A MODEL FOR THE DETERMINATION OF
OPTIMAL ELECTRIC GENERATING SYSTEM
EXPANSION PATTERNS

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ABSTRACT

A MODEL FOR THE DETERMINATION OF OPTIMAL ELECTRIC

GENERATING SYSTEM EXPANSION PATTERNS

by

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Long range electric generating capacity expansion planning requires consideration of a diverse range of issues including economic and financial evaluations, environmental protection, and overall system reliability. To determine the optimum system expansion plan, it is necessary to create a synthesis of combinations of possible technical alternatives, observe the intertemporal effects of the system along the dimensions of the problem, and choose the set of alternatives which best meets the objectives while satisfying all constraints.

A system of integrated techniques and computer codes (called the Generation Expansion Model) has been formulated to evaluate the economic, environmental, and reliability aspects of regional generation expansion strategies. The computer codes comprising the model are used serially and in an iterative manner to find the set of plant and site alternatives and the corresponding plant operating histories which will minimize the total present worth of all capital, operating, and fuel costs while satisfying the demand for electricity, fuel availability, site availability, pollution limits, and reliability constraints.

Prototypical versions of the three major submodels of the Generation Expansion Model exist; initial testing of the capabilities and sensitivities of the first two submodels and their interface is currently being performed.

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Project Definition.

Early in 1972, as part of a National Science Foundation funded program of energy studies at M.I.T., development began on an integrated set of techniques and computer programs for evaluating long-range electric power generating system expansion strategies. Of course, any realistic approach to the general expansion problem requires consideration of a diverse range of issues from economic and financial factors to environmental protection and to overall system security (reliability). The multifaceted nature of the problem results to a considerable extent from the conflict between society's requirements for more electric power and society's concern for environmental protection and resource conservation. It is compounded by a lack of adequate, inexpensive fuel supplies for present and future generating stations, curtailments or threats of curtailment of electric service in some areas, large capital funds requirements, and long lead times for the development of new technological options for generating electricity.

New systems analysis methods are being applied to these problems. These methods provide a framework for performing a careful and comprehensive accumulation of technical

data describing the alternatives, the system, and the environmental requirements. The objective of these techniques is to create a synthesis of combinations of technical alternatives and to select the optimal arrangement which satisfies all the given requirements.[1] When conventional methods of economic analysis are used wherein a simple ranking of feasible projects is developed in terms of the return on investment or present value, there is a serious danger of excessive "suboptimization". This ranking approach assumes the projects stand independently on their own merits and ignores how much the "desirability" of each project may be affected by other projects and by existing operations. To overcome this shortcoming it is necessary to look simultaneously at all pertinent projects as an integrated system as they evolve through time and affect each other.

An increasingly common approach to the problem consists essentially of carrying out a series of case studies. Considerable effort is devoted to arriving first at a feasible solution. Then the whole effort is resumed and another feasible solution is found and compared to the previous one; and so on. This trial-and-error approach can test only a limited number of solutions and there is little assurance that the best solution has been found. Any viable alternative requires techniques that can manipulate and store large amounts of information efficiently and can explore systematically a great number of alternatives and restrictions characterizing the

10

functioning of the electric system.[2]

This thesis documents the initial formulation of a framework or model within which economic, environmental and security (EES) aspects and their interactions in generation expansion strategies can be evaluated. The model, designated the Generation Expansion Model (GEM), actually consists of three integrated sub-models which are designed to be used serially and in an iterative fashion in determining least dollar cost generation expansion plans for regional electric systems. This functional division into sub-models provides a sequential approach for logical decision-making and results in some flexibility in application. Thus each sub-model can be used in certain related studies by itself.

In terms of input/output characteristics the Generation Expansion Model can be described as follows:

Given: 1. A set of decision variables consisting of plant alternatives, site alternatives, and plant operating histories.

2. The capital and unit fuel costs associated with each of the decision variables.

3. The fuel consumption rate of each of the decision variables.

4. The forced outage rate of each plant alternative.

5. A set of constraints describing site availability, air and thermal pollution

11

limits, system reliability, and fuel availability.

6. The projected electricity demand throughout the study period.

Find: The set of plant and site alternatives and the corresponding plant operating histories which will minimize the total present worth of all capital, operating, and fuel costs while satisfying the demand for electricity, fuel availability, site availability, pollution, and reliability constraints.

The model is capable of evaluating the costs and performance in a regional electric system of most of the feasible combinations of central generating plant and pollution abatement technologies, including advanced technologies which are not yet commercially available.

One sub-model of the Generation Expansion Model relies on linear programming to determine an optimal solution to the set of model equations and inequalities. The Simplex algorithm for the solution of linear programming problems is an intelligent search procedure in which only basic feasible solutions are examined and only a small portion of these. It proceeds toward the optimal solution in such a way that no solution examined is worse than any solution previously examined. It also indicates directions for improving the optimal

plan if certain restrictions are removed or generating plant costs are changed. It should be emphasized that the technique only aids, but does not substitute for, proper decision-making. The user remains responsible for correctly evaluating the intangible factors and uncertainties of the future when he derives the input data to the model. The derivation of the input data, then, requires careful use of experience, judgement, and intuition. By changing the uncertain input data the user can, however, test to see how sensitive the ultimate plan is to his assumptions and can then devote more attention to the truly sensitive areas.

Although the Generation Expansion Model is completely formulated conceptually, the small code needed to provide an interface between the second and third sub-models could not be programmed within the time constraints imposed on the publication of this thesis. Thus, the next chapter will discuss in some detail the complete model and the interactions of all three sub-models as it is presently conceived. The remaining chapters will be devoted, however, only to a detailed documentation of the completed versions of the first and second sub-models and their interactions.

The major computer codes used in the formulations to be presented on the following pages have not been originally contributed by the authors of this thesis. The authors do feel that their contributions include the development of the interactive framework of the overall model. The authors were

influenced by the suggestions of many sources in modifying and combining existing codes. In the next chapter, after a brief discussion of some of the issues that must be addressed in a regional expansion problem, the authors hope to acknowledge their considerable debt to several earlier researchers by first discussing the original papers and then the application of them to this thesis.

CHAPTER 2

THE GENERATION EXPANSION MODEL

2.1 The Generation Expansion Problem.

Comprehensive, rational, and systematic planning
methods applied to electric utility expansion and siting on a
regional scale are becoming increasingly essential. In the
past, electricity has been plentiful and cheap and utilities
have had little reason to plan jointly with their neighbors.

It now appears, early in the 1970's, that portions of
the electric utility sector may be approaching some limits to
their growth through traditionally independent determinations
and will be under increasing pressure to optimize the entire
regional electric system. A few of the factors that may force
the creation of more regional planning councils include the
continuing rapid growth in the demand for electricity, the
environmental protection movement, increasingly scarce re-
sources, system reliability, and capital market limitations.
Some of the implications of these considerations on system
planning are discussed below.

The national growth rate in the consumption of elec-
trical energy for the period 1970 to 1980 is estimated to be
7 percent compounded annually.[1] The doubling time for this
rate of growth is ten years. This means that one-half of the
capacity necessary to meet the 1982 expected energy demand

does not exist at this time.

With the advent of the ecological movement, environmental quality has become an important issue in generation expansion planning. Electric generating systems have a significant effect on the environment. For example, water quality is affected by the discharge of waste heat, chemicals, and radioactive materials from power plants. Air quality is affected by similar emissions of combustion products. Land use is affected by pumped storage facilities, transmission lines rights of ways, etc.

One of the objectives of a utility in planning system expansion is to minimize the effect on the environment or at least meet the standards set forth by the regulatory agencies. Meeting this objective is often difficult and expensive. In fact, finding suitable sites for power plant construction is fast becoming a problem. In the future, suitable sites may become a resource in increasingly short supply.

Another resource which is limited is that of the fuels required to produce electrical energy. There is enough coal to meet the national demand for several centuries. However, the combustion products of coal, particularly carbon dioxide, sulfur dioxide, and fly ash, pose a serious threat to the environment. The supply of oil and natural gas can be measured in decades. Even cheap uranium could become a limited resource if advanced nuclear technologies do not develop. Besides the problem of planning for limited resources with

uncertain costs, the utility planners must also evaluate several other trade-offs between the various fuels. For example, one of the most significant of these trade-offs is between the higher amount of waste heat associated with light water reactors and the air pollution associated with a fossil plant with its correspondingly lower amount of waste heat.

There is literally a plethora of different technologies which must be considered as alternatives when evaluating generation expansion plans. Current plant technologies include gas turbines, hydro power, pumped storage, fossil plants, light water reactors, and high temperature gas cooled reactors. Future possibilities include the breeder reactor, fusion, magnetohydrodynamics, solar energy, and possible improvements in the efficiency of existing units. There is a correspondingly long list of technologies associated with thermal and air pollution abatement equipment. The interaction of these technological alternatives is an important consideration in expansion planning. Some alternatives are complementary while others are mutually exclusive. For example, the fuel cycles of light water reactors and liquid metal fast breeder reactors appear to be complementary, with uranium fueled light water reactors initially supplying the plutonium fuel needed for the fast breeders and then ultimately consuming the excess plutonium produced by the breeders.

Reliability is another of the important factors which must be considered when planning generation expansion. This

was dramatically emphasized by the 1965 Northeast Blackout. Unit size and forced outage rate, system size, and the load shape have significant effects on the reliability of a system and must be considered in any comprehensive generation expansion planning effort.

Utilities have traditionally been among the most capital-intensive industries in the United States and their need for more money from the capital markets is growing tremendously. According to Business Week Magazine,[2] the industry required $1.4 billion in outside financing for new plant and equipment in 1965 but this year will require $9 billion in new capital with increases foreseen for the future. For a variety of reasons, including a drop in the compound earnings growth per share of Standard & Poor's utility group from 9.5 percent in 1960-65 to 1.5 percent last year, utilities are finding it more difficult to obtain inexpensive capital. Also, two-thirds of the AA-rated utility bonds floated this year have failed to sell out at the offering price. To help offset the problems of borrowing to cover inflated and escalated fixed asset costs, the utilities have turned to a variety of financing devices such as leases. A lease is a somewhat more complex financing instrument than either straight debt or common equity. To the utility, it involves long term financial obligations having nearly the same financial burden as a term loan and a lower effective interest rate than straight debt. Typically, large banks buy the equipment and hold it on their

books while leasing it to the utility. The financial attractiveness to the bank results in part from the investment tax credit provisions of the tax code. Initially, leasing was used principally to cover the costs of nuclear reactor cores, but Consolidated Edison Company, as an example, is now leasing gas turbines.

2.2 Discussion of Earlier Models.

Early in 1972, as part of a National Science Foundation funded program of energy studies at M.I.T., a decision was reached to develop techniques and computer programs for designing optimum power system expansion strategies, where the criterion of optimality involves economic, environmental and security (EES) aspects. The goal was to develop an integrated set of techniques and codes that could be used to provide inputs to complex public policy decision making processes, as well as to provide a method of estimating such factors as economies of scale and technical progress. Before formulating this integrated set, a review of many of the existing models used in expansion studies was made; several of the models that were most influential in the ultimate formulation of the model presented in this thesis are discussed below.

2.2.1 The Systems Analysis Model of the USAEC.

In 1966 the United States Atomic Energy Commission (USAEC) developed a system analysis model for the evaluation of potential nuclear expansion plans. Many of the systems

analysis techniques utilized by the USAEC, including linear programming, significantly influenced the formulation of the Generation Expansion Model. The USAEC model was first applied to a study of the relative benefits of alternative patterns of reactor development.[3] More recently, the model was used in a cost-benefit analysis of the liquid metal fast breeder reactor.[4] The latest revision to the USAEC model was published in April 1972.[5]

The USAEC model is composed of a series of computer codes which together constitute a mathematical model of the United States electric power supply sector. The information flow between the individual codes is shown in Figure 2.1. Cost performance data for each of the various reactor concepts and typical fossil plant data was developed at several national research laboratories including Oak Ridge and Pacific Northwest. The data was then normalized to a consistent set of ground rules at Oak Ridge before being input to the model.

The first code in the model is a mass balance generator named CLOTHO. The purpose of CLOTHO is to convert full power fuel requirements, supplied as data, to fuel requirements corresponding to assumed capacity factor histories. The mass flow data generated by CLOTHO is on a refueling batch basis. CLOTHO also interpolates the full power data at the end of the service life of the reactor so that the fuel mass balance terminates when the reactor is exactly thirty years old.

