No significant design or catalyst changes for hydrocrackers (since their widespread commercialization) are mentioned in the literature, but since some hydrocracker capacity was in place as of 1967, intermediate hydrocrackers are modeled as well as new ones. Both types are allowed to operate in either a normal or maximum gasoline mode, and the result is four modelled hydrocracker activities.

# CHAPTER 5

# ANALYSIS

The initial questions to be addressed by the vintaged refinery model are (a) the sensitivity of the model to upward sloping supply curves for crude oil, and (b) the characteristics of derived demand curves for capital and water. The procedures chosen to investigate these questions and the results of the analysis are described below.

## Procedures

The model used for this analysis includes:

1) Thompson *et al.*'s Refining Model as updated and vintaged;
2) Sections of Thompson *et al.*'s Organic Chemicals Model; and
3) Supply vectors which, piecewise, approximated hypothetical supply curves of varying elasticity for foreign crude.

It was deemed necessary to include some units from the Organic Chemicals Model because of the interrelated nature of the refining and petrochemical industries. These interactions include not only the obvious supply/demand relationships in which the petrochemical industry receives various petroleum fractions from the refinery, but also feedback loops in which the petrochemcial complex can supply the refinery with certain blending stocks and with ethylene, butylenes, and propylene for alkylation. The two industries compete for natural gas and natural gas liquids as inputs.

These connections make it very difficult to study the refining industry wihtout the organic chemicals industry. Such an analysis would require estimates of a tedious number of transfer prices and amounts for each solution of the refinery model. As an example of what could happen, the Organic Chemicals Model is capable of supplying a blending stock for gasoline consisting of $C_8$ or $C_9$ hydrocarbons. A "stand alone" refinery model sees this important source of blending stock as simply a supply column and may proceed to use this column to satisfy the entire right hand side requirement for gasoline, if the price is set too low. Thus, one would have the absurd result that the petrochemical industry is supplying the entire national requirement for gasoline. As both the prices and available quantities of petrochemical industry by-products are directly related to refinery operations and the price and quantity of processed crude oil, it is essential to endogenize in the model these sources of intermediate refinery inputs.

Upward sloping supply curves for foreign crude oil are approximated in the model by vectors which supply increments of crude oil at increasing prices. The prices at which the vectors supply the increments change with different assumptions about supply elasticity. As it is currently constructed, the model incorporates alternative linearized supply curves with constant elasticities of one, two, five, and infinity.

Three important refinery endproducts and two refinery inputs were studied to determine their resonse to upward sloping supply curves for Arabian crude oil. The end products examined were gasoline, distillate fuel oil, and residual fuel oil. The inputs studied were water and capital.

Price/quantity relationships for each of these five materials were studied under different assumptions about the supply elasticity of crude oil. Parametric runs were carried out which systematically varied the production requirements for gasoline, distillate, and resid while holding other requirements constant. In these runs quantity produced was the independent variable and marginal cost the dependent variable. The right hand side production requirements were varied from 0.5 to 1.5 times projected national production levels for 1985. Additional runs focused on the price of water or of capital as the independent variable, while quantity demanded was the dependent variable. Water price was varied from $.05/mgal to $2.00/mgal. Capital cost (in terms of the fraction of total investment allocated as an annual charge) was varied from 0.15 to 0.45 in increments of 0.03.

Results

Figures 8 through 10 plot the marginal costs (shadow prices) of the major refinery end products as a fraction of quantity demanded. Production costs of gasoline, distillate and resid are represented in Figures 8, 9 and 10 respectively. Each figure contains three different curves corresponding to three different assumptions about crude oil supply elasticity. A more detailed representation of production economics is presented in Table 1.

Figure 10 shows the refining industry's derived demand curve for water under differing assumption about crude oil supply electricity. Figures 12 and 13 depict capital/crude oil interrelationship under different crude oil supply elasticity scenarios. Figures 14, 15 and 16 show the effect of capital on long run costs and portray capital/long run cost/short run cost relationships.

An obvious conclusion to be drawn from Figure 8 through 10 is that the price of refinery end products is quite sensitive to the price elasticity of crude oil. This is reasonable since most of the cost of producing hydrocarbon products is accounted for by the cost of crude oil itself, especially at the base price assumed ($13/bbl). The close correspondence betwen crude supply elasticity and end product price indicates a limited ability on the part of the

Figure 8

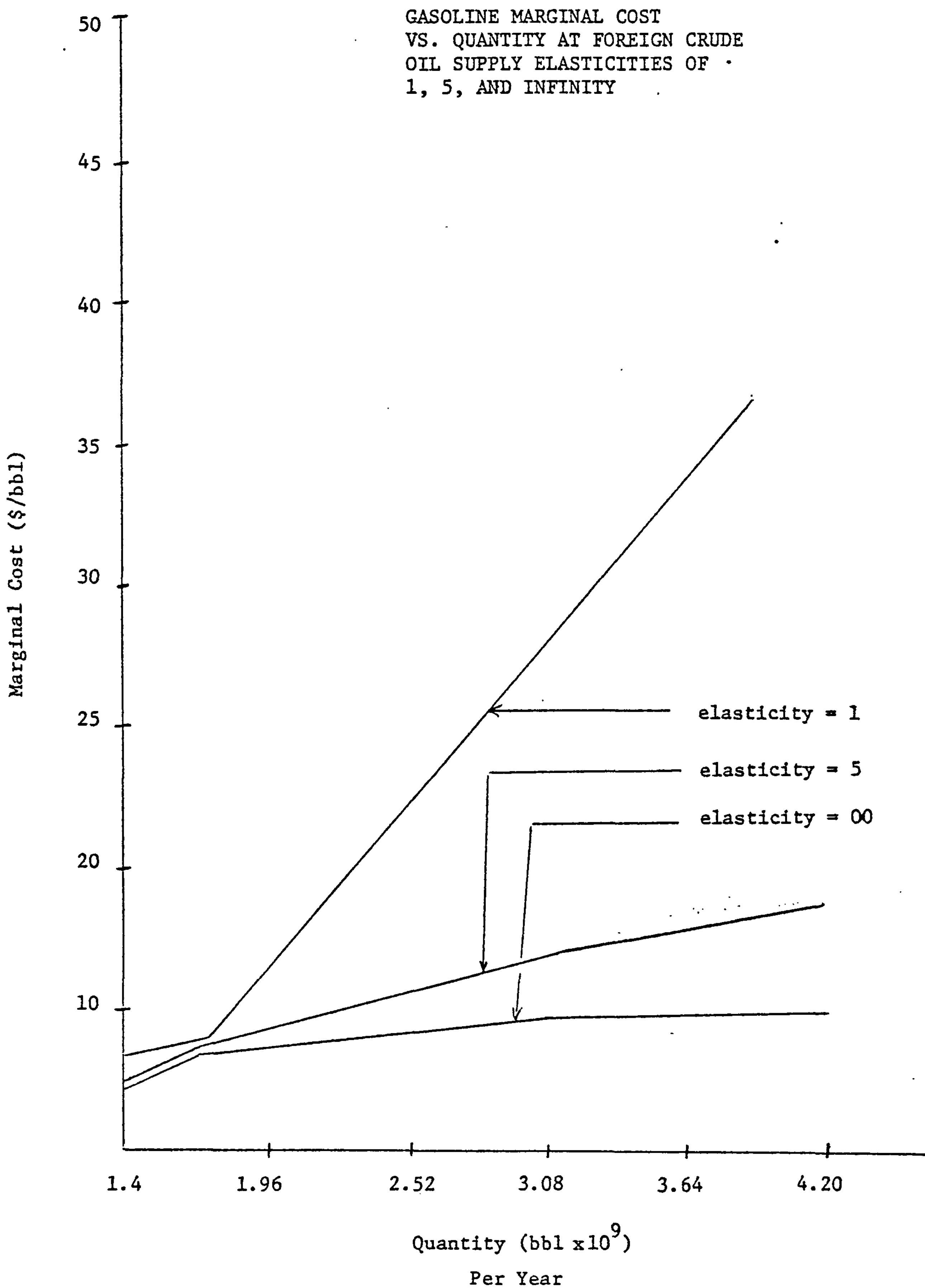

GASOLINE MARGINAL COST
VS. QUANTITY AT FOREIGN CRUDE
OIL SUPPLY ELASTICITIES OF
1, 5, AND INFINITY
Marginal Cost ($/bbl)
50
45
40
35
30
25
20
10
elasticity = 1
elasticity = 5
elasticity = 00
1.4
1.96
2.52
3.08
3.64
4.20
Quantity (bbl x10^9)
Per Year

Figure 9

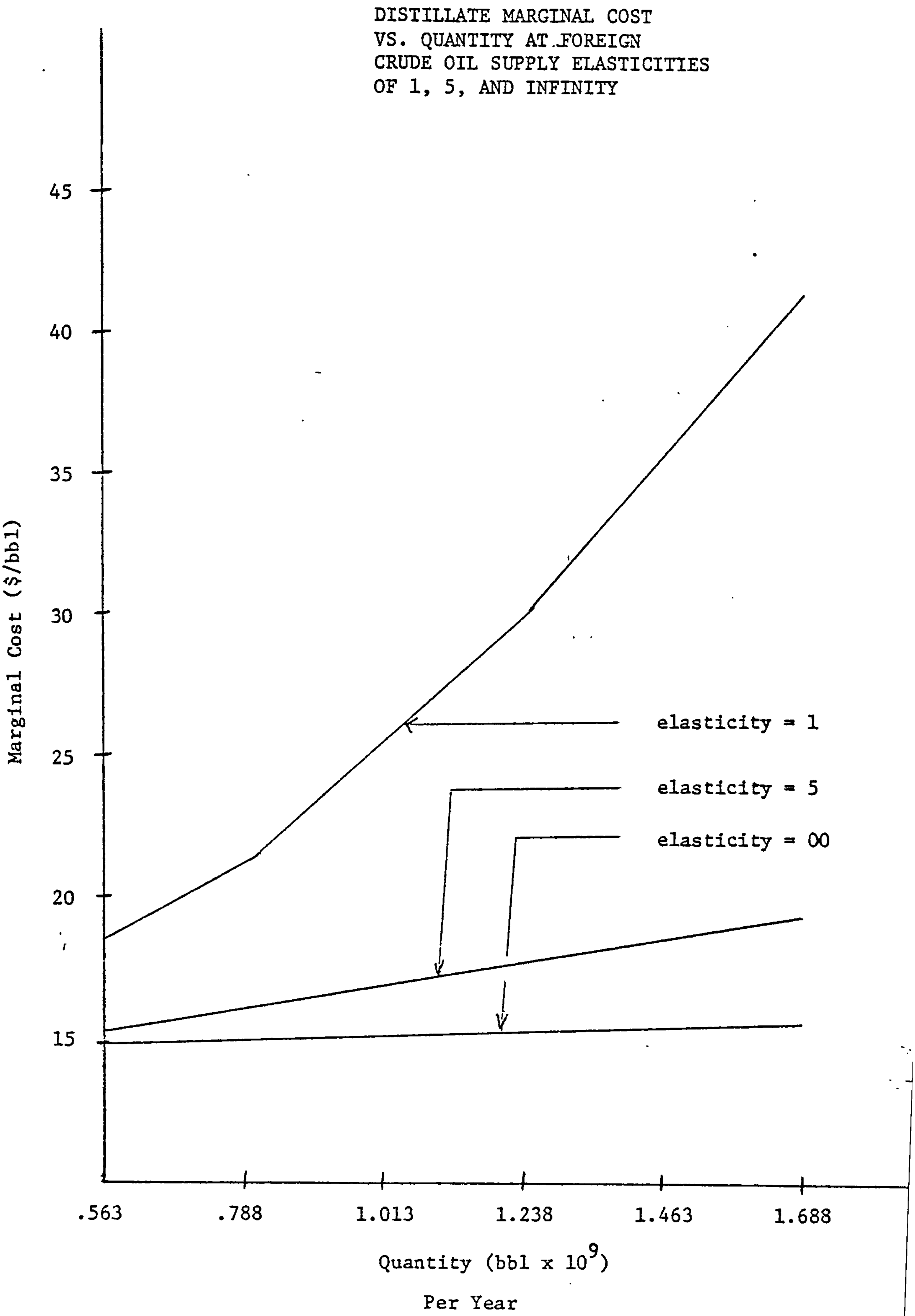

DISTILLATE MARGINAL COST
VS. QUANTITY AT FOREIGN
CRUDE OIL SUPPLY ELASTICITIES
OF 1, 5, AND INFINITY
Marginal Cost ($/bbl)
45
40
35
30
25
20
15
elasticity = 1
elasticity = 5
elasticity = 00
.563
.788
1.013
1.238
1.463
1.688
Quantity (bbl x 10^9)
Per Year

Figure 10

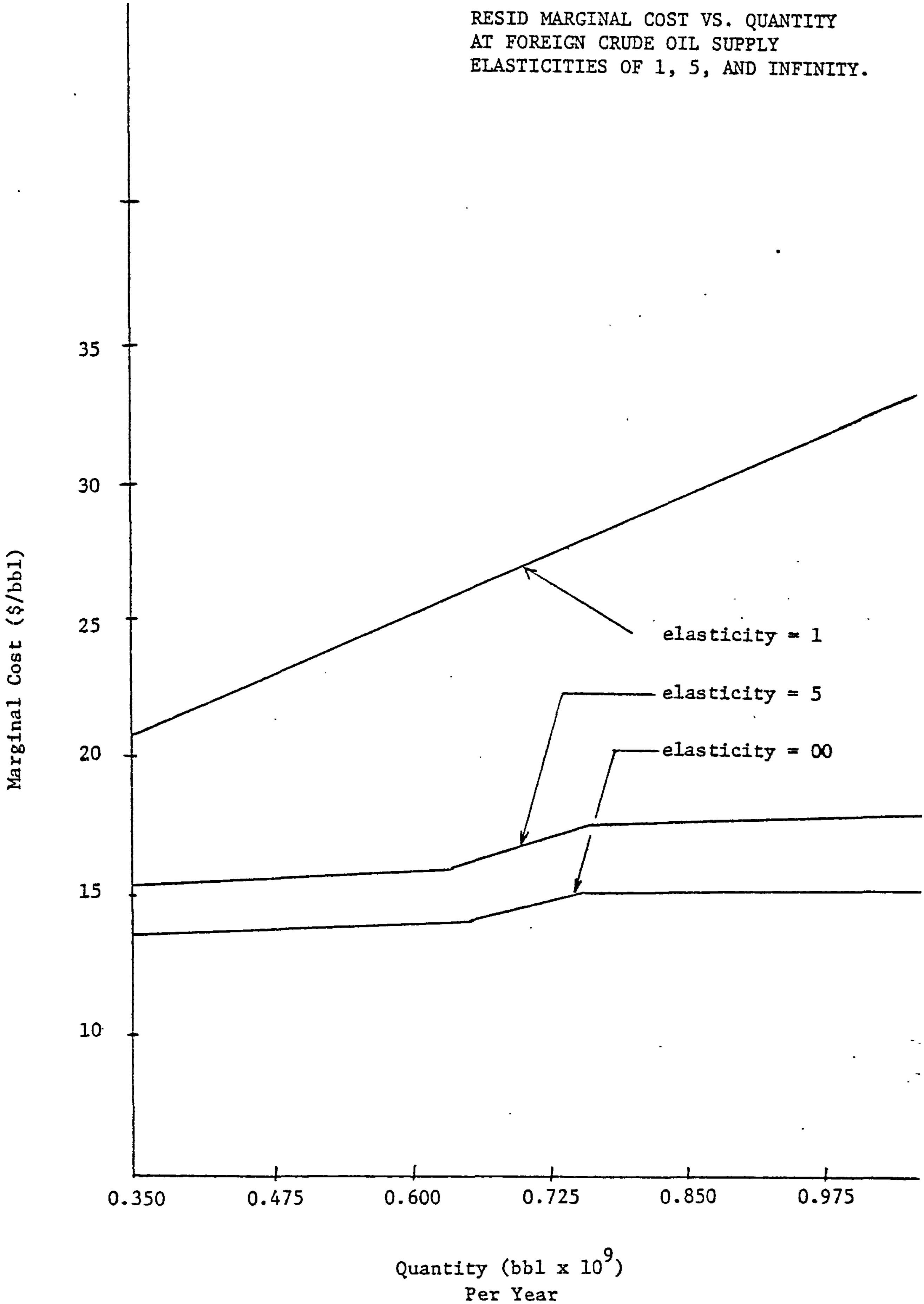

RESID MARGINAL COST VS. QUANTITY
AT FOREIGN CRUDE OIL SUPPLY
ELASTICITIES OF 1, 5, AND INFINITY.
Marginal Cost ($/bbl)
35
30
25
20
15
10
elasticity = 1
elasticity = 5
elasticity = 00
0.350
0.475
0.600
0.725
0.850
0.975
Quantity (bbl x 10^9)
Per Year

TABLE 1

SOME ECONOMIC IMPLICATIONS OF INCREASING GASOLINE PRODUCTION

| Gasoline Production Increment (bbl x $10^9$) | Crude Oil Increment (bbl x $10^9$) | Capital Investment Increment ($ x $10^9$) | M.C. Gasoline - M.V. Crude Oil ($/bbl) |
|---|---|---|---|
| Infinite Elasticity of Crude Oil Supply | | | |
| .28 (1.68) | 0.216 (1.402) | 1.338 (4.171) | .417 |
| .28 | 0.073 | 0.834 | .918 |
| .28 | 0.134 | 0.477 | 1.012 |
| .28 | 0.247 | 0.532 | 1.036 |
| .28 (2.8) | 0.172 (2.028) | 0.055 (6.569) | 1.488 |
| .28 | 0.339 | 0.820 | 1.670 |
| .28 | 0.273 | 0.675 | 1.600 |
| .28 | 0.277 | 0.755 | 1.676 |
| .28 (3.92) | 0.272 (3.189) | 0.943 (9.762) | 1.728 |
| Unitary Elasticity of Crude Oil Supply | | | |
| .28 (1.68) | 0.019 (1.147) | 0.717 (4.014) | -1.370 |
| .28 | 0.086 | 0.522 | -0.214 |
| .28 | 0.176 | 0.929 | 0.666 |
| .28 | 0.206 | 0.836 | 0.780 |
| .28 (2.8) | 0.263 (1.878) | 0.747 (7.048) | 0.804 |
| .28 | 0.172 | 2.622 | 0.935 |
| .28 | 0.220 | 1.317 | 0.801 |
| .28 | 0.261 | 0.770 | 0.582 |
| .28 (e.92) | 0.253 (2.784) | 0.788 (12.545) | 0.356 |

(Figures in parentheses indicate total magnitudes at given solution.)

Figure 11

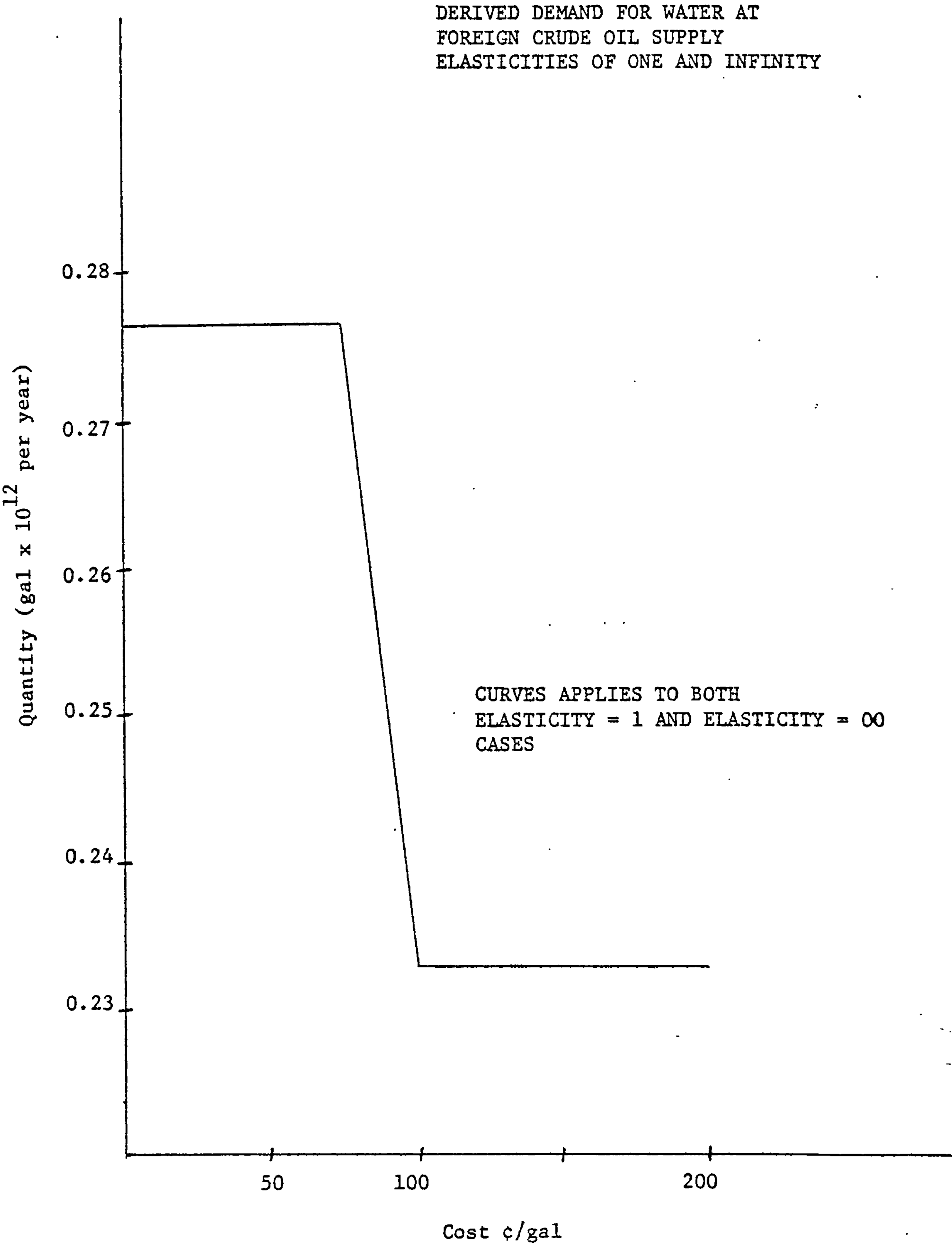

DERIVED DEMAND FOR WATER AT
FOREIGN CRUDE OIL SUPPLY
ELASTICITIES OF ONE AND INFINITY
CURVES APPLIES TO BOTH
ELASTICITY = 1 AND ELASTICITY = OO
CASES
Quantity (gal x 10^12 per year)
0.28
0.27
0.26
0.25
0.24
0.23
50
100
200
Cost ¢/gal