REACTOR AND FUEL SUPPLY
TASK FORCES

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┌──────────────┐
│ LWR          │
│ (SMS + JACK- │──────┐
│ SON AND      │      │
│ MORELAND)    │      │
└──────────────┘      │
                      │
┌──────────────┐      │
│ ADV. CONV.   │──────┤
│ (ORNL)       │      │
└──────────────┘      │
                      │
┌──────────────┐      │        ┌──────────────────┐
│ LMFBR        │──────┼───────▶│ NORMALIZATION    │
│ (ANL)        │      │        │ (ORNL)           │
└──────────────┘      │        └──────────────────┘
                      │
┌──────────────┐      │
│ THORIUM      │──────┤
│ (BNL)        │      │
└──────────────┘      │
                      │
┌──────────────┐      │
│ ALTERNATE    │──────┘
│ COOLANT      │
│ (ORNL)       │
└──────────────┘
```
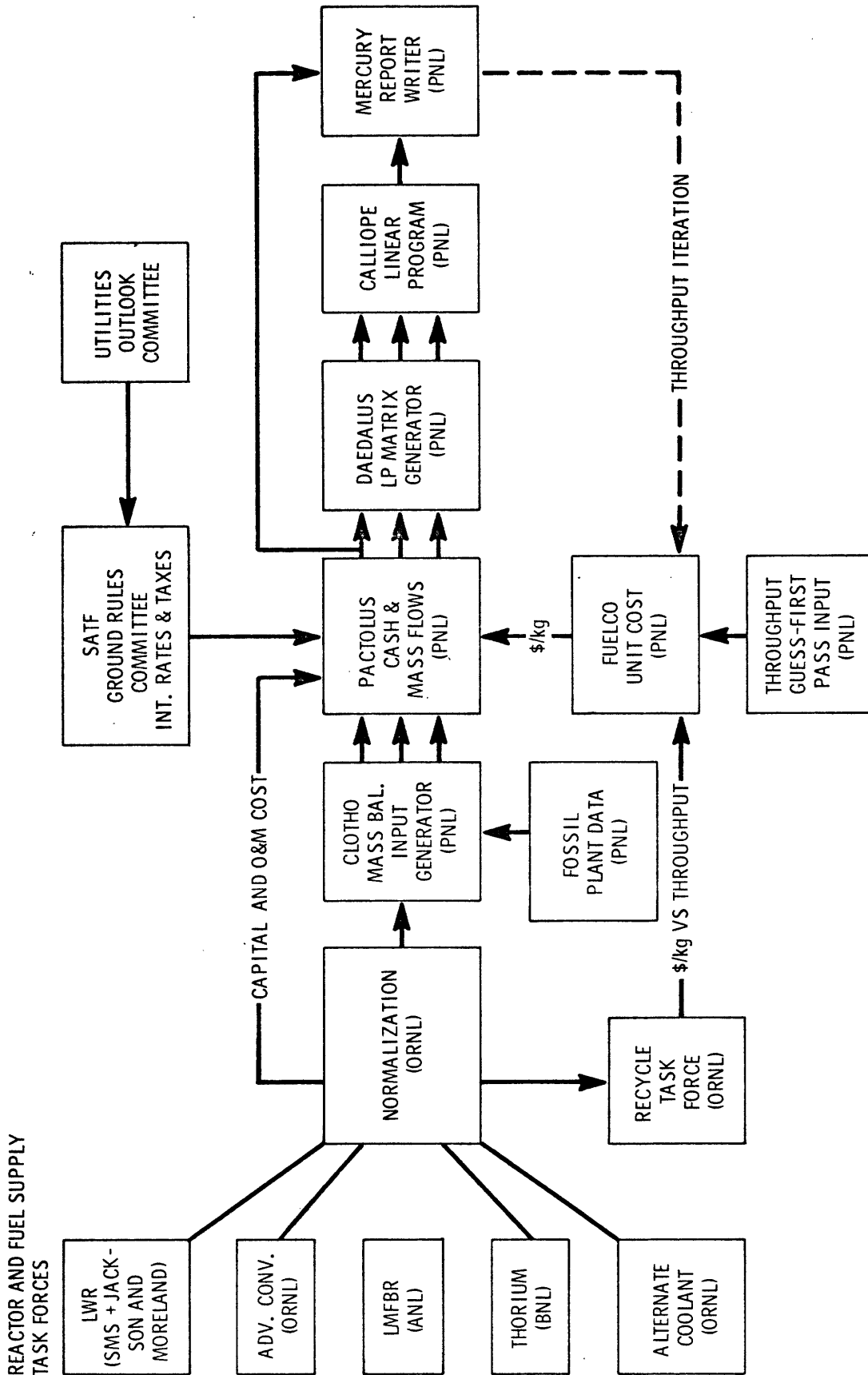
Fig. 2.1 The Systems Analysis Model of the USAEC

21

The mass flow requirements generated by CLOTHO are inputs to PACTOLUS, the next code in the series. The primary function of PACTOLUS is to develop a set of annual cash flows and fuel resource requirements for the entire life of each of the alternatives. The input data required by PACTOLUS consists of mass and energy balances (i.e. net fuel consumption and yearly power generation), capital costs, unit process costs, process times, and financial data such as capital structure, rates of return on capital, rates of taxation, depreciation method, and the debt retirement schedule. For each of the reactor concepts, then, PACTOLUS generates a set of mass and cash flows.

The heart of the USAEC model is a linear programming model which was designed to determine the optimal (least cost) generation expansion plan for the United States. The linear programming model consists of three codes, DAEDALUS, CALIOPE, and MERCURY. DAEDALUS is the matrix generator. It uses the data supplied by PACTOLUS to generate the coefficients of the linear programming formulation. CALIOPE is the code which solves the linear program and MERCURY is the report generator.

The objective function of the formulation is to minimize the total present worth of all capital, operating, and fuel costs. While selecting plants to meet electrical demand at lowest cost, the linear program must also satisfy other constraints. These constraints include the availability of fuel, rates at which new reactor concepts can be introduced

into the market place, and the inclusion of plants already constructed or scheduled for construction. The availability of U_3O_8 is allowed to increase as the price of the fuel increases.

There are several characteristics of the USAEC model which make it unsuitable for use in regional planning, especially in the context of some of the issues discussed earlier. Since the model was designed primarily to analyze competing reactor concepts, it was tailored specifically for large 1000 MWe plants. This type of plant will likely be operated as a base load unit and will therefore have a fairly predictable capacity factor history. For this reason, the operating histories of these plants were simply assumed and not included as decision variables in the model. However, if one allows the model to also choose smaller units, the nature of the interaction of the operating histories of the large units with the smaller units becomes interesting and perhaps decisive in the investment decision.

Another area in which the USAEC model was lacking, in the context of total fuel resources and environmental planning, was the treatment of fossil fueled plants. The original USAEC model had no treatment of the different types of fossil fuels and their associated effect on the environment and on cost. The USAEC model considered only a single fossil plant type as an alternative.

Finally, the USAEC model neglected entirely the issues

of pollution abatement and the environmental impact of the derived expansion plans. These issues cannot, however, be ignored in regional planning. Nuclear plants constructed to date have been less efficient thermally and their economic analysis usually must be penalized in order to meet thermal pollution standards. Similarly, the air pollution abatement equipment required for fossil plants can add a large expense to their construction and operating costs.

2.2.2 Marks' and Jirka's Environmental Screening Model.

An environmental screening model for the location of power generating facilities has been presented by Marks and Jirka.[6][7] The authors have proposed a method by which the effects of environmental controls on the expansion of power generating systems can be determined. According to the authors, these effects can be categorized as locational or cost. The purpose of their model is to determine the change in optimal plant location patterns and the associated change in the total system cost incurred by legal temperature limits on the water into which plant cooling water is discharged.

The model actually consists of two models. The first is a site evaluation model which determines the additional costs (both capital and operating) necessary to meet the legal temperature limits at a specific site. The second is an optimal plant location model. This model determines the minimum cost selection of a set of plant alternatives which will

satisfy the demand requirements for a given planning period.

The site evaluation model is a set of predictive models which determines the temperature effects of cooling water at a specific site. These models are comprised of scale models, mathematical models, and simulation models which determine the dispersion of fluid and temperature in the body of water into which the cooling water is being discharged. Characteristics of the site, discharge structure, and the body of water into which the discharge flows are parameters for these predictive models.

According to Marks and Jirka, these models can be used to determine whether a given plant at a given site will meet the legal temperature standards. If the plant does meet the temperature requirements, then there are no extra costs due to pollution abatement associated with it. However, if the limits are exceeded, then it indicates that certain abatement techniques have to be applied and additional costs are imposed.

The plant location model optimizes the location of new generating facilities in such a way as to minimize the total cost while meeting the predicted demand for a given time period. The authors have formulated this model as a zero-one mixed integer problem whose objective function is to minimize the total of all new plant construction costs, plant operating costs, pollution abatement costs, and power transmission costs. The decision variables consist of a set of zero-one integers

25

for each of the alternatives and a set of continuous variables representing the amount of energy shipped between points in the system. The constraint set includes meeting demand, capacity limits on facilities, and the conservation of energy within the system.

Although Marks' and Jirka's model is one of the few models that addresses the environmental and siting issues, it has several aspects which limit its usefulness for comprehensive regional generation expansion planning. First, only the base load components of the electric system are considered in the formulation of the model. Also operating histories are assumed for each of the plants. In these respects Marks' and Jirka's model is similar to the USAEC model described above. Finally the environmental screening model does not take into account the availability of the various fuels and their interaction.

2.2.3 Anderson's Linear Programming Formulations.

A paper by Dennis Anderson describes a number of models currently being used in Europe to evaluate generation expansion plans.[8] The author discusses three methods of optimization: marginal analysis, simulation, and global models. The techniques used in formulating those models include linear, non-linear, and dynamic programming.

The method of marginal analysis as applied to investment decisions is discussed first. According to Anderson, the

first step in using this method is to find a feasible solution, and then try to improve the solution by marginal substitutions which also produce a feasible solution. The author does not describe the method of selecting alternatives for marginal substitution and only briefly alludes to optimality criteria by stating that if the cost function is convex the method will lead to a global optimum.

The computation time required to evaluate a large number of alternatives is prohibitive using marginal analysis. Thus, in theory it is possible to use this method to determine optimal operating and plant expansion plans; however, in practice it is only feasible to use marginal analysis to evaluate general investment decisions such as the comparison of fossil and hydro alternatives.

The simulation models described next are designed only to determine optimal operating policy for a given system. In the first method described, the plants are arranged in ascending order of marginal fuel and operating costs. This order and the corresponding capacities are superimposed on the load duration curve for the period being studied. The total energy produced by each plant is found by integrating the corresponding section of the load curve for each plant. Since the total amount of energy each plant can produce in a given period is exogenous to this model, the model cannot be used to determine optimal storage reservoir operating policy or nuclear fueling schemes.

As a solution to the optimal storage reservoir operating policy problem, the author suggests a dynamic programming model. This model relies on a cost function which is developed using the load duration curve integration model. The author also refers to several other dynamic programming models which were formulated to treat hydro supplies stochastically, determine optimal operating policies for the complete range of thermal, nuclear, or hydro systems, and evaluate the purchase or sale of electric power.

Finally, Anderson discusses a linear programming formulation of the simulation model. The decision variables for this model are the amount of energy produced by each plant. Also, included in the model as decision variables are hydro storage quantities. Such considerations as transmission losses, fuel costs, and regional decision variables can also be incorporated into this model.

The global models discussed in the final section of the paper are designed to evaluate both investment and operating policy decisions simultaneously. Because the models include both investment and operating considerations over time, the dimensions of these models are much larger than those models previously discussed. Therefore these global models must contain some simplifying approximations to make their solution computationally feasible. According to Anderson the detail can be recaptured using the simulation or marginal analysis models to evaluate the plans developed by the global

screening model.

Both a linear and a non-linear formulation are presented as global models. The linear programming model includes both plant expansion and plant operation as explicit decision variables. The linear programming model can include such considerations as replacement, locational decisions, hydro storage capacities and policies, and simple nuclear fuel cycle optimization. The non-linear model includes investment decisions as explicit endogenous variables and operating policy as an implicit decision variable by assuming the available plant capacity will be operated at full power.

There are many issues pertinent to the production of electric power in the United States which are not included in the models presented by Anderson. Some of these considerations include reliability, environmental protection, siting, fuel supply, and the cost of capital. These issues would have to be incorporated into the models if they were to be useful for studying regional electric power supplies in the United States.

2.2.4 Probabilistic Simulation.

One feasible but inefficient method of determining an optimal expansion plan for a utility system is to simulate all the possible combinations of the various options and to choose the resulting combination that best meets the desired criteria of optimality. This technique requires the application of a

computer code that can simulate, over a period of many years, the operation of each of the different units in the system with reasonable accuracy and high computational speed. The calculation of the energy produced by each unit is complicated by the forced outages of the generating units, the need for routine maintenance, the variability of hydro inflows, and the ability of pumped storage plants to achieve a sub-optimization within a given day (or week).

One of the more suitable computer models that have been developed to overcome these difficulties is called probabilistic simulation.[9][10][11] The basis of this simulation method is the use of probability density distributions to describe the system loads and the generating unit forced outage performance, and the convolution of these distributions to produce a cumulative probability function containing information similar to that contained in a plant load duration curve. By successively alloting the required energy generation represented by this curve to plants in the reverse order of their generation cost, the expectation of the energy produced by each unit may be obtained as well as the system loss-of-load probability. The expectation of the amount of emergency energy purchased and the production and startup-shutdown costs for the entire system are also determined. Thermal plants are loaded and unloaded in the system according to some specified loading order; each plant can be represented with several different capacity blocks located at nonadjacent positions in the

loading order to more realistically represent overnight and weekend operation, the minimum load requirements of some plants, and the necessity of supplying sufficient spinning reserve. The treatment of the pumped-storage hydro units involves the search for an optimum pattern of pumping and generating during the simulation period to minimize the thermal system fuel costs while remaining within the constraints set by pump and generator capacities and the size of the upper reservoir.

To improve the efficiency of the search procedure for an optimal expansion plan, Booth has used probabilistic simulation techniques combined with a forward moving dynamic programming algorithm in an open loop feedback approach. In this method, a schedule of feasible expansion plans is formulated at each of several time steps using a dynamic programming code. The determination of the operating history and cost of each of the expansion alternatives is performed using the probabilistic simulation routine and the least cost plan is selected. Only the expansion decision for the first time period is taken, however, and then the model advances to reconsider the subsequent time periods after the first. Thus, the expansion plan is not fixed for an extended period into the future but is revised as new information becomes available about the operating histories of the chosen plants. A major difficulty with this approach is that the highly dimensional problem must be converted to an equivalent single dimension

problem to be capable of solution by standard forward dynamic programming methods, and considerable detail is thus sacrificed.

2.3 Structure of the Generation Expansion Model.

Although each of the models above was designed as a tool for the evaluation of electric power system generation expansion alternatives, there was no one model which addressed itself to all of the issues which are important in regional generation expansion planning in the United States. The purpose of the Generation Expansion Model is to determine optimal (least cost) generation expansion and operating plans for regional electric systems under economic, environmental, and reliability considerations. In formulating this model an attempt was made to include consideration of the more salient issues involved in regional planning; especially those discussed earlier such as demand growth, fuel supply, environmental quality and siting, reliability, technology, and the cost of money.

2.3.1 General Description.

In terms of input/output characteristics the Generation Expansion Model can be described as follows:

Given: 1. A set of decision variables consisting of plant alternatives, site alternatives, and plant operating histories.

2. The capital and unit fuel costs associated

with each of the decision variables.

3. The fuel consumption rate of each of the decision variables.

4. The forced outage rates of each of the plant alternatives.

5. A set of constraints describing site availability, air and thermal pollution limits, system reliability, and fuel availability.

6. The projected electrical demand throughout the study period.

Find: The set of plant and site alternatives and the corresponding plant operating histories which will minimize the total present worth of all capital, operating, and fuel costs while satisfying the demand for electricity, fuel availability, site availability, pollution, and reliability constraints.

The decision variables for the Generation Expansion Model consist of all the feasible plant and site alternatives and a corresponding set of air and thermal pollution abatement technologies. Also, the general operating histories of each type of plant selected are decision variables. The plant alternatives are characterized by plant type, plant capacity, fuel type, vintage, thermal and air pollution abatement technology, and site type. The model is capable of handling any

of the current plant technologies, including gas turbines, diesel, hydro, pumped storage, fossil steam, light water reactors, and high temperature gas cooled reactors. In addition it is possible to include as alternatives advanced technologies which are not yet commercially available such as the fast breeder, fusion, combined gas cycles, etc.

The model is capable of evaluating the costs and performance of many of the feasible combinations of plant and pollution abatement technologies. The thermal pollution abatement equipment includes various discharge structure designs, cooling ponds, spray ponds, and wet and dry cooling towers. Air pollution abatement equipment included in the model consists of scrubbers, precipitators, and various stack designs.

The site alternatives are specified by thermal pollution characteristics (coast, river, lake, etc.); air pollution characteristics (valley, plain, etc.); and land requirements. Associated with each type of site are environmental resources. These resources include the amount of water surface area available for the dissipation of waste heat, the amount of water available for consumptive use, the level of sulfur dioxide and particulate concentration which can be sustained, and the amount of land which is available. Associated with each type of plant, thermal and air pollution abatement equipment, and site combination is the amount of each of these resources necessary to meet the air and thermal discharge

34

limits. The environmental resource consumption will be determined for each alternative by the model.

Algebraically the Generation Expansion Model can be formulated as follows:

$$\text{minimize } z = \sum_{v=1}^{t} \sum_{j \in J} C_{jv} * X_{jv} + \sum_{t \in T} \sum_{v=-V}^{t} \sum_{j \in J} F_{jvt} * CAPFAC_{jvt} * PER_t * CAP_{jv} * X_{jv}$$

subject to: Meeting electric power and energy demand

Fuel availability

Pollution limits

Site availability

Reliability limit

where

C_{jv} = the present worth of the capital and operating costs of a plant of type j and vintage v (\$),

F_{jvt} = the present worth of the unit fuel costs of a plant of type j and vintage v (\$/kwhr),

PER_t = the length of period t (hr),

CAP_{jv} = the capacity of a plant of type j and vintage v (kw)

are known; and

X_{jv} = the number of plants of type j and vintage v,

$CAPFAC_{jvt}$ = the capacity factor in period t of the plants of type j and vintage v

are decision variables.

The generation Expansion Model (GEM) actually consists

of three integrated submodels: the Plant Evaluation Model
(PEV), the Plant Expansion Model (PEX), and the Plant Opera-
tion Model (POP). The structure of these models and the in-
formation flow between them is shown in Figure 2.2.

2.3.2 The Plant Evaluation Model.

The Plant Evaluation Model is a technical simulation
model whose function is to determine the capital and operating
costs, fuel consumption, and the environmental resource re-
quirements for each of the alternatives being considered. As
input data this model requires a list of the alternatives
being considered (plant, abatement technique, and site combi-
nations) and a set of thermal and air pollution limits to be
met. The model also requires a set of assumed capacity factor
histories for each alternative. The assumed histories are
used to estimate fuel requirements. GEM then uses the itera-
tive procedure described below to determine the optimal capa-
city factor history for each alternative. In order to
calculate the costs, fuel consumption, and resource require-
ments, PEV also needs data describing the capital and operating
cost and the performance of each of the plant and pollution
abatement types.

2.3.3 The Plant Expansion Model.

The next submodel in the series, the Plant Expansion
Model, is a linear programming model. The function of this
model is to determine the least cost capacity expansion plan

GENERATION EXPANSION MODEL

Plant Alternatives
Site Alternatives

Thermal Pollution Limits
Air Pollution Limits

Capacity Factor History (assumed)

Plant Evaluation Model

(Technical Simulation)

Site Requirements
Capital and Operating Costs
Fuel Consumption
Capacity Factor History

Site Availability
Energy and Peak Power Demand
Fuel Costs and Availability
Other Constraint Data

Plant Expansion Model

(Linear Programming)

Margin for Reserve Capacity
Capacity Factor History

Marginal Fuel Costs
Plant Expansion Plan

Power Demand Probability Distribution
Plant Outage Rates

Plant Operation Model

(Probabalistic Simulation)

Plant Expansion Plan
Expected Energy not Supplied
Loss of Load Probability
Capacity Factor History

Fig. 2.2   Functional Diagram of the Generation Expansion
Model

which will meet the projected electrical demand as well as other constraints such as fuel availability, site availability, committed plants and class introduction rates. The solution will be based on the assumed operating histories. Part of the data for PEX comes directly from PEV. This data includes the capital and operating costs, annual fuel consumption, environmental resource requirements, and the assumed capacity factor history for each plant. In effect the data from PEV is the coefficient data for the linear programming formulation. The data for the right hand side of the formulation is input directly to the model and includes the expected power and energy demand for each period of the study, the fuel availability and cost, the site availability, and a list of committed and constructed plants.

2.3.4 The Plant Operation Model.

The last submodel in the series is the Plant Operation Model. This model uses probabilistic simulation techniques to determine the optimal operating history for each of the plants selected by the Plant Expansion Model. If the capacity factor histories calculated by this model are not equal to the ones originally assumed, they are used as feedback to the Plant Evaluation Model. This process is continued until the plant operating histories converge on a solution.

The loss-of-load probability (LOLP) and the expected energy not supplied are also calculated in POP. If the LOLP

is too large (or too small) the margin of reserve capacity is recalculated and fed back to the peak power constraints in PEX. Again, as with the operating histories, the iterative process is continued until the reliability constraints are met.

A complete solution from the Generation Expansion Model consists of a set of plants and their corresponding operating histories which will meet the expected demand over the study period with the minimum cost. The generation expansion plan developed by GEM will meet several constraints such as thermal and air pollution standards, site availability, fuel availability, and some reliability criteria. A set of auxiliary output consisting of capital costs and annual cash flows for each alternative being considered, net fuel consumption of each plant and of the total system, and the loss-of-load probability and expected energy not supplied by the system will also be available from the model.

2.4 Proposed Uses of the Model.

2.4.1 Determination of Optimal Expansion Patterns and Sensitivity to Environmental and Reliability Considerations.

The primary function of the Generation Expansion Model is to evaluate regional generation plans for the United States. In conjunction with regional planning the model can be used to perform parametric studies to assess the cost of environmental and reliability standards. For example, one proposed study

would involve the New England region. The first step in this study would be to collect data including the cost and performance characteristics of each of the plant and pollution abatement technologies considered as feasible alternatives for the New England region in the next twenty years. The data to be collected would also include expected electric demand, site availability, and fuel costs. The model would then be run using this data, as well as current thermal and air pollution standards, and the current reliability criteria.

This first solution would be used as a base solution for parametric studies and sensitivity analysis involving environmental and reliability standards. For example, the base maximum temperature rise could be raised and lowered and its effect on the optimal solution observed. In this way the effect of environmental constraints on the cost of electricity, fuel consumption, and site utilization could be determined. A similar process would be used to evaluate the trade-offs between the cost of electricity and the level of system security.

2.4.2 Determination of the Value of Technological Advances.

The model can also be used to evaluate the effect of technological advances and break throughs and their timing on such factors as the cost of electricity, environmental impact, and fuel consumption. This type of study could be conducted in a similar fashion as the parametric studies discussed above. For example, the effect of the breeder reactor on the

40

optimal expansion plan for New England could be evaluated by including it as an alternative, running the model, and then comparing it to the base solution described above.

2.4.3 Determination of Aggregate Fuel Consumption.

GEM can be used as a national model to evaluate aggregate fuel consumption by the electric power industry. This type of study would be particularly useful in studying the interaction of nuclear technologies, such as the fast breeder and the light water reactors.

2.4.4 Evaluation of the Effect of Changes in Demand Patterns.

Although this model does not consider the demand for electricity as endogenous, GEM could be used to examine change in optimal generation expansion plans caused by changes in the amount and distribution of the demand for electricity. One such study might be to examine the effect of electric cars on the cost of electricity. Such vehicles would tend to increase the load factor of a system since they would be charged during off-peak hours. The increase in load factor would tend to increase the number of base load units in the optimal expansion plan. GEM could be used to determine this increase and also its effect on the cost of electricity.

CHAPTER 3

THE PLANT EVALUATION MODEL

3.1 Introduction.

The purpose of the Plant Evaluation Model (PEM) is to
evaluate the economic, environmental, and performance charac-
teristics of each of the generating plants which are to be
included as alternatives in a study. In doing this, the model
first determines if the plant can be designed to meet the pol-
lution limits for the specified site and its corresponding
ambient conditions. If this is possible, the model evaluates
the plant performance characteristics, such as capacity and
heat rate. PEM also will determine the corresponding annual
fuel consumption, environmental resource requirements, and
associated annual cash flows.

The purpose of this chapter is to provide a detailed
narrative discussion of the Plant Evaluation Model, the first
sub-model in the Generation Expansion Model, and of its data
requirements and the file structures created for storing this
data. A System Manual for the Generation Expansion Model has
been compiled as a separate report.[1] The System Manual con-
tains information necessary for the users of the Generation
Expansion Model. This information includes program listings,
input data formats, programming conventions, and lists of the
data stored in the files. The System Manual may be obtained

by contacting Professor Fred C. Schweppe or Professor David H. Marks, care of the Energy Laboratory, Massachusetts Institute of Technology.

3.1.1 Definition and Specification of Alternatives.

Before describing the Plant Evaluation Model in detail, it is important to understand what is meant by an alternative. In the Generation Expansion Model the numbers of each of the various alternatives to be built are the major decision variables. An alternative is defined by a base plant type, fuel type, nominal capacity, vintage year, site type, thermal pollution abatement technology, and air pollution abatement technology. For example, a 1000 MWe base loaded fossil plant, burning low sulfur oil, starting operation in 1975, built on the coast with a surface discharge and a precipitator would be an alternative. The number built of this type of plant would be the corresponding decision variable.

An important aspect of the fuel type is the fact that the model has the ability to handle variable fueling schedules and that the use of this feature is indicated in the specification of the fuel type. An example of a variable fueling schedule might be for a plant to burn gas for the first ten years of operation and then switch to oil for the remainder of its life. At this time the model is capable of handling twelve fossil fuels and twelve nuclear isotopes, exclusive of variable fueling schemes.

43

For the purposes of the Generation Expansion Model and this report, the vintage of a plant will refer to the year in which commercial operation commences. Further, it has been assumed that power production starts at the beginning of the vintage year. This does not mean, however, that nuclear fuel purchases and processing costs first occur in that year. PEM has the capability of accepting costs and nuclear fueling schemes which begin prior to the start of commercial operation.