Figure 12

DERIVED DEMAND FOR CAPITAL
AT FOREIGN CRUDE OIL SUPPLY
ELASTICITIES OF ONE AND INFINITY

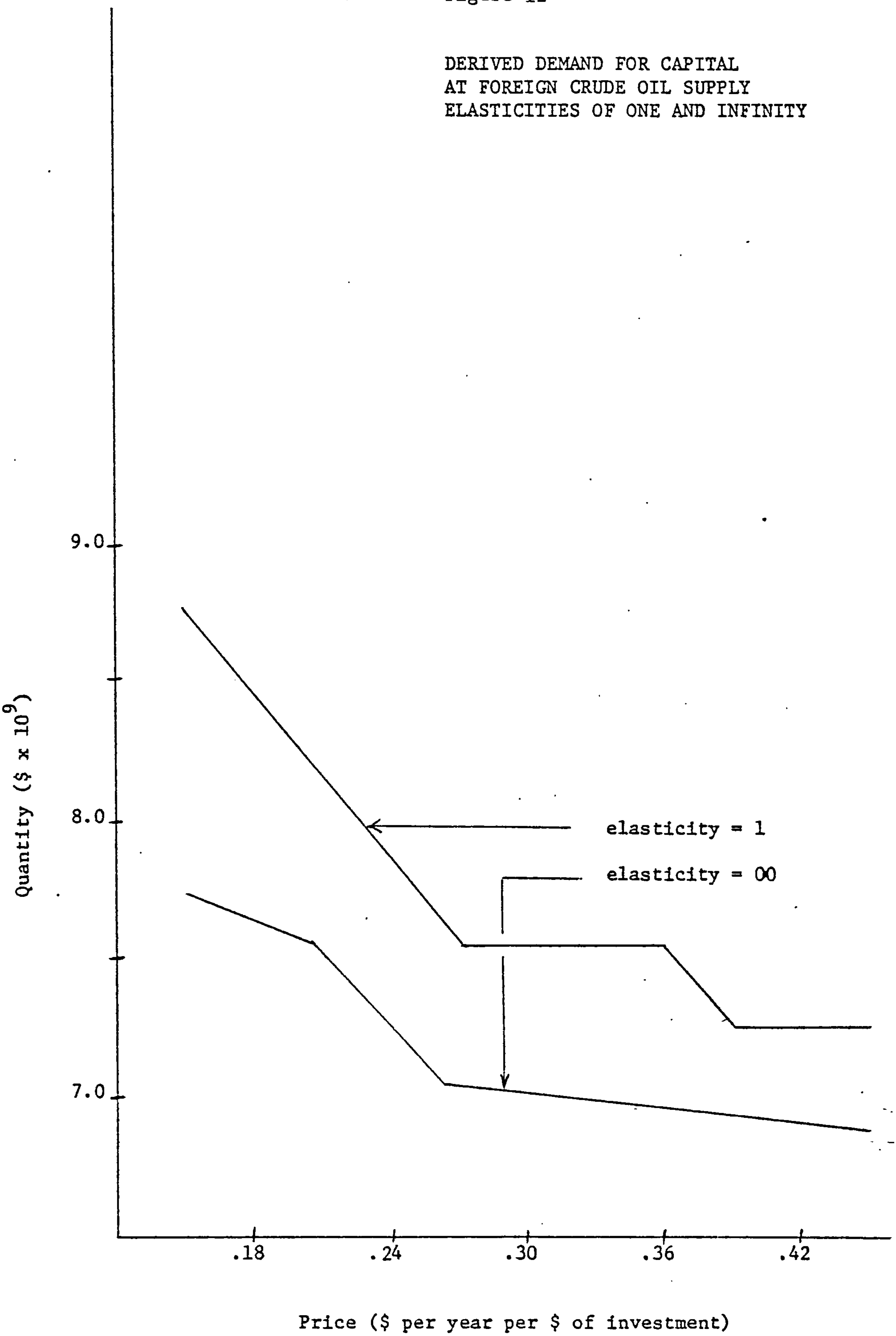
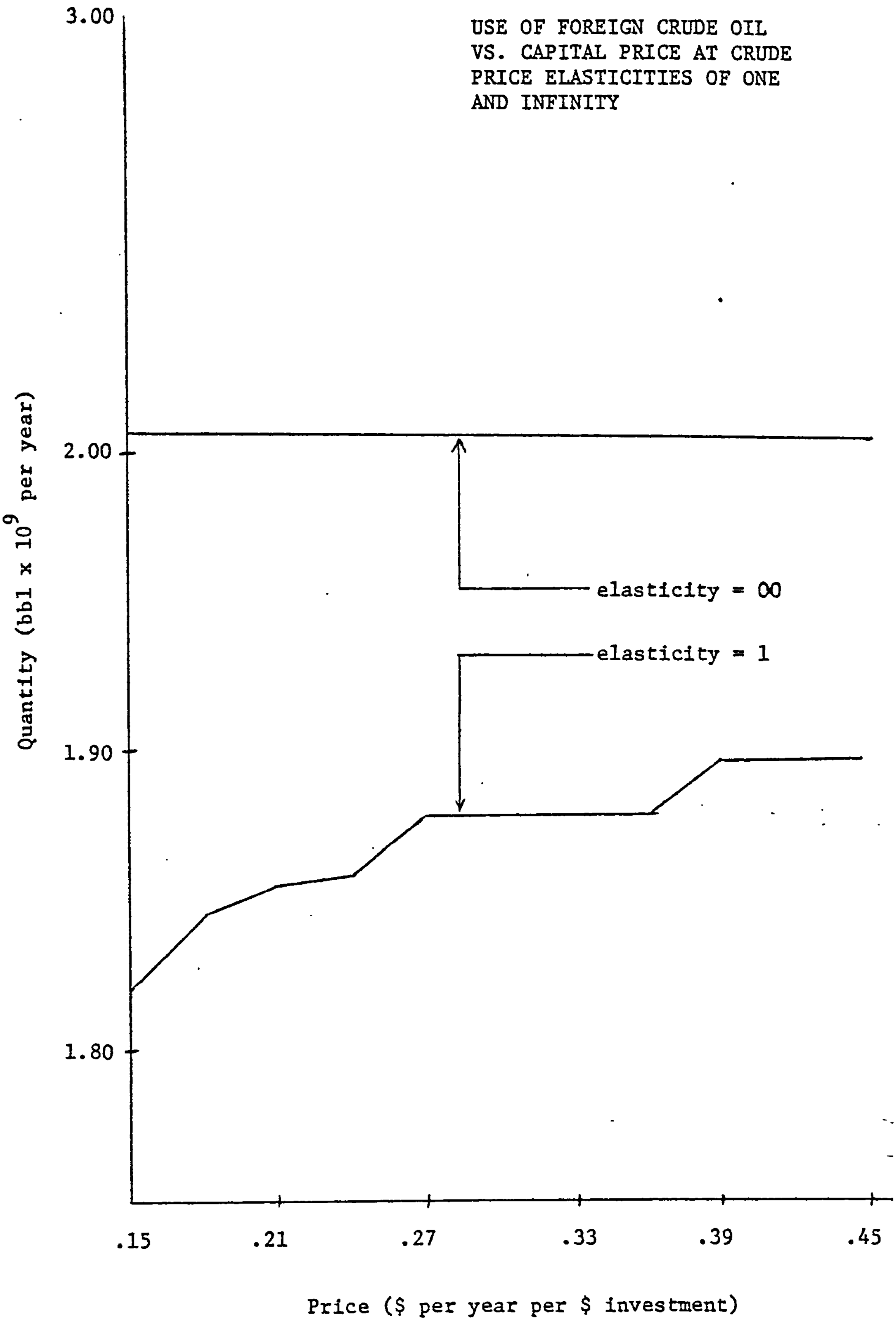


Figure 13


USE OF FOREIGN CRUDE OIL
VS. CAPITAL PRICE AT CRUDE
PRICE ELASTICITIES OF ONE
AND INFINITY
3.00
2.00
1.90
1.80
Quantity (bbl x $10^9$ per year)
elasticity = ∞
elasticity = 1
.15
.21
.27
.33
.39
.45
Price ($ per year per $ investment)

refinery to substitute capital for crude oil in the production of its three major end products. The curves in Figures 8 through 10 all have the same approximate shape and all indicate a much greater marginal cost difference between elasticity = 1 and elasticity = 5 than between elasticity = 5 and elasticity = infinity. Since elasticity is effectively infinity at present, this indicates that elasticity could change markedly without greatly affecting optimal refinery unit configuration.

Table 1 provides additional detail for analysis of gasoline production economics. The table shows the response of the model in terms of increased crude oil purchases and additional capital investment, to incremental gasoline production requirements. These responses are illustrated for two different assumptions about the elasticity of crude oil supply ($E = 1$, and $E = \infty$). Also shown is the difference between marginal cost of gasoline and marginal value of crude oil. With all other production requirements held constant, the amount of crude oil purchased and hence its marginal price is a function of gasoline requirements.

As one would expect, at almost every level of gasoline production the unitary elasticity case uses more capital and less crude than the infinite elasticity case. The only exceptions to this are at the lower end of the gasoline requirement range where marginal crude prices are not much different between the two cases. At the opposite extreme, where gasoline requirements are 40% higher than the base case value, the unitary elasticity case uses 87% of the crude and 125% of the capital used in the infinite elasticity case. Over the range of gasoline production indicated, the unitary and infinite elasticity cases expand capital usage 234% and 313% respectively. The respective increases in imported crude oil usage are 234% and 227%.

The negative values observed in the lower range of gasoline production for the unitary elasticity case are interesting in that they indicate a lower value for gasoline than for the crude oil which is processed to make gasoline. This can be rationalized by remembering that crude oil's value is determined not only by gasoline production but also by its coproducts. These coproducts have a higher shadow price than gasoline at very low gasoline production requirement levels.

Increasing gasoline requirements can be met by the model in one of two ways: First, the model may purchase more foreign crude oil and invest in the relatively simple equipment necessary to produce straight run gasoline. This is the option encouraged by an infinite crude oil supply elasticity. Second, the model may invest in more elaborate processing equipment to convert more of a given barrel of crude oil to gasoline. This is possible only if production of other major products exceeds current requirements. This second option is encouraged by higher crude oil prices (unitary elasticity) and/or lower capital prices.

The model's balancing of increased crude oil prices and increasingly expensive process configurations can be traced in the last column of Table 1 which gives the marginal cost of gasoline minus the marginal value of imported crude oil. This difference can be represented by

$D = (KP + C) - P$ where:

$D$ = difference (MCG - MVC)

$k$ = the proportion of the marginal crude oil barrel converted to gasoline

$P$ = price of the marginal crude oil barrel, and

$C$ = marginal processing cost per barrel of gasoline.

This can be rewritten $D = C - (1-k)P$,

If K increases, C will increase since an increase in k represents investment in more complex and expensive types of processing equipment. If P stays the same, which it does in the case of infinite elasticity, the difference observed is entirely dependent on C and K. As gasoline requirements increase both C and K will tend to go up with each additional increment of gasoline requirement, but due to the varying nature of the investment opportunities available, there is no certainty as to which one will go up the most.

Both the unitary elasticity case and the infinite elasticity case start from a refinery model configured to correspond to present U.S. refinery capacity which is still primarily based on cheap crude oil supplies. Therefore, for both cases, C tends to increase as gasoline requirement increase because opportunities exist to increase K substantially. This is done as more and more expensive foreign crude is purchased until K reaches an effective limit. At this point, in the infinite elasticity case, D becomes approximately constant because P is constant, K is constant, and therefore C which is a function of K is constant. This occurs at a gasoline production requirement of about $3.08 \times 10^9$ bbl in the infinite elasticity case in Table 1. A similar upper limit for K is reached in the unitary elasticity case for gasoline requirements of $3.08 \times 10^9$ bbl, but in this case since P is monotonically increasing, D declines instead of staying constant.

The derived demand curver for water in Figure 11 shows a step function totally insensitive to supply elasticity of crude oil. This reiterates the fact that there is no substitute for water but capital. The downward step in Figure 11 represents a shift fromtertiary treatment and discharge of streams containing substantial amounts of dissolved solids to partial recycle of these streams through desalters. The high cost per gallon at which this step is taken indicates it undesirability. Since the waste water streams within the model are classified according to solids content, one could expect to see additional downward steps if the price of water was increased even more. This, however, is not a realistic possibility.

Figures 12 and 13 portray the trade off between capital and crude oil at different supply elasticities of crude oil. The two curves in Figure 11 show that the quantity of capital invested at any capital price is substantially affected by the elasticity of crude oil supply, with the greater amount of capital always being used in the unitary elasticity case. One notes that for both cases the demand for capital is more elastic at the lower cost portion of the capital curve. This indicates that with capital, as with other inputs, a certain minimum amount is required to successfully meet right hand side requirements, and the capital will be invested regardless of price.

## Analysis of Capital Investment

With its detailed treatment of capital investment opportunities, the vintaged refinery model can be used to estimate long run total costs for a given slate of refinery products. This is so because the main factor affecting long run refining costs is the accumulation, and application of capital. Capital investment affects refining costs by:

a) Changing the size of the units involved (economies of scale), and

b) changing the mix of refining units aimed at producing a certain product slate.

These factors result in declining real costs for the production of a given slate of products over time. At any given level of capital application (corresponding to a fixed point in time) short run curves can be traced giving total cost as a function of requirements for a single product.

In Figure 14 total cost for the refinery is plotted as a function of gasoline requirements at three different levels of capital application. Total cost also depends on the other refinery products produced, but if the amounts of those products are held constant, total cost becomes a function of gasoline production alone, and the two dimensional curves in Figure 14 can be constructed.

Figure 15 shows the affect of capital application on total costs while Figure 16 shows a three dimensional representation of the cost surface formed by capital application and gasoline production. The points plotted in Figures 14, 15, and 16 are from the same series of runs. Only the perspective has been changed to show different viewpoints. If capital application can be thought of as a proxy for time, then Line ABC in Figure 15 can be considered a representation of long term total costs while Curves A, B, and C can be considered to represent short term total costs as a function of gasoline production.

The points in the figures were derived as follows. First, a base case was run in which the model was allowed essentially no capital investment opportunity. Capital was

FIGURE 14

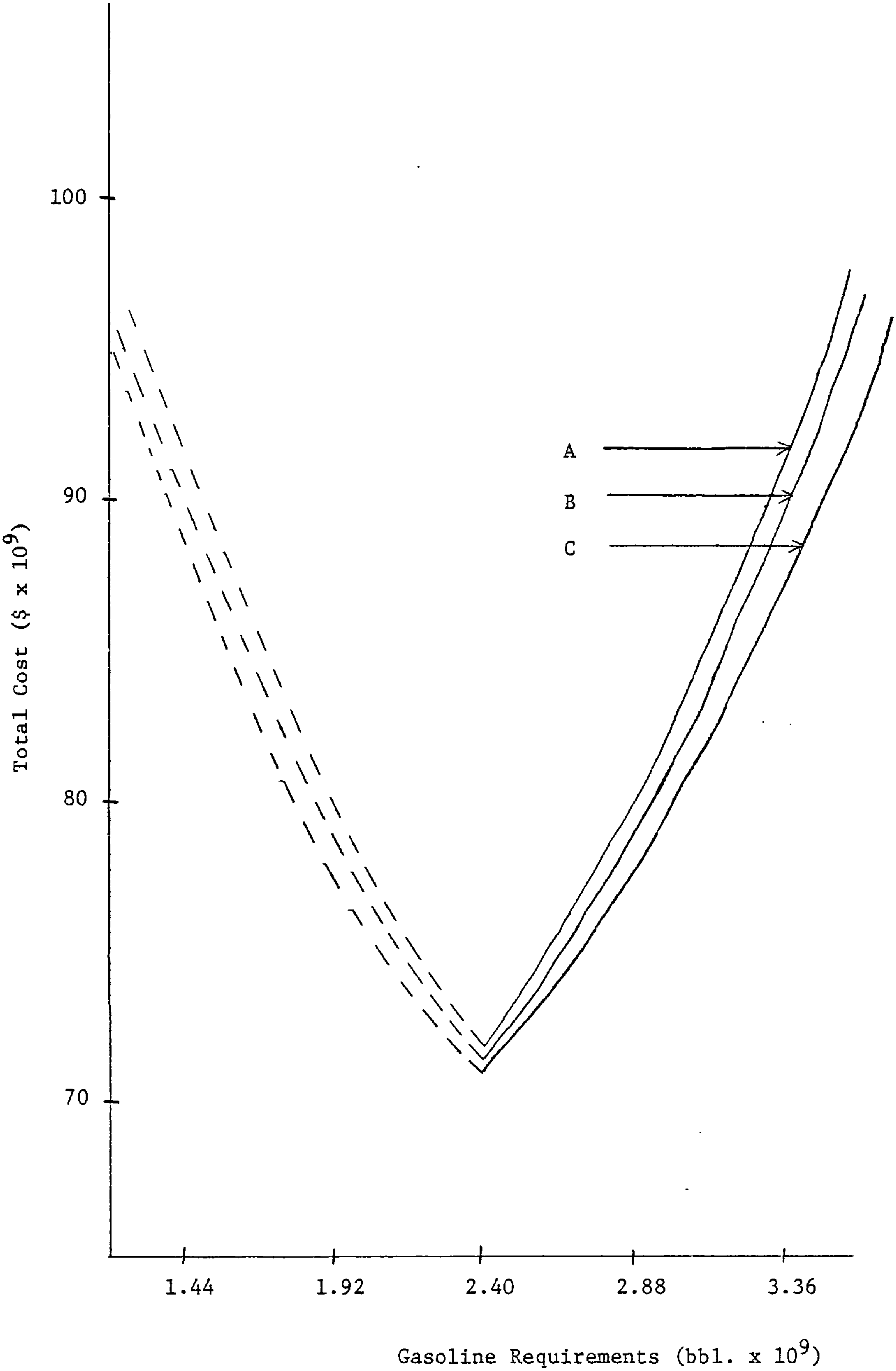

100
90
80
70
Total Cost ($ x 10^9)
A
B
C
1.44
1.92
2.40
2.88
3.36
Gasoline Requirements (bbl. x 10^9)