The capacity used to identify an alternative is simply a nominal capacity. The actual capacity, as well as other performance characteristics, will differ from the nominal capacity because of attached pollution abatement equipment and site related ambient conditions and will be calculated by PEM. A related consideration is the fact that the nominal capacity used to identify a plant actually represents a range of capacities for a given class of plant. The assumption here is that over a range of capacity the cost and performance characteristics of a plant remain constant. That is, the cost and performance characteristics of a plant can be represented as a step function of capacity. Awareness of this fact is useful in interpreting the solution of the linear programming Plant Expansion Model in which the decision variables may turn out to be proper fractions. For example, if the 1000 MWe plant mentioned earlier represents the range of capacities from 900 MWe to 1100 MWe, and the Plant Expansion Model determined that 5.5 of this type of plant should be built, then one

interpretation might be to build five 1100 MWe plants.

It is important to note that the model operates with site _types_ rather than specific individual site locations. The site types are primarily characterized by their relation to the performance of the thermal and air pollution abatement equipment. A set of ambient air and water conditions and a set of pollution limits is specified for each type of site.

A 28 character alphanumeric code is used to identify each of the various alternatives being considered during a run of the model. Four characters are used to identify each of the following seven alternative characteristics:

1. plant type,

2. fuel type,

3. plant size,

4. plant vintage,

5. site type,

6. thermal pollution abatement (TPA) technology,

7. air pollution abatement (APA) technology.

One word (four bytes on IBM series 370 computers) is used to store each of the seven characteristics. Figure 3.1 shows a detailed breakdown of the nomenclature format used to specify each of the alternatives. A list of actual naming conventions which have so far been defined is given in Appendix A of the System Manual for the Generation Expansion Model.

The first word of the identification code specifies the plant type. The first two characters of this word are

45
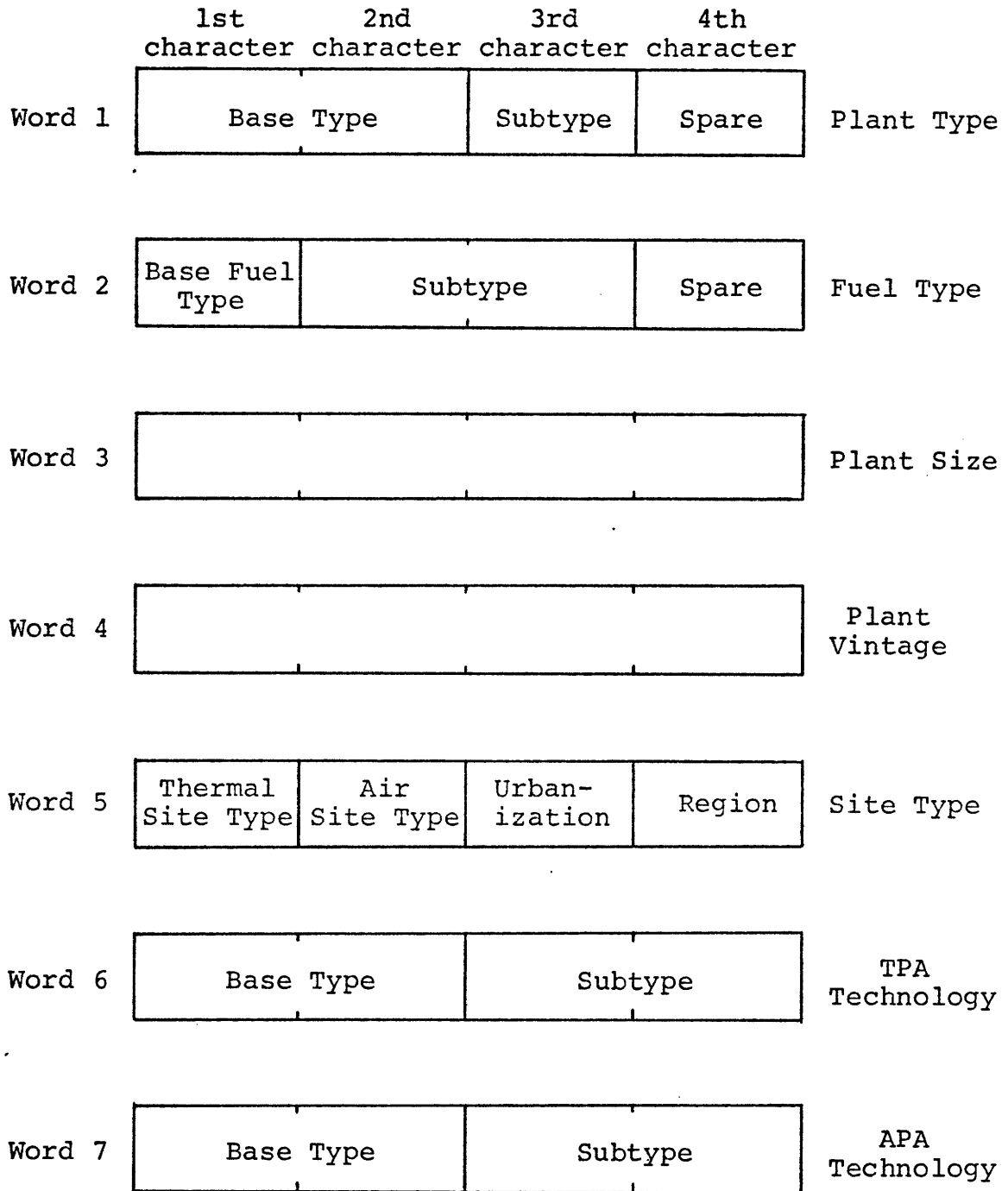
Figure 3.1
Alternative Specification

used to identify the base plant type, such as GT for gas turbine. The third character is used to specify various special characteristics of the base type. For example, the type of boiler firing in a fossil plant becomes important in determining the amount of particulate emission. For fossil plants the third character is currently used to specify tangential or cyclone firing. The fourth character is a spare and may be used to specify multiple unit plant combinations.

The second word is used to identify the fuel type. The first character of this word specifies the general class of fuel to be used by the plant, such as oil, coal, gas, or uranium. The second and third characters are used to specify various alternative characteristics of the base fuel type. These alternatives may include such considerations as sulfur content, ash content, mine mouth coal, enrichment, and burnup. The fourth character is currently a spare which could be used to identify variable fueling schemes.

The third and fourth words are stored as integer variables, as opposed to the alphanumeric information stored in the other five words. These words, however, must not contain more than four decimal digits each, since the formats used in the various codes comprising the model are designed for this limit. The third word contains the nominal plant size in MWe and the fourth word contains the calendar year in which commercial operation is to start.

The fifth word contains the specification of the site

type. The first and second characters are used to identify the site TPA and APA characteristics. This type of site characterization is necessary since the performance of the TPA or APA equipment is heavily dependent upon site conditions. For example a surface discharge for a given plant would produce completely different temperature responses in an estuary than it would in a lake. The third character is used to specify the surrounding population density which in turn is an indication of the background concentrations of air pollutants. The fourth character is a spare but may be used to identify regions in a national study or subregions in a regional study.

The sixth and seventh words are used to specify the TPA and APA equipment respectively. The first two characters of each specify the base type, such as SD for surface discharge or WL for wet limestone scrubbing. The third and fourth characters are used to specify any variations of the basic alternatives such as closed or open TPA cycles.

The formats described above and the naming conventions described in the System Manual are not absolute and have been chosen primarily to make identification of the various alternatives relatively easy. They may be changed or added to at the user's convenience. There are, however, several conventions that have explicit meaning to the various codes which constitute the model. Any changes in these conventions, as described in Appendix B of the System Manual, may require a programming change.

At this point an example may be helpful in understanding the contents and meaning of the 28 character identification assigned to each alternative. A tangentially fired, 1000 MWe, base loaded fossil unit, burning coal with 3.0 percent sulfur and 5.0 percent ash, starting commercial operation in 1975, built on a rural ocean site with a surface discharge and a tall stack would be specified as follows:

FBTN CMLN 1000 1975 OORN DINN TSNN

3.1.2 Data Requirements.

The Plant Evaluation Model has quite substantial data requirements, which include such widely diverse information as plant engineering performance characteristics and corporate financial descriptions. The purpose of this section is to provide a brief summary of these data requirements in order to demonstrate the flexibility and comprehensiveness of the model. A detailed description of the input data requirements and their corresponding formats is contained in Appendix C of the System Manual. In the next section the various outputs from the model are discussed to complete the overview of the Plant Evaluation Model's capabilities.

The first type of data which must be input to PEM is the performance and cost characteristics of each of the base plant types to be included as alternatives. The performance data consists of a set of rated conditions, the heat rate versus condenser back pressure relationship, a condenser

49

description, and the stack gas composition and flow. The cost data includes capital costs broken down by USAEC accounts,[2] indirect costs, salvage value, interim captial replacements, and fixed and variable operating costs. Included with the cost data is the plant depreciable life and the construction time.

Also required as data for each plant alternative are three sets of histories, where a history is defined as an estimate of the level of some characteristic of the plant for each year of the plant's life. The first of these is a projection of the availability of the plant. The availability will be used by the Plant Expansion Model (PEX) to derate the plant's capacity by the percent of time during which the plant is not available. The second set of history data which is required for each plant alternative is the capacity factor history. This is used in PEM to determine fuel consumption and in PEX to determine energy production. Finally, the full power fuel consumption history is required for each base plant type. For a nuclear plant this consists of a schedule describing the amount of each of twelve isotopes charged to or discharged from the reactor during each refueling cycle, assuming that the reactor operates at full power between refueling periods. For fossil plants this simply consists of the annual consumption of up to twelve types of fuel, assuming the plant operates at full power during that year.

A set of performance and cost data similar to that

required for each plant alternative is required for each of the TPA and APA technologies to be considered as alternatives. The cost data consists primarily of capital expenditures and fixed and variable operating costs. The specification of performance data for each of the alternatives is not so simple since each different technology has different engineering characteristics. Therefore the performance data for the various TPA and APA equipments cannot be generalized and each different type requires a set of data which is designed especially to describe the performance of that particular piece of equipment.

The user must also specify as input information the financial data necessary to calculate the weighted average cost of capital to the regional electric utility. This includes the fractions of debt and equity in the firm's capital structure, the required return to equity and debt holders, and the rates (federal and state income tax rates and any local revenue tax rate). The user may also desire to input an annual lump sum tax payment in dollars. Property tax rates and property insurance rates may be input. Nuclear liability insurance may be provided as either a fixed dollar cost per year, a unit dollar cost per thermal megawatt of rated capacity, or both. The user optionally has four methods for retiring the debt associated with the project and two methods for calculating the depreciation charges.

The user may, depending on the number of different

fuel types he desires to consider, input time-varying price

schedules for U_3O_8, ThO_2, fissile Pu, ^{233}U, and as many as

twelve types of fossil fuel. He may also desire to specify

market prices for twelve nuclear isotopes.

For nuclear plants, the user must input unit cost

schedules, time delays, and any efficiency losses for such

fuel cycle processes as shipping, enrichment, fabrication, re-

processing, and conversion.

Finally a set of data is required which describes the

ambient conditions and pollution limits at each site. The am-

bient conditions consist of air and water temperatures, wind

speeds and directions, and background levels of SO_2 and par-

ticulates. The formats for the pollution limits have been

chosen to conform to the format of the currently defined stan-

dards. The thermal pollution limits which must be specified

for each site consist of the allowable temperature rise, the

mixing zone size, and the maximum temperature. The air pol-

lution limits consist of emission limits for SO_2 and particu-

lates, and annual, 24 hour, and 3 hour limits on the ground

level concentrations of SO_2 and particulates.

As can be seen from the above description, the data

requirements for the Plant Evaluation Model are not insignifi-

cant. The reason for including this detail is to ensure that

the model is sensitive to those issues which were discussed

earlier, such as the environment, reliability, economics, and

technology. Depending on the objectives of the particular

study for which the model is being used, some of the data may not be required and other data may be aggregated. For example, if a particular study is not addressed to environmental problems NONE may be specified for the TPA and APA alternatives and no data will be required to describe them. Of course none of the associated costs, environmental resource requirements, or effects on plant performance will be included in the solution.

3.1.3 Model Outputs.

A brief discussion of the primary outputs of the Plant Evaluation Model is included in this section to complete the overall picture of the model's capabilities. Appendix A contains sample outputs from most of the codes comprising PEM, and the reader may find it helpful to refer to that section at this time. To reduce the volume of output that would be obtained in a typical case study involving multiple iterative steps, much of the output is optional at the user's request. During intermediate iterations the user will probably only use PEM to update the information stored on disk files which is required by PEX. Then, when the procedure has converged on a solution, the user can request a detailed set of output in order to completely document the solution.

The primary purpose of the Plant Evaluation Model is to provide new or updated information on each alternative being considered in the Plant Expansion Model. This information is stored in File 16 on a direct access storage device.

A detailed description of the contents of File 16 and all of
the other files used by the model is contained in Appendix E
of the System Manual. The output placed in File 16 consists
of the present worth of the cash flows associated with the
alternative, the estimated annual consumption and sometimes
production of various fuels, the actual plant capacity, annual
energy production, heat rate, and the set of environmental re-
source requirements for each plant alternative.

The annual cash flow data produced in PACTOLUS in-
cludes all capital and operating costs, taxes, debt interest
and principal repayment, depreciation, and fuel reprocessing
charges. Two cumulative present worth sums are calculated
from this data and provided as output to File 16. One sum in-
cludes the charges for fuel or ore as calculated from the
input price schedules; the other sum excludes the actual fuel
costs. The use of these two different sums will be described
in the next chapter.

As currently implemented, the Plant Evaluation Model
determines the plant requirements for each of four environmen-
tal resources: heat dissipation capacity, consumptive use of
water, land, and air pollution level. The heat dissipation
capacity is the area measured in acres required for the dis-
sipation of the waste heat discharged from the plant. The
consumptive use of water, measured in cubic feet per second,
includes evaporative losses and any water consumed in plant
processes. The land requirement of a plant, measured in acres,

includes not only the land on which the plant is built, but also any exclusion zone required for nuclear plants. The air pollution level index is meant to be a relative measure of the amount of additional air pollution which can be sustained at a particular type of site. However, a method for evaluating a single aggregate index which measures this additional capacity was not developed, and this index is currently assigned a value of one for all plants. The model does, however, determine if the specified disaggregated air pollution limits can be met (as well as the associated costs of doing so).

3.2 The Plant Evaluation Model Structure.

The Plant Evaluation Model consists of a set of several computer codes and a large data base to supply information to and store the information generated by the codes. PLANT and PACTOLUS are the two major codes which constitute the Plant Evaluation Model. The remaining codes, described in Appendix C of the System Manual, are primarily designed to generate and maintain the data base.

3.2.1 PLANT.

The function of PLANT is to determine the capital and operating costs, performance characteristics, and environmental resource requirements for each plant and store the information on File 11 for use by PACTOLUS. In doing this, PLANT designs the TPA and APA equipment to meet the specified pollution limits and calculates the corresponding costs and

environmental resource requirements. These costs and resource requirements are added to those of the base plant type to determine the total for the plant.

In the PLANT program the operating costs are actually unit operating costs and are broken down into two components: fixed and variable. The fixed component is that portion of the operating cost which is independent of the level of operation and is given in units of $/year. The variable portion is assumed to be a linear function of the plant capacity factor (CF) and is measured in units of $/% CF/year in the PLANT model. The variable portion of the operating cost is converted to $/MWth/year before being sent to PACTOLUS where the total annual operating cost is calculated.

The structure of the PLANT program can be broken down into the three sections shown on Figure 3.2, one section each for the plant calculations, the TPA equipment calculations, and the APA equipment calculations. The main program performs all of the calculations associated with the base plant type and sums all plant, TPA, and APA costs and environmental resource requirements to determine the total for each plant alternative. The TPA and APA calculations are performed by a set of subroutines which correspond to each of the abatement equipment types.

In processing a plant alternative, the PLANT model first determines the amount of waste heat which must be rejected with the plant operating at full load. PLANT passes
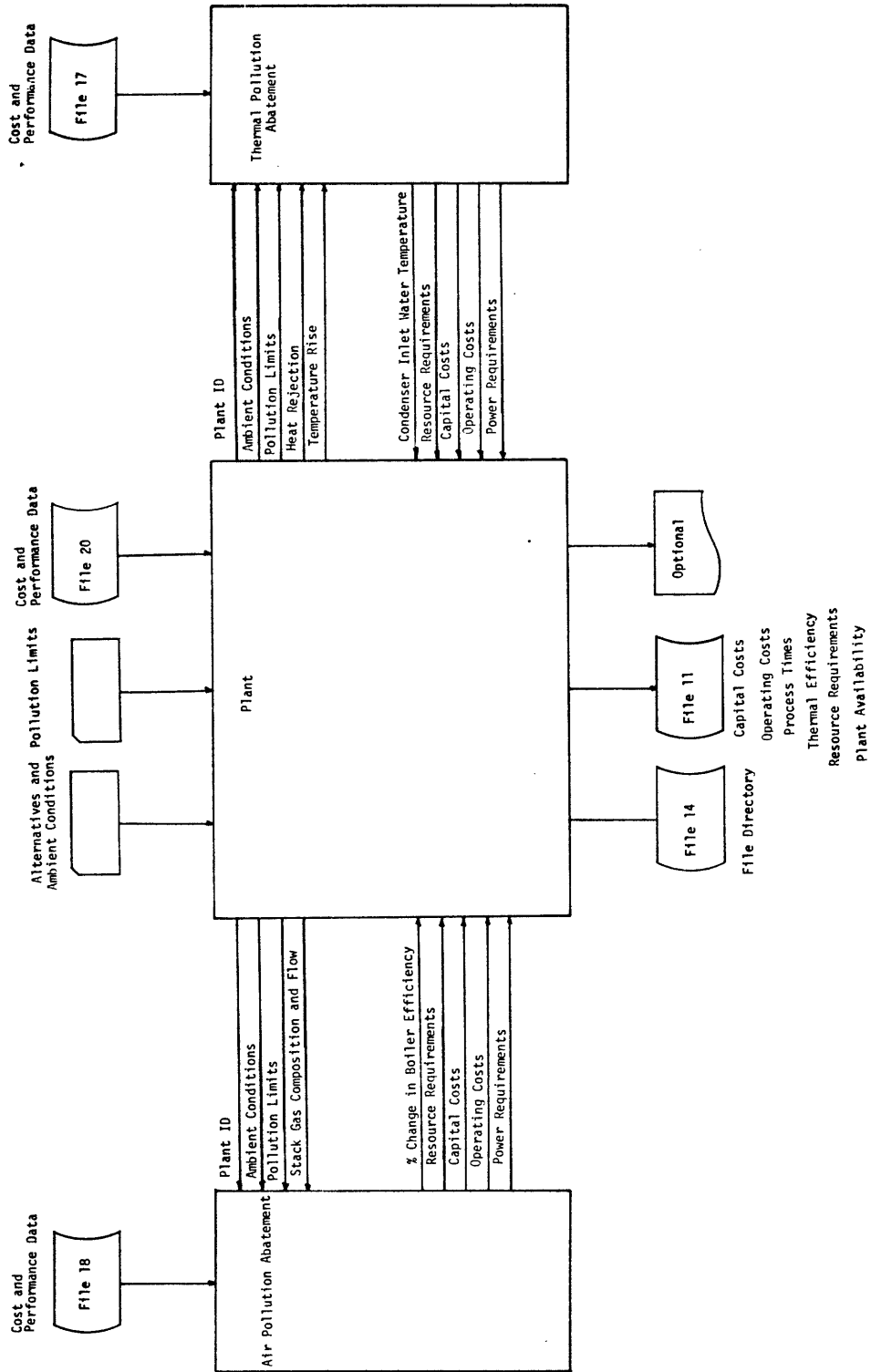
Fig. 3.2 The PLANT computer model

that information along with the plant I.D., the corresponding

pollution limits and ambient conditions, and the condenser

temperature rise to the applicable TPA subroutine as specified

in the plant I.D.

The TPA subroutine determines if the equipment can be

designed to meet the specified pollution limits. If it cannot,

a fatal error indicator is passed to the main routine and the

alternative is not processed further. Otherwise, the sub-

routine determines the condenser inlet water temperature, the

capital and operating costs, the environmental resource re-

quirements, and any power requirements, and passes them back

to the main program.

The next step in the process is the calculation of the

condenser performance and its effect on the overall plant per-

formance. After completion of that step, PLANT passes the

plant I.D., the corresponding pollution limits and ambient

conditions, the stack gas composition and flow, and the boiler

efficiency to the corresponding APA subroutine. As in the TPA

subroutines, the APA subroutine first determines if the equip-

ment can be designed to meet the specified pollution limits.

If it can, the routine calculates the capital and operating

costs, environmental resource requirements, power requirements,

and any change in boiler efficiency, and passes them back to

the main program.

The model then determines the effect of the APA equip-

ment on the plant performance and calculates the net plant

capacity and the net plant heat rate. Finally PLANT writes
this information along with the totals of the costs and en-
vironmental resources, the availability history (supplied as
data to PLANT), and various process times on File 11 for use
by PACTOLUS.

The TPA and APA subroutines were written by other
members of the research team and will not be discussed in de-
tail here. The thermal pollution abatement subroutines were
written and documented by Shiers[3] and the air pollution abate-
ment subroutines by Ruane.[4] The COMMON statements used for
communication between PLANT and the abatement routines are
discussed in Appendix F of the System Manual.

3.2.2 PACTOLUS.

The calculation of annual fuel usage and the cost of
power of each alternative is performed by PACTOLUS,[5][6] a pro-
gram developed at the Pacific Northwest Laboratory for the
USAEC. The objectives of PACTOLUS are to: transform plant
investment, operating data, and fuel cycle cost and timing in-
formation into annual material and discounted cash flow sched-
ules; calculate taxes; and transmit this information for use
in the regional aggregate expansion model. The calculations
are based on discounted cash flow techniques, standard methods
for determining depreciation and debt repayment, tax rates,
and the capital structure assumed for the regional utility.

To accomplish these objectives, PACTOLUS proceeds
logically through essentially three phases. In the first

59

phase, the amount of each of up to twelve fuel types for fossil plants, or twelve isotopes for nuclear plants, is specified to be consumed for each operating year of the plant. This is accomplished by adjusting the full power fuel consumption history stored on a magnetic disk file for each class of alternatives to agree with the capacity factor operating history that is proposed for the particular alternative being processed. For nuclear reactors this is done on a refueling batch-by-batch basis for both the core and the blanket, if one exists.

In the second phase, PACTOLUS determines the timing and value of the cash flows needed to purchase and process these amounts of fuel, based on input price schedules for the fuel and for fuel processing services. For nuclear units, this includes determining the value and timing of the many different processes that constitute the nuclear fuel cycle; it includes, for example, the value and timing of purchases for the required U_3O_8 ore and its processing through the gaseous diffusion plants. Pre- and post-burnup shipping and reprocessing charges and credits and their timing are calculated. Fixed and variable costs and any interim capital replacement charges are determined for each year. Finally, in a nuclear power plant a large fuel inventory must be maintained in the reactor throughout the life of the plant. The annual fuel expense for income and property tax calculations is a "book" expense and is strongly influenced by the accounting method

used for income determination and fuel inventory valuation. The allowable fuel deductions are calculated at the user's option by any of five different methods, including LIFO and FIFO. In the last phase, PACTOLUS calculates the gross revenues and annual tax payments, depreciation charges, bond interest and principal repayment, and a levelized cost of power from the alternative. An annual cash balance sheet is prepared. Finally, the contribution of each of the fixed and variable cost components to the total unit cost of energy is also calculated and reported at the user's option.

The cost of capital used to discount the cash flows associated with the project is determined by the usual weighted average formula $r = (1-\tau)r_b f_b + r_s f_s$, where the r_x's represent the return to debt or equity holders respectively, the f_x's represent the fraction of debt or equity in the capital structure of the regional utility, and τ is the corporate tax rate. Although the formula is commonly used, there are some theoretical difficulties with applying a cost of capital for the existing firm to new projects which might have significantly different risk characteristics than the existing assets. Myers,[7] in a recent paper, has shown that the weighted average formula gives the correct hurdle rate under the following sufficient, but perhaps not necessary, conditions:

1. The project under consideration offers a constant, perpetual stream of cash flows, and is expected to make a permanent contribution to debt capacity.

2. The project does not change the risk characteristics of the firm's assets.

3. The firm is already at its target debt ratio, and adoption of the project will not lead the firm to change that ratio.

4. The firm's currently held assets are expected to generate a constant perpetual after tax cash flow per annum.

The important point is that when the user is evaluating short-lived, high risk projects that do not contribute much to the capacity of the firm for debt financing, the model may be using a discount factor that is too low and may be biasing the results. For most projects undertaken by utilities, the conditions that Myers gives do not seem to be significantly violated.

3.2.3 Data Base and Information Flow.

As mentioned above, a substantial data base has been implemented as an integral part of the Generation Expansion Model. The function of the data base is threefold. First, it is used to store the original data describing each of the various plant and abatement technologies. This information includes cost and performance data, fuel utilization data, and nuclear fuel industry data. Secondly, the data base acts as a medium by which information is transferred between the various codes comprising the model. And finally, it is used to store intermediate results for use in subsequent iterations.

The data base is made up of a system of disk files. Figure 3.3 contains a diagram of the file system for the Plant Evaluation Model, and Appendix E of the System Manual contains a complete description of the entire file system and its contents. In PEM, all but one of the data sets (files) are organized as direct access files and require directories which map the record identifiers into the corresponding relative file addresses. Files 10, 12, 13, 17, 18 and 20 each contain their own directory. In File 14, which is sequentially organized, a master directory of the files used by PACTOLUS is stored. This master directory consists of the subdirectories for Files 10, 11, 12 and 13.

Files 17, 18 and 20 are the data files for the PLANT program and contain the cost and performance data for each of the TPA, APA, and plant alternatives respectively. Files 11 and 14 are created by PLANT and used as data by PACTOLUS. File 11 contains the total capital and operating costs, capacity, heat rate, availability, and environmental resource requirements for each of the plant alternatives being considered. As indicated above, File 14 contains the master directory for each of the data files used by PACTOLUS. Files 12 and 13 contain the full power fuel utilization histories for the fossil and nuclear plants respectively. File 13 contains the directory for both files. File 10 contains nuclear fuel industry data, such as fabrication, reprocessing, and reconversion costs and losses, for each of the nuclear plant types. File
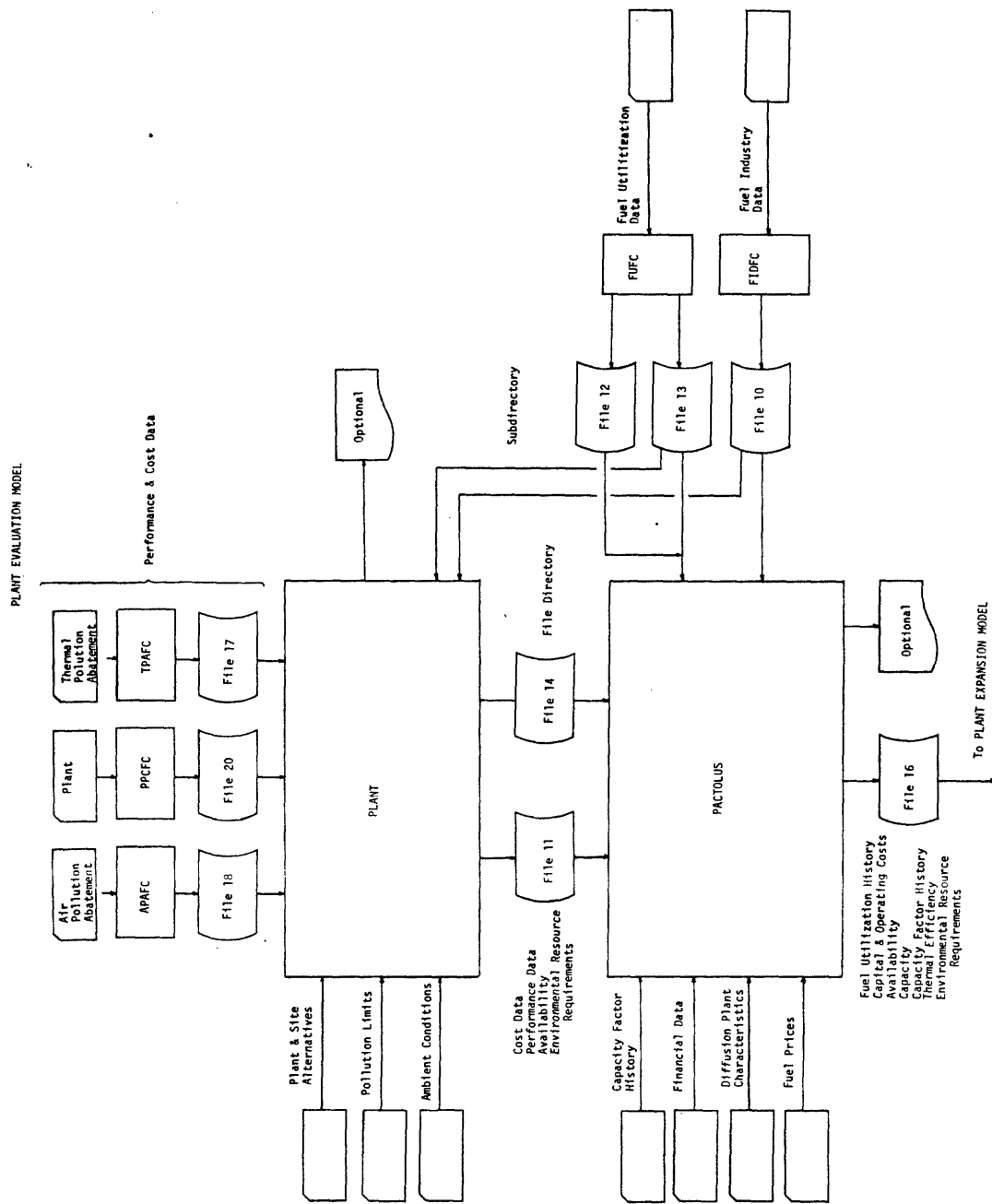
Fig. 3.3a   The Generation Expansion Model Information Flow

PLANT OPERATION MODEL

PLANT EXPANSION MODEL
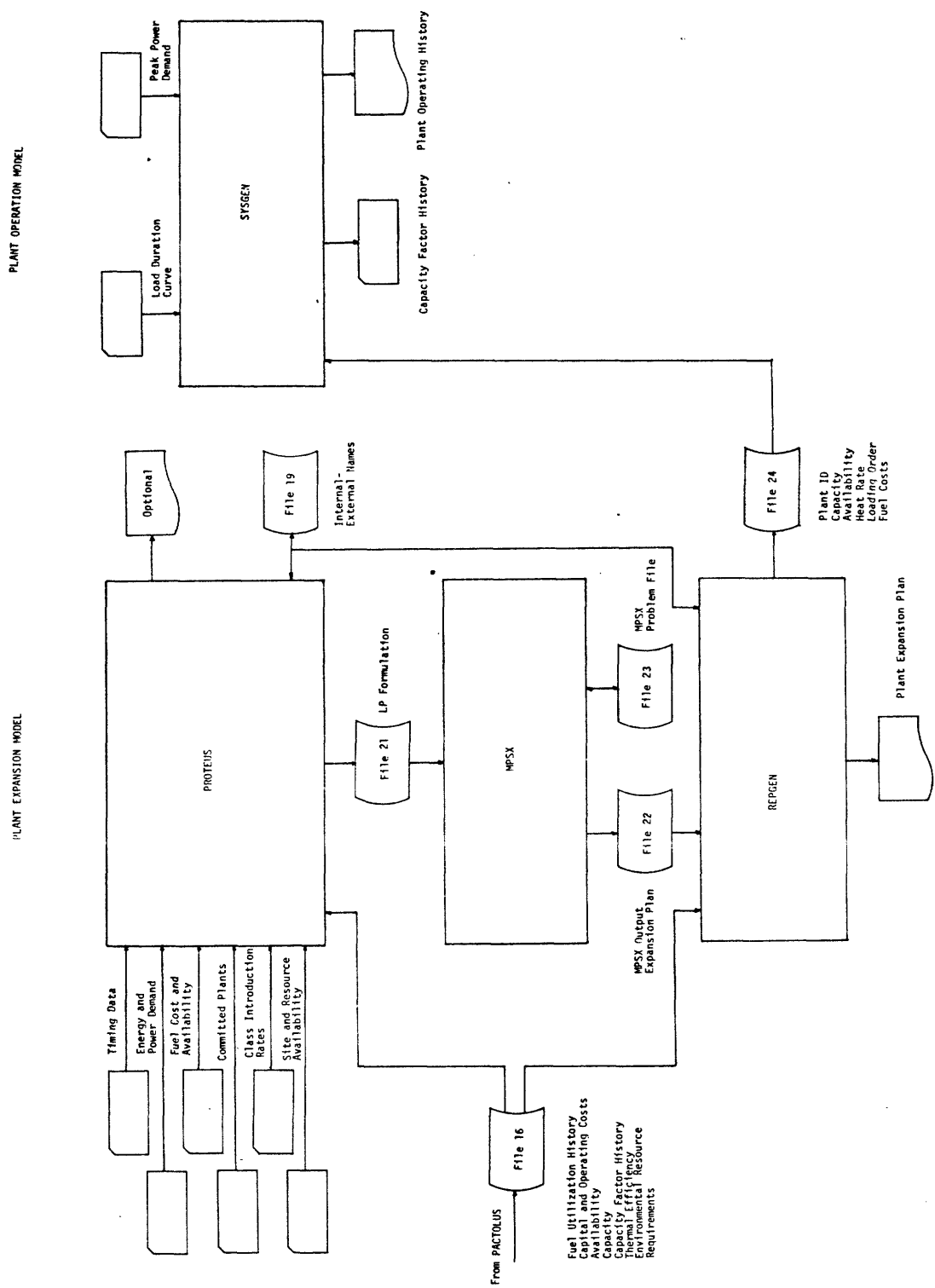
Fig. 3.3b The Generation Expansion Model Information Flow

65

16 is created by PACTOLUS and is used as data by PROTEUS, the linear programming matrix generator. The data on this file completely describes each alternative and consists of the fuel utilization history, capital and operating costs, availability history, capacity, conversion efficiency, capacity factor history, and environmental resource requirements for each plant alternative. For a detailed description of the contents and structure of each of these files the reader is referred to the System Manual.

Also shown in Figure 3.3 is the set of programs which comprise the Plant Evaluation Model. The two major codes, PLANT and PACTOLUS, were discussed briefly earlier in this chapter and will be described in more detail in the remaining sections of this chapter. The other programs are file maintenance programs whose functions are to create and maintain the data files used by PLANT and PACTOLUS. There are two sets of these codes. The first, designated by the suffix FC, is shown in Figure 3.3. The functions of these are to read a set of data records from cards and either add those records to the file or update the corresponding record if it already exists on the file. The second set of file maintenance codes is designated by the suffix FI. The function of these programs is to initialize the directories of each of the corresponding files. The effect of these programs is to empty the directory and destroy any data which previously existed on the file. Each of the file maintenance programs is described in more

detail in Appendix C of the System Manual.

3.3 PLANT.

The primary function of the PLANT program is to determine the combined performance, environmental resource requirements, and capital and operating costs for each combination of base plant technology, thermal pollution abatement technology, and air pollution abatement technology specified to it as an alternative. In doing this the program insures that the design and performance of the pollution abatement equipment is such that the plant is in conformance with the specified pollution limits. Then the effect of the pollution abatement equipment and the ambient conditions on the overall performance, i.e. net capacity and heat rate, of the plant is determined. Finally, the subroutines corresponding to each of the specified pollution abatement technologies and the main program which performs plant calculations determine the capital and operating costs, the environmental resource requirements, and the power requirements of the associated equipment. These are each summed in the main program to obtain a grand total for the plant alternative.

The purpose of this section is to give a detailed description of the logic and calculations which constitute the PLANT program. Documentation of the TPA and APA subroutines can be found in references three and four of this chapter.

The primary data or input for the PLANT program consists of the contents of the three files which hold the cost

and performance data for each of the plant, TPA, and APA types
(Files 20, 17 and 18 respectively), and two sets of cards.
One of the card sets contains the pollution limits and ambient
conditions for each of the site types to be included, and the
other set contains the list of plant alternatives to be pro-
cessed by PLANT. There must be site data for each site type
included in the list of plant alternatives. If PLANT does not
have site data for the site type specified in an alternative,
that alternative will not be processed.

Because of space limitations, PLANT is capable of
storing the pollution limits and ambient conditions of only
ten site types simultaneously. This does not mean, however,
that PLANT cannot process more than ten site types in any one
run. When PLANT finishes processing one list of plant alter-
natives and its corresponding set of site data, the program
checks to see if another set of site data and list of plant
alternatives follows those previously processed. If so, then
PLANT reads and processes that data. This procedure is con-
tinued until a card signifying end-of-data is encountered or
the output files, Files 11 and 14, are filled. A complete de-
scription of the card input stream for the PLANT program is
contained in Appendix C of the System Manual.

The first step in the PLANT program is to read the
subdirectories for files 10, 12, 13 and 20 into core. These
will be used later in the program to retrieve data and to con-
struct the master directory for PACTOLUS. The subdirectories

for Files 17 and 18, the pollution abatement data files, are read later in the program and will be discussed later in this section. Next a card is read that contains the number of site types and the number of plant alternatives which will be described by the card sets that follow it. This card also contains an indicator which signals the end-of-data. If the end of the input stream has not been reached, the program reads the set of pollution limits and ambient conditions. The program then processes each of the plant alternatives as described below.

First, COMMON is initialized by calling subroutine INIT. Then the name of the next alternative is read and checked to see if it has previously been processed. If it has, an error message is printed and the name of the next alternative is read. If it has not, the list of pollution limits and ambient conditions is searched to find the set which corresponds to the site type specified in the name of the plant alternative. If PLANT cannot find the corresponding set, the appropriate error message is printed and the next alternative processed. Otherwise the relative position of the data record on File 20 which corresponds to the current plant type is located by searching the directory for that file.

Then PLANT branches according to the type of plant. Currently PLANT is capable of making two different types of performance calculations. One of these includes all plant types whose prime movers are steam turbine-generators. These