FIGURE 15

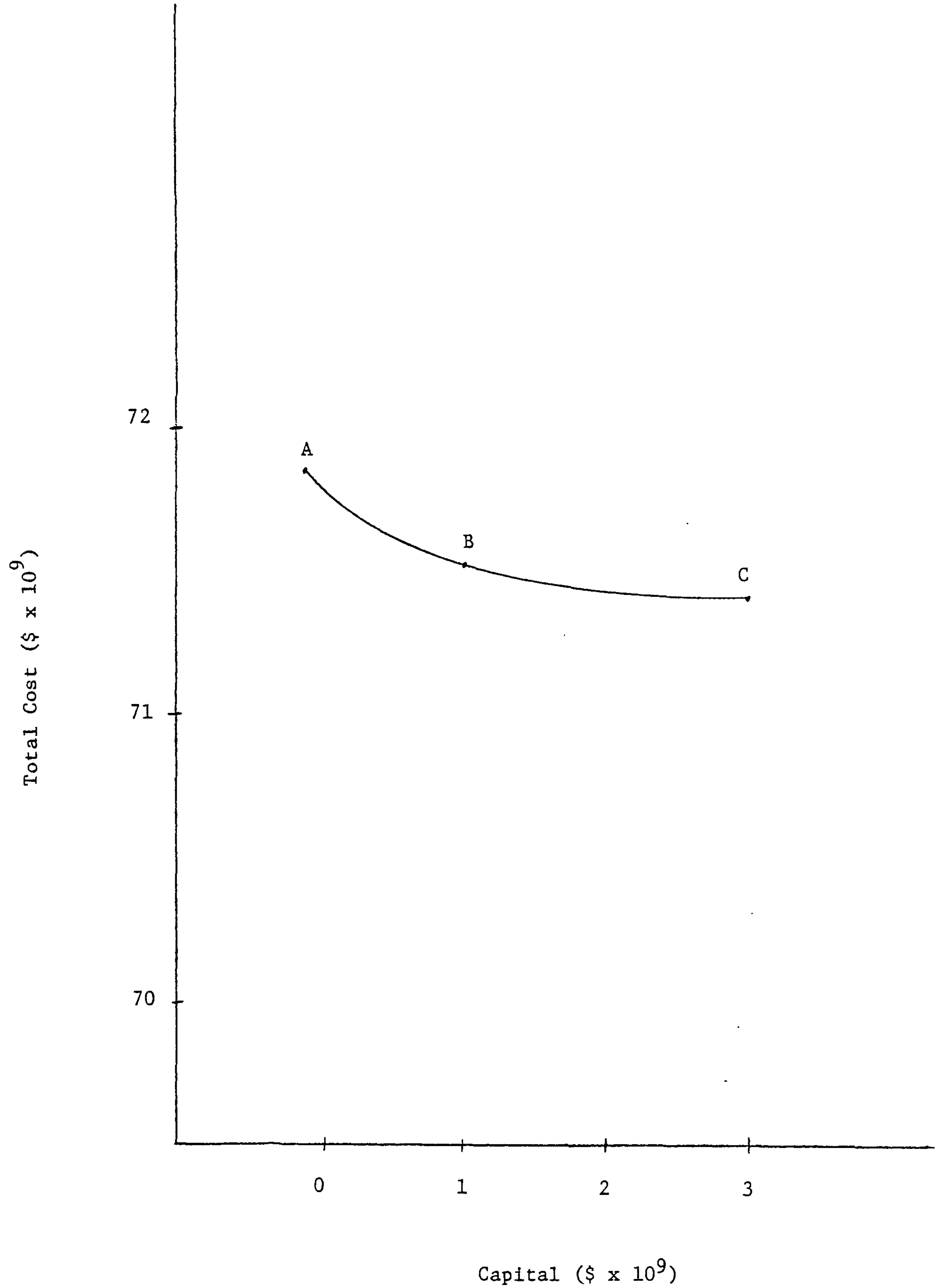
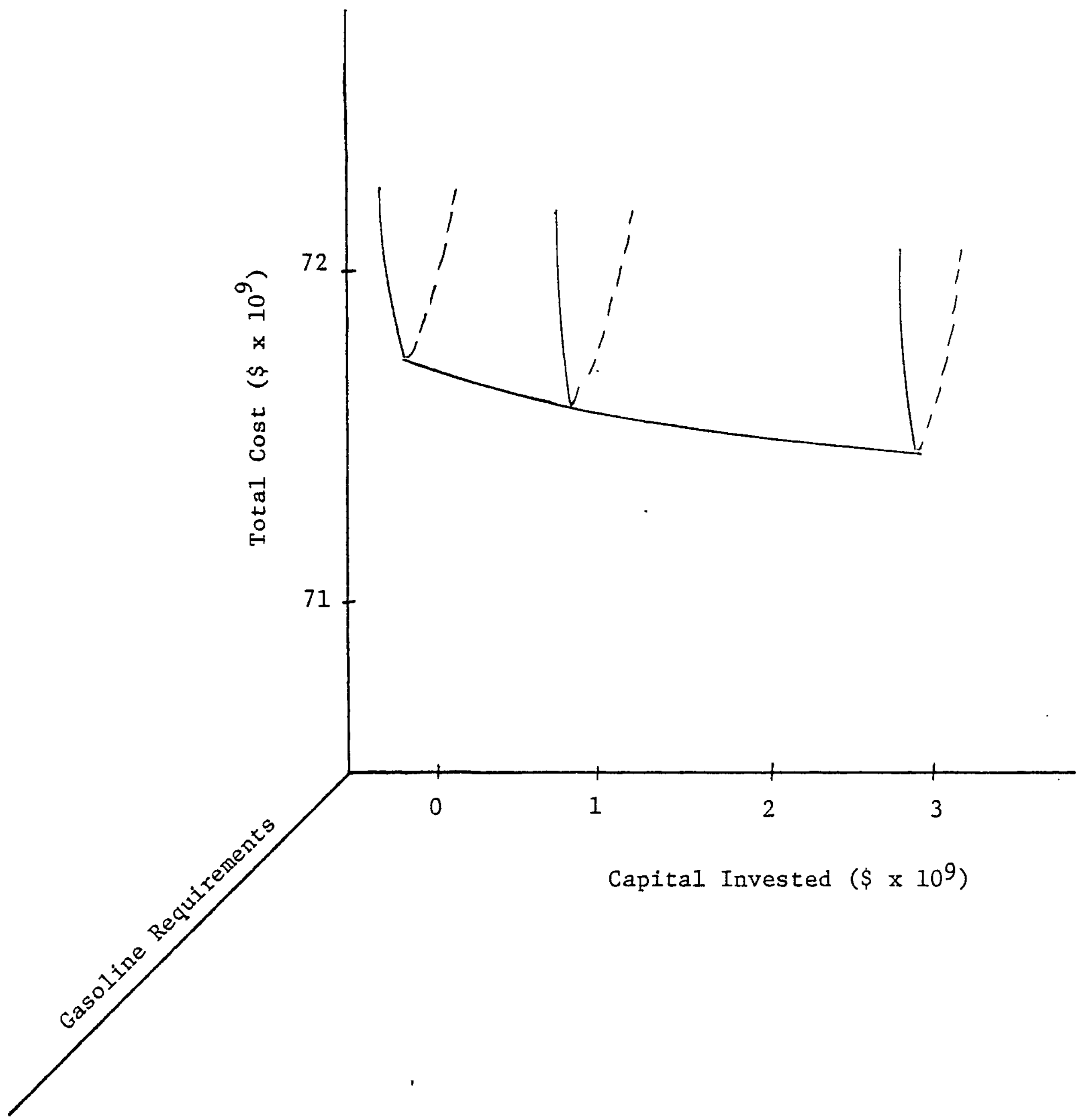


FIGURE 16


72
71
Total Cost ($ x $10^9$)
0
1
2
3
Capital Invested ($ x $10^9$)
Gasoline Requirements

provided to maintain feasibility, but at such a high rate that almost none was used. At this zero capital level parametric analysis was carried out on the right hand side gasoline requirements. This analysis gave Curve A in Figure 14. Next, the model was allowed one billion dollars to invest in capital equipment and a second base case was run. This run established the investment levels in various types of equipment, given one billion dollars in available capital. Right hand side equipment capacity constraints were then adjusted upward to reflect the investments indicated in the base case run. With these adjustmens made, available capital was again set to zero and a second parametric run made on gasoline requirement. This run gave Curve B in Figure 14. The steps necessary to get from Curve A to Curve B were repeated in going from Curve B to Curve C, the only difference being the size of the capital "step" made (two billion dollars vs. one billion).

It is not permissable to simply increase the amount of capital available to the vintaged refinery model as a method of simulating future short run cost curves. Such a formation would give the model a degree of freedom not found in the real world since each respective level of required gasoline production could be optimized globally by committing total available capital in an optimal way. In fact, capital will already have been committed to the refinery configuration which optimizes the base case. Short run costs must be determined within the bounds of that configuration.

Note that the short run cost curves shown in Figures 14 and 16 are denoted along one side. This has been done because only the right side of these curves could be traced by this model. With the capital structure as it is in the vintaged refinery model, no charge is made for unused existing capital. Therefore, no penalty for less than full capacity operation is assessed and costs decrease monotonically with decreasing gasoline requirement. The curves' dotted section is symmetric to the solid section as drawn, but this need not be true. A modeling formulation capable of tracing both halves of the short run cost curves has been suggested by Mr. Dae Hong Chiang. It is shown in Figure 17.

Usefulness

In the past, one of the criticisms of most linear programming policy analysis has been that the models show only optimal equilibrium solutions without showing the path which led to them. In other words the dynamics of policy analysis has been neglected. Modelers generally choose some date far enough in the future that one can assume that equlibrium has in fact occurred. The problem with this approach is that if one assumes a long enough time period to assure equilibrium, some of the other assumptions of the analysis may not hold. Assumptions about prices for raw

FIGURE 17

| | OLD USED | OLD UNUSED | OLD UPDATED | NEW USED | NEW UNUSED | NEW BUILD | TRANSFER 1 | TRANSFER 2 | CAPITAL SUP | |
|---|---|---|---|---|---|---|---|---|---|---|
| VARIABLE COST | X | | | X | | | -1 | | | = 0 |
| FIXED COST | X | X | | X | X | | | -1 | | = 0 |
| CAPACITY (OLD) | 1 | 1 | 1 | | | | | | | = OLD CAPACITY |
| CAPACITY (NEW) | | | -1 | 1 | 1 | -1 | | | | = NEW CAPACITY |
| CAPITAL | | | X | | | X | | | -1 | = 0 |
| INPUTS | X | | | X | | | | | | ≤ RESOURCES |
| OUTPUTS | X | | | X | | | | | | ≥ REQUIREMENTS |
| OBJECTIVE FCN | | | | | | | 1 | 1 | X | |

materials or technical coefficients of industrial processes may be inaccurate in the long run.

The step by step method outlined above may be used as an approach to handling the dynamics of an intermediate term analysis. It could give the policy maker two vital pieces of information:

1) An estimate of a reasonable time limit for policy implementation.

2) An appreciation of the interrelated nature of not just energy and environmental policy but of energy, environmental, and capital policy.

Many national policies are formulated with arbitrary time limits for implementation, i.e., boiler fuel conversion by 1985 or best available (pollution control) technology by 1984. Also, these policies are formed independently of each other and also independent of policies affecting capital formation such as investment tax credits or long term capital gains tax rates. An analytical method which uses capital as a proxy for time in formulating long run and short run cost curves could force the attention of law makers to the interrelated nature of these policy questions.