include all the current nuclear and fossil plants. This type of calculation can also be used, however, for gas turbines and combined cycles. The second type of performance calculation is much simpler and includes hydro and pumped storage plants.

If the current alternative corresponds to one of the steam turbine-generator types PLANT reads the cost and performance data from the corresponding data record on File 20 that was located earlier. This data consists of rated conditions, condenser performance characteristics, turbine cycle performance as a function of condenser back pressure, stack gas composition and flow (for fossil plants), and a set of capital and operating costs. A detailed description of this data may be found in Appendix E of the System Manual.

The next step in the process is the calculation of the rated thermal power of the heat source and the heat rejected from the plant through the condenser and circulating water system. It is assumed that the maximum output of the heat source is fixed and only the plant heat rate and efficiency will be affected by changes in performance caused by the pollution abatement equipment. It is this assumption which allows us to determine the full power fuel consumption outside of the model. The rated thermal power of the plant, RTP (MWe), is calculated as follows:

$$RTP = (RC*RNTHR*100)/(EFFB*3412.75), \quad (3-1)$$

where RC is the rated capacity in MWe, RNTHR is the rated net turbine heat rate in BTU/kwhr, and EFFB is the boiler

70

efficiency in percent. The heat rejection, QR (BTU/hr) is calculated as follows:

$$QR = RC*1000*(RNTHR-3412.75). \qquad (3-2)$$

As can be seen from the above formula, the heat rejection is calculated on the basis of full power design conditions.

It should be noted at this time that all design and performance calculations made by PLANT are assumed to be under worst case conditions. This means that the same ambient conditions used to design the equipment are also used in determining performance characteristics such as heat rate and power requirements. This also means that all performance calculations are done at full load, and changes in heat rate due to changes in load are not factored into the fuel consumption calculations performed later in PACTOLUS. The amount of data and the extra computer code required to evaluate each alternative across a full range of loads and ambient conditions would not only be prohibitive but, further, would not add a significant amount of accuracy to the overall model which is intended for long range planning.

After the heat rejection and thermal power calculations have been made, PLANT then calls subroutine TPA. This subroutine has two functions. The first is to determine the relative position of File 17 of the first data record corresponding to the TPA type specified in the plant alternative identifier, and the second is to call the corresponding subroutine.

The data for each of the TPA subroutines is stored on File 17, a formatted direct access data set, each record of which is in card image form. The reason the formatted card image record format was chosen is twofold. First, each of the various TPA subroutines has widely varying data requirements. A record format and file design was needed which could handle any amount of data in any form. Secondly, the card image format was chosen to make the transition from the debugging stage to the production stage as simple as possible. A new TPA subroutine can be debugged without running the PLANT program by using cards as input and then added to PLANT with only minor changes in the coding to allow it to read data from File 17.

Upon being called, the TPA subroutine first determines if the directory for File 17, located on the first eleven records of that file, has been read into core. If not, it reads the directory. Next, the subroutine searches the directory for the relative position of the first record containing data corresponding to the TPA type specified in the plant alternative identification. The relative position of that record is stored in TPACOM(2), an element in COMMON block CNTRL. Communication between PLANT and the abatement subroutines is done through several COMMON blocks, including CNTRL. The contents of these blocks are described in Appendix F of the System Manual.

After the data has been located, TPA calls the corresponding abatement subroutine. This is implemented by a

series of logical IF statements which check for valid TPA types. When a match is made, the corresponding subroutine is called. If no match is made, then an error message is printed, and TPACOM(2), which indicates a fatal error, is set equal to zero. As stated earlier, the function of the thermal abatement subroutine is to design the corresponding equipment so that the specified pollution limits are met and then to determine the corresponding condenser circulating water inlet temperature, capital and operating costs, environmental resource requirements, and power requirements. This information is communicated to PLANT through the COMMON described in the System Manual. If NONE was specified as the TPA type, then all costs, resource requirements, and power requirements are set equal to zero and the condenser circulating water inlet temperature is set equal to the ambient water temperature.

Next subroutine COND is called to determine the actual condenser back pressure. Given the condenser surface area, A (ft^2), the condenser U-factor, U (BTU/hr-ft^2-°F), the cooling water temperature rise, TR (°F), the heat rejected, QR (BTU/hr) and the inlet water temperature, Tl (°F), the performance of a condenser can be characterized by the following relationship:

$$QR = A*U*LMTD ,$$ (3-3)

where the log mean temperature difference, LMTD, is expressed by

$$LMTD = \frac{T2 - Tl}{\ln \left(\frac{TS - Tl}{TS - T2}\right)} .$$ (3-4)

73

T2 is the circulating water outlet temperature and

TS is the saturation temperature of the steam in the condenser.
It can be shown that:[8]

$$TS = T1 - \frac{TR}{\alpha} , \qquad (3-5)$$

where

$$\alpha = \frac{A*U*TR}{QR} . \qquad (3-6)$$

It is this relationship which is used in COND to de-
termine the steam saturation temperature. Function PSAT,
which determines steam saturation pressure as a function of
temperature, is then called, with TS as its argument, to de-
termine the condenser back pressure. The functional relation-
ship between the saturation temperature and pressure of steam
used in COND is taken from the 1967 ASME Steam Tables.[9]
Finally, condenser back pressure is converted from psia to
inches of mercury and passed back to PLANT.

The net turbine heat rate at the actual back pressure
is determined using a method recommended by General Elec-
tric.[10,11,12] Five points on the curve representing the rela-
tionship between the valves wide open (VWO) net turbine heat
rate for the plant and the corresponding condenser back pres-
sure are input to PLANT from File 20. The VWO net turbine
heat rate is determined at the rated back pressure and the
actual back pressure, NTHRR and NTHRA respectively, by perfor-
ming a five point Lagrangian interpolation on the heat rate
versus back pressure curve. Then the change in heat rate, ΔHR,

due to the change in back pressure is found as follows:

$$\Delta HR = (NTHRA-NTHRR)/NTHRR . \qquad (3-7)$$

The net turbine heat rate at the actual condenser back pressure, NTHR, is computed as follows:

$$NTHR = RNTHR * (1 + \Delta HR) . \qquad (3-8)$$

Next PLANT calls subroutine APA which is analogous to subroutine TPA, only it is associated with the APA equipment. Subroutine APA first locates the position of the data on File 18 which corresponds to the APA type specified in the plant alternative name. It stores the relative position of the first record of that data in APACOM(2) and then calls the corresponding air pollution abatement subroutine. The function of the APA subroutines is similar to that of the TPA subroutines except that instead of determining the condenser water inlet temperature the APA routines must calculate and return to PLANT any change in boiler efficiency caused by the corresponding equipment.

To complete the performance calculations for steam turbine-generator type plants the model first determines the corrected boiler efficiency, EFFB (%). Then the actual plant capacity, MWE (MWe), and the actual <u>plant</u> heat rate, NPHR (BTU/kwhr), are calculated as follows:

$$MWE = \frac{RTP*EFFB}{NTHR*100} , \text{ and} \qquad (3-9)$$

$$NPHR = RTP*3412.75/MWE . \qquad (3-10)$$

Finally the capital and operating costs, power equipment,

and environmental resource requirements for the plant alternative are obtained by summing all the individual values corresponding to the plant, TPA, and APA equipment. This information along with the performance data and availability history, supplied as input to PLANT, is then written on File 11 for later processing by PACTOLUS.

The performance calculations for pumped storage and hydro plants are considerably simpler. No TPA or APA subroutines are called. The only performance calculation is the determination of an equivalent thermal power. All other information such as costs and efficiency are input to the program. As with the steam turbine-generator types a set of data describing the cost and performance characteristics is written on File 11.

The final step in the processing of any alternative is the addition of that record to the master file directory for PACTOLUS. This directory includes the relative position of data records corresponding to the plant alternatives in Files 10, 12, 13 and 20. Since the entries in File 11 and the corresponding entry in the master directory are made in sequential fashion, the order of the directory implicitly contains the directory for File 11. For example, if a particular alternative were the fifteenth entry in the directory, the relative position of the corresponding data on File 11 would be 15.

The addition of an alternative to the master directory is the last step in the processing of any alternative. PLANT

next checks to see if there are more alternatives to be pro-
cessed. If not, the last function of PLANT is to write the
master directory onto File 14.

3.4 PACTOLUS.

As mentioned earlier, PACTOLUS calculations may be
considered essentially in three phases. The first phase de-
termines the amount of fuel consumed, or sometimes produced,
by the plant alternative on a refueling interval basis. The
second phase calculates the annual expenditures and credits
for fuel or ore and for fuel cycle processes. Some summary
printed output is also optionally available. Finally, taxes,
debt payments, and depreciation are calculated, and a cash
flow report is generated. Also, in this final phase the user
may optionally ask for a detailed fixed and variable break-
down of the components comprising the levelized cost of power
from the alternative.

This section of the chapter presents a reasonably de-
tailed overview of the functional flow of information through
the major subroutines of PACTOLUS. The reader who is not
interested in this detail should proceed to the next section.
Figures 3.4 and 3.5 are a convenient reference for this dis-
cussion; they list and briefly describe each major subroutine
in PACTOLUS. The first phase of PACTOLUS calculations ends
after subroutine CLOTHO; the second phase ends when subroutine
PWRCO is called.
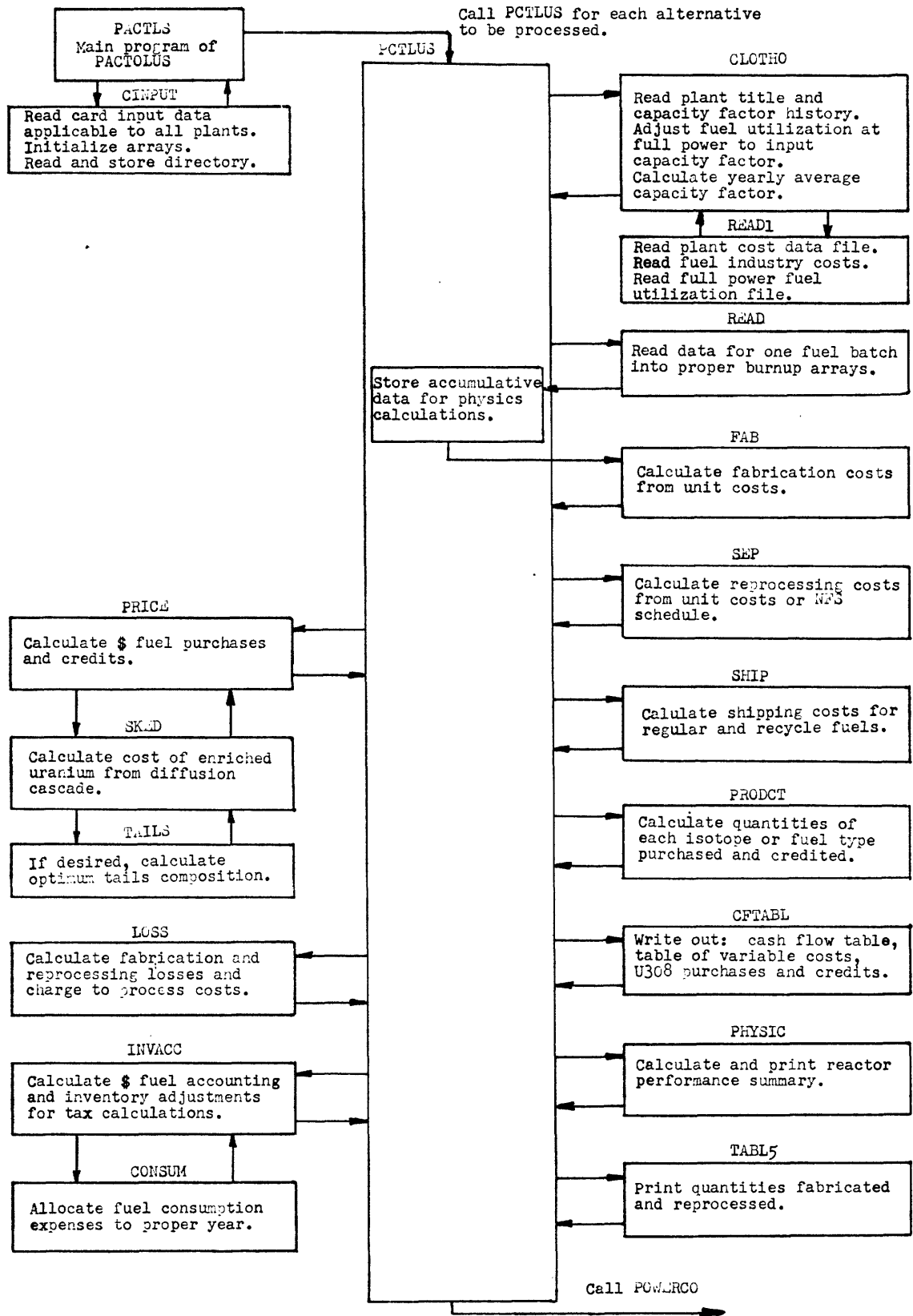
Fig. 3.4 Major Subroutines in PACTOLUS
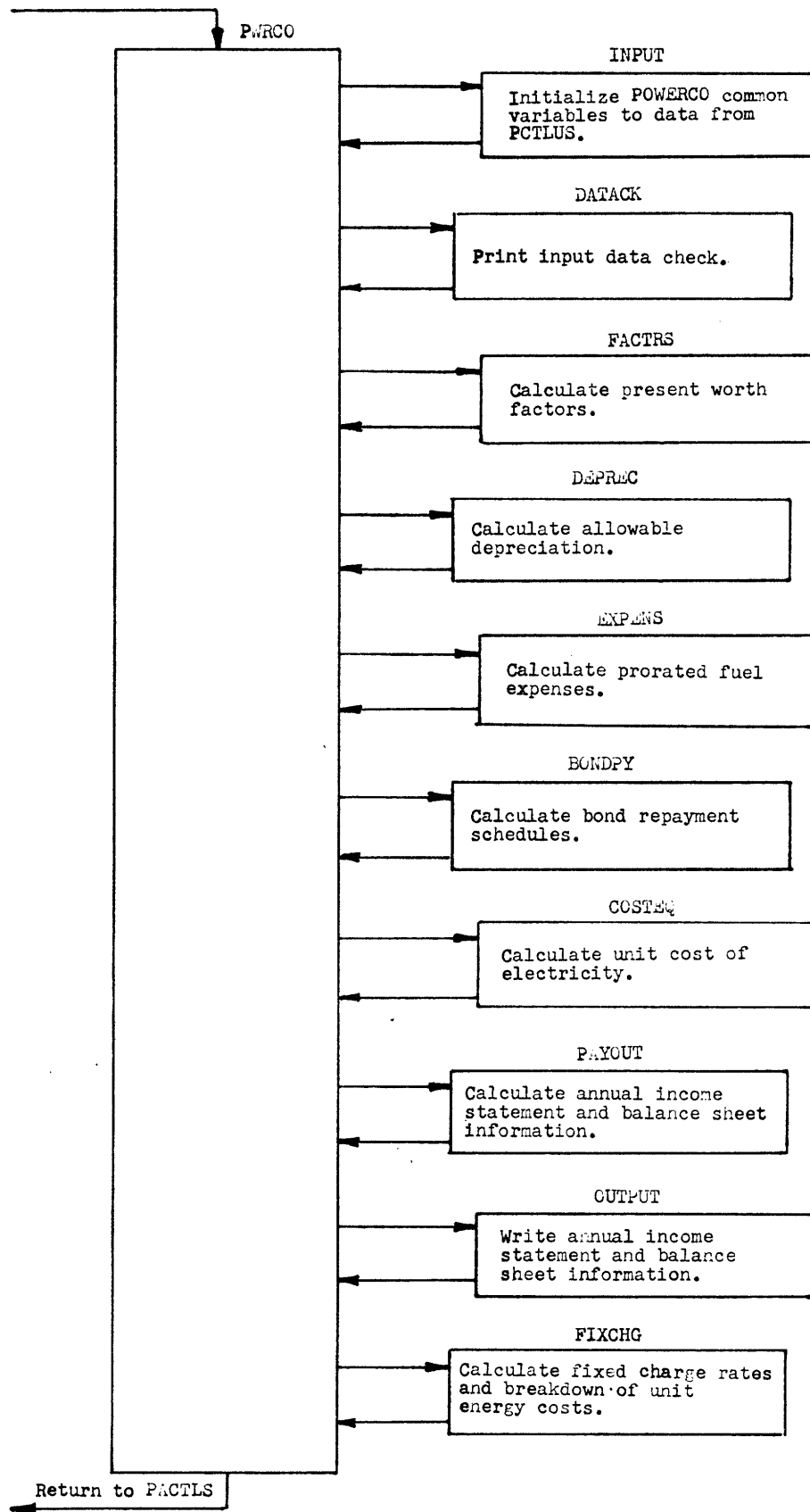
Fig. 3.5 Major Subroutines in POWERCO

79

PACTOLUS was written at the Battelle Memorial Institute of the Pacific Northwest Laboratories for the USAEC. To avoid confusion, the reader who is familiar with the original version should remain aware that the version of PACTOLUS used here has many minor but necessary programming alterations in order to function properly within the Generation Expansion Model.

The main program of PACTOLUS is designated PACTLS. This short routine has only two functions. First, it calls subroutine CINPUT to read certain data from punched cards which will apply for all alternatives being considered in the case study. The remaining function of PACTLS is to call subroutine PCTLUS once for each alternative. After PCTLUS has processed an alternative, PACTLS tests to see if more alternatives remain to be processed. If they do, PACTLS calls PCTLUS again; if all the alternatives in the case have been processed, PACTLS stops, and the newly created or updated File 16 can be used in the Plant Expansion Model.

CINPUT is a subroutine that reads various input data from punched cards. Each alternative in the case study is evaluated using this consistent data; the specific data to be supplied is listed along with the input formats in Appendix C of the System Manual. One data matrix read by CINPUT is the fuel price schedule. Prices may be input for U_3O_8, ThO_2, fissile Pu (this one price will apply for both ^{239}Pu and ^{241}Pu isotopes), ^{233}U, and for up to twelve different fossil fuels

that might be used by different plant alternatives in the case study. As many as 70 different annual price lists for these fuels may be specified. If the user desires to input a different price for one of the fuels in a given year, he must also specify again the price of all the remaining fuels or they will be assigned a zero market value for that year. If no fuel prices have been listed for a year in which a fuel purchase or credit occurs, the code will interpolate linearly between the values for those years that bracket the time period in question. If the fuel purchase occurs before the first input price list or after the last, the code uses the first or last specified price, respectively. Some time invariant market values may also be provided for twelve important nuclear isotopes, including ^{233}U, ^{239}Pu, and ^{241}Pu. If the user has already opted, however, to input non-zero time-varying prices for these isotopes, the variable prices will override the invariant prices. This feature is intended to provide the option of changing these isotope prices based on the time schedule of prices determined in the previous iteration by the Plant Expansion Model. CINPUT also reads File 14, the master file directory. If this is an update of a previous iteration, CINPUT updates the iteration counter stored in the first record of File 16. Although CINPUT will search the entire directory to locate the records applicable to the plant alternative, some efficiency is achieved if the alternatives are processed in the same order in PACTOLUS in successive iterations.

Subroutine PCTLUS is called next to completely process one alternative. PCTLUS is actually the main logic of the PACTOLUS code in subroutine form, and it directs the functioning of the remaining subroutines.

The first subroutine called by PCTLUS is CLOTHO; CLOTHO was originally written as a separate code by Battelle-Northwest.[13] In the USAEC systems analysis studies, the data output of CLOTHO is written on magnetic tape to be read subsequently by PACTOLUS. Here, communication between PACTOLUS and CLOTHO is achieved through the use of COMMON. To reduce storage requirements this same COMMON area is shared by later routines.

CLOTHO reads punched cards to obtain the seven word name, discussed earlier in this chapter, and the proposed capacity factor history for the alternative being processed. If the first character of the fuel type word in the name is a "U", "P", or "T", the alternative is designated a nuclear plant; different processing and reporting occurs for nuclear and non-nuclear alternatives in the remainder of PACTOLUS. The capacity factor history is input as a step function composed of a series of period-average capacity factors. The lengths of the periods are variable so that each period may have a different length or, if more convenient, each period may have the same length. The operating lifetime of the alternative is determined from the number and length of these periods. This step function format for the capacity factor

history is different than the USAEC format and the internal coding of CLOTHO is somewhat different in this version.

Subroutine READ1 is called by CLOTHO to read the data records, stored on disk files, appropriate to the alternative. An annual average availability is calculated for the plant from the input step function availability history. The fueling schemes, or amounts of the twelve fuel types used each year, that are input for non-nuclear alternatives are stored in the proper vectors; a fueling scheme, once specified, remains in effect for all subsequent years until the user specifies a new fueling scheme. For fossil plants, the annual requirement for fuel is approximated as being consumed at mid-year. For both fossil and nuclear units, if the input fuel utilization is calculated for other than rated power, it may be corrected to full power in an approximate manner by using input multipliers. For nuclear units, the refueling history is on a batch-by-batch basis with charging and discharging times in full power years, not calendar years.

Subroutine READ1 returns to CLOTHO for further processing of the refueling data for nuclear plants. CLOTHO adjusts the refueling time of each batch of a graded-fueled reactor for both the core and any blanket regions until a refueled region would be discharged after the last year of operating life. CLOTHO can also be used for a continuously fueled reactor in the following manner: the first "batch" of fuel in the input data represents the charge, at the beginning of life,

and the discharge, at the end of life, of the equilibrium core. The remaining "batches" of fuel in the input data represent the accumulation of small amounts of fuel charged and discharged over short time intervals; this is a reasonable approximation of the actual purchasing and reprocessing of fuel for these reactors.

Once the code determines that a refueling would occur after the end of the operating life of the station, that batch and all remaining input fuel batches are ignored. The equilibrium refueling data is used to refuel all core and blanket regions for their final refueling, and then linearly interpolated to the end of the station life to determine the fuel concentrations upon shutdown.

A yearly average capacity factor is calculated for the alternative being processed. If the periods of the input capacity factor history are not single years, the average is over those periods comprising the calendar year. This yearly capacity factor is compared with and reduced, if necessary, so as not to exceed the station availability. The annual full-power fuel consumption of fossil plants is reduced by multiplying it by the capacity factor to determine the actual annual fuel consumption. Finally, if the user has requested printed output a report is produced listing the entire fueling history of the alternative. This completes the first phase of PACTOLUS.

In the next phase of PACTOLUS the timing and value of the net cash flows required to purchase and reprocess the fuel

are determined. PCTLUS processes each fuel batch separately, cycling through the applicable subroutines once for each batch until all batches have been considered. For non-nuclear alternatives a fuel batch consists of the annual fuel consumption of up to twelve possible fuels; for nuclear alternatives, it consists of as many as twelve nuclear isotopes in a refueling batch charged and then later discharged, but not necessarily at yearly intervals. For fossil plants, determining the cash flows for fuel is a simple problem and not all the subroutines in this phase are called. For nuclear plants, the problem is much more complicated, with cash flows occurring for ore purchase, conversion and enrichment, fabrication, reprocessing, losses, and sale of bred or residual fuel. An additional complication is the inventory accounting charge for the fuel in the reactor.

For nuclear alternatives, PCTLUS calls subroutine FAB to compute fuel fabrication charges. Fabrication consists of the conversion of the raw fuel materials into finished fuel assemblies, including any conversion charges such as UF_6 to UO_2 and the costs of cladding and hardware. Fabrication costs are calculated from an input unit cost schedule, in dollars per kilogram of heavy metal in the finished fuel output from the fabrication plant. The unit cost schedule may be input as a single number or it may vary over time; the unit cost in any one year is calculated in the same manner as discussed for determining fuel prices. An additional fabrication charge, if

specified by the user, will be computed for plutonium and ^{233}U-bearing fuels. Separate costs may be specified for core and blanket regions of a reactor. If the batch is part of the initial fuel loading, the fabrication cost is included in the initial core investment. The timing of the fabrication charge, as with all other process charges, is determined from the specified delays in the nuclear fuel cycle.

For nuclear alternatives, subroutine SEP computes the chemical reprocessing costs incurred following fuel irradiation. Two options are available for computing these costs. The first option is a unit cost approach similar to the fabrication cost calculation. Different unit cost schedules may be specified for core and blanket fuels; following the usual practice, these costs are based on the kilograms of heavy metal charged to the reactor. These costs may optionally be computed from a model of the Nuclear Fuel Services reprocessing price schedule.[2] This model determines a reprocessing charge for the batch in a plant having a basic reprocessing time and cleanup time depending on the enrichment of the original fuel and the size of the reprocessing plant in kilograms per day. A conversion charge for converting the discharged uranium to UF_6 is included.

Subroutine SHIP determines for all alternatives the value and timing of costs associated with fuel shipments. For fossil fueled alternatives a single pre-consumption unit shipping charge may be specified. For nuclear alternatives the

user may specify two pre-fabrication shipping charges (for standard and recycle fuels), two post-fabrication shipping charges, a post-irradiation charge, and a post-reprocessing charge for shipment to the final destination. The post-irradiation shipping charge is based on the mass of heavy metal charged to the reactor since the mass converted to energy is assumed negligible. It also includes a discounted charge associated with the subsequent disposal of waste material. The post-reprocessing charge is based only on the heavy metal isotopes remaining after the fission products have been removed. For fuel batches in the initial reactor loading, the pre-irradiation shipping charges are added to the value of the initial core investment.

Subroutine PRICE calculates the direct cash expenditures for raw fuel materials. For non-nuclear alternatives, this charge is the quantity of a given type of fuel times the price of the fuel at the time of purchase. The calculation is more complicated for nuclear alternatives. For all nuclear isotopes considered, except ^{235}U, ^{236}U, and ^{238}U, the purchase charge is just the quantity of the isotope in kilograms times the unit cost of the isotope in dollars per kilogram; this unit cost is either the time invariant isotope price or the non-zero time-varying price if one has been given. If the reactor is being fueled on a ^{233}U recycle program, the charges for the ^{235}U, ^{236}U, and ^{238}U isotopes are also the quantities times the (time-invariant) unit costs. If the reactor is not

recycling ^{233}U but is on the more usual ^{235}U fuel cycle or a plutonium recycle program, the uranium fuel cost is determined in subroutines TAILS and SKED. If the fuel batch is part of the initial reactor loading, the fuel purchase cost is added to the other costs comprising the initial core investment. Fuel credits for discharged fuel are determined in the same manner as fuel purchases.

Subroutines TAILS and SKED are used to determine the costs of ^{235}U-enriched uranium fuel processed by the USAEC gaseous diffusion plants. In the diffusion plants, F kilograms of feed material of gaseous uranium hexafluoride, UF_6, containing x_F weight fraction of ^{235}U, is made to diffuse through thin-walled porous diffusion barriers to produce P kilograms of product gas enriched in the lighter ^{235}U isotope to x_p weight fraction; W kilograms of residual gas or tails are also produced containing x_W weight fraction ^{235}U. The cost of enriched product is then made up of the cost of feed in the form of UF_6 plus the cost of "separative work" done by the diffusion plant less any value of the tails:

$$C_U*P = C_F*F + C_S*S - C_W*W , \qquad (3-11)$$

where C_U = unit cost of enriched uranium in the form of UF_6, in \$/kgU,

C_F = unit cost of uranium feed in the form of UF_6, in \$/kgU,

C_S = unit cost of separative work, in \$/kgSW, and

c_W = unit value of discharged tails, in \$/kgU.

The charge for enriched uranium can then be calculated if expressions can be derived for the factors in the above equation. The unit cost of separative work, c_S, and any value for the tails, c_W, must be input by the user. The quantity of product gas, P, is determined by the kilograms of ^{235}U, ^{236}U, and ^{238}U in the fuel being charged or discharged. Because of the material balance on uranium, P + W = F; similarly, the ^{235}U material balance is $Px_P + Wx_W = Fx_F$. Thus, W and F are found to be given by

$$\frac{W}{P} = \frac{x_P - x_F}{x_F - x_W} \qquad (3\text{-}12)$$

and

$$\frac{F}{P} = \frac{x_P - x_W}{x_F - x_W} .\qquad (3\text{-}13)$$

The weight fraction of ^{235}U in the feed, x_F, is specified by the user and is normally that of natural uranium, $x_F = .00711$; the enrichment of the product x_P is determined by the quantities of the isotopes charged or discharged. Only x_W remains to be determined in these relations for W and F.

The "separative work", S, done in producing the P kilograms of product is related to the total amount of UF_6 gas which has to be compressed in carrying out the desired enrichment. It is given by:[6]

$$S = P(2x_P-1) \ln \frac{x_P}{1-x_P} + W(2x_W-1) \ln \frac{x_W}{1-x_W}$$

$$- F(2x_F-1) \ln \frac{x_F}{1-x_F} \qquad (3-14)$$

Again, all factors in this equation have been discussed except x_W.

The unit cost of uranium feed in the form of UF_6, C_F, may be calculated from the input time-varying cost of U_3O_8, the fractional efficiency of the process converting U_3O_8 to UF_6, and the unit cost of the conversion process which is specified by the user.

Finally, the user has two options to specify x_W, the last factor needed in the above equations. First he may input x_W; this simulates the actual USAEC operation of the diffusion plants at one value of x_W. The user may also, however, opt to let the code calculate on optimum tails composition. This is the purpose of subroutine TAILS. This optimum is found by substituting the expressions for F, W, and S into the original cost equation, differentiating with respect to x_W, and setting the result equal to zero. This yields:

$$\frac{C_F-C_W}{C_S} = (2x_F-1) \ln \frac{x_F(1-x_O)}{x_O(1-x_F)} + \frac{(x_F-x_O)(1-2x_O)}{x_O(1-x_O)} \qquad (3-15)$$

where x_O is the optimum value for x_W.

TAILS solves this equation by iteration. With x_W

determined, TAILS calls subroutine SKED to determine the cost of the uranium from the total cost equation. SKED also calculates a price for ninety weight-percent enriched uranium for reporting purposes. It then determines the amount of U_3O_8, tails, and separative work required for fuel batches charged to the reactor and the equivalent amount of U_3O_8, tails, and separative work credited to the reactor for the discharged fuel. These material totals properly account for losses in the other fuel processing steps.

The dollar value of the processing losses is determined in subroutine LOSS. This includes the fabrication, reprocessing, and conversion steps, plus the value of the decay of fissile ^{241}Pu because of time delays in the nuclear fuel cycle. The fuel losses are assumed to have the same unit values as the material charged to the process. The value of the losses is not included with fuel purchases and credits; ultimately, they are added to the respective expenditures for the fuel processing steps.

Subroutine PRODCT adds the quantity of each of the twelve fossil fuels or twelve nuclear isotopes in the fuel batch to the proper time-phased cumulative fuel usage array. Fuel processing losses are properly considered.

PCTLUS has now completely processed one "batch" of fuel. A test is made to determine if all the fuel batches over the plant lifetime have been considered. If they have not, PCTLUS returns to subroutine FAB and the next batch; if

all batches have been considered, some summary and reporting subroutines are called. These subroutines include: CFTABL, whose function is to optionally print tables summarizing capital expenditures, operating cash flows, variable fuel costs, and uranium purchases and credits; PHYSIC, whose function is to calculate and report some useful reactor physics parameters for the nuclear alternatives; and TABL5, whose function is to print the annual cumulative quantities of the fuel types purchased and reprocessed.

Before PCTLUS can proceed to the final phase to determine financing charges and taxes to be included in the economic evaluation of the alternative, the allowed deductable fuel expenses and in-core fuel inventory adjustments for nuclear plants must be determined. PACTOLUS has five options for determining annual fuel expenses for income and property tax calculations. First, the direct cost method may be chosen and the actual fuel expenditure or receipt charged to the year in which it occurs. Second, in the standard cost inventory accounting method all fuel expenses are directly proportional to energy production. The standard cost is obtained by dividing total lifetime fuel expense by total energy production; the annual fuel expense is the product of the standard cost and the annual energy production. When consistent fuel and fuel processing price trends exist or when large price fluctuations occur, it is difficult to interpret the resulting annual deduction. The remaining three options in PACTOLUS are LIFO,

which stands for "last-in, first-out"; FIFO, or "first-in, first-out"; and a weighted-average option intermediate between LIFO and FIFO. The FIFO method most nearly represents the physical flow of fuel through the reactor and the inventory replacement value of the current fuel inventory; however, it may not evaluate properly the current cost of fuel consumption. Conversely, in the LIFO method inventory is valued as if the units most recently added to inventory (last-in) were the first units consumed and sold (first-out). Ending inventory is therefore assumed to consist of the oldest fuel and is measured at the cost of this oldest fuel. Advocates of LIFO contend that it matches the "economic" flow of fuel, properly evaluating the current value of fuel consumption but of course misstating the current inventory replacement value. The weighted average method calculates an average cost depending on the amounts of fuel remaining in inventory and the prices existing in the year in which they were purchased. Subroutine INVACC performs the detailed accounting of these last three options for a U_3O_8 account, a separative work account, fabrication and reprocessing accounts, and plutonium and ^{233}U accounts. INVACC calls subroutine CONSUM when necessary to allocate the consumption and sale quantities to the units of fuel in inventory at different price levels.

With the allowed annual fuel expenses determined, PCTLUS calls subroutine PWRCO to determine the taxes and financing charges for the alternative. PWRCO is actually the

main program logic, in subroutine form, of a cash flow code called POWERCO that was developed at Oak Ridge National Laboratory.[14] [15] PWRCO first calls two subroutines, INPUT and DATACK, to initialize variables in common for PWRCO, combine some previously determined data vectors, and optionally print an input data check.

Subroutine FACTRS determines the yearly discount factor, referenced to the year in which the plant begins operation. As discussed earlier, this discount factor is based upon the concept of a weighted-average cost of capital to the firm. Future cash flows and power generation will be discounted by these factors to determine their present worth. In PACTOLUS, the total yearly cash flow and power generation is assumed to occur at mid-year for discounting purposes; the user may, however, select any other time during the year from which to discount these flows.

Two options are available in subroutine DEPREC to calculate the deductible depreciation expense: the straight-line method and an accelerated method called sum-of-the-years-digits. In straight-line depreciation, the capital asset is depreciated at a uniform annual rate over its useful life. In the years-digits method, the numbers 1, 2, 3,...n are added, where n is the estimated depreciable life. The depreciation rate for each year is a fraction in which the denominator is the sum of these n digits and the numerator is for the first year, n; for the second year, n-1; etc. In both methods, these

annual deductions must be modified slightly if there are any interim capital replacements.

Subroutine EXPENS adds the proper dollar value of the allowed fuel expenses to the correct array for income tax calculations. If the standard cost inventory accounting method was selected, the prorated fuel expenses are calculated in this routine.

Debt interest payments are also a deductible expense from taxable income. In PACTOLUS, the user may select several optional methods of debt repayment. One option is to maintain over the life of the project the same outstanding debt-to-equity ratio as was initially specified for financing the project. Interest payments may alternatively be calculated in such a manner as to maintain a single uniform annual payment for both interest and repayment of principal. Another option is to calculate interest as a residual calculation after determining a uniform annual payment for reduction of principal. Finally, the user may input a delayed date at which to begin uniform payments for principal reduction. The interest payments under these options, except for the first one, are calculated in subroutine BONDPY. If a constant debt-to-equity ratio is specified, the effective bond interest expense is recovered through the discounting factor along with the return on equity. As noted previously, the weighted average cost of capital concept should be used with care if the risk characteristics of the project differ significantly from the firm's

currently held assets.

With the deductible expenses determined, the unit cost
of energy for a project is calculated by equating the income
and outlay cash flows and using the same cost of capital for
discounting both streams; this calculation is done in subrou-
tine COSTEQ. The cost of energy from the alternative which
just equates the present worth of the income and outlay cash
streams is the levelized cost of energy. In COSTEQ, capital
investments including interim capital replacements are simply
entered as cash outlays at the time incurred. Salvage values
and recoverable investments are credited at the time and value
received. Non-depreciable investments, including working
capital, are treated as cash outlays at the beginning of the
project and as cash receipts at the end of the project.

After the unit cost of energy is calculated, POWERCO
calculates the gross revenues and annual income tax payments
and prepares annual income statements over the life of the
alternative. A complete schedule of cash outlays plus a
schedule of the outstanding liability accounts are printed at
the user's option. These calculations are performed and re-
ported in subroutines PAYOUT and OUTPUT. Before returning to
subroutine PCTLUS, the user may optionally choose to have cal-
culated and reported the contribution of each of the fixed and
variable cost components to the total unit cost of energy in
subroutine FIXCHG.

One further step is required to completely process the

alternative. PACTOLUS must create or update, if this is an iteration, the appropriate record in File 16 containing summary information about the alternative. This task is accomplished in subroutine TPWRIT. A complete listing of the data stored in File 16 is given in Appendix E of the System Manual. This information includes various descriptive items such as the plant lifetime, capacity, and efficiency. Some "costs" associated with the plant are listed, including total capital funds requirements, debt and equity requirements, environmental abatement equipment capital expenditures, and the total present worth of all capital and operating expenses both including and excluding the present worth of fuel expenses. Resource utilization is specified. Finally, the record contains a series of vectors listing the annual availability and capacity factor of the alternative, the usage of each of the twelve fossil fuels for non-nuclear alternatives, and the usage of ^{233}U, fissile Pu, U_3O_8, depleted uranium tails, and separative work for nuclear alternatives.

After the new record for this alternative is written, TPWRIT tests to see if this is the last alternative in the case study. If it is not, the program returns to subroutine PACTLS and then to PCTLUS to process the next alternative. If this is the final alternative, TPWRIT writes in the first record of File 16 the number of alternatives in the case and the current index counter of this iteration. TPWRIT then returns to PACTLS and the program stops.

This version of PACTOLUS is written for the IBM 370 series model 165 computer at M.I.T. Compiled in FORTRAN H, the program load module requires 204 K bytes of computer storage.

CHAPTER 4

THE PLANT EXPANSION MODEL

4.1 Introduction.

4.1.1 Purpose.

The second submodel in the series of three that comprise the Generation Expansion Model is called the Plant Expansion Model. The function of this model is to determine the least cost generation expansion plan which will provide the projected electrical energy demand and not violate other constraints on fuel availability, site availability, and new class introduction rates. The amount of energy generated by each plant in each period of the study is not included in this model as a decision variable; the energy generated by each alternative is determined by the last submodel in an iterative fashion. The optimal plan determined by this submodel will be based on the predetermined operating histories.

Much of the data needed for the coefficients of the equations in this model is stored in File 16 and was discussed in the previous chapter. This data includes the capital and operating costs, annual fuel consumption, environmental resource requirements, and the capacity factor history for each plant. Some other data needed for the model is entered from punched cards. This data includes the expected power and energy demand for each period of the study, the fuel

availability and cost, the site availability, and a list of committed and constructed plants.

4.1.2 Structure.

The Plant Expansion Model has three functional sections. The first section, named PROTEUS, is a matrix generator code. The subroutines comprising PROTEUS read the input card data, check it for completeness, and perform any manipulations necessary to convert the data into the required form for the linear programming code. The final function of PROTEUS is to read the data stored in File 16 by PACTOLUS, and write it plus the card data into File 21. File 21 contains data in card image form in the required format for use by the linear programming code.

The second functional section of the Plant Expansion Model is the linear programming code designated MPSX (Mathematical Programming System Extended).[1][2][3] MPSX is an IBM system supplied program with capability to solve linear, separable, and integer mathematical programming problems. It uses the revised simplex method of solution with bounded variables and range constraints.

The last functional section of the Plant Expansion Model has been named REPGEN. This is the section of the Generation Expansion Model which could not be completed in time for inclusion in this report. Conceptually, however, the functions served by this code are easy to identify. First,

it must interpret the brief output of MPSX and summarize the results in a more extended form. Second, it must include some data in this report which is not used by MPSX but which is useful information about the selected generation expansion plan. This data includes such items as the total capital funds needed for the solution and the cumulative separative duty work required from the gaseous diffusion plants. The necessary numbers for these types of calculations are stored in File 16 for each alternative. Finally, REPGEN must provide an interface with the Plant Operation Model which follows the Plant Expansion Model. The Plant Operation Model is a probabilistic simulation code named SYSGEN that has been used for several years at M.I.T. REPGEN must present the chosen generation plan on a period-by-period basis in the format required by the SYSGEN code.

4.2 The Linear Programming Formulation.

As mentioned above, the purpose of the Plant Expansion Model is to select plant alternatives over a specified time period such that the projected demand for electricity is satisfied at the minimum present-worth cost. This cost includes charges sufficient to cover depreciation, tax payments, operating and fuel costs, and the required return on investment. Many other factors enter into the decision to purchase a given plant alternative. In this model, some of the more important of these factors are included as a set of constraints which

cannot be violated by the generation expansion plan selected by the linear programming code. The major decision variables are, of course, the numbers of the given types of plants to be built for operation commencing in year v. These decision variables are denoted $\underline{X}_{jv}$, where $\underline{X}_{jv}$ is the number of plants of type j built for operation in year v. To improve the clarity of the model formulation below, all decision variables will be underlined.

There are a number of other decision variables in the model, several of which appear along with the $\underline{X}_{jv}$'s in the algebraic objective function to be minimized. However, a discussion of these variables will be postponed at this point since their rationale depends on the model constraints. Following the discussion of the model constraints below, the exact formulation of the objective function will be specified. Following that discussion, the equations of the model will be summarized and a complete list of variables in the model will be tabulated.

4.2.1 Peak Power Requirement Constraint.

This constraint is written to guarantee that sufficient generating capacity is chosen by the model such that the peak electrical power required in each period can be supplied to an acceptable probability limit. An exact formulation of the constraint would be

$$\text{Pr} \left\{ (\widehat{\text{MAXLOAD}}_t - \sum_{j \in J} \sum_{v=-V}^{t} \widetilde{\text{PAV}}_{jvt} * \text{CAP}_{jv} * \underline{X}_{jv}) > 0 \right\} \leq e,$$

$$t=1...T \qquad (4-1)$$

102

where

$\widetilde{MAXLOAD}_t$ = the maximum power required in period t,

$\widetilde{PAV}_{jvt}$ = the availability in period t of plant type j and vintage v,

CAP_{jv} = the electrical power capacity of plant type j and vintage v, and

$\underline{X}_{jv}$ = the number of plants built of type j and vintage v.

The summation over the vintage v, where vintage denotes the first period of operation of the plant, includes all the plants in the case study from the earliest plant, which begins operation -V time periods before the start of the problem, to those plants selected to begin operation in period t. The summation over the index j includes all types of plants. $\widetilde{MAXLOAD}_t$ and $\widetilde{PAV}_t$ are stochastic variables. This constraint requires an acceptably small value, e, for the probability that the maximum power demand exceeds the aggregate available capacity in each period t.

There are several difficulties in using the constraint as it is written. First, it is not clear what the optimal value of e should be. The correct value can only be determined after a difficult benefit-cost calculation of the value to society from a secure power supply. It appears that the value for e is usually chosen from experience. Another difficulty with the constraint is that it involves a very complex calculation using the probability distributions for $\widetilde{MAXLOAD}_t$

and the availabilities, $\widetilde{PAV}_{jvt}$. Further it is unlikely that the distributions for the $\widetilde{PAV}$'s are known by the user. Usually, only the expected values of the availabilities are known or can be assumed, and the Generation Expansion Model is formulated with only the expected values as input data. With this simplification in mind, the peak power requirement constraint may be written as

$$Pr\left\{(\widetilde{MAXLOAD}_t - \sum_{j\epsilon J} \sum_{v=-V}^{t} PAV_{jvt}*CAP_{jv}*\underline{X}_{jv}) > 0\right\} \leq e$$

where the PAV's are now the mean expected values. The constraint can then be reformulated in terms of the normalized cumulative probability function for $\widetilde{MAXLOAD}_t$:

$$F\left[\frac{\sum\sum PAV_{jvt}*CAP_{jv}*\underline{X}_{jv} - Exp(\widetilde{MAXLOAD}_t)}{\sigma(\widetilde{MAXLOAD}_t)}\right] \geq 1-e \quad (4-2)$$

or

$$\sum_{j\epsilon J}\sum_{v=-V}^{t} PAV_{jvt}*CAP_{jv}*\underline{X}_{jv} \geq Exp(\widetilde{MAXLOAD}_t)$$

$$+F^{-1}(1-e)*\sigma(\widetilde{MAXLOAD}_t). \quad (4-3)$$

The constraint is still relatively complicated, requiring knowledge of the complete distribution for $MAXLOAD_t$. A final simplifying definition is made to improve the tractability of the equation; define a function ξ_t as follows:

$$\xi_t = \frac{F^{-1}(1-e)*\sigma(\widetilde{MAXLOAD}_t)}{Exp(\widetilde{MAXLOAD}_t)}$$

The peak power constraint may then be simplified to

$$\sum_{j \in J} \sum_{v=-V}^{t} PAV_{jvt} * CAP_{jv} * \underline{X}_{jv} \geq MAXLOAD_t * (1 + \xi_t) \quad ,$$

$$t = 1. \ . \ .T$$

$$(4-4)$$

where

ξ_t may be interpreted as the margin of spare available capacity over and above what is required to meet the mean expected demand in period t.

The variables $MAXLOAD_t$ and PAV_{jvt} are now the mean expected quantities. Some of the rigor lost in simplifying this constraint in the Plant Expansion Model can then be regained in the Plant Operation Model which follows it. If the loss-of-load probability calculated by the Plant Operation Model for the selected generation expansion plan is too small or too large, it may result in an iteration of the Plant Expansion Model with different values specified for ξ_t. The spare available capacity margin may also be used to generate alternate expansion plans if the user wishes to observe the sensitivity of system costs as a function of the loss-of-load probability.

4.2.2 The Energy Demand Constraint.

The constraint which ensures that the energy demanded by consumers is supplied by the system is quite similar to the power requirement constraint. The manner in which pumped

storage hydro plants are included in the constraint requires some care since the energy they generate is stored energy that has been generated by the other plants in the system. The constraint requires that the energy produced in period t by all plants built before period t, except the pumped storage hydro plants, minus the transmission and pumping energy losses associated with the pumped storage plants, must be greater than or equal to the expected energy demand in period t. Algebraically,

$$\sum_{j \notin PS} \sum_{v=-V}^{t} PER * CAPFAC_{jvt} * CAP_{jv} * \underline{X}_{jv}$$

$$- \sum_{j \in PS} \sum_{v=-V}^{t} (1/\eta_{jv} - 1) * PER * CAPFAC_{jvt} * CAP_{jv} * \underline{X}_{jv} \geq ED_t, \qquad t=1. \ . \ .T$$

$$(4-5)$$

where

        PER = the length of a time period of the study,

  $CAPFAC_{jvt}$ = the predetermined capacity factor for plant type j and vintage v in the time period t,

    η_{jv} = the overall efficiency of a pumped storage hydro plant of type j and vintage v (energy supplied by the hydro plant/energy supplied to the hydro plant), and

    ED_t = the expected energy demand in period t.

The constraint does not allow energy to be stored in one time period for use in the following period. All of the energy generated by the pumped storage plants is implicitly included in the capacity factor histories for that period of the other types of plants.

4.2.3 Committed and Constructed Plants.

This constraint ensures that the status quo of the actual system at the beginning of the case study is simulated. For plants already constructed, the constraint is

$$\underline{X}_{jv} = XC_{jv} \quad , \qquad (4-6)$$

for all vintages v=-V to zero and all j types of plants. XC_{jv} is the number of plants of type j and vintage v that have been built. It is not necessary to include this constraint for classes of plants that have not been constructed. For plants committed for construction in the initial time periods of the model, the constraint is

$$\underline{X}_{jv} \geq XC_{jv}, \qquad (4-7)$$

where XC_{jv} is now the number of plants of type j that have been committed for operation beginning in vintage period v.

4.2.4 The Class Introduction Rate Constraint.

This constraint serves to limit the rate at which new technologies for generating electricity can be introduced into the market place. If he elects to employ this constraint, the user must determine the upper bound on the number of plants in the ith class of plant types that can be constructed in vintage period v; he must also specify this upper bound for all periods in which the construction of the class is constrained. The formulation of the constraint is

$$\sum_{j \epsilon R_i} \underline{X}_{jv} \leq XR_{iv} \quad , \qquad (4-8)$$

107

where XR_{iv} is the cumulative number of plants in the ith class
of plant types that may be built in vintage period v, and R_i
denotes the set of plant types included in the ith class.
Note that several types of plants, for example, all types of
PuO_2-fueled nuclear reactors, can be specified as being in a
given class for the purpose of this constraint.

4.2.5 Site Constraints.

The site constraints are included in the linear pro-
gramming formulation in order to limit the number of sites and
their corresponding environmental resources. This is done so
that the effect of any scarcity in sites on the optimal expan-
sion plan can be examined.. Two sets of site constraints are
included in the model; one for hydro and pumped storage plants
and one for thermal plants. For the purposes of these con-
straints, the site requirements for hydro plants are considered
to be different from those for thermal plants. That is to say
that a hydro plant would never be built on a thermal site and
vice versa. The site requirements, or size, for a hydro site
are measured in terms of the capacity of the largest hydro or
pumped hydro plant which can be built on that site. The hydro
site constraints are formulated as follows:

$$\sum_{j \in HS_h} \sum_{v=1}^{T} X_{jv} \leq NHSA_h , \qquad (4-9)$$

where

HSZ_h = the size of a hydro site measured in terms of

108

the capacity (MWe) of the largest hydro or
pumped storage plant which can be built on that
site,

HS_h = the set of all hydro and pumped hydro plants
with capacity HSZ_h or greater, and

$NHSA_h$ = the number of hydro sites available which can
support hydro or pumped storage plants with
capacity HSZ_h or greater.

To be more specific about the site availability let

NH_h = the number of hydro sites available which can
support hydro or pumped storage plants with
exactly capacity HSZ_h, then

$$NHSA_h = \sum_{i=h}^{H} NH_i \ . \qquad (4\text{-}10)$$

As can be seen, for this formulation it is assumed that only
one plant per site will be built. Further, it is assumed
that there is a single resource associated with the hydro
sites, that being the maximum capacity of a plant which can
be built on that site.

The hydro site constraints require that the set of all
hydro and pumped storage plants built with capacity HSZ_h or
larger must be less than or equal to the number of sites which
can support plants with capacity HSZ_h or larger. Perhaps an
example would help exemplify these constraints. Suppose there
exist sites with the following sizes and in the following
number.

h	HSZ_h	NA_h	$NHSA_h$
1	500	3	6
2	1,000	2	3
3	1,500	1	1

Also let there be three types of hydro plants which can be considered as alternatives with the decision variable designations and capacities shown below.

Designation	Capacity (MWe)
$\underline{X}_1$	500
$\underline{X}_2$	1,000
$\underline{X}_3$	1,500

The constraint set generated by the situation described above would then be as follows:

$$\underline{X}_1 + \underline{X}_2 + \underline{X}_3 \leq 6 \qquad (4\text{-}11)$$

$$\underline{X}_2 + \underline{X}_3 \leq 3 \qquad (4\text{-}12)$$

$$\underline{X}_3 \leq 1 \ . \qquad (4\text{-}13)$$

The thermal site constraints are similar to the hydro site constraints except that they measure site size in terms of the four environmental resources. The thermal site constraints are formulated as follows:

$$\sum_{j \varepsilon TS_{alcws}} \sum_{v=1}^{T} \underline{X}_{jv} \leq NTSA_{alcws} \ , \qquad (4\text{-}14)$$

where

$\qquad TS_{alcws}$ = the set of all thermal plants which require

110

site type s with at least the quantity of

environmental resources as indexed by a, l,

c and w as defined below.

a - indexes the level of air pollution,

l - indexes the amount of land,

c - indexes the consumptive use of water, and

w - indexes the heat dissipation capacity.

$NTSA_{alcws}$ = the number of sites of type s available

which can support thermal plants with the

environmental resource requirements indexed

by a, l, c and w or greater.

As with the hydro site constraints, the thermal site

constraints only permit one plant to be built per site.

4.2.6 The Fuels Constraints.

The market situation for the fuels which might be

consumed by electric generating plants is often complex and

unclear. In some cases, new fuel contracts cannot be negoti-

ated because adequate future supplies are simply not available.

In other cases, expanding demand for the fuel means only that

higher prices will be paid to cover the increased costs of

drilling deeper wells or importing from more distant supplies.

In still other cases, notably the nuclear fuels ^{233}U and fis-

sile plutonium, supplies for future plants can only be bred

from fertile materials inserted in plants which are presently

operating, since these fuels are no longer found to exist

naturally. The set of algebraic constraints needed to simulate the diverse conditions mentioned above must be complete but must allow considerable flexibility in application. It is believed that the fuel constraints below, patterned after the fuel constraints in the USAEC systems analysis model discussed in Chapter 2, meet these criteria.

Completeness is achieved by including constraints in the model for the availability of ^{233}U, fissile plutonium, depleted uranium tails, U_3O_8, and each of twelve types of fossil fuels which may be defined in a case study. Flexibility is maintained in several ways. First, the user has several optional methods of applying these constraints. They may be entirely omitted. They may be used to accumulate the usage of a certain type of fuel for reporting purposes. Or they may be used to require a higher market price for a fuel as a function of its cumulative demand. Finally, they may be used to simply reflect a different price schedule over time for a fuel than the price schedule entered in PACTOLUS for the earlier economic evaluations performed there. When changing the price of fuel used by the plant from the schedule used in PACTOLUS, the new fuel prices should reflect the altered tax deductions for fuel expenses.

With appropriate definitions, or re-definitions, of the variables in the model, the user can achieve a final degree of flexibility. As an example, pre-production of ^{235}U-enriched fuel by the USAEC gaseous diffusion plants might be simulated

by defining a new plant alternative that consumes electricity and U_3O_8 at the beginning of the case and discharges ^{235}U- enriched UF_6 in later periods.

Several of the nuclear fuel constraints are written such that the nuclear plants selected in the generation expansion plan cannot consume more fuel by the end of a given period than the total of the net contributions to the fuel stockpile in all previous periods from all other plants. That is, fuel stockpiles are maintained at a surplus; no borrowed fuel material is permitted to cross the boundaries of the model from some other stockpile. When the Generation Expansion Model is used for case studies that are national in scope, these constraints may not be unreasonable. They are probably less justified in a regional case study and the user may wish to initialize the stockpile levels so that these constraints are not binding. A similar difficulty arises if the user opts to require the price of a certain fuel to rise as a function of the cumulative demand for the fuel. Several researchers have estimated the quantities of fuels available at different price levels as a function of the cumulative demand for the fuel. If the Generation Expansion Model is being used in a regional study, the quantities of fuel available at different price levels as a function of regional demand are probably impossible to determine. In this case the user might elect to define only one price level for the fuel and specify that the price at this one level rises over time based on the results

of other global models.

4.2.6.1 The ^{233}U Stockpile Constraint.

This constraint requires that the net contribution (discharge minus fabrication) of ^{233}U-fuel from all contributing reactors in a given time period plus the stockpile of ^{233}U-fuel from the previous period must equal the ^{233}U stockpile at the end of the period.

$$\sum_{j \in N} \sum_{v=-V}^{t} U233P_{jvt} \, \underline{X}_{jv} + \underline{U233}_{t-1} = \underline{U233}_{t} \, ,$$

$$t = i. \, . \, .T \qquad (4\text{-}15)$$

where

$\qquad U233P_{jvt} = $ the net contribution of ^{233}U to the ^{233}U stockpile in period t by a nuclear plant of type j and vintage v, and

$\qquad \underline{U233}_{t} = $ the amount of ^{233}U in the stockpile in period t.

The constraint initializing the quantity of fuel in the ^{233}U-stockpile at the beginning of the study period is

$$\underline{U233}_{0} = U2330 \qquad (4\text{-}16)$$

$\qquad$ where U2330 is input from punched cards.

The linear programming code will not permit the decision variables $\underline{U233}_{t}$ to be negative in a feasible solution. Thus, no ^{233}U may be consumed until it is produced.

4.2.6.2 The Fissile Plutonium Stockpile Constraint.

The constraint describing the mass balance of the

fissile plutonium stockpile (^{239}Pu and ^{241}Pu) is quite similar

to the ^{233}U stockpile equation. It requires that the net con-

tribution (discharge minus fabrication) of fissile plutonium

from all contributing reactors in a given time period plus the

stockpile of fissile plutonium from the previous period must

equal the fissile plutonium stockpile at the end of the time

period.

$$\sum_{j\epsilon N}\sum_{v=-V}^{t} PUP_{jvt}*\underline{X}_{jv} + \alpha *\underline{FSPU}_{t-1} = \underline{FSPU}_{t} \ ,$$

$$t=1. \ . \ .T$$

$$(4-17)$$

where

PUP_{jvt} = the net contribution of fissile plutonium

to the plutonium stockpile in period t by a

nuclear plant of type j and vintage v,

$\underline{FSPU}_{t}$ = the quantity of fissile plutonium in the

stockpile in period t, and

α = the fraction of fissile plutonium remaining

after a one time period decay of an assumed

mix of 15% ^{241}Pu and 85% ^{239}Pu.

The constraint initializing the quantity of fuel in the pluto-

nium stockpile at the beginning of the study period is

$$\underline{FSPU}_{0} = PU0 \qquad\qquad (4-18)$$

where PU0 is input from punched cards.

The linear programming code will not permit the decision vari-

ables $\underline{FSPU}_{t}$ to be negative in a feasible solution, and the

stockpile will therefore be maintained at a surplus.

4.2.6.3 The Depleted Uranium Tails Stockpile Constraint.

The last stockpile constraint is applied to the material balance of the ^{235}U-depleted uranium tails. In many respects this constraint is similar to the other stockpile constraints. One difference is that the material balance in the stockpile is permitted to be at a deficit. A deficit in this stockpile will then be entered into the constraint describing the U_3O_8 purchases for the same period. In this manner, a tails deficit in a given period will require a compensating purchase of U_3O_8 in the same period. The equation is

$$\sum_{j \in N} \sum_{v=-V}^{t} TAILP_{jvt} * X_{jv} + TAIL_{t-1} = TAIL_t - NTAIL_t ,$$

$$t=1. . .T$$

$$(4-19)$$

where

$TAILP_{jvt}$ = the net contribution (fabrication minus discharged fuel credit) of depleted tails to the tails stockpile in period t by a nuclear plant of type j and vintage v,

$TAIL_t$ = the surplus tails in the stockpile in period t, and

$NTAIL_t$ = the amount of the deficit in the tails stockpile in period t.

The deficit in the stockpile, $NTAIL_t$, will then be added to the purchases of U_3O_8 in period t. The linear

programming code will select a generation expansion plan such that either $\underline{TAIL}_t$ is non-negative and $\underline{NTAIL}_t$ is zero, or vice versa. Thus ($\underline{TAIL}_t$ minus $\underline{NTAIL}_t$) may be either positive or negative, and this difference represents the material balance in the stockpile. The constraint that initializes the tails stockpile is

$$\underline{TAIL}_0 = TAIL0 , \qquad\qquad (4-20)$$

where TAIL0 is entered from punched cards.

4.2.6.4 The U_3O_8 Consumption Constraint.

This constraint requires the cumulative U_3O_8 purchases at **all** price levels to be sufficient to provide for the net consumption (fabrication minus discharge credits) of all nuclear reactors during the period plus any U_3O_8 required to replenish a deficit in the tails stockpile. Mathematically,

$$\sum_{j\epsilon N} \sum_{v=-V}^{t} U3O8C_{jvt}*\underline{X}_{jv} + \underline{NTAIL}_t = \sum_{m\epsilon M_1} \underline{NFP}_{1mt} ,$$

$$t=1. . .T \quad (4-21)$$

where

$U3O8C_{jvt}$ = the net consumption of U_3O_8 by a plant of type j and vintage v in period t, and

$\underline{NFP}_{1mt}$ = the amount of U_3O_8 (index f=1) purchased at price level m in period t.

The sum over the price level index, m, includes all purchases at all input price levels. In this model, there are thirteen types of fuel that can be purchased from sources