# CHAPTER 6

# MODEL DOCUMENTATION

This chapter has some of the modeling conventions found in the vintaged refinery model, and a few bits of information which may be useful in running the model. The modeling conventions covered are essentially the ones not documented elsewhere. The present model is the end result of an evolutionary process in which an initial refinery model was upgraded to a more comprehensive model, which in turn was vintaged. The basic structure of the vintaged model is the same as that of those earlier models, and for a complete understanding of the assumptions behind that structure the investigator should refer to (4) and (41).

One possible source of confusion in using the refinery model is the manner in which the row and column definitions have been set up. The names in the definitions section differ with the names actually in the model in that the model names all have a prefix letter. Most of the model names have the prefix letter P or O, while a few vectors, representing exogenous inputs for the most part, have prefixes of F or X. The P prefix indicates that these vectors or rows represent refinery units of flows. The O prefix indicates units of the organic chemicals industry.

The F and X prefixes are simply conventions used to separate exogenous supply vectors from the others. In looking up definitions all prefixes should be dropped.

Definitions are separated into four sections:

1) Row definitions for the Integrated Industry Model (IIM)

2) Column definitions for the Integrated Industry Model

3) Row definitions for the Vintaged Refinery Model (VRM)

4) Column definitions for the Vintaged Refinery Model (VRM)

Since the IIM contains a nonvintaged refinery model, many of its definitions are identical to those for the Vintaged Refinery Model. Those definitions common to both are contained in the IIM sections. The new definitions associated only with the Vintaged Refinery Model are in the VRM sections. Appendix C contains a set of summary statistics on the size, density, and other numerical characteristics of the model.

## Important Modeling Conventions

Supply curves - Four constant elasticity supply curves for imported crude oil are incorporated in the model by piecewise linear approximation. Elasticities of 1.0, 2.0, 5.0, and infinity are represented. It is assumed (arbitrarily) that the first billion barrels of imports are available at a price of $13/BBL (column XARC1000, upper bounded at 1.0). Additional supplies are available in linearized steps of 0.05 billion barrels up to a total of 3 billion barrels (columns XARC1050 through XARC3000, all upper bounded at 0.05). To ensure feasibility a final step of 1 billion barrels is included (column XARC4000, upper bounded at 1.0). As may be noted, the last four characters of the names for these supply columns represent the cumulative supply of imports (in million barrels per year) obtainable by involing all columns up to and including the given column at upper bound.

The appropriate prices for each supply increment depends upon the price elasticity of supply. To account for four alternative price elasticities with the same set of linearized columns, an intermediate cost accounting row is specified for each elasticity (XARCPE01, XARCPE02, XARCPE05, XARCEPEIN). Each supply column has an etry in each of these rows representing the appropriate supply price for each elasticity. See Figure 18. The four rows are set equal to zero and a cost accounting column is specified for each (XCOSTE01, XCOSTE02, XCOSTE05, XCOSTEIN) to "sum up" the accumulated supply costs for these supply columns. As will be described below, specifying an objective function coefficient of 1.0 for one of these columns effectively selects a linearized supply curve corresonding to the chosen

| | VECTORS SUPPLYING INCREMENTS OF CRUDE OIL | | | | | | | COST TRANSFER VECTORS | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | XARC1000 | XARC1050 | XARC1100 | . . . | XARC2950 | XARC3000 | XARC4000 | XCOSTE01 | XCOSTE02 | XCOSTE05 | XCOSTEIN |
| XARCPE01* | 13.0 | 13.65 | 14.30 | | 38.35 | 39.00 | 52.00 | -1.0 | | | |
| XARCPE02 | 13.0 | 13.33 | 13.64 | | 22.42 | 22.61 | 26.38 | | -1.0 | | |
| XARCPE05 | 13.0 | 13.13 | 13.25 | | 16.18 | 16.24 | 17.32 | | | -1.0 | |
| XARCPEIN | 13.0 | 13.0 | 13.0 | | 13.0 | 13.0 | 13.0 | | | | -1.0 |
| XARCRUDE | 1.0 | 1.0 | 1.0 | | 1.0 | 1.0 | 1.0 | | | | |
| XOBJ75 | | | | | | | | 1.0** | 0.0 | 0.0 | 0.0 |

* XARC ROWS SPECIFY (PER BARREL) PRICES FOR CRUDE OIL INCREMENTS AT SPECIFIED ELASTICITIES

** A "1.0" ENTRY IN XOBJ75 FOR THIS COLUMN SPECIFIES SELECTION OF AN ELASTICITY OF 1.0



FIGURE 18

elasticity.

(Note: it was desired for purposes of symmetry and keeping basis changes to a minimum when changing from one elasticity to another to treat the infinite elasticity curve just like the other three. This would have implied, by definition, a constant price of $13/BBL for all supply increments. In practice, however, this leads to perfect ties in the optimization and possible cycling problems depending on the sophistication of the LP code. To avoid this problem, each supply increment under infinite elasticity is specified to cost $0.00001 more per barrel than the previous increment. This is a negligible increase in terms of model results, but it ensures no ties and that the supply columns enter the basis in the same order for the other elasticities.)

Wastewater treatment - Formerly extensive wastewater treatmentdetail in the refinery model has been greatly simplified in the vintaged version. This has been done by including only treatment costs in the model rather than extensive materials balances for waste streams. Under the assumption that a minimum of teritary treatment would be required by 1985 (the modeled time frame), all process activities ( with a few exceptions noted below) contain an entry representing the costs of tertiary treatment of the wastewater streams resulting from a unit activity level of that process. These costs are collected in row PWWTTERT and transferred to intermediate cost accounting row POBJ72 by column PXWWTERT.

The option for zero discharge is allowed for by classifying the treated waste streams of all processes into a number of categories based on the costs of further treatment and recycle. (The costs are primarily affected by the dissolved solids content of the waste streams.) As shown in Figure 19, the volume of the waste stream for each process is recorded in one of a collection of rows named PRC00035, PRC0016, and the like. A set of transfer columns (Named PWR00035, PWR0016, and the like) recycle these waste streams at a cost recorded in row PWWTZDIS. Column PXWWZDIS transfers the costs accumulated in PWWTZDIS to row POBJ72. Recycled water is collected in row PRCCTWTR where it is used by vectors representing cooling towers using recycle water for makeup.

If the PRC rows are set greater than or equal to zero, the model has the option of recycling the waste streams dependent upon the costs of alternative water sources. By setting these rows equal to zero, the user can force the model to recycle all waste streams regardless of cost. A row named PRCDMIN is included for symmetry to control operation of column PDMINCWT which is a demineralizer that discharges its concentrated brine stream. If this row is set greater than or equal to zero, the model may choose between

| | REPRESENTATIVE REFINERY UNITS WITH WASTE WATER STREAMS | | | | | | | | | VECTORS FOR RECYCLE OF WASTE WATER | | | | | | | | | TREATMENT COST ACCOUNTING | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | PHSR1 | PHSR2 | PXARCX | PHPXROLG | PHKGS2 | PHDISTHS | PHDLSTMD | PUCF0 | | PWR00035 | PWR00085 | PWR0016 | PWR0030 | PWR0055 | PWR0090 | PWR0175 | PWR0290 | | PXWWTERT | | PXWWZD1S |
| POBJ72 | | | | | | | | | | | | | | | | | | | 1.0 | | 1.0 |
| PWWTTERT | .0033 | .004 | .009 | .0035 | 0.16 | 0.08 | 0.11 | | | | | | | | | | | | -1.0 | | |
| PRC00035 | 2.0 | | | | | | | | | -1.0 | | | | | | | | | | | |
| PRC00085 | | 2.0 | | | | | | | | | -1.0 | | | | | | | | | | |
| PRC0016 | | | 6.7 | | | | | | | | | -1.0 | | | | | | | | | |
| PRC0030 | | | | 0.7 | | | | | | | | | -1.0 | | | | | | | | |
| PRC0055 | | | | | 7.0 | | | | | | | | | -1.0 | | | | | | | |
| PRC0090 | | | | | | 4.2 | | | | | | | | | -1.0 | | | | | | |
| PRC0175 | | | | | | | 3.9 | | | | | | | | | -1.0 | | | | | |
| PRC0290 | | | | | | | | 1.13 | | | | | | | | | -1.0 | | | | |
| PWWTZDIS | | | | | | | | | | 0.00035 | 0.00085 | 0.0016 | 0.0030 | 0.0055 | 0.0090 | 0.0175 | 0.029 | | | | -1.0 |
| PRCCTWTR | | | | | | | | | | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | | | | |

FIGURE 19

PDMINCWT and PDMINCWZ, an expensively reconfigured zero discharge unit. If PRCDMIN is set equal to zero, the model is forced to use PDMINCWZ. Row PRCCTWTR should always be set equal to zero.

There are a few minor exceptions to this convention, all referring to processes for which it is cheaper to configure for zero discharge (via terminal recycle) than to add the process wastes to a common pool for tertiary treatment. For such processes (.e.g, PFLXKH1N, a new flex coker) the column vector has entries directly in PRCCTWTR and PWWTZDIS. No PWWTTERT entry is recorded.

Air emissions constraints - Particulate control by efficient electrostatic precipitators has been assumed for all units burning ash containing fuels. Sulfur oxide controls are specified in terms of allowed emissions of $SO_2$ (in pounds) per million BTU of coal or liquid fuel combusted. Coal fired boilers (all assumed to be new) are controlled according to the new source performance standard of 1.2 lbs $SO_2$/MMBTU of coal. Oil fired boilers (for which there were no clear estimates of the age distribution of capacity) are controlled according to a compromise standard of 1.05 lbs $SO_2$/MMBTU of oil; the new source performance standard is 0.8 lb $SO_2$/MMBTU of oil.

These controls are imposed via rows PULSO2C (for coal) and PULSO2O (for oil). Since the magnitude of the constraint is dependent upon an unknown amount of fuel combustion, the following "credit/debit" approach is used. All $SO_2$ emitting combustion activities are unitized on 1 MMBTU of fuel. The entry in the PULSO2 row for the burn column is specified as the <u>difference</u> between the emission rate for the process (which is additionally recorded in row PEASO2) and the applicable standard. By then constraining the PULSO2 row to be less than or equal to zero, the weighted average emission from all combustion activities is contrained to be less than or equal to the standard. This standard may be changed by appropriate additive adjustments to the entries in rows PULSO2C and PULSO2O.

Similar emission constraints have been applied as an indirect constraint on the sulphur content of marketed distillate and residual fuel oils. This is done by unitizing all fuel oil sales columns on 1 MMBTU and constructing constraint rows perfectly analogous to those described above. These rows are XULSO2D for distillate and XULSO2R for resid. The entries in these rows are the differences between emissions and the new source performance standard for oil combustion (0.8 lbs $SO_2$/MMBTU).

<u>Capital investment</u> - Capital investments in a modeling solution may take the form of new construction or update construction. The model also contains vectors which represent existing new plants and existing updated plants. These differ

from additional new construction and updates in that the latter contain a capital charge which covers depreciation and return on investment.

Vectors which reflect these added capital charges may be structured in several ways. First, a vector representing a new existing unit may simply be duplicated and a capital investment requirment added. This is a convenient way to proceed when: (a) the vectors to be reproduced are short and (b) more than one type of new construction is possible. In the case of reformers, for instance, the vectors are realtively short (16 entries) and three types of new construction are available: semi-regenerative, cyclic, and continuous. These units have somewhat different output profiles as well as different capital requirements. Therefore, a separate vector exists for each reformer new construction option, ane the convention has been carried over to the reformer update options as illustrated in Figure 20.

A second type of construction scheme is illustrated by the cat cracker vectors illustrated in Figure 7 of Chapter 4. These vectors are relatively long, and new construction and update opportunities are homogenous. Therefore, it is convenient to include specialized new construction and update vectors which simply relax the capacity constraints on the existing vectors.

The accounting row for capital investment (PNEWCN72)

| | EXISTING OLD | | EXISTING UPDATED | | NEW UPDATE | | EXISTING NEW | | NEW BUILD | | | | | | CAPITAL COST |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | PREF05 | PREF06 | PREFE09 | PREFE10 | PREFB09 | PREFB10 | PREF25 | PREF26 | PREF29 | PREF30 | PREF33 | PREF34 | PREF37 | PREF38 | |
| POBJ72 | 0.30 | 0.30 | 0.28 | 0.28 | 0.28 | 0.28 | 0.20 | 0.20 | 0.20 | 0.20 | 0.24 | 0.24 | 0.27 | 0.27 | 0.3 |
| PNEWCN72 | | | | | 0.49 | 0.49 | | | 1.21 | 1.21 | 1.39 | 1.39 | 1.64 | 1.64 | -1.0 |
| PVLREF | 0.71 | 0.67 | 0.76 | 0.72 | 0.76 | 0.72 | 0.83 | 0.79 | 0.83 | 0.79 | 0.86 | 0.82 | 0.88 | 0.84 | |
| ZULXREFO | 1.0 | 1.0 | | | 1.0 | 1.0 | | | | | | | | | |
| ZULXRFOC | | | 1.0 | 1.0 | -1.0 | -1.0 | | | | | | | | | |
| ZULXREFN | | | | | | | 1.0 | 1.0 | | | | | | | |

POBJ72 - COST ACCOUNTING ROW
PNEWCN72 - CAPITAL INVESTMENT
PVLREF - REFORMATE
ZULXREFO - UPPER LIMIT ON EXISTING OLD REFORMER CAPACITY
ZULXRFOC - UPPER LIMIT ON CONVERTED OLD REFORMER CAPACITY
ZULXREFN - UPPER LIMIT ON EXISTING NEW REFORMER CAPACITY

FIGURE 20.

contains entries representing actual investment requirements. An appropriate annual charge for this capital investment is recorded in the objective function by means of a transfer column (PCAPCOST). If desired, it would be possible to (a) constrain the supply of capital by placing a bound on this column, (b)provide a separate column activity to represent internal funds, or (c) construct a set of columns to represent a piecewise linear capital supply curve (as has been done for improved crude oil). A combination of b and c would have the double advantage of 1) being the closest approximateion to reality and 2) providing a means of estimating an internal rate of return on capital generated within the industry. To address this problem adequately, one would require a supply curve for external capital as well as rough estimates of internally generated capital.