outside the boundaries of a region. U_3O_8 is the first one to be considered and it is assigned the index f=1. The other twelve types are the twelve fossil fuels discussed in the previous chapter and they are assigned the indexes f=2 through f=13. The fossil fuel constraints will be discussed below.

The decision variables $\underline{NFP}_{lmt}$ are included in the model in two other places. First, a separate equation is written for the amount of U_3O_8 available at each price level m. Second, at the user's option the variables $\underline{NFP}_{lmt}$ may appear explicitly in the objective function of the model. In the objective function, they are multiplied by the discounted unit fuel cost appropriate for price level m and added to the other costs of the generating system. Since the linear programming code is attempting to minimize this total cost, the quantity of fuel available at the least expensive price level will always be consumed first. Obviously, if enough fuel is not available at any price level to include a given plant in the solution, the program will reject that plant. It is also possible, however, that the program will begin selecting otherwise more expensive plants if building more of one type of plant would require use of fuel at a higher price level.

4.2.6.5 The Fossil Fuel Consumption Constraint.

The equation describing the consumption of the twelve fossil fuel types is similar to the U_3O_8 consumption constraint. The equation is

$$\sum_{j \varepsilon F} \sum_{v=-V}^{t} FC_{fjvt} * \underline{X}_{jv} = \sum_{m=M_f} \underline{NFP}_{fmt} \quad ,$$

$$t=1. \ . \ .T$$
$$f=2. \ . \ .13 \qquad (4-22)$$

where

> FC_{fjvt} = the amount of fuel of type f (f=2 through 13)
>
> consumed by a plant of type j and vintage v
>
> in period t, and
>
> $\underline{NFP}_{fmt}$ = the amount of fuel of type f purchased in
>
> period t at price level m.

The summation over the index m is over all price

levels specified for type f fuel.

4.2.6.6   The Fuel Availability Constraint.

The constraint limiting the amount of fuel available

at a given price level is

$$\sum_{t=1}^{T} \underline{NFP}_{fmt} \leq UFA_{fm} \quad ,$$

$$f=1. \ . \ .13$$
$$m=1. \ . \ .M_f \qquad (4-23)$$

where

> UFA_{fm} = the quantity of fuel type f available at
>
> price level m.

This constraint requires the amount of fuel type f at

price level m purchased over all periods in the case study to

not exceed the quantity of type f fuel available at price

level m.

4.2.7 The Objective Function.

The objective function of the linear programming model is to minimize the total present worth of all capital, operating, and fuel costs, including tax payments and indirect interest charges, that are incurred with the chosen generation expansion plan. The objective function is

$$\text{minimize } z = \sum_{j \in J} \sum_{v=1}^{T} C_{jv} * \underline{X}_{jv} + \sum_{f=1}^{13} \sum_{m \in M_f} \sum_{t=1}^{T} CFP_{fmt} * \underline{NFP}_{fmt} , \qquad (4-24)$$

where

C_{jv} = the present worth at the start of the study period of all capital and operating charges, tax payments, and interest charges incurred for a plant of type j and vintage v, and

CFP_{fmt} = the present worth direct cost of a unit of type f fuel at price level m in period t.

All costs are discounted to the first period of the case study. The C_{jv}'s are discounted by the individual discount factor for the plant that was calculated in PACTOLUS. The unit fuel costs are discounted by an average discount factor supplied as input to the model by the user.

Actually there are three optional formulations for the complete linear programming model that may be selected by the user; these formulations will be discussed in the next section. Two of the formulations permit the use of what is designated the "reduced objective function". In the reduced objective

120

function, the fuel consumption variables, $\underline{NFP}_{fmt}$, do not appear explicitly. Rather than separating out the fuel consumption in this case, the charges for fuel consumption are included directly in the C_{jv} factors based on the fuel price schedules entered for the PACTOLUS economic evaluations.

4.2.8 Formulation Variations.

As mentioned above, there are three optional variations in the Plant Expansion Model formulation. Each variation consists of a different combination of the equations discussed in the previous sections. The method by which the user selects the different formulations is discussed in Section 4.3.1.

The first formulation is designated Formulation One, or the Full Formulation. As the name implies, the complete objective function and all of the constraint equations are used in this formulation.

Formulation Two is called the Reduced Objective Function Formulation. In this case, all of the constraint equations are used in the model, but the aggregate fuel consumption quantities at the different price levels, $\underline{NFP}_{fmt}$, are not included in the objective function as separate variables. In the PACTOLUS calculations discussed in the previous chapter, two cost figures are determined for each alternative and are written on File 16 for use by the Plant Expansion Model. The first cost figure is the present worth at the beginning of the vintage year of all capital, operating, and

121

fuel costs, tax payments, and interest charges incurred with each plant alternative. The second cost includes the same factors included in the first cost except that the present value of all direct expenses for U_3O_8 or the twelve fossil fuels is omitted. In the Full Formulation version, the matrix generator will automatically characterize the plant alternative by this second cost. The fuel consumed by the plant will be aggregated with that consumed by the other plants and priced at the new price levels in the objective function. In the Reduced Objective Function Formulation, the matrix generator will choose the first cost coefficient and will not include the aggregate fuel consumption variables in the objective function. The direct expenses for fuel are still implicitly included in the expansion plan costs to be minimized, of course, but they are based on the fuel prices entered as data in PACTOLUS. The fuel constraint equations may still be used in Formulation Two to limit the availability of fuel. The aggregate consumption variables, $\underline{NFP}_{fmt}$, are still calculated and may be used in the report generator as useful information about the selected generation expansion plan.

Formulation Three is designated the Formulation Without Fuel Constraints. If the user selects this option, the matrix generator will not include any of the fuel constraints discussed above in Section 4.2.6; it will also choose, obviously, the "reduced objective function" to be minimized.

4.2.9 Horizon Conditions.

In all investment modeling studies using models similar to the one described above, the user must remain aware of the myopic nature of the model. The model looks ahead only a finite number of periods whereas electric generating systems will continue to exist well beyond this time. Post horizon generating opportunities would obviously affect the chosen generation expansion plan if they were included in the study; their exclusion biases the solution from the true optimum. One way to reduce this bias, although it will not completely eliminate it under all conditions, is to extend the case study and data well beyond the desired end of the study. In this way, the manager's best estimates of the immediate post horizon projects will actually be included in the model.

A related reason for extending the study period is to ensure that all fuel consumed by the chosen plants is properly considered in the expansion plan. This is especially important when using the Full Formulation version of the model. If excess fuel is available for the forseeable future and all fuel costs are already included in the cost coefficient generated in PACTOLUS, this should not be a problem.

Finally, the user must be aware that the selected expansion plan is only optimal in light of the set of investment opportunities that have been defined for the study. If important options have been omitted, the selected plan cannot possibly be the true optimum.

The final section of this chapter discusses in some detail the computer codes in the Plant Expansion Model and the data they require.

4.2.10 Plant Expansion Model - Linear Programming Formulation Summary.

Objective Function.

The Complete Objective Function:

$$\text{minimize } z = \sum_{j \epsilon J} \sum_{v=1}^{T} C_{jv} * \underline{X}_{jv} + \sum_{f \epsilon F} \sum_{m \epsilon M_f} \sum_{t=1}^{T} CFP_{fmt} * \underline{NFP}_{fmt}$$

$$(4-24)$$

The Reduced Objective Function:

$$\text{minimize } z = \sum_{j \epsilon J} \sum_{v=1}^{T} CT_{jv} * \underline{X}_{jv} \qquad (4-25)$$

Constraint Set.

Peak Power Requirement:

$$\sum_{j \epsilon J} \sum_{v=-V}^{t} PAV_{jvt} * CAP_{jv} * \underline{X}_{jv} \geq MAXLOAD_t * (1 + \xi_t) \quad (4-4)$$

$$t = 1. \; . \; .T$$

Energy Demand

$$\sum_{j \notin PS} \sum_{v=-V}^{t} PER * CAPFAC_{jvt} * CAP_{jv} * \underline{X}_{jv}$$

$$- \sum_{j \epsilon PS} \sum_{v=-V}^{t} (1/\eta_{jv} - 1) * PER * CAPFAC_{jvt} * CAP_{jv} * \underline{X}_{jv} \geq ED_t$$

$$t = 1. \; . \; .T$$
$$(4-5)$$

Committed and Constructed Plants

$$\underline{X}_{jv} = XC_{jv} \qquad\qquad\qquad (4-6)$$
$$j=1. \; . \; .J, \; v=-V. \; . \; .0$$
$$\underline{X}_{jv} \geq XC_{jv} \qquad\qquad\qquad (4-7)$$
$$j=1. \; . \; .J, \; v=1. \; . \; .T$$

124

Class Introduction Rates

$$\sum_{j \in R_i} \underline{X}_{jv} \leq XR_{iv} \qquad i=1...I \qquad (4\text{-}8)$$

Site Constraints

$$\sum_{j \in HS_h} \sum_{v=1}^{T} \underline{X}_{jv} \leq NHSA_h \qquad h=1...H \qquad (4\text{-}9)$$

$$\sum_{j \in TS_{alcws}} \sum_{v=1}^{T} \underline{X}_{jv} \leq NTSA_{alcws}$$

$$\text{for all } a, 1, c, w, s \text{ indexes} \qquad (4\text{-}14)$$

Fuel Constraints

$$\underline{U233}_0 = U2330 \qquad (4\text{-}16)$$

$$\sum_{j \in N} \sum_{v=-V}^{t} U233P_{jvt} * \underline{X}_{jv} + \underline{U233}_{t-1} = \underline{U233}_t \qquad (4\text{-}15)$$

$$t=1...T$$

$$\underline{FSPU}_0 = PU0 \qquad (4\text{-}18)$$

$$\sum_{j \in N} \sum_{v=-V}^{t} PUP_{jvt} * \underline{X}_{jv} + \alpha * \underline{FSPU}_{t-1} = \underline{FSPU}_t \qquad (4\text{-}17)$$

$$t=1...T$$

$$\underline{TAIL}_0 = TAIL0 \qquad (4\text{-}20)$$

$$\sum_{j \in N} \sum_{v=-V}^{t} TAILP_{jvt} * \underline{X}_{jv} + \underline{TAIL}_{t-1} = \underline{TAIL}_t - \underline{NTAIL}_t \qquad (4\text{-}19)$$

$$t=1...T$$

$$\sum_{j \in N} \sum_{v=-V}^{t} U3O8_{jvt} * \underline{X}_{jv} + \underline{NTAIL}_t = \sum_{m \in M_1} NFP_{1mt} \qquad (4\text{-}21)$$

$$t=1...T$$

125

$$\sum_{j \in F} \sum_{v=-V}^{t} FC_{fjvt} * \underline{X}_{jv} = \sum_{m \in M_f} \underline{NFP}_{fmt} \qquad (4-22)$$

$$f=2. \ . \ .13$$
$$t=1. \ . \ .T$$

$$\sum_{t=1}^{T} \underline{NFP}_{fmt} \leq UFA_{fm} \qquad (4-23)$$

$$m=1. \ . \ .M_f$$
$$f=1. \ . \ .13$$

Summary of Major Variables

Decision Variables.

$\underline{X}_{jv}$ — the number of plants of type j built in period v.

$\underline{NFP}_{fmt}$ — the number of units of fuel of type f purchased at price level m in period t.

$\underline{U233}_t$ — the amount of ^{233}U in the ^{233}U stockpile at the end of period t. (kg ^{233}U)

$\underline{FSPU}_t$ — the amount of fissile plutonium in the plutonium stockpile at the end of period t. (kg Pu)

$\underline{TAIL}_t$ — the surplus of uranium in the tails stockpile at the end of period t. (kg U)

$\underline{NTAIL}_t$ — the deficit of uranium in the tails stockpile at the end of period t. (kg U)

Coefficients

C_{jv} — the total present worth of all capital and operating costs (excluding fuel costs) associated with a plant of type j built in period v. ($)

126

CFP_{fmt} — the present worth of a unit of fuel of type f purchased at price level m in period t. ($/unit)

PAV_{jvt} — the availability in period t of a plant of type j built in period t. (fraction)

PER — the length of period t. (hours)

$MAXLOAD_t$ — the expected peak power required during period t. (MW)

ξ_t — the margin of spare available capacity in period t over and above what is needed to meet the expected power requirement.

ED_t — the expected energy demand during period t. (MWhr)

XC_{jv} — the number of plants of type j that are committed to be built in period v.

$U2330$ — the amount of ^{233}U in the ^{233}U stockpile in period 0. (kg U)

$PU0$ — the amount of fissile plutonium in the plutonium stockpile in period 0. (kg Pu)

$TAIL0$ — the amount of depleted uranium tails in the tails stockpile in period 0.

UFA_{fm} — the amount of fuel of type f available at price level m.

$NHSA_h$ — the number of sites available which can support a hydro plant of at least capacity h.

$NTSA_{alcws}$ — the number of sites of type s available which can support a thermal plant generating a units of air pollution, and requires at least l land, w water for cooling, and c water for consumptive use.

CAP_{jv} — the capacity of a plant of type j built in period v. (kw)

$CAPFAC_{jvt}$ — the capacity factor in period t of a plant of type j built in period v. (fraction)

η_{jv} — the ratio of the amount of energy which will be produced by a pumped hydro plant of type j built in period v to the amount which must be supplied to it.

$U233P_{jvt}$ — the net contribution (discharge-fabrication) of ^{233}U to the ^{233}U stockpile in period t by a plant of type j built in period v. (kg ^{233}U)

PUP_{jvt} — the net contribution (discharge-fabrication) of plutonium to the plutonium stockpile in period t by a plant of type j built in period t. (kg Pu)

α — the fraction of fissile plutonium remaining after decay during one year.

$TAILP_{jvt}$ — the net contribution (discharge-fabrication) of tails to the tails stockpile in period t by a plant of type j built in period v. (kg U)

$U3O8C_{jvt}$ — the net consumption (fabrication-discharge) of U_3O_8 in period t by a plant of type j in period v. (kg U)

FC_{fjvt} - the net consumption of fuel type f in period t by a

   plant of type j built in period v.

4.3 PROTEUS.

   The IBM Mathematical Programming System - Extended
(MPSX) is used to solve the Plant Expansion Model linear pro-
gramming formulation discussed in the previous section. The
function of PROTEUS is to produce a description of the formu-
lation in a suitable format for input to the MPSX system.
This format, described in the MSPX User's Manual, requires that
the data be in card image form. PROTEUS reads data describing
the cost coefficients and the right hand sides of the equa-
tions from cards and plant alternative coefficient data from
File 16, generates the matrix data describing the problem, and
writes the formulation on File 21 in the format required by
MPSX. Then File 21 is specified as the input data set for the
MPSX system.

   PROTEUS consists of two major sections of code, sub-
routine MATT and subroutine LPOUT. MATT, which is called
first, reads the cost and right hand side data from cards,
checks the data for errors and completeness, and finally pro-
cesses the data for LPOUT. LPOUT uses the data on File 16
describing each plant alternative and the data supplied by
MATT to generate the matrix data describing the linear pro-
gramming formulation; it then writes the formulation descrip-
tion on File 21 in a format suitable for input to the MPSX

system.

4.3.1 Subroutine MATT.

The first step in MATT is to read into core the eleven sets of cards required as data by PROTEUS. These cards contain such information as peak power and energy demand histories for the entire study period, fuel availability and costs, committed and constructed plants, and site availability. A detailed description of the content of these cards and their formats may be found in Appendix C of the System Manual.

Each set of cards is preceded by a card with a keyword identifying the set. Some of the card sets contain only the card with the keyword on it. For example, the last card set in the input deck consists of only a single card with the keyword END on it. The TIME DATA card set also consists of a single card; however, it contains other data such as the year in which the study is to start, the first year of the period in which the study is to end, the length of each period, and the discount rate which will be used to present-worth the fuel prices.

LOAD DATA is the keyword which identifies the card set containing the peak load and energy demand history. This card set consists of one card for each period in the study and contains the number of the period, the expected peak power demand during that period in MW, the total expected energy demand during that period in millions of MWhr, and the margin for

130

spare available capacity as a fraction.

There are three mutually exclusive ways of describing the fuel data, each of which corresponds to one of the three possible formulations discussed earlier. For Formulation One, the Full Formulation, thirteen subsets of data are required. Each subset contains data describing the availability and cost of the thirteen fuel types and is preceded by a card with the keyword FUEL DATA on it. In the linear programming formulations and in PROTEUS fuel type one corresponds to U_3O_8 and fuel types two through thirteen correspond to fossil fuel types one through twelve as defined in File 12. Up to five price levels and corresponding fuel availabilities are allowed for each type of fuel. The cost of fuel for each price level must be entered for each period in the study. The cost and availability of U_3O_8 are input in $/million kg and millions of kgs respectively. The fossil fuel data is entered similarly in the units used in FUFC and PACTOLUS to describe the fuel consumption.

For Formulation One availability and cost data must be entered for each of the thirteen types of fuel, even if the availability is specified as zero. If Formulation One has been specified both the fuel constraints and the fuel consumption variables are included in the formulation and the fuel consumption variables are included in the objective function. The plant costs, C_{jv}, will not include the fuel costs.

If no fuel data is entered, then PROTEUS selects

131

Formulation Two, the Reduced Objective Function Formulation. In this case the fuel constraints and the fuel consumption variables are still included in the formulation; however, the fuel consumption variables are not included in the objective function. Instead, the fuel costs are implicitly included in the plant cost.

Formulation Three, the Formulation Without Fuel Constraints is indicated by entering a single card with the keyword NO FUEL on it. This card signals PROTEUS to generate the formulation without fuel constraints and without fuel consumption variables. As with Formulation Two, the fuel costs are included in the plant costs.

If Formulations One or Two have been specified the initial condition of the stockpiles must be input. This is accomplished by entering a card with the keyword STOCKPILE on it, as well as the initial conditions of the ^{233}U, plutonium, and tails stockpiles in millions of kilograms, thousands of kilograms and thousands of kilograms respectively.

To include committed or constructed plants in the formulation, a card with the keyword COMMITTED PLANT DATA must be entered followed by a list of plant alternatives and the corresponding number committed or constructed. As discussed earlier, the constructed plant constraints are written as equalities and the committed plant constraints are written as lower bounds. To choose the correct formulation, PROTEUS compares the plant vintage year with the starting year of the

study. If the vintage year is earlier than the study start year, the constraint is written as an equality; otherwise it is written as a lower bound.

The class introduction rate data, if any is to be included, is preceded by a card with the keyword INTRODUCTION RATE DATA on it. The data which follows that card consists of a list of plant alternatives to be included in a class and the upper limit, XR, on the number of plants belonging to that class which may be built. This constraint adds a great deal of flexibility to the model since it may be used for purposes other than limiting the rate at which new technologies may be introduced to the system. For example, this constraint can be used to exclude alternatives from the solution by including them as one class of plants and setting the corresponding XR to zero.

The site availability data is entered on two sets of cards, one for the hydro constraints, preceded by the keyword HYDRO SITE DATA, and one for the thermal site constraints, preceded by the keyword THERMAL SITE DATA. The hydro site data consists of up to five sets of hydro site sizes and the corresponding number available. The size of a hydro site is currently measured in terms of the capacity, in MWe, of the largest hydro or pumped storage plant which could be built on that site. Further, each site size entered as data represents a range of possible sizes. If it is possible to build a hydro or pumped storage plant which requires a hydro site larger

than any available site the user must be careful to enter an upper limit on the available site sizes with a zero availability. The thermal site data is entered in a similar fashion as the hydro site data except that four site sizes and the site type must be input. The four thermal site sizes include the air pollution level index, the amount of land available, in acres, the amount of water available for consumptive use, in cubic feet per second, and the amount of water surface area available for heat dissipation, in acres. As with the hydro data, if it is possible to build a plant which consumes more of the environmental resources than are available at the largest site, an upper limit on the site sizes must be entered with zero availability.

After all the data cards have been read, MATT then checks the data for completeness and processes the data for use in LPOUT. If load data has not been entered for each time period in the study, or if fuel availability has been entered but not for all types, the corresponding error message is printed and processing of LPOUT is prohibited. Further, if fuel data has been entered, fuel prices must be input for each price level specified and for each time period in the study.

If no errors are encountered in the data check, MATT sums the site availability data to determine the number of sites available which can support plants requiring sites with resource sizes greater than or equal to the sizes specified

in the site data. Next MATT converts all fuel prices to millions of dollars and present-worths them from the middle of their respective periods back to the starting year of the study. Finally, just before transfer of control is made to LPOUT, MATT calls subroutine GEORGE to print the input data that has been processed for use in LPOUT.

4.3.2 Subroutine LPOUT.

The purpose of LPOUT out is to generate a data set describing the linear programming formulation in a format recognizable by the MPSX system. As such, it is necessary to discuss some of the conventions required by MPSX before describing in more detail the operation of LPOUT.

There are seven sets of data which may be input to MPSX to describe a linear programming formulation; five of these are required. Each set of data is preceded by an indicator card, similar to the keyword card used in PROTEUS, which identifies the following card set. The first card in the input stream must be a NAME card and must contain the name of the current problem. The next set of cards contains the name of each of the rows to be included in the formulation. This set of data is preceded by a ROWS indicator card and is one of the required sets. The matrix coefficient data follows the row definition data and is preceded by a COLUMNS indicator card. Every non-zero coefficient in the matrix as well as the corresponding row and column identification must be included

with this required set of data. The next set of cards contain
the right-hand side constraint vector and is preceded by an
RHS indicator card. The next two sections, designated BOUNDS
and RANGES, are not required; they contain any bounds or
ranges, respectively, on the decision variables. Finally, the
last card in the deck must be the ENDATA indicator card.

To identify columns, or decision variables, MPSX re-
quires a name with no more than eight characters. However,
the plant I.D.'s used throughout the Generation Expansion Model
require 28 characters. In order to overcome this problem, the
28 character name is condensed to the five most significant
characters and a three digit serial number is generated to
complete the eight character column name for MPSX. The first
two characters of a column name are the first two characters
of the plant type; the third character is the decade of the
vintage year; the fourth and fifth characters are the third
and fourth digits of the plant size. The last three characters
of the MPSX name are the serial number which starts at one for
the first plant and is indexed by one for each succeeding
plant alternative.

LPOUT consists of six sections of code; each corres-
ponds to one of the sets of data to be input to the MPSX sys-
tem. The first section writes the NAME indicator with the
corresponding problem name on File 21. The next section of
code generates a name for each row to be included in the for-
mulation and writes these names on File 21 preceded by the

ROWS indicator. For MPSX the objective function is included as a row and is named COST by LPOUT. The other rows are given a concatenated name consisting of an abbreviated constraint type identification and the number of the period. For example, the peak load constraint for the second period would be named MAXL02.

The column data is generated in two steps. First, for each plant the corresponding data record is read from File 16. The total present worth at the vintage year of the alternative is present-worthed back to the start of the study using the corresponding discount factor supplied by PACTOLUS. If Formulations Two or Three are specified the present-worth plant cost will include the direct fuel expenses.

The cost is written on File 21 as a coefficient in the COST row. Next the available capacity and energy production coefficients are determined for the plant and included in the corresponding rows and columns. The available capacity of the plant is the average availability for the period. Finally, the corresponding coefficients for any other constraints, including fuel constraints if they have been specified, are written on File 21. · This step is carried out for each plant alternative in File 16. The second step in generating the column data is to write the coefficients for the fuel consumption and stockpile decision variables if Formulations One or Two have been specified.

Next, the right-hand side and bounds sections are

137

written on File 21. Included in the right-hand side constraint vector are the period peak power demands, in MW, the period energy demand, in MWhr, any introduction rates or committed plants, site availability, and the fuel availability if Formulations One or Two have been chosen. The bounds data includes any constructed plants and the initial conditions of the fuel stockpiles. Finally the ENDATA indicator is written on File 21.

Before ending this discussion of PROTEUS, the matrix generator, it may be helpful to review some of the data conventions which are adopted for use in this model. For the data coming from PACTOLUS on File 16 the following units apply: all costs are in millions of dollars, electric power and energy are in MW and MWhr respectively, ^{233}U and plutonium consumption are in thousands of kilograms, tails and U_3O_8 consumption in millions of kilograms, and the fossil fuel consumption is in the units that were input to FUFC. For the data input to PROTEUS from cards, the following conventions apply: peak power demand is in MW, expected energy demand is in millions of MWhrs, and all fuel prices are input in dollars per unit specified in File 16. For the linear programming formulation produced by PROTEUS, these conventions apply: all electric power is measured in MW, electric energy in MWhr, costs in millions of dollars, and fuel consumption in the units in which they were input.

CHAPTER 5

SUMMARY AND RECOMMENDATIONS

A computer model for the determination of optimal
generating system expansion patterns under economic, environ-
mental and reliability considerations has been described. The
model incorporates the complexities of power system generation
expansion planning into a framework which is amenable to com-
prehensive analysis and provides a tool to develop information
and insight for practical decision making. The inputs to the
model consist of a set of possible plant alternatives with
their associated costs, performance, fuel consumption, and
site requirements, a set of constraints describing site avail-
ability, air and thermal pollution limits, system reliability,
and fuel availability, and the projected electrical demand
throughout the study period. From these the model selects the
set of plants which will minimize the total present worth of
all capital, operating, and fuel costs, while satisfying the
demand for electricity, fuel availability, site availability,
pollution and reliability constraints.

The model is intended to be a large scale survey and
planning model and is not intended to be used for detailed de-
sign work. The expansion plans and plant operating histories
determined by the model should not be taken as absolute.
There are many issues and intricacies which exist in the real
world but not in the model. Instead, the plans selected by

the model should be used as a basis for studies by more detailed design systems.

As formulated the Generation Expansion Model consists of three submodels which are operated serially in an iterative fashion. As implemented the model consists of a set of computer codes and a corresponding data base. Although the entire model has been formulated and the major codes written and tested the model has not been fully integrated. As of the writing of this report the computer code needed to interface the Plant Expansion Model with the Plant Operation Model has not been programmed. Therefore the Generation Expansion Model has only been operated and initially tested through the first two submodels. Contained in Appendix B are several test cases for which the Plant Evaluation Model and the Plant Expansion Model were run in conjunction.

Including plant operating histories as decision variables in the model, then, can only be accomplished presently by hand preparation of the interface data cards. However, the fully integrated and operational portion of the model still provides a powerful and useful tool for determining power generation expansion plans. Sensitivity studies examining the base loaded portion of the electric system can be performed by selecting several reasonable capacity factor histories for each of the base loaded units and using them for a consistent evaluation of the different generating technologies. The benefits to the electric system, in terms of total cost

140

reduction and insensitivity to rising fuel prices, limited

quantities of available resources including capital funds, or

postponements in the introduction dates, can be evaluated for

projected new technological options. Of course, the model can

be used to evaluate entire generating systems if the user is

willing to project typical operating histories for the other

types of plants. Further, sensitivity studies can be done to

determine the effect of the assumed operating histories on the

solution.

As currently implemented the operational portion of

the model provides most of the capabilities of the total model.

The operational section is versitile in that the user has the

ability to vary a wide range of parameters and to observe their

effect on the optimal expansion plan. As such, the model has

the capability of factoring environmental and siting considera-

tions into the analysis of power system expansion and can

easily be used to perform the economic-environmental tradeoff

analysis discussed earlier. Sensitivity studies can be made

simply by changing the pollution limits input to the model and

rerunning it. Further, it can be used for actual planning

purposes. For example, a utility can run the model to deter-

mine if cooling towers will be necessary to meet thermal pol-

lution standards and also to determine their effect on the

overall plan and its economics.

Already the model results have shown a marked sensiti-

vity to plant availability. Although the entire model is

required to fully evaluate the importance of this factor in generation expansion planning, the model as currently implemented can be used to partially determine the sensitivities of the model to plant availability.

In order to fully automate the model the small code necessary to communicate the output of the linear programming solution to the simulation program must be written and included in the model. This code, designated REPGEN, is intended to serve two purposes. First it is meant to be the primary report generator for the entire model. Its output will consist of the optimal expansion plan and the associated operating histories, as well as a complete performance and financial description of each alternative. The second function of REPGEN is to determine the loading order of each of the plant alternatives in the expansion plan and communicate that information to SYSGEN, the Plant Operation Model.

After REPGEN is implemented, the model must be thoroughly tested and its limitations determined. Several of the individual computer codes have already been thoroughly tested by their original authors and other organizations, and they are well known in the field. The original version of PACTOLUS, the plant economics code, has been used for over six years in USAEC studies. No major revisions were necessary to adapt PACTOLUS to function within the Generation Expansion Model and the version installed here has been tested against published sample problems. Similarly a version of SYSGEN, the

probabilistic simulation code, has been used for several years in studies conducted by the Nuclear Engineering Department at M.I.T. and other organizations. While we are confident of the methods and adequacy of the individual programs, unforseen problems will almost certainly occur when the model is completed and run as a fully integrated unit. These problems cannot be anticipated at this stage of the model's development, and a thorough period of testing must be conducted before the users can be completely confident in the operation of the overall model.

Several additional recommendations with respect to the use of the model and its possible extensions are included below. First, it is not clear if the proposed iterative search for ξ_t, the margin of spare available capacity in the peak electric load demand constraint, is an efficient way of satisfying the reliability criteria. It may be possible to determine the marginal contribution of each plant to the loss-of-load probability. This factor could be used to modify the expected plant availability in the peak load constraint, and it might lead to a quicker solution for the optimal value of ξ_t.

The second suggestion is to run the expansion model as a mixed integer programming problem with the plant alternatives specified as integer variables and the fuel consumption as continuous variables. As currently implemented the Plant Expansion Model allows fractional plants to be built. The

integer programming formulation would correct this problem.

It is clear from experience gained in running the model that quite often it is desirable to update or change a single piece of information stored in one of the records of the data base. With the current version of the model all the data in that record must be regenerated and often several codes must be re-run. Therefore it is suggested that a set of data file management programs be written to make the updating process more efficient.

The value of the Generation Expansion Model will come through use. It is not meant to yield a single answer indicating the "optimal" expansion plan for a regional power system, but more to show the sensitivity of the issues involved in power system planning. The model should be used as a learning tool to gain insight into the considerations that affect power system planning and to discover the relationships among them. Environmental awareness, increasing demand, and the impending Energy Crisis have forced electric utilities and public policy makers into a difficult situation since they must plan for multiple conflicting objectives. It is hoped that the model will aid in the resolution of these conflicts. We feel that the Generation Expansion Model has the potential to fulfill these goals.

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APPENDIX A

The following pages contain sample printed reports from the major computer codes in the Plant Evaluation Model. Several of these reports are only printed if the user selects that option; the proper method for doing so is identified in the System Manual. In some cases, the format of the report varies depending on the particular type of plant alternative being processed. In other cases, selecting different options in the input card deck for the code will produce additional printing. These options are also listed in the System Manual. Reports from the following codes have been included in this appendix:

PLANT PERFORMANCE AND COST DATA

RECORD ID: LWU1 URO1 1000 1970

FILE: 20   RELATIVE POSITION: 9   •   FILE CREATED: 1/07/73   FILE UPDATED: 1/18/73   UPDATE NUMBER: 5

NET TURBINE HEAT RATE (RATED)	1000.00					BTU/KWHR
CAPACITY (RATED)	1000.00					MWE
BACK PRESSURE (RATED)	2.00					IN HGA
BOILER EFFICIENCY	100.00					%
AUXILIARY POWER	0.0					% RATED CAPACITY
CONDENSER SURFACE AREA	70000.00					SQFT
CONDENSER U-FACTOR	610.00					BTU/HR/SQFT/F
CIRCULATING WATER TEMP RISE	2.00					F
NET TURBINE HEAT RATE (VWO)	10450.00	10750.00	10750.00	11550.00	12350.00	BTU/KWHR
BACK PRESSURE	1.00	2.00	4.00	11.00	23.00	IN HGA
FUEL HEAT EQUIVALENT	0.0					BTU/LB
SULFER CONTENT	0.0					%R
ASH CONTENT	0.0					%W
TOTAL GAS FLOW	0.0					ACFM
GAS TEMPERATURE ENTERING STACK	0.0					F
COST SPECIAL MATERIALS (DEP)	0.0					$
COST SPECIAL MATERIALS (NON-DEP)	0.0					$
COST THERMAL PLANT	0.0					$
COST TURBINE PLANT	24500000.					$
COST ELECTRIC PLANT	0.0					$
COST INDIRECT	0.0					$
COST OTHER CAPITAL	0.0					$
NONFUEL WORKING CAPITAL	2.0					% WORKING CAPITAL
RECOVERABLE LAND COST	0.0					$
SALVAGE VALUE OF PLANT	100000000.					$/YR
PLANT FIXED OPERATING COST	20000.00					$/%CF/YR
PLANT VARIABLE OPERATING COST	0.0					% PLANT INVESTMENT/YR
INTERIM CAPITAL REPLACEMENTS	30.00					YR
DEPRECIABLE LIFE	8.00					YR
CONSTRUCTION TIME	1.00					
FUEL INVENTORY MULTIPLIER	1.00					
FUEL THROUGHPUT MULTIPLIER	0.0					
THERMAL POWER MULTIPLIER	0.0					
HEAT DISSIPATION CAPACITY						SQFT
CONSUMPTIVE USE OF WATER	100.00					CFS
LAND						ACRES

AVAILABILITY   0.85 0.91
STARTING YEAR   1970 1975

FUEL INDUSTRY DATA

RECORD IC: LWUI UR71 1300

FILE: 10   PFLATIVE POSITION: 5   FILE CREATED: 1/02/73   FILE UPDATED: 1/07/73   UPDATE NUMBER: 2

CORE FARRICATION LOSSES   C.45   %
BLANKET FARRICATION LOSSFS   0.45   %
REPROCESSING LOSSES   0.54   %
RECONVERSION LOSSES   0.0   %

******

COST DATA

FIRST YEAR COSTS APPLICABLE   1965.00   2004.00
CORE FUEL FAB COST-$/KG   91.67   39.67
CORE FUEL REP COST-$/KG   42.50   23.00
BLANKET FUEL FAB COST-$/KG   0.0   0.0
BLANKET FUEL REP COST-$/KG   0.0   0.0
ADDITIONAL FAB COST-$/KG   16.00   10.00

151

FUEL DISTRIBUTION DATA
(FUEL CYCLE)

RECORD IDENTIFICATION FROM 1970 1973

FILE ID   RELATIVE POSITION: ?   FILE CREATED: 1/03/73   FILE UPDATED: 1/04/73   UPDATE NUMBER: 2

FABRICATION TIME   25.0   DAYS   SHIPPING COST, POST-SEPARATION   0.0 $/KG
PRE-REACTOR PREPARATION TIME   30.0   DAYS   SHIPPING TIME, POST-SEPARATION   30.00   DAYS
POST-REACTOR COOLING TIME   150.0   DAYS   SHIPPING COST, RECYCLE FUEL, POF-FAB   0.0 $/KG
REPROCESSING TIME   30.0   DAYS   SHIPPING COST, RECYCLE FUEL, PRE-IRR   0.45 $/KG
SHIPPING COST, POF-FAB   0.0 $/KG   NUMBER OF CORE REGIONS   3
SHIPPING TIME, POF-FAB   32.0   DAYS   NUMBER OF BLANKET REGIONS   0
SHIPPING COST, PRE-IRRADIATION   0.55 $/KG   NUMBER OF BATCHES IN REGION   3
SHIPPING TIME, PRE-IRRADIATION   10.0   DAYS   0-GRADED REFUELING, 1-CONTINUOUS REFUELING 0
SHIPPING COST, POST-IRRADIATION   3.04 $/KG   TOTAL REACTOR VOLUME   100.00 LITERS
SHIPPING TIME, POST-IRRADIATION   32.0 $/KG   REFUELING TIME MULTIPLIER   1.00

****

NUCLEAR FUEL UTILIZATION

U238	U235	...	PU239	PU240	PU241	PU242	NP237	TIME YR	TIME EXPOSURE MWD/MT	CR ID

INSTALLATION PERFORMANCE AND COST DATA

(INPUT TO PACTOLUS)

RECORD ID: LWUI UR01 1000 1970 RVR1 WMC1 NONE

FILE: 11   RELATIVE POSITION: 2   FILE CREATED 1/08/73

AMBIENT CONDITIONS AND POLLUTION LIMITS

MAXIMUM TEMPERATURE RISE	4.00	F	SO2 EMISSION LIMIT	0.0	LB/MBTU
MAXIMUM TEMPERATURE	84.00	F	SO2 GND LEVEL CONC ANNUAL MEAN	0.0	MICROGM/CUM
MIXING ZONE SIZE	6.00	ACRES	SO2 GND LEVEL CONC 24 HOUR MAX	0.0	MICROGM/CUM
DRY BULB TEMPERATURE	75.00	F	SO2 GND LEVEL CONC 1 HOUR MAX	0.0	MICROGM/CUM
WET BULB TEMPERATURE	70.00	F	PARTICULATE EMISSION LIMIT	0.0	LB/MBTU
DEW POINT	65.00	F	PART GND LEVEL CONC ANNUAL MEAN	0.0	MICROGM/CUM
WIND SPEED	10.00	MPH	PART GND LEVEL CONC 24 HOUR MAX	0.0	MICROGM/CUM
WATER TEMPERATURE	80.00	F	PART GND LEVEL CONC	0.0	MICROGM/CUM

PERFORMANCE DATA

PLANT NET HEAT RATE	10727.26	BTU/KWHR
PLANT CAPACITY	988.14	MWE
THERMAL POWER	3106.00	MWT
CONDENSER BACK PRESSURE	2.81	IN HGA
TPA POWER REQUIREMENT	8.94	MW
APA POWER REQUIREMENT	0.0	MW
PLANT AUXILIARY POWER REQUIREMENT	0.0	MW

ENVIRONMENTAL RESOURCE REQUIREMENTS

		PLANT	TPA EQUIP.	APA EQUIP.	TOTAL
HEAT DISSAPATION CAPACITY	ACRES	0.0	0.0	0.0	0.0
CONSUMPTIVE USE OF WATER	CFS	0.0	34.33	0.0	34.33
LAND	ACRES	100.00	3.21	0.0	103.21
AIR POLLUTION LEVEL		0.0	0.0	1.00	1.00

AVAILABILITY

AVAILABILITY	0.85 0.91 0.0
STARTING YEAR	1970 1975 2010

FINANCIAL DATA

COST SPECIAL MATERIALS (DEP)	0.0	$
COST SPECIAL MATERIALS (NON-DEP)	0.0	$
COST THERMAL PLANT	0.0	$
COST TURBINE PLANT	245000000.	$
COST ELECTRIC PLANT	0.0	$
COST TPA EQUIPMENT	5667214.00	$
COST APA EQUIPMENT	0.0	$
COST INDIRECT	0.0	$
COST OTHER CAPITAL	0.0	$
NONFUEL WORKING CAPITAL	0.0	$
RECOVERABLE LAND COST	0.0	$
SALVAGE VALUE	0.0	$
TOTAL PLANT FIXED OPERATING COST	100000.00	$/YR
TPA FIXED OPERATING COST	0.0	$/YR
APA FIXED OPERATING COST	0.0	$/YR
TOTAL PLANT VARIABLE OPERATING COST	837.09	$/MWTYR
TPA VARIABLE OPERATING COST	0.0	$/MWTYR
APA VARIABLE OPERATING COST	0.0	$/MWTYR
INTERIM CAPITAL REPLACEMENTS	0.0	% PLANT INVSTMNT/YR
DEPRECIABLE LIFE	30.00	YR
CONSTRUCTION TIME	8.00	YR

RECORD ID3 L401 URO1 1000 1970 RVR1 WMC1 NONE

NUMBER OF TOWER UNITS	698081.81			
RELATIVE RATING FACTOR	0.97			
AIR FLOW RATE	260855072.	LB/HR	60005408.0	CFM
WATER FLOW RATE	359505664.	LB/HR	719011.75	GPM
L/G	1.38			
PACKING HEIGHT	20.80	FT		
PACKING PRESSURE DROP	0.31	IN H2O		
FAN EFFICIENCY	86.00	%		
FAN HORSEPOWER	3372.68	HP		
PUMP HEAD	40.80	FT		
PUMP EFFICIENCY	96.00	%		
PUMP HORSEPOWER	8617.30	HP		
WET BULB TEMPERATURE	70.00	F		
APPROACH	14.03	F		
WATER TEMP ENTERING TOWER	104.00	F		
WATER TEMP LEAVING TOWER	84.00	F		
AIR ENTHALPY ENTERING TOWER	33.88	BTU/LB		
AIR ENTHALPY LEAVING TOWER	61.43	BTU/LB		
AIR DENSITY ENTERING TOWER	0.072	LB/CUFT		
EVAPORATION	6168652.00	LB/HR		
DRIFT	107851.52	LB/HR		
BLEED	1434311.00	LB/HR		
MAKEUP	7710814.00	LB/HR		
CAPITAL COST	5.40	$/TU		
FIXED OPERATING COST	0.0	$/YR/TU		
VARIABLE OPERATING COST	0.0	$/%CF/YR/TU		
PIPE COST	1.50	$/GPM		
TOWER CAPITAL COST	3769641.00	$		
PUMP CAPITAL COST	919056.19	$		
PIPE CAPITAL COST	1078517.00	$		

INPUT CHECK FOR PACTOLUS CASE RUN ON   1/07/73

                                                      CREATE
3 -2   0 9 1 4
1   2   0.520   0.0423   0.1000   0.1000   0.0025   332000. 0.0   0.07   0.0
0.50   0.03   0.04   0.032   0.0
1 26.00   2.50   0.0   162.0   0.00711 0.0   0.0   0.0 0.0
0.0125 0.0   14.00 0.0   0.0   0.0   0.0   9.17   0.0
2 1967   6.58   2.70   5.70

2000   11.95   6.00   9.00

THE INPUT CAPACITY FACTOR AND TIME INTERVALS FOLLOW FOR PLANT: LWUI UROI 1000 1970 RVRI WMCI NONE
0.80 0.80 0.80 0.80 0.80 0.80 0.80 0.80 0.80 0.79 0.77 0.76 0.74 0.73 0.71 0.69 0.68 0.66 0.64
0.63 0.61 0.59 0.57 0.56 0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0
1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00 1.00
1.00 1.00 1.00 1.00 0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0   0.0

ELECTRIC POWER COSTS
AS CALCULATED
BY THE

PACTOLUS CODE
ON
1/07/73

D. FARRAR AND F. WOODRUFF
THIS IS A SAMPLE PROBLEM
MASS. INSTITUTE OF TECHNOLOGY

PLANT IDENTIFICATION: LWU1 URC1 1000 1970 RVR1 WMC1 NONE
THE CAPACITY FACTOR AND AVAILABILITY OF THIS POWER PLANT IS AS FOLLOWS OVER ITS 30.0 YEAR LIFE.

YEAR	PERCENT CAPACITY	PERCENT AVAILABILITY
1970	0.80	0.85
1971	0.80	0.95
1972	0.80	0.85
1973	0.80	0.85
1974	0.80	0.85
1975	0.80	0.85
1976	0.80	0.80
1977	0.80	0.80
1978	0.80	0.80
1979	0.80	0.80

YEAR	PERCENT CAPACITY	PERCENT AVAILABILITY
1980	0.80	0.91
1981	0.80	0.91
1982	0.80	0.91
1983	0.80	0.91
1984	0.80	0.91
1985	0.79	0.91
1986	0.77	0.91
1987	0.76	0.91
1988	0.74	0.91
1989	0.73	0.91

YEAR	PERCENT CAPACITY	PERCENT AVAILABILITY
1990	0.71	0.91
1991	0.69	0.91
1992	0.68	0.91
1993	0.66	0.91
1994	0.64	0.91
1995	0.63	0.91
1996	0.61	0.91
1997	0.59	0.91
1998	0.57	0.91
1999	0.56	0.91

YEAR	PERCENT CAPACITY	PERCENT AVAILABILITY
2000	0.0	0.91
2001	0.0	0.91
2002	0.0	0.91
2003	0.0	0.91
2004	0.0	0.91
2005	0.0	0.91
2006	0.0	0.91
2007	0.0	0.91
2008	0.0	0.91
2009	0.0	0.91

YEAR	PERCENT CAPACITY	PERCENT AVAILABILITY
2010	0.0	0.91
2011	0.0	0.91
2012	0.0	0.91
2013	0.0	0.91
2014	0.0	0.91
2015	0.0	0.91
2016	0.0	0.91
2017	0.0	0.91
2018	0.0	0.91
2019	0.0	0.91

THIS A 3 REGION REACTOR.

SUMMARY OF FUEL USAGE
KILOGRAMS OF ISOTOPES

TH232	PA233	U233	U234	U235	U236	U238	PU239	PU240	PU241	PU242	NP237	TIME	EXPOS	C/B	RGN
0.0	0.0	0.0	0.0	647.3	0.0	28776.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	C	1.
0.0	0.0	0.0	0.0	345.6	52.0	28431.7	119.1	31.5	12.3	1.9	4.1	1.3	12418.0	C	3.
0.0	0.0	0.0	0.0	785.7	0.0	28639.6	3.3	3.0	3.0	0.0	0.0	0.3	0.0	C	2.
0.0	0.0	0.0	0.0	217.5	92.4	28039.3	147.8	66.2	34.0	10.6	12.2	3.0	27655.9	C	2.
0.0	0.0	0.0	0.0	717.9	0.0	28736.1	0.0	0.0	0.0	0.0	0.0	0.0	7.0	C	1.
0.0	0.0	0.0	0.0	276.4	74.1	28741.0	139.0	50.9	22.5	5.6	7.9	2.1	20041.7	C	2.
0.0	0.0	0.0	0.0	538.8	0.0	28444.5	0.0	0.0	0.0	0.0	0.0	1.3	0.0	C	3.
0.0	0.0	0.0	0.0	295.4	136.4	27872.0	154.1	63.5	33.8	9.5	13.4	4.1	28968.2	C	
0.0	0.0	0.0	0.0	538.8	0.0	28484.5	0.0	0.0	0.0	0.0	0.0	2.1	0.0	C	
0.0	0.0	0.0	0.0	280.6	108.3	27843.4	154.9	66.1	32.2	10.4	14.1	5.0	30115.8	C	
0.0	0.0	0.0	0.0	938.8	0.0	28484.5	0.0	0.0	0.0	0.0	0.0	3.0	0.0	C	
0.0	0.0	0.0	0.0	275.3	109.1	27833.6	155.0	66.9	32.6	10.7	14.3	6.0	30523.9	C	

END DATA

PLANT ID: LWU1 URC1 1C00 1970 RVR1 WMC1 NONE

STATION DESCRIPTION
STATION STARTUP DATE   1970.0
STATION RATED THERMAL POWER   2106.0   MW(TH)
THERMAL TO ELEC. CONV. (EFFICIENCY NET)   31.8   PCT
TONS OF FUEL LOADED (REACTOR ONLY)   38.3   TONNE
STATION LIFETIME   30   YRS

PLANT CHARGES
BOND INTEREST RATE   4.2   PCT
EARNING RATE ON EQUITY (AFTER TAX)   10.0   PCT
NUCLEAR LIABILITY COST PER YEAR   33200.0 $/YR
NUCLEAR LIABILITY COST PER MW YR(TH)   0.0 $/MWY
PROPERTY INSURANCE   0.2   PCT/YR
PLANT FIXED OPERATING COST   100000. $/YR
FEDERAL INCOME TAX RATE   40.0   PCT
STATE INCOME TAX RATE   3.2   PCT
PROPERTY TAX RATE   3.2   PCT/YR
STATE GROSS REVENUE TAX RATE   4.0   PCT
COMBINED STATE AND LOCAL TAXES   0.711 $/YR
INTERIM CAPITAL REPLACEMENTS   0.0   PCT/YR

CAPITAL COSTS
CONSTRUCTION TIME   8.0   YRS
SPECIAL MATERIALS, NON-DEPRECIABLE   0.0 $
SPECIAL MATERIALS, DEPRECIABLE   0.0 $
THERMAL PLANT EQUIPMENT   0.0 $
TURBINE PLANT EQUIPMENT   265000000. $
ELECTRIC PLANT EQUIPMENT   0.0 $
AIR POLLUTION ABATEMENT EQUIP.   506721400. $
THERMAL POLLUTION ABATEMENT EQUIP.   0.0 $
INDIRECT COSTS   0.0 $
OTHER CAPITAL COSTS   0.0 $
LAND AND LAND RIGHTS   0.0 $
NET SALVAGE VALUE OF PLANT   0.0 $
WORKING CAPITAL(RECOVERABLE)   0.0 $

FIXED PROCESS TIMES
URANIUM ENRICHMENT AND LEAD TIME   162.   DAYS
PRE-FABRICATION SHIPPING TIME   32.   DAYS
TIME IN FABRICATION   25.   DAYS
SHIP FROM FABRICATOR TO REACTOR SITE   10.   DAYS
PRE-REACTOR INVENTORY TIME   30.   DAYS
POST-REACTOR COOLING PERIOD   150.   DAYS
TIME TO SHIP FUEL TO REPROCESS SITE   32.   DAYS
REPROCESSING TIME (OPTIONALLY DETERMINED IN CODE) 30.   DAYS
SHIP TO FINAL DESTINATION   30.   DAYS

SHIPPING CHARGES
PRE-FABRICATION SHIPPING COST (U)   0.0 $/KG
FABRICATION TO REACTOR SITE.(U)   0.55 $/KG
PRE-FABRICATION SHIPPING COST.(RECYC FUEL)   0.0 $/KG
FABRICATION TO REACTOR SITE.(RECYC FUEL)   0.45 $/KG
REACTOR SITE TO REPROCESSING PLANT   3.55 $/KG
COST TO SHIP TO FINAL DESTINATION   0.0 $/KG
REPROCESSING CHARGES
REPROCESSING PLANT THROUGHPUT   0.0   KG/DAY
REPROCESSING PLANT OPERATING COST   0.0 $/DAY

FIRST CORE PURCHASE
FABRICATION CHARGE   7520447.0 $
SHIPPING CHARGE   48550.3 $
FUEL PURCHASE   1497091.0 $
FUEL FABRICATION LOSSES   67565.9 $
INTEREST CHARGES   1580854.0 $

URANIUM CASCADE PRICE SCHEDULE PARAMETERS
COST OF FEED (SEE TABLE 2)
CONVERSION COST   2.50 $/KG
FEED COMPOSITION   0.711 PCT
COST OF SEPARATIVE DUTY   26.00 $/KG
TAILS VALUE   0.0 $/KG

ISOTOPE PRICES (MAY BE OVERRIDDEN BY TIME VARYING INPUT DATA)

Isotope	Price	Unit	Isotope	Price	Unit	Isotope	Price	Unit
U235	14.00	$/GM	PU239	9.17	$/GM	PU241	9.17	$/GM
U238	0.21	$/GM	U234	0.0	$/GM	PU240	0.0	$/GM
U236	0.0	$/GM	PU242	0.0	$/GM	NP237	0.0	$/GM

RESOURCE UTILIZATION

CONSUMPTIVE USE OF WATER (CFS)	LAND USE (ACRES)	AIR POLLUTION LEVEL INDEX
HEAT DISSIPATION CAPACITY (ACRES)		
0.0	34.3	133.2	1.

TABLE 1
YEARLY COSTS IN MILLIONS OF DOLLARS

YEAR	CAPACITY FACTOR PCT	FUEL PURCHASE	FUEL CREDIT	FABRICATION CHARGE	REPROCESSING CHARGE	PRE-BURNUP SHIPPING CHARGE	POST-BURNUP SHIPPING CHARGE	FUEL LOSS CHARGE	VARIABLE OPERATING CHARGE	TOTAL
1970	80.0	7.204	0.0	0.0	0.0	0.0	0.0	0.0	2.080	9.284
1971	80.0	7.266	2.939	4.882	1.151	0.032	0.136	0.081	2.080	12.660
1972	80.0	7.340	2.669	2.389	1.139	0.016	0.106	0.048	2.080	10.448
1973	80.0	7.424	2.395	2.347	1.126	0.016	0.106	0.047	2.080	10.750
1974	80.0	7.492	3.392	2.309	1.110	0.016	0.106	0.051	2.080	10.072
1975	80.0	7.371	3.008	2.270	1.095	0.016	0.106	0.050	2.080	9.980
1976	80.0	7.251	2.988	2.232	1.081	0.016	0.106	0.049	2.080	9.826
1977	80.0	7.132	3.063	2.194	1.066	0.016	0.106	0.049	2.080	9.580
1978	80.0	7.012	3.099	2.159	1.053	0.016	0.106	0.048	2.080	9.375
1979	80.0	13.672	3.393	2.125	1.039	0.016	0.106	0.048	2.080	15.996
1980	80.0	6.663	3.096	2.091	1.026	0.016	0.106	0.047	2.080	8.933
1981	80.0	6.251	3.385	2.059	2.715	0.016	0.211	0.247	2.083	9.893
1982	80.0	6.440	6.159	4.025	0.990	0.032	0.106	0.092	2.080	7.606
1983	80.0	12.555	3.383	1.968	3.979	0.016	0.106	0.045	2.080	14.666
1984	80.0	6.153	3.079	1.943	1.925	0.016	0.211	0.045	2.080	9.287
1985	79.2	12.415	6.132	3.798	0.947	0.032	0.106	0.089	2.059	13.317
1986	77.5	6.271	3.049	1.363	1.864	0.016	0.211	0.345	2.015	9.232
1987	75.8	12.668	6.059	3.635	0.916	0.032	0.106	0.090	1.971	13.356
1988	74.2	6.394	3.032	1.775	0.906	0.016	0.106	0.045	1.929	8.143
1989	72.5	6.441	3.735	3.404	1.760	0.016	0.211	0.062	1.885	10.824
1990	70.8	13.016	6.128	1.607	0.874	0.032	0.106	0.075	1.841	11.503
1991	69.2	6.576	3.083	1.657	0.862	0.032	0.106	0.346	1.799	7.980
1992	67.5	6.623	3.102	1.626	1.691	0.016	0.211	0.046	1.755	8.866
1993	65.8	6.670	6.244	3.157	2.828	0.032	0.106	0.094	1.711	6.354
1994	64.2	6.718	3.147	1.530	2.816	0.016	0.106	0.047	1.669	7.755
1995	62.5	13.585	3.162	1.496	0.303	0.016	0.106	0.348	1.625	14.517
1996	60.8	6.069	3.177	1.462	2.791	0.016	0.106	0.348	1.581	7.695
1997	59.2	6.927	3.200	1.427	3.778	0.016	0.106	0.348	1.539	7.636
1998	57.5	6.975	3.216	1.391	1.516	0.016	0.211	0.049	1.495	8.437
1999	55.8	0.0	3.231	1.354	2.737	0.016	0.106	0.067	1.451	8.496
2000	0.0	0.0	15.825	0.0	2.185	0.0	0.317	0.068	0.0	-13.256

PLANT IC: LWU1 URU1 1000 1970 RVR1 WMC1 NCNE

TABLE 2

YEAR	REPROCESSING CHARGE, $/KG BLKT	REPROCESSING CHARGE, $/KG CORE	REPROCESSING TIME, DAYS BLKT	REPROCESSING TIME, DAYS CORE	FABRICATION CHARGE, $/KG BLKT	FABRICATION CHARGE, $/KG CORE	VARIABLE PARAMETERS U233 OR PU FAB PENALTY	U233 PRICE $/GM	UFEED PRICE $/LB U3O8	PU 239 PRICE $/GM	PU 241 PRICE $/GM	THO2 PRICE $/LB
1962	0.0	0.0	0.0	0.0	0.0	95.67	16.46	14.00	6.58	9.17	9.17	0.0
1963	0.0	39.11	0.0	30.00	0.0	94.34	16.31	14.00	6.58	9.17	9.17	0.0
1964	0.0	38.72	0.0	30.00	0.0	93.00	16.15	14.00	6.58	9.17	9.17	0.0
1965	0.0	38.25	0.0	30.00	0.0	91.67	16.00	14.00	6.58	9.17	9.17	0.0
1966	0.0	37.72	0.0	30.00	0.0	90.34	15.85	14.00	6.58	9.17	9.17	0.0
1967	0.0	37.23	0.0	30.00	0.0	89.00	15.69	14.00	6.58	9.17	9.17	0.0
1968	0.0	36.74	0.0	30.00	0.0	87.67	15.54	14.00	6.74	9.17	9.17	0.0
1969	0.0	36.25	0.0	30.00	0.0	86.34	15.38	14.00	6.91	9.17	9.17	0.0
1970	0.0	35.73	0.0	30.00	0.0	85.00	15.23	14.00	7.07	9.17	9.17	4.98
1971	0.0	35.32	0.0	30.00	0.0	83.67	15.08	14.00	7.23	9.17	9.17	4.98
1972	0.0	34.78	0.0	30.00	0.0	82.34	14.92	14.00	7.39	9.17	9.17	4.98
1973	0.0	34.18	0.0	30.00	0.0	81.00	14.77	14.00	7.56	9.17	9.17	4.98
1974	0.0	34.04	0.0	30.00	0.0	79.67	14.62	14.00	7.72	9.17	9.17	4.98
1975	0.0	33.65	0.0	30.00	0.0	78.34	14.46	14.00	7.88	9.17	9.17	4.98
1976	0.0	33.26	0.0	30.00	0.0	77.00	14.31	14.00	8.04	9.17	9.17	4.98
1977	0.0	32.53	0.0	30.00	0.0	75.67	14.15	14.00	8.21	9.17	9.17	4.98
1978	0.0	32.18	0.0	30.00	0.0	74.34	14.00	14.00	8.37	9.17	9.17	4.98
1979	0.0	31.57	0.0	30.00	0.0	73.00	13.85	14.00	8.53	9.17	9.17	4.98
1980	0.0	31.14	0.0	30.00	0.0	71.67	13.69	14.00	8.73	9.17	9.17	4.98
1981	0.0	30.79	0.0	30.00	0.0	70.34	13.54	14.00	8.86	9.17	9.17	4.98
1982	0.0	30.06	0.0	30.00	0.0	69.00	13.38	14.00	9.02	9.17	9.17	4.98
1983	0.0	29.69	0.0	30.00	0.0	67.67	13.23	14.00	9.18	9.17	9.17	4.98
1984	0.0	29.31	0.0	30.00	0.0	66.34	13.08	14.00	9.35	9.17	9.17	4.98
1985	0.0	28.53	0.0	30.00	0.0	65.00	12.92	14.00	9.51	9.17	9.17	4.98
1986	0.0	28.12	0.0	30.00	0.0	63.67	12.77	14.00	9.67	9.17	9.17	4.98
1987	0.0	31.14	0.0	30.00	0.0	62.34	12.62	14.00	9.83	9.17	9.17	4.98
1988	0.0	30.79	0.0	30.00	0.0	61.00	12.46	14.00	10.00	9.17	9.17	4.98
1989	0.0	30.06	0.0	30.00	0.0	59.67	12.31	14.00	10.16	9.17	9.17	4.98
1990	0.0	29.69	0.0	30.00	0.0	58.34	12.15	14.00	10.32	9.17	9.17	4.98
1991	0.0	29.31	0.0	30.00	0.0	57.00	12.00	14.00	10.49	9.17	9.17	4.98
1992	0.0	28.53	0.0	30.00	0.0	55.67	11.85	14.00	10.65	9.17	9.17	4.98
1993	0.0	28.12	0.0	30.00	0.0	54.34	11.65	14.00	10.81	9.17	9.17	4.98
1994	0.0	27.72	0.0	30.00	0.0	53.00	11.54	14.00	10.97	9.17	9.17	4.98
1995	0.0	27.30	0.0	30.00	0.0	51.67	11.38	14.00	11.14	9.17	9.17	4.98
1996	0.0	26.87	0.0	30.00	0.0	50.34	11.23	14.00	11.30	9.17	9.17	4.98
1997	0.0	26.43	0.0	30.00	0.0	49.00	11.08	14.00	11.46	9.17	9.17	4.98
1998	0.0	25.52	0.0	30.00	0.0	47.67	10.92	14.00	11.67	9.17	9.17	4.98
1999	0.0	25.06	0.0	30.00	0.0	46.34	10.77	14.00	11.79	9.17	9.17	4.98
2001	0.0	24.75	0.0	30.00	0.0	45.00	10.62	14.00	11.95	9.17	9.17	4.98

162

PLANT ID: LWU1 URC1 1000 1970 RVR1 WMC1 NONE

TABLE 2
URANIUM PURCHASES AND CREDITS

YEAR	URANIUM PRICE $/LB	TAILS COMPOSITION PCT	90 PCT ENR URANIUM PRICE $/GM	U3O8 PURCHASED TONS	SEPARATIVE WORK PURCHASED TONNE	TAILS PRODUCED TONNE U	EQUIVALENT U3O8 CREDITED TONS	EQUIVALENT SEPARATIVE WORK CREDITED TONNE	TAILS CONSUMED TONNE U
1962	6.58	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1963	6.58	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1964	6.58	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1965	6.58	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1966	6.58	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1967	6.58	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1968	6.74	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1969	6.91	0.251	10.50	547.5	241.2	332.5	76.3	17.1	30.0
1970	7.07	0.248	10.62	244.2	124.4	158.3	57.2	8.0	15.6
1971	7.23	0.246	10.69	243.5	124.9	157.7	41.1	1.5	3.4
1972	7.39	0.244	10.78	242.6	125.4	157.1	62.5	13.9	19.9
1973	7.56	0.242	10.87	241.6	126.0	156.3	58.3	9.1	16.8
1974	7.72	0.240	10.96	240.6	126.5	155.5	56.8	8.5	15.6
1975	7.88	0.238	11.05	234.4	123.1	150.7	58.3	9.5	17.2
1976	8.04	0.236	11.14	228.4	119.7	146.1	56.8	8.5	17.7
1977	8.21	0.235	11.22	222.6	116.5	141.7	58.8	9.5	17.4
1978	8.31	0.233	11.30	217.1	113.3	137.5	59.5	10.0	17.6
1979	8.52	0.231	11.38	211.9	110.3	133.4	59.2	9.9	17.4
1980	8.70	0.228	11.53	406.7	211.6	255.3	59.5	10.1	34.7
1981	8.96	0.277	11.60	197.3	101.6	122.2	59.2	10.0	17.5
1982	9.02	0.226	11.66	192.9	98.9	118.8	59.6	10.4	17.6
1983	9.18	0.223	11.74	373.0	189.9	227.8	59.6	13.5	34.8
1984	9.35	0.222	11.85	181.2	91.7	109.8	119.0	21.0	17.2
1985	9.51	0.221	11.91	180.9	92.0	218.4	59.3	10.4	33.5
1986	9.67	0.219	12.03	360.8	184.8	109.9	117.4	23.4	16.4
1987	9.83	0.217	12.09	179.9	92.8	217.0	58.3	10.1	16.1
1988	10.00	0.215	12.22	358.9	186.4	108.1	57.9	9.9	32.5
1989	10.16	0.214	12.28	179.0	93.6	107.9	116.1	20.2	16.1
1990	10.32	0.213	12.35	178.7	93.9	215.0	57.9	10.1	16.2
1991	10.45	0.211	12.48	356.3	188.6	137.1	58.0	12.3	32.2
1992	10.65	0.210	12.55	177.7	94.8	106.9	115.7	20.6	16.1
1993	10.81	0.208	12.62	177.4	95.3	106.4	57.8	10.4	16.0
1994	10.97	0.207	12.76	177.0	95.6	106.1	57.8	10.4	16.0
1995	11.14	0.206	12.83	176.7	95.9	211.5	57.7	13.6	16.0
1996	11.30	0.205	12.91	176.4	192.8	105.4	57.8	10.6	16.0
1997	11.46	0.204	13.06	351.8	96.9	211.5	57.7	10.6	15.9
1998	11.62	0.201	13.08	175.4	96.9	0.0	57.7	10.6	16.0
1999	11.75	0.201	13.15	0.0	0.0	0.0	57.6	10.6	15.9
2000	11.95	0.200		0.0	0.0	0.0	316.0	107.0	128.7

TABLE 4
REACTOR PROPERTIES TABLE

INITIAL FULL POWER SPECIFIC POWER, MW/TONNE HEAVY METAL	35.2
YIELD, FISSILE KG PER MWE-YEAR	-0.595
YIELD, KG PU PER MWE-YEAR	0.282
YIELD, KG U235 PER MWE-YEAR	-0.877
YIELD, KG U233 PER MWE-YEAR	0.0
SPECIFIC INVENTORY, KG OF FISSILE MATERIAL PER MEGAWATT ELECTRICAL	2.19
TONS OF U308 MINED PER MWE-YEAR	0.234
TONS OF U308 MINED PER MWTH-YEAR	0.075
KILOGRAMS FISSIONED PER TON OF U308 MINED	5.14
KG SEPARATIVE DUTY PER MWE-YR	155.27
TONS OF U308 CONSUMED	5126.1
TONNES OF SEPARATIVE DUTY CONSUMED	3394.7
KG FABRICATED PER MWE-YR	51.1
AVERAGE PLANT CAPACITY FACTOR, PER CENT	73.7

TABLE 5
KILOGRAMS FABRICATED EACH YEAR
(BEFORE LOSSES)

YEAR	TH232	PA233	U233	U234	U235	U236	U238	PU239	PU240	PU241	PU242	NP237	TOTAL
1962	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1963	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1964	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1965	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1966	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1967	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1968	0.0	0.0	0.0	0.0	2160.6	0.0	86511.7	0.0	0.0	0.0	0.0	0.0	88672.2
1969	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1970	0.0	0.0	0.0	0.0	1846.1	0.0	57726.5	0.0	0.0	0.0	0.0	0.0	59112.6
1971	0.0	0.0	0.0	0.0	643.0	0.0	28613.3	0.0	0.0	0.0	0.0	0.0	29256.3
1972	0.0	0.0	0.0	0.0	943.0	0.0	28613.3	0.0	0.0	0.0	0.0	0.0	29556.3
1973	0.0	0.0	0.0	0.0	942.2	0.0	28614.1	0.0	0.0	0.0	0.0	0.0	29556.3
1974	0.0	0.0	0.0	0.0	942.4	0.0	29053.7	0.0	0.0	0.0	0.0	0.0	29556.5
1975	0.0	0.0	0.0	0.0	903.1	0.0	28653.1	0.0	0.0	0.0	0.0	0.0	29556.5
1976	0.0	0.0	0.0	0.0	903.3	0.0	28653.6	0.0	0.0	0.0	0.0	0.0	29556.8
1977	0.0	0.0	0.0	0.0	867.5	0.0	28639.8	0.0	0.0	0.0	0.0	0.0	29538.9
1978	0.0	0.0	0.0	0.0	850.3	0.0	28707.2	0.0	0.0	0.0	0.0	0.0	29557.3
1979	0.0	0.0	0.0	0.0	833.5	0.0	28724.3	0.0	0.0	0.0	0.0	0.0	29557.5
1980	0.0	0.0	0.0	0.0	817.4	0.0	28740.5	0.0	0.0	0.0	0.0	0.0	29557.9
1981	0.0	0.0	0.0	0.0	1585.7	0.0	57527.7	0.0	0.0	0.0	0.0	0.0	29557.9
1982	0.0	0.0	0.0	0.0	772.3	0.0	29786.2	0.0	0.0	0.0	0.0	0.0	59116.4
1983	0.0	0.0	0.0	0.0	1505.6	0.0	57611.8	0.0	0.0	0.0	0.0	0.0	59116.5
1984	0.0	0.0	0.0	0.0	747.4	0.0	28811.3	0.0	0.0	0.0	0.0	0.0	59117.4
1985	0.0	0.0	0.0	0.0	747.4	0.0	28811.3	0.0	0.0	0.0	0.0	0.0	29558.7
1986	0.0	0.0	0.0	0.0	1494.7	0.0	57622.7	0.0	0.0	0.0	0.0	0.0	59117.4
1987	0.0	0.0	0.0	0.0	747.4	0.0	28811.3	0.0	0.0	0.0	0.0	0.0	59117.4
1988	0.0	0.0	0.0	0.0	1494.7	0.0	57622.7	0.0	0.0	0.0	0.0	0.0	59117.4
1989	0.0	0.0	0.0	0.0	747.4	0.0	28811.3	0.0	0.0	0.0	0.0	0.0	29558.7
1990	0.0	0.0	0.0	0.0	747.4	0.0	28811.3	0.0	0.0	0.0	0.0	0.0	29558.7
1991	0.0	0.0	0.0	0.0	747.4	0.0	28811.3	0.0	0.0	0.0	0.0	0.0	29558.7
1992	0.0	0.0	0.0	0.0	1494.7	0.0	57622.7	0.0	0.0	0.0	0.0	0.0	59117.4
1993	0.0	0.0	0.0	0.0	747.4	0.0	28811.3	0.0	0.0	0.0	0.0	0.0	59117.4
1994	0.0	0.0	0.0	0.0	747.4	0.0	28811.3	0.0	0.0	0.0	0.0	0.0	29558.7
1995	0.0	0.0	0.0	0.0	747.4	0.0	28911.3	0.0	0.0	0.0	0.0	0.0	29558.7
1996	0.0	0.0	0.0	0.0	747.4	0.0	28911.3	0.0	0.0	0.0	0.0	0.0	29559.7
1997	0.0	0.0	0.0	0.0	747.4	0.0	28911.3	0.0	0.0	0.0	0.0	0.0	29558.7
1998	0.0	0.0	0.0	0.0	747.4	0.0	28911.3	0.0	0.0	0.0	0.0	0.0	29558.7
1999	0.0	0.0	0.0	0.0	747.4	0.0	28911.3	0.0	0.0	0.0	0.0	0.0	29558.7

TABLE 6
KILOGRAMS REPROCESSED EACH YEAR
(AFTER LOSSES)

YEAR	TH232	PA233	U233	U234	U235	U236	U238	PU239	PU240	PU241	PU242	NP237	TOTAL
1962	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1963	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1964	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1965	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1966	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1967	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1968	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1969	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1970	0.0	0.0	0.0	0.0	343.7	51.7	28327.9	118.5	31.3	11.9	1.9	4.1	28891.0
1971	0.0	0.0	0.0	0.0	274.9	73.7	28088.5	138.2	50.6	21.8	5.6	7.9	28661.2
1972	0.0	0.0	0.0	0.0	216.1	91.9	27858.1	147.0	65.8	30.0	10.5	12.1	28431.8
1973	0.0	0.0	0.0	0.0	293.8	105.8	27771.5	153.3	63.2	29.8	9.4	13.3	28390.2
1974	0.0	0.0	0.0	0.0	273.1	107.7	27693.0	154.1	65.7	31.2	10.3	14.0	28355.2
1975	0.0	0.0	0.0	0.0	273.8	108.5	27633.3	154.2	66.5	31.6	11.6	14.2	28342.5
1976	0.0	0.0	0.0	0.0	241.5	107.0	27697.3	153.9	65.3	31.0	10.2	13.9	28360.7
1977	0.0	0.0	0.0	0.0	284.5	104.0	27704.6	153.5	64.7	33.7	10.0	13.7	28369.6
1978	0.0	0.0	0.0	0.0	281.8	103.9	27739.0	152.1	63.7	29.8	9.5	13.1	28395.6
1979	0.0	0.0	0.0	0.0	285.3	103.9	27777.9	150.7	62.2	28.9	9.1	12.4	28427.2
1980	0.0	0.0	0.0	0.0	569.2	193.3	55654.8	297.1	127.6	55.4	16.8	23.3	56931.5
1981	0.0	0.0	0.0	0.0	285.2	97.5	27877.7	146.4	58.3	26.5	7.8	10.8	28505.1
1982	0.0	0.0	0.0	0.0	286.6	69.0	27911.9	144.7	56.7	25.6	7.3	10.2	28532.8
1983	0.0	0.0	0.0	0.0	571.3	171.6	55915.0	285.4	109.5	48.6	13.4	19.1	57136.5
1984	0.0	0.0	0.0	0.0	286.9	82.2	28030.9	143.4	52.9	23.2	6.2	9.3	28601.6
1985	0.0	0.0	0.0	0.0	572.5	157.5	56381.5	276.9	132.5	44.3	11.4	16.7	57263.4
1986	0.0	0.0	0.0	0.0	283.4	76.4	23069.6	137.2	50.2	21.5	5.5	8.0	28651.7
1987	0.0	0.0	0.0	0.0	283.5	76.3	23070.3	137.1	50.1	21.4	5.5	8.0	28651.8
1988	0.0	0.0	0.0	0.0	565.2	152.9	50137.4	274.3	100.7	43.1	10.9	16.0	57300.5
1989	0.0	0.0	0.0	0.0	282.9	76.4	28069.2	137.1	50.2	21.5	5.5	8.0	28650.7
1990	0.0	0.0	0.0	0.0	282.0	76.0	28039.1	137.2	50.3	21.5	5.5	8.7	28653.7
1991	0.0	0.0	0.0	0.0	560.3	152.8	56139.1	274.1	100.5	43.0	10.9	15.9	57302.6
1992	0.0	0.0	0.0	0.0	282.9	76.4	23069.4	137.1	50.3	21.5	5.5	8.0	28651.0
1993	0.0	0.0	0.0	0.0	284.2	76.4	28069.0	137.1	50.2	21.5	5.5	8.0	28651.4