Important Specifications for a Model Run

Objective function - The appropriate objective function for the model is XOBJ75, and it is to be minimized. XOBJ75 represents total annual production and resource supply costs in 1975 dollars. There are actually very few entries in XOBJ75; most cost accounting is provided by an intermediate row POBJ72 which measures costs in 1972 dollars. A transfer column (FATOBJ75) converts the costs in POBJ72 to 1975 dollars and transfers them to XOBJ75. Similarly, column PCAPCOST converts the accumulated capital investment requirments in row PNEWCN72 to 1975 dollars and then allocates a specified proportion of this investment (say 0.3) as an annual capital charge in XOBJ75.

Right hand side - The right hand side for the model is RHS85 which represents two important types of model constraints. One set of specifications projected net annual production requirements for 1985. The other set represents estimated existing capacities of various kinds of production units (ZULX-rows); these are expressed in terms of units of production per year. All magnitudes in the right hand side have been scaled by $10^{-9}$ for manageability.

Bounds - A bound set (named SUPBND) containing appropriate upper bounds for the crude oil and natural gas liquids supply columns has been included in the data deck. The format of this part of the deck may have to be revised for compatibility with certain LP codes. There is no special reason to alter any of these bounds unless the user is dissatisfied with the approximations used for domestic supplies of crude oil and natural gas liquids (columns XUSCSUP and XNGLSUP). The bounds for the linearized imported crude oil supply curves should not be altered without due considerations of the impact of the alteration on the curvature of the curve and the accuracy of the calculated prices at each step.

Selection of crude oil price elasticity - Each model run requires a special 0-1 setting of four coefficients in in XOBJ75 which together specify the modeler's choice of the price elasticity of supply for imported crude oil. As indicated in Figure 18, these coefficients occur in four columns (XCOSTE01, SCOSTE02, SCOSTE05, SCOSTEIN) which transfer the accumulated supply costs for crude oil (contained in rows XARCPE01, XARCPE02, XARCPE05, XARCPEIN) to the objective function. The last two characters of these row and column names indicate the price elasticity to which the accounting is relevant; i.e., one, two, five, and infinity, respectively. Only one of the four objective function entries should be set to 1.0 for a given run; all others must be set to 0.0. Selection of a price elasticity of one has been illustrated in Figure 18.

Parametrics: right hand side - Needless to say, any entry in RHS85 is a legitimate subject for parameterization. In the present study parametrics have been performed on three rows (PLLGSL, PLLDIST, PLLRESID) which represent the net production requirements for gasoline and distillate and residual fuel oils, respecitvely. The "alternate" right hand sides necessary under most LP algorithms to formulate parametric variations have been included with the data deck. There are six such alternatives, each with only one entry as follows:

| | |
|---|---|
| RHSUGSL | RHS85 entry for PLLGSL |
| RHSDGSL | RH585 entry for PLLGSL times -1. |
| RHSUDIST | RHS85 entry for PLLDIST |
| RHSDDIST | RHS85 entry for PLLDIST times -1. |
| RHSURESD | RHS85 entry for PLLRESID |
| RHSDRESD | RHS85 entry for PLLRESID times -1. |

As can be seen, these alternates are defined to map out proportional changes in the original right hand side entries for the three products. Given positivity of the parametric parameter (often called THETA), RHSU alternates map out increases relative to the original entry and RHSD alterates map out decreases. The value of THETA is conveniently the proportional change in the original entry.

<u>Parametrics: objective function</u> - In principle any cost coëfficient can be parameterized, but it should be remembered that since most production costs are entered in the intermediate row POBJ72, it would be necessary to parameterize on an internal matrix row rather than on the objective function. The two most sensible subjects of parameterization (and those used in the present study) are the costs of capital and water withdrawals. For convenience these cost coefficients are entered directly in XOBJ75. Appropriate "change" rows have been included in the data deck. These rows have been formulated according to the same proportional change philosophy employed for the right hand sides. Four free rows were created as follows:

| | |
|---|---|
| ZOFUCAPC | PCAPCOST entry in XOBJ75 |
| ZOFDCAPC | PCAPCOST entry in XOBJ75 times -1. |
| ZOFUWTRP | FATRIVER entry in XOBJ75 |
| XOFWTRP | FATRIVER entry in XOBJ75 times -1. |

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# APPENDIX A

# CALCULATIONS AND SOURCES

# CALCULATIONS

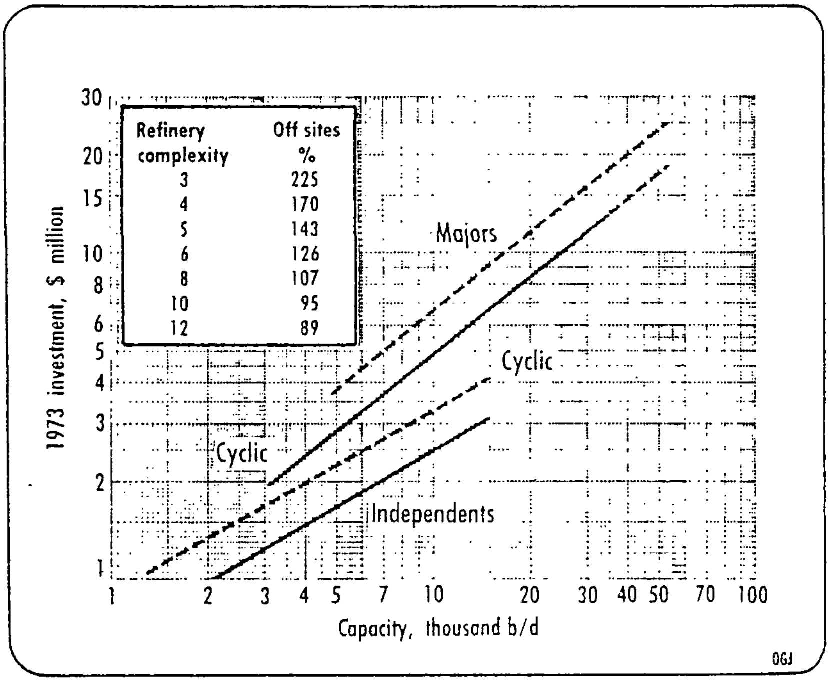
Calculations of objective function values and capital necessary for new construction were based on Figures 22 through 27, all taken from Nelson's Costimating series in the Oil and Gas Journal. Where separate curves are given for majors and independents, the curve for the majors was used. Where groups of curves covering different operating conditions present a range of costs for any given size, a unit near the center of the range was chosen.

Some of the curves contain "Refinery complexity" factors. These are constants used to estimate the offsites investment which must accompany any direct investment in a major refinery unit. Such facilities as in plant roads, utlities plants, administrative facilities, or additional processing investment contribute to this type of investment. Since additional processing equipment is included in the calculating of the factor, offsites investment is inversely proportional to refinery complexity.

The capital calculations made in this study do not include offsites investment for two reasons: First, the refinery model contains all major refinery units. Thus its complexity is high and its offsites factor low. Second, increasing capital requirements by some arbitrary factor would not increase the quality of the analysis or sharpen the

Figure 22

## Cost of reforming units




## Statistical data for reforming plants

| | Capacity, $10^6$ b/d U.S. | Capacity, $10^6$ b/d World | Nelson inflation index | Productivity* | Cost index 1949 | Cost index 1973 |
|---|---|---|---|---|---|---|
| 1949 | 0.02 | — | ‡100 | 1.00 | 100 | 87 |
| 1950 | 0.05 | — | 105 | 0.98 | 107 | |
| 1955 | 0.52 | — | 132 | 1.04 | 126 | |
| 1960 | 1.91 | 3.24 | 163 | 1.39 | 118 | |
| 1962 | 2.01 | 3.66 | 170 | 1.66 | 102 | |
| 1964 | 2.05 | 4.21 | 181 | 2.12 | 86 | |
| 1966 | 2.08 | 4.78 | 195 | 2.59 | 75 | |
| 1968 | 2.39 | 5.69 | 218 | 3.10 | 70 | |
| 1969 | 2.52 | 6.29 | 236 | 3.39 | 70 | |
| 1970 | 2.78 | 6.75 | 261 | 3.24 | 80 | 74 |
| 1971 | 2.90 | | 290 | 3.30 | 88 | 81 |
| 1972 | 3.17 | | 314 | 3.27 | 96 | 89 |
| 1973 est. | 3.27 | | 335 | 3.09 | 108 | 100 |
| 1974 est. | 3.40 | | 357 | †3.40 | 105 | 97 |
| 1975 est. | — | | — | †3.50 | — | — |

*Major (or government) refiners. †Reduced because of shortage of contractors. ‡139.7 based on the regular Nelson 1946 basis.

Taken from The Oil and Gas Journal

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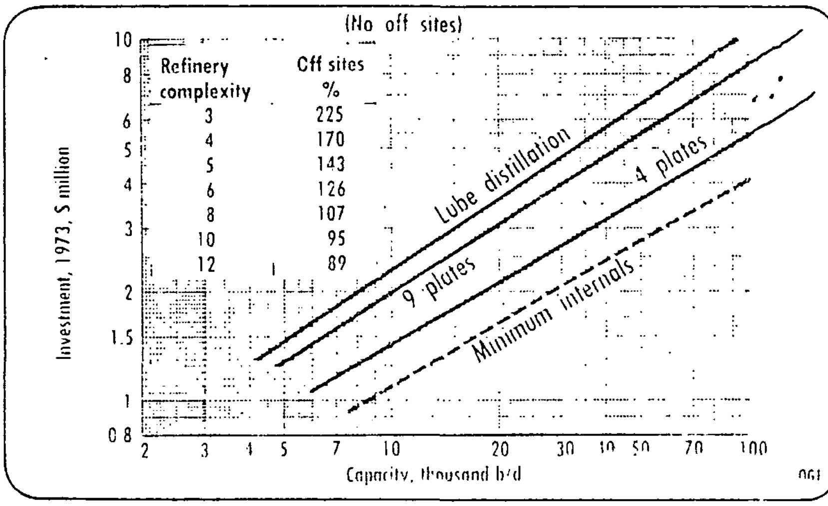
Figure 23

## Cost of vacuum plants




## Vacuum plant statistics*

| Year | Column* | U.S. capac. $10^6$ b/sd (1) | Nelson inflation (2) | Productivity (3) | Cost index on 1946 (4) | Cost index on 1973 (5) |
|---|---|---|---|---|---|---|
| 1946 | | 0.90 | 100 | 1.00 | 100 | 64.1 |
| 1952 | | 1.26 | 163.6 | 1.04 | 157 | |
| 1954 | | 1.54 | 179.8 | 0.99 | 182 | |
| 1956 | | 2.62 | 195.3 | 0.99 | 197 | |
| 1958 | | 3.17 | 213.9 | 1.10 | 194 | |
| 1960 | | 3.48 | 228.2 | 1.25 | 183 | |
| 1962 | | 3.67 | 237.6 | 1.38 | 172 | |
| 1964 | | 3.75 | 252.1 | 1.56 | 162 | |
| 1966 | | 3.88 | 273.0 | 1.79 | 152 | |
| 1968 | | 4.12 | 304.1 | 2.00 | 152 | |
| 1970 | | 4.52 | 364.9 | 2.40 | 152 | 97.4 |
| 1971 | | 4.74 | 406.0 | 2.65 | 153 | 98.2 |
| 1972 | | 4.85 | 438.5 | 2.75 | 154 | 98.8 |
| 1973 | | 5.15 | 468.5 est. | 3.00 | 156 | 100.0 |
| 1974 est. | | 5.50 | 500.0 | 3.40 | 147 | 94.1 |

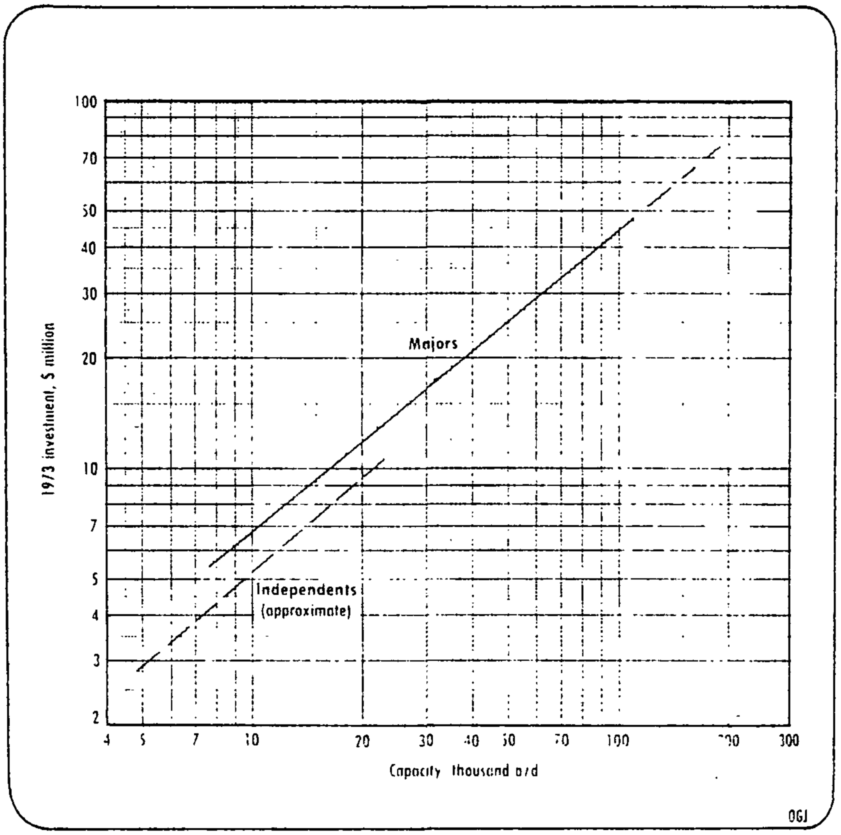
*Columns explained in footnotes.
(1) World capacity better basis but statistics doubtful.
(2) Nelson Refinery (Inflation) Construction Cost Index, first issue each month, OGJ.
(3) Skill in design and construction of vacuum plants.
(4) Cost index based on 1946. Column (2) divided by Col. (3).
(5) Cost index based on 1973.

Taken from The Oil and Gas Journal

March 4, 1974 Page 100

Figure 24

Cost of catalytic-cracking plants




Statistics on catalytic cracking units (majors only)

| | U.S. capacity $10^6$ b/d | Nelson inflation index | Productivity | Cost Index 1946 | Cost Index 1973 |
|---|---|---|---|---|---|
| 1946 | about 0.8 | 100.0 | 1.0 | 100 | 177 |
| 1948-1963—See Prod. Costimating No. 18, Aug. 9, 1965, p. 102. | | | | | |
| 1968 | 5.80 | 304 | 6.08 | 50 | 88 |
| 1969 | 5.80 | 329 | *7.5 | 44 | 78 |
| 1970 | 5.86 | 365 | *7.5 | 49 | 87 |
| 1971 | 5.97 | 406 | *7.7 | 53 | 94 |
| 1972 | 5.83 | 438 | 8.4 | 52 | 92 |
| 1973 est. | †5.56 | 469 | 8.28 | 57 | 100 |
| 1974 est. | | 500 | ‡8.3 | 60 | 106 |
| 1975 est. | | | ‡8.6 | | |

*Few plants. Read from curve.
†Recycling decreasing, and improved catalyst maintains gaso. yield.
‡Low because contractors busy and few plants built.

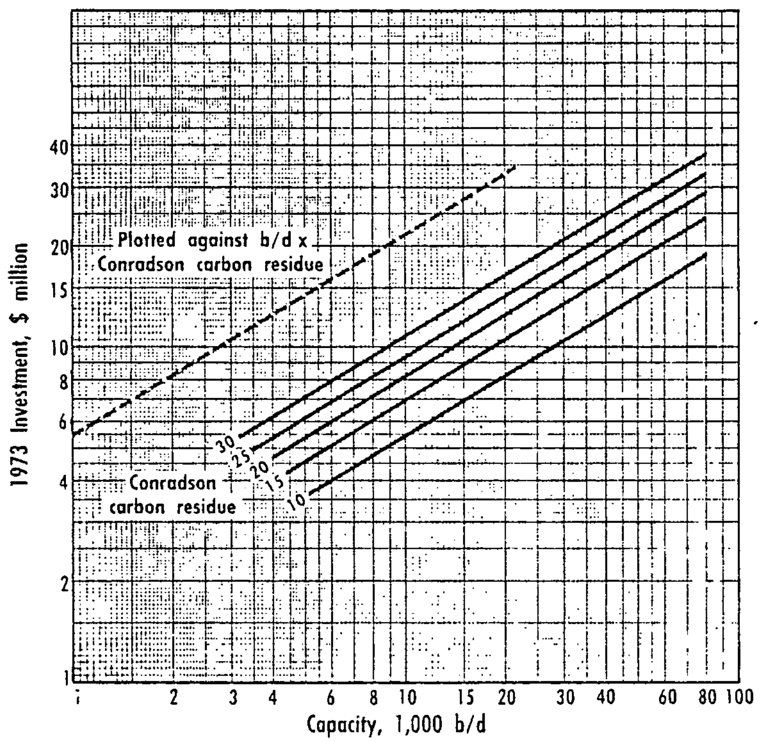
Taken from The Oil and Gas Journal

April 15, 1974 Page 66

Figure 25

# Investment cost of coking plants (revised)*

(*Fluid type, see graph; delayed type, reduce fluid type costs by 14%)




NOTE: (1) add 14% for fluid type royalty, (2) no off sites; (3) no calciner

OGJ

## Coking-plant statistics

| Year | U.S. capacity, b/sd | Nelson inflation | Productivity | Cost index 1946 | Cost index 1973 |
|---|---|---|---|---|---|
| 1946 | 102,000 | 100.0 | 1.00 | 100 | 32 |
| 1950 | 158,000 | 146.2 | 1.13 | 129 | |
| 1960 | 475,000 | 228.2 | 1.16 | 197 | |
| 1962 | 520,000 | 237.6 | 1.14 | 209 | |
| 1964 | 535,000 | 252.1 | 1.15 | 220 | |
| 1966 | 621,000 | 273.0 | 1.19 | 230 | |
| 1968 | 715,000 | 304.1 | 1.27 | 239 | |
| 1970 | 835,000 | 364.9 | 1.48 | 246 | 79 |
| 1971 | 920,000 | 406.0 | 1.43 | 284 | 91 |
| 1972 | 975,000 | 438.5 | 1.47 | 298 | 95 |
| 1973 | 1,008,000 | 468.5 | 1.50 | 312 | 100 |
| 1974 | 1,025,000 | 522.7 | *1.52(1.23) | 425 | 136 |
| †1975 | 1,040,000 | 594 | *1.53(1.34) | 427 | 142 |
| †1976 | 1,096,000 | 681.5 | *1.56(1.42) | 470 | 156 |
| †1977 | 1,130,000 | 768 | 1.57 | 490 | 157 |
| †1978 | 1,190,000 | 854 | *1.58(1.66) | 515 | 165 |

*Panic caused by shortages led to prices based on uncertainty and supply rather than costs of labor and basic materials. †Estimate.

Taken from the Oil and Gas Journal

May 24, 1976 Page 60

Figure 26

## Topping-plant statistics*

| Year Col.* | World 10, b/d (1) | Nelson inflation (2) | Productivity (3) | Cost indexes 1946 (4) | Cost indexes 1973 (5) |
|---|---|---|---|---|---|
| 1929 | | 72.0 | 0.92 | 78 | 37 |
| 1938 | | 76.8 | 0.94 | 62 | |
| 1946 | 8.0 | 100.0 | 1.00 | 100 | |
| 1952 | 12.1 | 163.6 | 0.93 | 176 | |
| 1956 | 20.0 | 213.9 | 1.05 | 203 | .. |
| 1960 | 22.1 | 228.2 | 1.13 | 202 | ... |
| 1962 | 24.4 | 237.6 | 1.22 | 195 | . |
| 1964 | 28.6 | 252.1 | 1.37 | 184 | ... |
| 1966 | 32.4 | 273.0 | 1.59 | 172 | ... |
| 1968 | 38.8 | 304.1 | 1.88 | 162 | ... |
| 1970 | 41.9 | 364.9 | 2.25 | 162 | 78 |
| 1971 | 45.7 | 406.0 | 2.09 | 194 | 93 |
| 1972 | 48.7 | 438.5 | 2.22 | 198 | 95 |
| 1973 est. | 49.6 | 468.5 | 2.25 | 208 | 100 |
| 1974 est. | 52.1 | 500.0 | 2.35 | 213 | 103 |

*Meaning of columns explained in footnotes.
(1) Free-world
(2) U.S. inflation, Nelson Refinery (Inflation) Const. Cost Index, 1st week each month in OGJ.
(3) Skill attained in design, programming, erection, etc., in building for major refiners.
(4) Column 2 over Col. 3, based on 1946 = 100.
(5) Same as Col. 4 except based on 1973.

## Cost of crude-distillation units

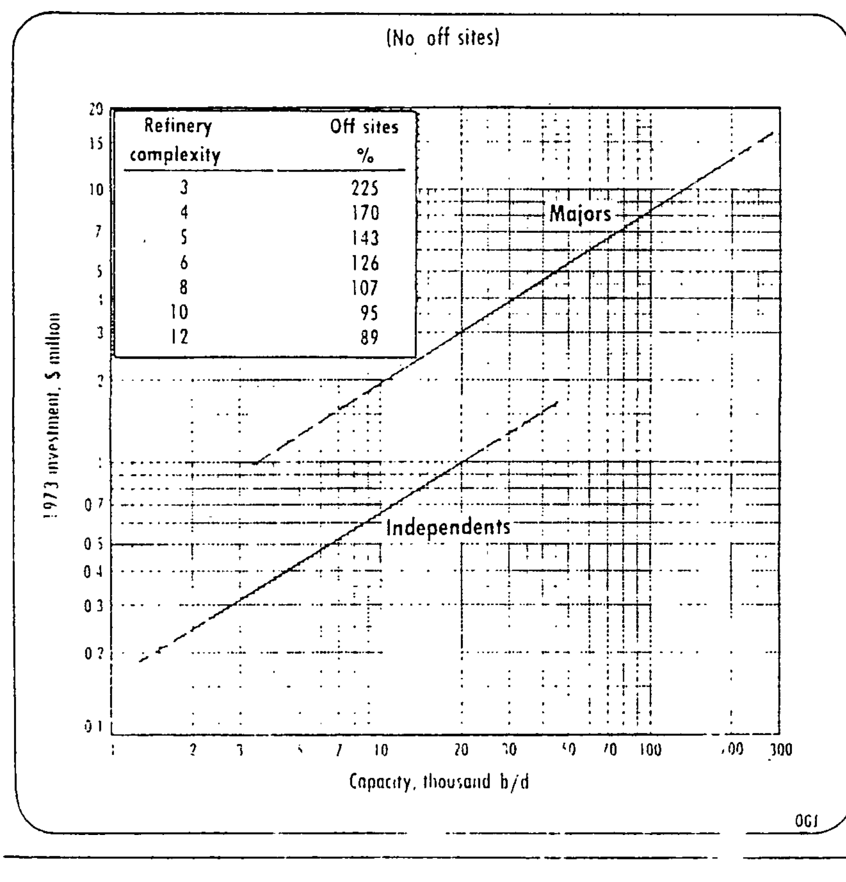



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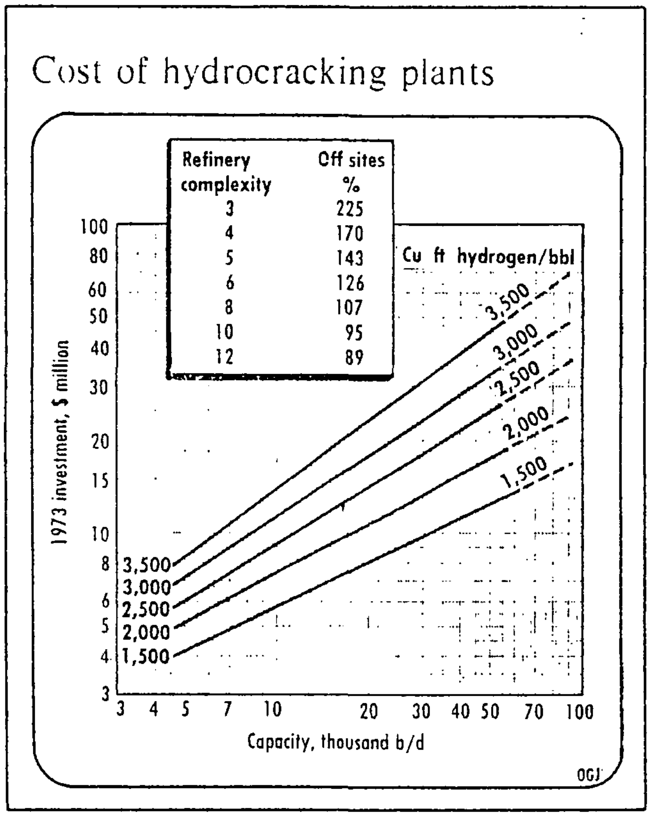
Figure 27




Taken from the Oil and Gas Journal

February 25, 1974 Page 120

distinctions among the policy options being analyzed.

All capital figures are for the U.S. Gulf Coast in 1972. For this reason, capital requirements are somewhat understated for the U.S. as a whole. In any regional study appropriate adjustments would have to be made for objective function values and capital requirements on a region by region basis (see Figure 21). This exercise along with adjustment of regional unit capacities and crude oil types would be sufficient for a detailed study of a given refinery region, or for comparisons among regions.

Figure 21

Table 2

**Approximations of location factors***

| | |
|---|---|
| Gulf Coast | 1.00 |
| New Jersey, U.S.A. | 1.27 |
| California, U.S.A. | 1.08 |
| Louisiana, U.S.A. | 1.08 |
| Great Lakes, U.S.A. | 1.09 |
| Hawaii, U.S. Equip. | 1.15 |
| Hawaii, Japan Equip. | 1.03 |
| Caribbean | 0.92 |
| Finland | 1.02 |
| Italy | 0.81 |
| Germany | 0.82 |
| France | 0.85 |
| Japan | 0.74 |
| India | 0.94 |
| Kuwait | 0.95 |
| Ghana | 1.04 |

*Values from other sources vary greatly from these computed values.

Taken from Oil and Gas Journal

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# APPENDIX B

# COMPUTER PROGRAMS

**Program I: converts LP data found in file "REFINE" to binary format.**

```
      IDENT    3767TAYL$THESIS,FRANK                                  00000101
      USERID   HQMSFC1385$THESIS                                      00000102
      PROGRAM  MPS                                                    00000103
      EXTEND                                                          00000104
      PRMFL    E*,R,R,UH/FLIBB/MPSPF                                  00000105
      PRMFL    **,R,R,UH/PLIBB/MPS                                    00000106
      LIMITS   10,50K                                                 00000107
      FILE     AA,,20R                                                00000108
      FILE     BB,,20R                                                00000109
      FILE     CC,,20R                                                00000110
      FILE     DD,,5R                                                 00000111
      FILE     EE,,5R                                                 00000112
      PRMFL    PT,W,R,HQMSFC1385/REFPROB                              00000113
      DATA     IN                                                     00000115
ILE   REFINE                                                          00000116
      SELECTA  HQMSFC1385/REFINE                                      00000117
ND***                                                                 00000118
      DATA     I*                                                     00000120
      PREPRO                                                          00000121
      TITLE    REFINERY PROBLEM                                       00000122
      SET      KJLIST=OFF                                             00000123
      CONVERT  SOURCE=REFINE/IN,IDENT=INFO,CHKROW                     00000124
      ENDLP                                                           00000125
      ENDJOB                                                          00000126
```

**Program II: solves the L.P. problem using binary data set created by Program I**

```
$       IDENT     3767TAYL$THESIS,FRANK
$       USERID    HQMSFC1385$THESIS
$       PROGRAM   MPS
$       EXTEND
$       PRMFL     E*,R,R,UH/FLIBB/MPSPF
$       PRMFL     **,R,R,UH/PLIBB/MPS
$       LIMITS    05,50K
$       FILE      AA,,20R
$       FILE      BB,,20R
$       FILE      CC,,20R
$       FILE      DD,,5R
$       FILE      EE,,5R
$       PRMFL     XP,R,R,HQMSFC1385/REFPROB
$       FILE      AI,X1,1L,NEW,PBASIS
$       FILE      EI,X2,1L,OLD,BASPEOS
$       DATA      IN
$       SELECTA   HQMSFC1385/ELASMOD
$       DATA      I*
        PREPRO
        TITLE     REFINE
        SETUP     SOURCE=INFO/XP
        SET       OBJ=XOBJ:75,RHS=RHS3:5,FIR1=5,RF1=CAB
        SET       SCALE=1.0
        SET       NIPP=1
        SET       NFS=TRAC,UNB=OOPS,CHK=OUT
        LDBASIS   SOURCE=PBASIS/EI
        RESET     ITERNO
        SET       DETAIL=ON
        MODIFY    SOURCE=EMOD:PEOS/IN
        SET       DETAIL=OFF
        CRASH
        PRIMAL
        BLANK     AI
        PUNCH     IDENT=PBASIS/AI
OUT     OUTPUT    ALL
        ENDLP
TRAC    TRACE     INFEAS,SO
        INVERT
        OUTPUT    ALL
        ENDLP
OOPS    SET       DETAIL=ON
        ABOUND
        OUTPUT    ALL
        ENDLP
CAB     SET       RF1=CAB1,FIR1=50
CAB1    BLANK     AI
        PUNCH     IDENT=PBASIS/AI
        LOGIC     NINFS.GT.0,RET
        SET       NIPP=3
RET     CURRENT
$       ENDJOB
```

**Program III: summarizes refinery capacity data by date, unit, and state.**

```
 IDENT    3767TAYL$THESIS,FRANK
 USERID   HQMSFC1385$THESIS
 LIMIT    1,30,1000
 OPTION   FORTRAN
 FORTRAN
      DATA A/"A"/
      DATA TEX/"TEX"/
      DATA ARK/"ARK"/
      DATA LOU/"LOU"/
      DATA OKL/"OKL"/
      DATA CAL/"CAL"/
      DATA MON/"MON"/
      DATA UTA/"UTA"/
      DATA COL/"COL"/
      DATA WYO/"WYO"/
      DATA WAS/"WAS"/
      DATA XXXX/"XXXX"/
      DATA BLANK/"    "/
      DATA BL/"  "/
      DIMENSION FIRM(5)
      DIMENSION Z(6)
      DIMENSION Q(6)
      DIMENSION COM(400)
      DIMENSION PL(400)
      INTEGER ITIME(400)
      DIMENSION RNO(400)
      GCTOT=0.0
      ETOT=0.0
      WTOT=0.0
      ITRIP=0
      EDUP=0.0
      GCDUP=0.0
      WDUP=0.0
      L=0
      INUM = 64
      DO 25 I = 1,829
      READ(3,10,END=26)IDATE,FIRM,ALOC,Z(1),Q(1),Z(2),Q(2),Z(3),Q(3),
     CZ(4),Q(4),Z(5),Q(5),Z(6),Q(6)
 5    FORMAT(1X,I2,4X,A4,A4,A4,A4,A3,1X,A3,1X,F6.2,4X,A1)
 10   FORMAT(1X,I2,1X,A4,A4,A4,A4,A3,1X,A3,1X,10(F6.2,A1,1X))
        IF(IDATE.NE.0) GO TO 8
      IDATE = INAME
      GO TO 12
  8   IF(IDATE.EQ.INUM) GO TO 40
 11   INAME= IDATE
      GO TO 12
 12   IF(FIRM(1).NE.BLANK) GO TO 9
      FIRM(1) = FNAM1
      FIRM(2) = FNAM2
      FIRM(3) = FNAM3
      FIRM(4) = FNAM4
      GO TO 13
```

Program III: continued

```
 9 FNAM1 = FIRM(1)
   FNAM2 = FIRM(2)
   FNAM3 = FIRM(3)
   FNAM4 = FIRM(4)
13 DO 24 M = 1,6
   IF(Q(M).NE.A) GO TO 24
14 WRITE(6,5)IDATE,FIRM,ALOC,Z(M),Q(M)
   L=L+1
   COM(L)=FIRM(1)
   PL(L)=ALOC
   ITIME(L)=IDATE
   RNO(L)=Z(M)
   IF(ALOC.EQ.TEX.OR.ALOC.EQ.LOU.OR.ALOC.EQ.OKL.OR.ALOC.EQ.ARK)
  CGO TO 28
   IF(ALOC.EQ.CAL.OR.ALOC.EQ.MON.OR.ALOC.EQ.WYO.OR.ALOC.EQ.WAS.
  COR.ALOC.EQ.COL.OR.ALOC.EQ.UTA)GOTO 27
   ETOT = ETOT + Z(M)
   GO TO 24
28 GCTOT=GCTOT+Z(M)
   GO TO 24
27 WTOT=WTOT+Z(M)
24 CONTINUE
25 CONTINUE
   GO TO 26
40 WRITE(6,30) ETOT,GCTOT,WTOT
   ETOT = 0.0
   GCTOT=0.0
   WTOT=0.0
   GO TO 11
30 FORMAT("INTERMEDIATE A UNITS",10X,"EAST",2X,F8.2,4X,"GULF",
  C2X,F8.2,4X,"WEST",2X,F8.2)
31 FORMAT("NEW A UNITS",10X,"EAST",2X,F8.2,4X,"GULF",
  C2X,F8.2,4X,"WEST",2X,F8.2)
26 WRITE(6,31)ETOT,GCTOT,WTOT
   DO 50 M=1,400
   IF(COM(M).EQ.XXXX) GO TO 50
   IF(COM(M).EQ.0) GO TO 50
   DO 45 J=1,400
   IF(COM(M).EQ.COM(J).AND.PL(M).EQ.PL(J).AND.RNO(M).EQ.RNO(J))
  CGO TO 44
   GO TO 45
44 IF(J.EQ.M)GO TO 45
   WRITE(6,55)COM(M),ITIME(M),COM(J),ITIME(J),RNO(M)
   COM(J)=XXXX
   IF(PL(J).EQ.TEX.OR.PL(J).EQ.ARK.OR.PL(J).EQ.OKL.OR.PL(J).EQ.LOU)
  CGO TO 46
   IF(PL(J).EQ.CAL.OR.PL(J).EQ.MON.OR.PL(J).EQ.WYO.OR.PL(J).EQ.COL.
  COR.PL(J).EQ.WAS.OR.PL(J).EQ.UTA)GO TO 47
   EDUP=EDUP+RNO(M)
   GO TO 48
46 GCDUP=GCDUP+RNO(M)
   GO TO 48
```

**Program III: continued**

```
47 WDUP=WDUP+RNO(M)
48 IF(ITIME(M).EQ.64.OR.ITIME(M).EQ.65.OR.ITIME(M).EQ.66)
  CGO TO 57
   GO TO 45
57 IF(ITRIP.EQ.1)GO TO 45
   ITRIP=ITRIP+1
   WRITE(6,56)EDUP,GCDUP,WDUP
   EDUP=0.0
   GCDUP=0.0
   WDUP=0.0
45 CONTINUE
50 CONTINUE
55 FORMAT(2X,A4,2X,I2,2X,A4,2X,I2,2X,F6.2)
56 FORMAT("DUPLICATE TOTAL",10X,"EAST",2X,F8.2,4X,"GULF",2X,F8.2
  C,4X,"WEST",2X,F8.2)
   WRITE(6,56)EDUP,GCDUP,WDUP
   STOP
   END
    EXECUTE
    DATA     03
    SELECTA SPREAD
    ENDJOB
```

# APPENDIX C

Computer Output

PRNAM=INFO : : OBJ=OBJD :CAPC : RHS=RHSD :RESD :

*** SETUP SUMMARY ***

| | TYPE | NO. | NO. NON-NULL | AVERAGE NON-NULL |
|---|---|---|---|---|
| ROWS USED | Z | 21 | 992 | 47.238095 |
| ROWS USED | P | 48 | 367 | 7.6458333 |
| ROWS USED | M | 137 | 2757 | 20.124088 |
| ROWS USED | F | 10 | 130 | 13.000000 |
| ROWS USED | R | | | |
| NULL ROWS USED | | | | |
| TOTAL ROWS | | 216 | 4246 | 19.657407 |
| STRUCTURAL COLUMNS USED | Z | | | |
| STRUCTURAL COLUMNS USED | P | 497 | 4028 | 8.1046278 |
| STRUCTURAL COLUMNS USED | M | | | |
| STRUCTURAL COLUMNS USED | F | | | |
| STRUCTURAL COLUMNS USED | R | 44 | 218 | 4.9545455 |
| STRUCTURAL COLUMNS USED | I | | | |
| STRUCTURAL COLUMNS USED | S | | | |
| NULL STRUCTURAL COLUMNS USED | | | | |
| TOTAL STRUCTURAL COLUMNS USED | | 541 | 4246 | 7.8484288 |
| RHS COLUMNS USED | Z | 7 | 73 | 10.428571 |
| NULL RHS COLUMNS USED | | | | |
| TOTAL RHS COLUMNS | | 7 | 73 | 10.428571 |

| ROW TYPE | ROW KJ | COL KJ | STRUCTURAL ELEMENT SIZES MAX ABS ELEMENT | ROW KJ | COL KJ | MIN AB ELEMEN | AVERAGE ABS. VALUE OF NON-NULLS |
|---|---|---|---|---|---|---|---|
| Z | 75 | 249 | 3500.0000+ | 143 | 610 | .00030000+ | 84.453021+ |
| P | 175 | 223 | 100.00000+ | 91 | 338 | .01600000+ | 8.9473838+ |
| M | 4 | 244 | 3100.0000+ | 152 | 257 | .00100000+ | 75.244727+ |
| F | 169 | 753 | 52.000000+ | 19 | 291 | .00020000+ | 1.5621454+ |

OVERALL STRUCTURAL DENSITY IN MATRIX USED 3.6335319
NUMBER OF EXPLICIT ZEROES IGNORED -- 7
LONGEST COLUMN HAS 28 ELEMENTS. FIRST OF 1 COLUMNS IS OMEG:0:
NUMBER OF GROUPS = 0
NUMBER OF PACKETS = 0
NUMBER OF SSETS = 0