1994	0.0	0.0	0.0	0.0	283.1	76.4	28069.5	137.1	50.2	21.5	5.5	8.0	28651.2
1995	0.0	0.0	0.0	0.0	293.0	76.4	28069.4	137.1	50.2	21.5	5.5	8.0	28651.0
1996	0.0	0.0	0.0	0.0	283.6	76.3	23070.2	137.1	50.2	21.5	5.5	8.0	28652.3
1997	0.0	0.0	0.0	0.0	566.7	152.7	56139.9	274.1	100.4	43.0	10.9	15.9	57303.6
1998	0.0	0.0	0.0	0.0	283.6	76.3	28077.3	137.1	50.1	21.5	5.5	8.0	28652.2
2000	0.0	0.0	0.0	0.0	1187.6	172.5	84547.6	309.9	113.6	48.6	12.4	18.0	86410.0

INPUT DATA

CARD 2
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ROAD REPAYMENT PROPORTIONAL
SUM OF YEARS DIGITS DEPRECIATION
PROPERTY INSURANCE, $M/YR                       0.0267
NUCLEAR LIABILITY, $M/YR                         C.3320
FRACTION OF INITIAL INVESTMENT IN BONDS          0.5200
BOAD INTEREST RATE                               C.0423
UTILITY EARNING RATE (AFTER TAXES)               0.1000
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CARD 3
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FEDERAL INCOME TAX RATE                          C.5000
STATE INCOME TAX RATE                            C.0300
STATE GROSS REVENUE TAX RATE                     C.0400
PROPERTY TAX RATE                                0.0320
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PLANT DATA FILE
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PLANT THERMAL GENERATED POWER                  2105.9976
NET ELECTRICAL POWER TO SYSTEM                  988.1357
STATION OPERATING LIFE, YEARS                         30
FIRST YEAR OF OPERATION                             1970
DEPRECIABLE LIFE, YEARS                          30.0000
PROJECT LIFE, INCL. CONSTRUCTION, YR             38.6594
PLANT INVESTMENT, $M                            250.6672
INITIAL CORE INVESTMENT, $M                      24.1645
NON-FUEL WORKING CAPITAL, $M                         0.0
INVESTMENT IN POLLUTION ABATEMENT,$M              5.0672   (INITIAL FINANCING)
RECOVERABLE COST OF LAND, $M                         0.0   (INITIAL FINANCING)
RECOVERABLE COST OF SPECIAL MATL.,$M                3.0   (INITIAL FINANCING)
TOTAL INITIAL FINANCING                         274.8315   (INCLUDED IN PLT. INVESTMENT)
NET SALVAGE VALUE OF PLANT, $M                      0.0    (INITIAL FINANCING)
INTERIM CAPITAL REPLACEMENTS, $M/YR                 0.0    (INITIAL FINANCING)
NON-FUEL VARIABLE OPERATING COST, $M/YR          2.6000    (AT 100% PLANT FACTOR)
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ANNUAL INPUT DATA,   EXPENSES IN $M/YR

PLANT IDENTIFICATION   LWU1 UR01 1000 1970 KVR1 MMC1 NONE

	YEAR	LOAD FACTOR	FUEL PURCHASES	FABRICATION COST	REPROCESS COST	U-PU CREDIT	BASE OPERATING COST	VARIABLE OPERATING COST
1	1970	0.80000	7.20372	0.0	0.0	0.0	0.10000	2.08000
2	1971	0.80000	7.26639	4.97978	1.27230	2.93856	0.10000	2.08000
3	1972	0.80000	7.34002	2.43839	1.25923	2.66944	0.10000	2.08000
4	1973	0.80000	7.42437	2.39679	1.24412	2.39517	0.10000	2.08000
5	1974	0.80000	7.42239	2.35904	1.23206	3.09181	0.10000	2.08000
6	1975	0.80000	7.37142	2.31967	1.21714	3.10816	0.10000	2.08000
7	1976	0.80000	7.25351	2.24070	1.21266	2.98768	0.10000	2.08000
8	1977	0.80000	7.13100	2.74155	1.19465	3.06276	0.10000	2.08000
9	1978	0.80000	7.01219	2.23699	1.17522	3.05931	0.10000	2.08000
10	1979	0.80000	13.67178	2.17214	1.16155	1.08957	0.10000	2.08000
11	1980	0.90000	6.66370	2.13772	1.14873	3.75603	0.10000	2.08000
12	1981	0.80000	6.55371	2.10512	2.24726	3.08442	0.10000	2.08000
13	1982	0.80000	6.64940	4.11651	1.17493	0.15205	0.10000	2.08000
14	1983	1.00000	12.55079	2.01123	1.11797	3.08333	0.10000	2.08000
15	1984	0.40000	6.14971	1.58431	2.15273	3.07031	0.10000	2.08000
16	1985	0.79200	12.41070	1.18633	1.34553	6.01324	0.10000	2.05422
17	1986	0.77500	6.27127	1.93387	2.01141	3.04967	0.10000	2.01500
18	1987	0.75900	12.66750	3.72401	1.04471	6.05019	0.10000	1.97080
19	1988	0.74200	6.31774	1.82013	1.22791	3.03177	0.10000	1.92920
20	1989	0.72500	6.44142	3.50377	2.02406	3.03505	0.10000	1.88500
21	1990	0.70800	13.01556	1.77813	0.59575	6.12758	0.10000	1.84383
22	1991	0.69200	6.57035	1.70311	0.59465	3.08349	0.10000	1.79923
23	1992	0.67500	6.62275	1.64136	0.91857	3.10195	0.10000	1.75500
24	1993	0.65800	6.66902	1.24983	0.56026	6.24376	0.10000	1.71080
25	1994	0.64200	6.71037	1.57663	0.93829	3.14693	0.10000	1.66920
26	1995	0.62500	13.58523	1.54250	0.92632	3.16189	0.10000	1.62503
27	1996	0.60800	6.80927	1.50899	0.91345	3.17720	0.10000	1.58080
28	1997	0.59200	6.52171	1.47148	0.93077	3.19981	0.10000	1.53920
29	1998	1.57500	6.67511	1.43410	1.74433	3.21591	0.10000	1.49500
30	1999	0.55900	0.0	1.40179	0.07304	3.23125	0.10000	1.45080
31	2000	0.0	0.0	0.0	2.50977	15.82534	0.10000	0.0

EXPENSES BEFORE FEDERAL INCOME TAX, $M

PROBLEM IDENTIFICATION   LWUI UPO1 1)C) 157) RVR1 HMC1 NONE

	YEAR	5.867 PCT PRESENT WORTH FACTOR	FUEL OPERATING EXPENSES	ANNUAL FUEL EXPENSES	NON-FUEL OPERATING EXPENSES	DEPRECIATION	BOND INTEREST	TOTAL STATE INCOME AND REVENUE TAXES
1	1570	C.77150	7.20372	8.96206	11.95905	16.17206	3.02260	2.22707
2	1571	3.91804	10.57993	8.96206	11.69167	14.55486	5.70972	2.20299
3	1572	C.86716	8.36818	8.96206	11.42429	14.01579	5.62509	2.22972
4	1573	0.81911	8.67011	8.96206	11.15652	13.47673	5.49039	2.25797
5	1574	C.77372	7.99167	8.96206	10.88954	12.93766	5.35707	2.28615
6	1575	C.73C84	7.90004	8.96206	10.62216	12.39859	5.20458	2.31492
7	1576	3.69034	7.74618	8.96206	10.35478	11.85952	5.34437	2.34392
8	1577	C.65208	7.49774	8.96206	10.08741	11.32045	4.87464	2.37321
9	1578	0.61595	7.29487	8.96206	9.82003	10.78138	4.69279	2.43285
10	1579	C.58192	13.91587	8.96206	9.55265	10.24231	4.49901	2.43286
11	1590	C.54557	6.85278	8.96206	9.28527	9.70324	4.44276	2.45874
12	1591	C.51912	7.81347	8.96206	9.01789	9.16417	4.23110	2.48928
13	1592	C.49C35	5.52018	8.96206	8.75051	8.62510	4.03140	2.51947
14	1593	C.46318	12.53697	8.96206	8.48314	8.08604	3.77294	2.55142
15	1594	0.43751	7.20727	8.96206	8.21576	7.54697	3.65785	2.57906
16	1595	3.41326	11.25914	9.87243	7.92753	7.00790	3.42095	2.57937
17	1596	3.39016	7.21731	8.68199	7.61600	6.46883	3.26842	2.56228
18	1597	C.36873	11.38715	8.49155	7.30442	5.92976	3.03383	2.50765
19	1598	0.34830	6.21399	8.31231	6.99544	5.39069	2.89300	2.47408
20	1589	3.32930	8.93927	8.12186	6.68387	4.85162	2.64518	2.43985
21	1590	C.31C76	5.66183	7.73142	6.37229	4.31255	2.45855	2.40379
22	1591	0.29354	6.18764	7.75218	6.06331	3.77348	2.29266	2.37097
23	1592	C.27728	7.11129	7.56173	5.75173	3.23441	2.05551	2.33642
24	1593	3.26191	4.64277	7.37129	5.44015	2.69534	1.84072	2.30120
25	1594	C.24740	12.08583	7.19205	5.13118	2.15628	1.57481	2.27138
26	1595	C.23369	6.11453	7.00161	4.81560	1.61721	1.34011	2.23676
27	1596	C.22C74	6.09676	6.81116	4.5C802	1.07814	1.25713	2.19758
28	1597	C.20853	6.94163	6.63192	4.19904	0.53907	1.03600	2.16642
29	1598	0.19695	-0.95142	6.44149	3.86746	0.0	0.81656	2.13134
30	1599	3.18694	-13.25556	6.25103	3.57588	-0.53907	0.61862	2.09561
31	2000	C.17573		0.0	1.85771	0.0	0.25125	-0.06327

169

CALCULATION OF FEDERAL INCOME TAX, $M

PROBLEM IDENTIFICATION   LWU1 URJI 1000 1970 RVRI WMCI NONE

YEAR	POWER UNITS (M MWH)	TOTAL POWER SALES	TOTAL TAX DEDUCTIBLE EXPENSES	TAXABLE INCOME (FEDERAL)	FEDERAL INCOME TAX	TOTAL CASH EXPENDITURES	TOTAL CASH RECEIPTS
1970	6.93053	49.86255	42.34280	7.51574	3.75587	25.14972	49.86255
1971	6.93053	49.86255	43.12128	6.74127	3.37064	27.84520	49.86255
1972	6.93053	49.86255	42.25693	7.60562	3.90281	25.82530	49.86255
1973	6.93053	49.86255	41.34373	8.51881	4.25941	26.34439	49.86255
1974	6.93053	49.86255	40.43245	9.43010	4.71505	25.88240	49.86255
1975	6.93053	49.86255	39.50227	10.36028	5.18014	26.01724	49.86255
1976	6.93053	49.86255	38.56464	11.29791	5.64896	26.09384	49.86255
1977	6.93053	49.86255	37.61774	12.74481	6.12241	26.08275	49.86255
1978	6.93053	49.86255	36.65907	13.20340	6.61174	26.11948	49.86255
1979	6.93053	49.96255	35.68886	14.17369	7.03085	32.93823	49.86255
1980	6.93053	49.86255	34.85234	15.01051	7.53226	26.11234	49.86255
1981	6.93053	49.86255	33.96447	15.79803	7.99904	27.31967	49.86255
1982	6.93053	49.86255	32.88850	16.37404	8.48702	25.28317	49.86255
1983	6.93053	49.86255	31.85556	18.00699	9.03349	32.02432	49.86255
1984	6.93053	49.86255	30.96167	18.90083	9.45044	27.45247	49.86255
1985	6.86173	49.36394	29.30220	19.55574	9.77787	31.54294	49.36394
1986	6.71396	48.30437	29.57748	19.77683	9.86344	27.23678	48.30437
1987	6.56649	47.24481	27.26720	19.97762	9.94081	31.18332	47.24481
1988	6.42817	46.24751	26.16551	20.18201	10.09133	25.77452	46.24751
1989	6.28030	45.18794	24.74231	20.44557	10.22279	23.28571	45.18794
1990	6.13232	44.12839	23.47858	20.64581	10.32491	28.76283	44.12839
1991	5.99492	43.13115	22.25253	20.37857	10.43929	25.35420	43.13115
1992	5.84704	42.07155	20.93974	21.13176	10.50388	25.76530	42.07155
1993	5.72237	41.01196	19.64773	21.36227	10.63163	23.26569	41.01196
1994	5.57176	40.01472	18.52503	21.63904	10.84452	24.33293	40.01472
1995	5.41448	38.95512	17.01526	21.93687	10.96393	33.21852	38.95512
1996	5.27121	37.89557	15.85233	22.04353	11.09177	23.94186	37.89557
1997	5.12363	36.89830	14.57245	22.32584	11.16292	23.02512	36.89830
1998	4.94137	35.83875	13.27084	22.76150	11.24395	24.24138	35.83875
1999	4.83405	34.77914	12.00203	22.77735	11.34353	16.10860	34.77914
2000	0.0	0.0	2.04568	-2.04568	-1.02284	-12.48397	0.0

170

PROBLEM IDENTIFICATION   LAGI INPUT 1000 1570 RVRI WMC1 NOVF

YEAR	TOTAL CASH FLOW	OUTSTANDING BONDS	EQUITY CAPITAL NOT RECOVERED	BOND INTEREST	EARNINGS ON UNRECOVERED EQUITY	BONDS REPAID	RECOVERY OF EQUITY
1 1970	24.71204	142.61234	131.91916	3.02260	6.43885	7.93073	7.32067
2 1971	22.01735	134.94164	124.59448	5.70972	12.42245	2.00084	1.84693
3 1972	24.03756	132.09383	122.75154	5.62529	12.27516	3.19143	2.94591
4 1973	23.51816	126.28740	118.30563	5.49009	11.98057	3.14470	2.90280
5 1974	23.29015	126.04470	116.92293	5.35707	11.67329	3.05255	3.32774
6 1975	23.24531	123.03964	115.57508	5.20458	11.35751	3.78727	3.49594
7 1976	23.76871	118.62917	110.57415	5.04437	11.03792	4.01253	3.73387
8 1977	23.77933	115.23742	106.37526	4.87402	10.63753	4.29916	3.96846
9 1978	23.74367	110.24366	102.43640	4.67279	10.29068	4.58399	4.22861
10 1979	16.47436	104.55966	94.17919	4.47931	5.31782	1.3299)	1.22763
11 1980	23.74051	100.33926	90.95058	4.44770	5.67506	5.00383	4.61889
12 1981	23.54248	95.57593	42.33168	4.29110	9.23317	4.72387	4.35773
13 1982	24.70535	89.47471	87.97394	4.13142	8.79740	6.11029	5.64027
14 1983	17.23453	84.67431	82.11360	3.77294	8.23337	2.12075	2.51147
15 1984	22.41038	79.67941	72.42719	3.65795	7.90222	5.63740	5.16960
16 1985	17.91023	74.62757	74.62757	3.47056	7.42526	3.60609	3.32870
17 1986	21.04558	77.66755	71.32347	3.20642	7.11239	5.5456R	5.11909
18 1987	16.96479	71.77143	66.24477	3.03381	6.67048	3.32929	3.07319
19 1988	23.47279	61.92953	62.35158	2.84300	6.31316	5.85875	5.40808
20 1989	16.09224	62.33873	57.72356	2.64613	5.77235	4.1275	4.07266
21 1990	15.36556	5.12173	53.05741	2.44352	5.36508	3.92181	3.62014
22 1991	18.01695	54.17391	53.07305	2.23262	5.05307	5.60624	5.17499
23 1992	16.19624	48.56966	44.35221	2.04551	4.44557	5.37788	4.68728
24 1993	17.54627	43.01576	40.16043	1.64472	4.01684	6.28613	5.83258
25 1994	15.61187	37.32743	34.36531	1.77431	3.46758	5.54962	3.12181
26 1995	8.93461	31.66133	29.74433	1.34311	2.92440	1.96149	1.81061
27 1996	14.54371	25.71353	27.43743	1.25713	2.74334	5.22768	4.82555
28 1997	13.27314	24.49181	22.01743	1.04133	2.26074	5.18772	4.78867
29 1998	11.59737	19.63443	17.11915	0.81656	1.78192	4.67942	4.31947
30 1999	13.07655	14.56962	14.49965	0.44697	1.34597	8.08521	8.31693
31 2000	12.43957	9.93165	5.82276	0.25125	0.54828	6.37591	5.60853

UTILITY ANALYSIS

CCST OF POWER CALCULATION

PROBLEM ICENTIFICATION   LWU1 UROI 10CO 1S70 KVR1 WMC1 NONE

PCWER COST, MILLS/KWHE   7.1947

ANNUAL FIXEC COSTS, $/KWE   34.5811

    DEPRECIAHLE PLANT   30.8562
    NCN-FUEL WORKING CAPITAL   0.4372
    FUEL WCRKING CAPITAL   3.2877   (INCLUDES ANNUAL FIXED OPERATING COSTS OF   0.4323 $M/YR)

OPERATING COSTS, MILLS/KWHE   1.5690

    OPERATICN AND MAINTENANCE   0.3451
    FUEL CYCLE   1.2239

REVENUE TAXFS   0.2767

172

COST OF POWER CALCULATION

FUEL CYCLE ANALYSIS

PROBLEM IDENTIFICATION   LWU1 URO1 1UCO 1970 RVR1 WMC1 NONE

POWER COST, MILLS/KWHE   7.1947

	CASH PER KWH	ANNUAL EXPENSES	INCOME(3) TAXES	CAPITAL RECOVERY	TOTAL CHARGES
DEPRECIABLE PLANT	2.0545	0.9376	0.8639	3.1616	4.9631
OPERATING AND MAINTENANCE COSTS (1) FIXED	0.0948	0.0703	0.0	0.0	0.0703
VARIABLE	0.3451	0.3585	0.0	0.0	0.3589
FUEL CYCLE COSTS (2) FIXED	0.1319	0.0212	0.2139	0.2938	0.5288
VARIABLE	1.2239	1.2729	0.0	0.0	1.2729
TOTAL	3.0501	2.6609	1.0778	3.4553	7.1940

(1) DETAILS OF OPERATING AND MAINTENANCE COSTS

	CASH PER KWH	EXPENSES	REVENUE TAXES	FIXED CHARGES	CAPITAL RECOVERY	INCOME TAXES	TOTAL CHARGES
OPERATING EXPENSES	0.3079	0.4127	0.0145	-0.0493	-0.0285	-0.0208	0.3779
RECOVERABLE LAND COSTS	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NUCLEAR LIABILITY	0.0520	0.0520	0.0020	-0.0020	-0.0011	-0.0008	0.0520

(2) DETAILS OF FUEL CYCLE COSTS

	CASH PER KWH	INDIRECT	DIRECT	EXPENSES	REVENUE TAXES	FIXED CHARGES	CAPITAL RECOVERY	INCOME TAXES	TOTAL CHARGES
FUEL PURCHASES									
INITIAL CORE		0.0429	0.0062	0.0429	0.0144	0.3159	0.1825	0.1334	1.5587
REPLACEMENT FUEL			1.2296	1.2296	0.0456	-0.0896	-0.3518	-0.3378	0.3731
FABRICATION									1.1856
INITIAL CORE		0.0158	0.0398	0.0198	0.0066	0.1460	0.0843	0.0616	0.5383
REPLACEMENT FUEL			0.3545	0.3545	0.0141	-0.0027	-0.0015	-0.0011	0.1724
REPROCESSING									0.3659
INITIAL CORE			0.0388	0.0	0.0003	0.0064	0.0037	0.0227	0.1801
REPLACEMENT FUEL			0.1985	0.1985	0.0067	-0.0318	-0.0184	-0.0134	0.0067
FUEL CREDIT									0.1734
INITIAL CORE			-0.3657	0.0	-0.0019	-0.0478	-0.0276	-0.0202	-0.4753
REPLACEMENT FUEL			-0.5586	-0.5586	-0.0164	0.1494	0.0863	0.0631	-0.0497
									-0.4256
MODERATOR AND FUEL CARRIER RECOVERY			0.0	0.0	0.0	0.0	0.0	0.0	0.0

(3) INCLUDES REVENUE TAXES.

173

FIXED CHARGE CALCULATIONS

PROBLEM IDENTIFICATION   LWU1 URU1 LOCO 1S70 RVR1 WMC1 NONE

FIXED CHARGE RATE ON DEPRECIABLE CAPITAL   0.1347   (INCLUDES PLANT PROPERTY TAX, INSURANCE, REPLACEMENTS, SALVAGE)
FIXED CHG RATE ON NONDEPRECIABLF INVESTMENT   0.1260

CONSTANT ANNUAL INCOME REQUIRED, $M   48.9442

TOTAL TAX-DEDUCTIBLE EXPENSES, $M   34.3746

FUEL WORKING CAPITAL, $M   20.2807   (EXCESS OF FUEL COST OVER AMORTIZED, RECOVERABLE D2O OR SALT)

POWER COST, MILLS/KWHE   7.1946

174

APPENDIX B

TEST PROBLEM

The test problem described in this section was used to perform a joint test of the Plant Evaluation Model and the Plant Expansion Model. Much of the data used in the problem does not reflect current conditions, and the results are only meant to illustrate the functioning of the model. The data describing the plant alternatives was taken primarily from various sections of the Interconnected New England Generation Study - Report No. 4, published in 1971, and from a report entitled Generating Plant Investment Estimates, Heat Rate Data and Forced Outage Rates for New England Power Planning, prepared by Ebasco Services, Incorporated, in 1969.

Four types of plants were included in the test problem; gas turbines (GT), peaking fossil units (FP), base loaded fossil units (FB), and light water reactors. Only one size gas turbine was considered while three capacities were considered for each of the other plant types; thus, there were ten possible plant alternatives in each period of the study.

Some of the most pertinent data for each of the ten alternatives is displayed in Table A-1. The capital costs and heat rates are from Report No. 4. The capital costs used for the fossil plants are the "basic" plant costs listed in that report. The nuclear plant costs are the "installed" plant costs quoted in the same report and include cooling tower
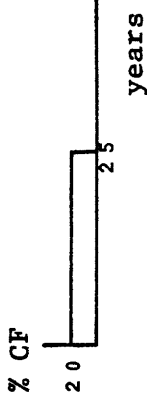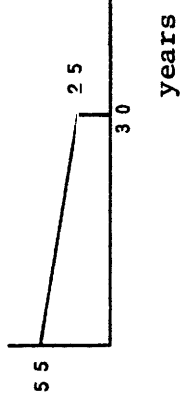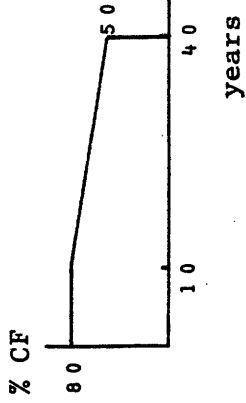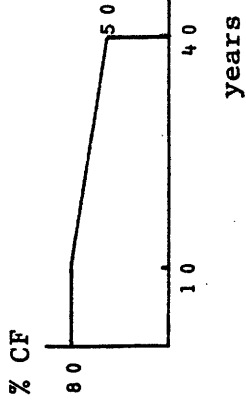
Type	Capacity MWe	Heat Rate BTU/kwhr	Fuel Type	Cap. Cost $/kw	Land Acres	Availability Im.	Availability Mat.	Capacity Factor History
GT	100	11,300	3	100	5	.85	.85	
FP	400	10,600	2	125	20	.92	.92	
FP	800	10,600	2	100	40	.90	.92	
FP	1,000	10,600	2	90	50	.88	.92	
FB	1,000	8,900	2	93	80	.85	.91	
FB	1,500	8,900	2	84	120	.83	.89	
FB	2,000	8,900	2	84	160	.80	.85	
LW	1,000	10,600	1	245	100	.85	.91	
LW	1,500	10,500	1	220	150	.83	.89	
LW	2,000	10,400	1	215	200	.80	.85	

Table A-1   Plant Performance and Cost Data for Test Problem

costs. Three types of fuel are consumed: U_3O_8 (Type 1) by the nuclear plants, heavy oil (Type 2) by the fossil plants, and light oil (Type 3) by the gas turbines. A time-varying function for the availability is used. The immature rate prevails during the first five years of each plant's operation and the mature rate is used from the five year point to end of life.

As initial conditions the following set of constructed plants was postulated:

Type	MWe	#
GT	100	2.0
FP	800	6.0
FB	1000	6.6
LW	1000	1.0

The following plants were excluded from the list of plant alternatives in the first period of the study (1975-1979): 1000 MWe fossil peak, and 1500 MWe and 2000 MWe fossil base and light water plants. A complete list of the plant alternatives in the test problem is shown in the output of PROTEUS contained later in this appendix. Also shown in the output of PROTEUS are the capacity, availability in the first year, total present worth of all costs with and without fuel costs included, and the levelized cost of electricity for each plant as calculated by PACTOLUS. The prices used in determining the fuel costs were input to PACTOLUS as follows:

Fuel Type	1965 Price	2065 Price	Rise in Price
1. (U_3O_8)	$6.00/lb	$16.00/lb	$0.10/year
2. (heavy oil)	$2.00/bbl	$ 5.00/bbl	$0.03/year
3. (light oil)	$2.70/bbl	$ 5.70/bbl	$0.03/year

As noted earlier PACTOLUS linearly interpolates to obtain fuel prices for the years not input.

Five test cases were run using the data described above. In all of them the study period started in 1975 and was 35 years long with an additional 15 years added to help discount possible end effects. The peak load used in all five cases started at 20,000 MWe in the first period and grew at the rate of 8.0% per year. The margin for spare available capacity, ξ_t, was 0.05 for each period. The energy demand in each period was as follows for all but the second test case.

Period	Years	Energy Demand (Million MWhr)
1	1975 - 1979	579
2	1980 - 1984	900
3	1985 - 1989	1,322
4	1990 - 1994	1,940
5	1995 - 1999	3,060
6	2000 - 2004	4,590
7	2005 - 2009	6,600
8	2010 - 2014	9,700
9	2015 - 2019	14,280
10	2020 - 2024	20,950

The MPSX output containing the optimal expansion plan for each of the test cases is included at the end of this appendix. These results are summarized in Table A-2.

Table A-2 Test Problem Results

Period	Base Case Type	MWe	#	Rising System CF Type	MWe	#	Limited Sites Type	MWe	#	Formulation One Type	MWe	#	Formulation One High Fossil Fuel Cost Type	MWe	#
1975-1979	GT	100	8.9	GT	100	55.2	GT	100	8.9	GT	100	8.9	GT	100	8.9
	FP	800	11.0	FB	1,000	4.7	FP	800	11.0	FP	800	11.0	FP	800	11.0
1980-1984	FP	1,000	3.5	FP	1,000	4.5	FP	800	3.5	FP	800	3.5	FP	800	3.5
	FB	1,500	5.3	FB	1,500	4.5	FB	1,500	5.3	FB	1,500	5.3	FB	1,500	5.3
1985-1989	GT	100	40.4	GT	100	23.1	GT	800	40.4	FP	1,000	7.9	GT	100	40.4
	FB	1,500	8.4	FB	1,500	9.6	FB	1,500	8.4	FB	1,500	5.6	LW	1,500	8.4
1990-1994	GT	100	80.0	FB	1,500	17.2	GT	100	80.0	GT	100	72.7	GT	100	80.0
	FB	1,500	11.8				FB	1,500	11.8	FB	1,500	12.3	LW	1,500	11.8
1995-1999	FP	1,000	17.0	LW	2,000	22.5	FP	1,000	17.0	FP	1,000	13.8	FP	1,000	14.8
	LW	2,000	12.3				LW	2,000	12.3	FB	1,500	18.0	LW	1,500	17.4
2000-2004	GT	100	96.9	LW	2,000	37.2	GT	100	92.1	FP	1,000	13.8	GT	100	94.8
	LW	2,000	22.8				LW	1,500	6.9	FB	1,500	26.0	LW	2,000	22.8
							LW	2,000	17.7						
2005-2009	GT	100	321.7	LW	2,000	41.2	GT	100	293.2	FP	1,000	53.0	FP	1,000	57.6
	LW	2,000	28.7				LW	1,500	38.8	FB	1,500	20.9	FB	1,500	18.1

181

The first case, designated the Base Case, was run using Formulation Three, the formulation without fuel constraints or fuel consumption variables. The cost, C_{jv}, of each plant alternative is the total present worth of all capital, operating, and _fuel_ costs. As can be seen from the summary table the optimal plant mix consists of peaking units and gas turbines in the first period. This is due to the heavily base loaded mix in the constructed plants which make up the initial conditions. As time progresses the mix becomes more base loaded. Further at the start of the study, when fossil fuel prices are relatively inexpensive, all the plants built burn fossil fuel. Further into the study, when fuel prices have risen, the nuclear units become more attractive. Although the prices of all three types of fuel increase over time, it is the nature of the nuclear plant energy costs to be relatively insensitive to fuel prices. This may be seen from the following example taken from the test problem:

Type	Size	Vintage	Energy Cost (mills/kwhr)
FB	1000	1975	5.730
LW	1000	1975	6.856
FB	1000	2005	7.029
LW	1000	2005	6.837

The model chooses plants to satisfy the energy constraint on the basis of cheapest cost per unit of energy production. The peak power constraint tends to be satisfied with plants exhibiting low costs per unit of available capacity.

Thus, for the base loaded plants which exhibit economies of scale and increasing efficiency with increasing capacity, the model chooses the plant with the largest capacity. This aspect of the model may be observed in the Base Case. In choosing the light water plants the model always selects the largest or the one with 2000 MWe capacity.

The second case was chosen to illustrate the effect of system capacity factor on the optimal plant mix. In this case the system capacity factor was allowed to gradually rise and reach 100% in the sixth period of the study. With 100% system capacity factor the system load remains constant at the peak demand level throughout the period. The results were as would be expected. As the system became more base loaded the optimal plant mix did the same until in period 4 when all subsequent capacity additions were base loaded fossil units or light water reactors.

The siting constraints were tested in the third case. Since the Plant Evaluation Model was run without the TPA or APA subroutines, land was the only environmental resource which could be constrained. The land requirements for the gas turbines and the fossil peaking units were input at 50 acres/GWe, the base loaded fossil plants at 80 acres/GWe, and the nuclear units at 100 acres/GWe. For the third case the number of sites with greater than 190 acres of available land were limited to thirty. The 2000 MWe nuclear units were the only plants which required more than 190 acres. As can be

seen from the results summarized in Table A-2, exactly 30 nuclear units were built. When these were no longer available the model switched to the next best plant, the 1500 MWe nuclear units.

In the fourth test case the fuel constraints were tested. The fuel costs input to PROTEUS were exactly those input to PACTOLUS and included in the plants for the first three cases. The discount rate used in PROTEUS to present-worth the fuel costs was equal to the rate calculated for each of the plants by PACTOLUS. The amount of fuel available was set to a very large number for each of the three types.

The results of this run were quite different from those of the Base Case. The nuclear units were replaced by the base loaded fossils and peaking fossils substituted for gas turbines, particularly toward the end of the study period. The explanation for this phenomena can be seen in light of the horizon conditions discussed in Chapter 4. With Formulation One, the Full Formulation, costs are included only for the fuel which is consumed during the study period. With the other two formulations, however, fuel costs which are incurred outside the study period are included. For example, the C_{jv} for a 2000 MWe nuclear unit built in 2020 includes fuel costs which would be incurred through the year 2059, or 35 years after the last year of the actual formulation as input to MPSX.

Since the base loaded units are chosen on the basis of

total cost per unit of energy the model will tend to choose the base loaded units with the lowest capital costs toward the end of the study if Formulation One is used. The reason for this is clear. The total fuel costs over the projected life of these plants is not included. Therefore the fuel component of the cost of energy is greatly reduced and the fossil plants with their smaller capital cost component appear more attractive.

The fifth and last test case was exactly the same as the fourth except the price of all fossil fuels was raised 70¢/bbl. This made the nuclear units attractive earlier in the study and enabled them to enter the solution before the horizon conditions made the fossil units more attractive. From these last two solutions it can be seen how important it is to fully understand the nature of the formulation used, the nature of the horizon conditions and their effect on the solution.

The last section of this appendix contains the output of PROTEUS and portions of the MPSX output for each of the five cases. In the PROTEUS output the external name refers to the 28 character name given to each alternative; the internal name refers to the corresponding character name used in MPSX. In the MPSX output, the section headed ROWS contains an entry for the objective function and for each constraint used. The objective function is named COST, the peak load constraint MAX, and the energy demand constraints ED. Each constraint name is

suffixed with the corresponding period number. The section headed COLUMNS contains an entry for each of the decision variables; the column headed activity contains the numbers of each type to be built. The column REDUCED COST contains the amount by which the cost, C_{jv}, of that variable would have to be reduced to bring it into the solution.

PROTEUS OUTPUT

INTERNAL-EXTERNAL NAME CORRESPONDENCE

INTERNAL NAME	EXTERNAL NAME								CAPACITY MWE	AVAILABILITY 1ST YEAR	PW WITH FUEL MILLION $	PW WITHOUT FUEL MILLION $	LEVELISED COST MILL $/MWHR
GT601001	GTNN	CNN1	100	100	1965	1965	NONE NONE NONE NONE		100.00	0.850	29.25	16.717	13.327
FP6C8CC2	FFNN	CNN2	800	800	1965	1965	NONE NONE NONE NONE		749.95	0.900	309.72	168.119	7.330
FB710003	FBNN	CNN2	1000	1000	1570	1570	NONE NONE NONE NONE		999.95	0.850	522.51	188.805	5.514
LW710CC4	LWU1	URO1	100	100	1975	1570	NONE NONE NONE NONE		999.96	0.850	651.08	611.398	6.070
GT7C1CC5	GTNN	CNN1	400	430	1975	1975	NONE NONE NONE NONE		100.00	0.850	30.54	16.743	13.914
FP7C4CC6	FPNN	CNN2	800	803	1975	1975	NONE NONE NONE NONE		399.97	0.920	182.76	91.294	8.650
FP7C8CC7	FFNN	CNN2	1000	1000	1975	1975	NONE NONE NONE NONE		799.95	0.900	331.48	148.555	7.845
FB710CC8	FPNN	CNN2	1030	1030	1975	1975	NONE NONE NONE NONE		999.95	0.850	543.02	189.215	5.730
LW710CC9	LWU1	URO1	130	130	1980	1980	NONE NONE NONE NONE		999.96	0.850	649.71	637.962	6.856
GT8C1C10	GTNN	CNN1	400	400	1980	1983	NONE NONE NONE NONE		100.00	0.850	31.18	16.755	14.207
FPEC4011	FPNN	CNN2	800	800	1980	1983	NONE NONE NONE NONE		399.97	0.920	188.20	91.403	8.908
FPEC8C12	FFNN	CNN2	1030	1030	1980	1983	NONE NONE NONE NONE		799.95	0.900	342.36	148.772	8.103
FPE10013	FPNN	CNN2	1000	1000	1980	1983	NONE NONE NONE NONE		999.94	0.880	411.28	169.290	7.787
FH810014	FBNN	CNN2	1500	1500	1980	1983	NONE NONE NONE NONE		999.95	0.850	563.54	189.624	5.946
FBE15015	FBNN	CNN2	2000	2030	1980	1983	NONE NONE NONE NONE		1499.92	0.830	822.53	261.652	5.786
FBE20016	FBNN	CNN2	1030	1030	1980	1983	NONE NONE NONE NONE		1359.90	0.800	1096.21	348.378	5.784
LW810C17	LWU1	URO1	1500	1500	1980	1983	NONE NONE NONE NONE		999.96	0.850	648.14	604.346	6.039
LWE1>018	LWU1	URO1	2000	2030	1980	1983	NONE NONE NONE NONE		1499.62	0.830	903.70	838.570	6.359
LWE20019	LWU1	URO1	2030	2030	1985	1983	NONE NONE NONE NONE		1399.98	0.800	1181.10	1099.255	6.231
GTEC1C20	GTNN	CNN1	130	130	1985	1985	NONE NONE NONE NONE		100.00	0.850	31.82	16.768	14.501
FPEC4C21	FPNN	CNN2	400	430	1985	1985	NONE NONE NONE NONE		399.97	0.920	193.64	91.511	9.165
FPEC8C22	FFNN	CNN2	800	800	1985	1985	NONE NONE NONE NONE		799.95	0.900	353.25	148.490	8.360
FPE10023	FPNN	CNN2	1030	1030	1985	1985	NONE NONE NONE NONE		999.94	0.880	424.88	169.562	8.044
FB810024	FBNN	CNN2	1500	1500	1985	1985	NONE NONE NONE NONE		999.95	0.950	584.05	190.033	6.163
FBE15325	FBNN	CNN2	2000	2030	1985	1985	NONE NONE NONE NONE		1499.92	0.800	853.30	262.266	6.003
FFE20C26	FFNN	CNN2	2030	2030	1985	1985	NONE NONE NONE NONE		1399.90	0.800	1137.24	349.198	6.000
LWE1CC27	LWU1	URO1	1000	1000	1985	1985	NONE NONE NONE NONE		999.96	0.850	646.57	600.749	6.823
LWE15020	LWU1	URO1	1500	1500	1985	1985	NONE NONE NONE NONE		1499.62	0.830	901.37	833.221	6.342
L4E20029	LWU1	URO1	2030	2030	1985	1985	NONE NONE NONE NONE		1999.98	0.900	1178.02	1088.203	6.215
GTSC1C30	GTNN	CNN1	130	130	1990	1990	NONE NONE NONE NONE		100.00	0.850	32.47	16.781	14.794
FPS04C31	FPNN	CNN2	400	430	1990	1990	NONE NONE NONE NONE		399.97	0.920	199.08	91.620	9.423
FPSC8C32	FFNN	CNN2	800	800	1990	1990	NONE NONE NONE NONE		799.95	0.900	364.13	149.207	8.618
FPS10033	FPNN	CNN2	1030	1030	1990	1990	NONE NONE NONE NONE		999.94	0.880	438.48	169.834	8.302
FA910034	FANN	CNN2	1030	1030	1990	1990	NONE NONE NONE NONE		999.95	0.850	604.57	190.443	6.379
FBS15035	FBNN	CNN2	1530	1530	1990	1990	NONE NONE NONE NONE		1499.92	0.830	884.07	262.882	6.219
FES20C36	FENN	CNN2	2030	2030	1990	1990	NONE NONE NONE NONE		1999.90	0.800	1178.28	350.018	6.217
LWS10C37	LWU1	URO1	1000	1000	1990	1990	NONE NONE NONE NONE		1999.96	0.850	645.33	597.491	6.809
LWS15038	LWU1	URO1	1500	1500	1990	1990	NONE NONE NONE NONE		1499.62	0.830	899.51	828.379	6.329
LW920039	LWU1	URO1	2030	2030	1990	1990	NONE NONE NONE NONE		1999.98	0.800	1175.58	1081.819	6.202
GTSC1C40	GTNN	CNN1	130	130	1995	1995	NONE NONE NONE NONE		100.00	0.850	33.11	16.794	15.087
FP904041	FPNN	CNN2	400	430	1995	1995	NONE NONE NONE NONE		399.97	0.920	204.52	91.729	9.681
FPSC8C42	FFNN	CNN2	800	800	1995	1995	NONE NONE NONE NONE		799.95	0.900	375.01	149.425	8.075
FPS10043	FPNN	CNN2	1000	1000	1995	1995	NONE NONE NONE NONE		999.94	0.880	452.09	170.107	6.559
FA910044	FFNN	CNN2	1000	1000	1995	1995	NONE NONE NONE NONE		999.95	0.850	625.09	190.853	6.596
FBS15C45	FBNN	CNN2	1530	1530	1995	1995	NONE NONE NONE NONE		1499.92	0.830	914.85	263.497	6.436
FUS20046	FUNN	CNN2	2030	2030	1995	1995	NONE NONE NONE NONE		1359.90	0.830	1219.31	350.840	6.433
LWS10C47	LWU1	URO1	1000	1000	1995	1995	NONE NONE NONE NONE		949.96	0.850	644.81	594.979	6.804
LW915048	LWU1	URO1	1500	1500	1995	1995	NONE NONE NONE NONE		1499.62	0.830	898.74	824.639	6.324
LW920049	LWU1	URO1	2030	2030	1995	1995	NONE NONE NONE NONE		1999.98	0.800	1174.57	1076.891	6.197
GTCC1C50	GTNN	CNN1	130	130	2000	2000	NONE NONE NONE NONE		100.00	0.850	33.75	16.807	15.380
FPCC4C51	FPNN	CNN2	400	430	2000	2000	NONE NONE NONE NONE		399.97	0.920	209.96	91.838	9.938
FPCC8C52	FFNN	CNN2	800	800	2000	2000	NONE NONE NONE NONE		749.95	0.900	385.89	149.643	9.133
FPC10053	FPNN	CNN2	1000	1000	2000	2000	NONE NONE NONE NONE		999.94	0.850	465.69	170.379	8.817
FBC10054	FBNN	CNN2	1530	1530	2000	2000	NONE NONE NONE NONE		999.95	0.850	645.60	191.263	6.812
FBS15355	FBNN	CNN2	2000	2000	2000	2000	NONE NONE NONE NONE		1499.92	0.830	945.63	264.115	6.652
FE020C56	FFNN	CNN2	2030	2030	2000	2000	NONE NONE NONE NONE		1359.90	0.800	1260.34	351.659	6.650
LWC1C057	LWU1	URO1	1030	1030	2000	2000	NONE NONE NONE NONE		999.96	0.850	645.42	593.608	6.810

ID												
LW015056	LWU1	URO1	150C	2C0C	NONE	NCNE	NONE	1499.62	0.830	899.65	822.604	6.330
LW020059	LWU1	URO1	2000	2000	NONE	NCNE	NONE	1999.98	0.800	1175.77	1076.208	6.203
GTCC1C40	GTNN	CNN1	100	2005	NONE	NCNE	NONE	100.00	0.850	34.40	16.820	15.674
FP004061	FPNN	CNN2	40C	2005	NONE	ACNE	NONE	399.97	0.920	215.40	91.947	16.196
FPCC8C62	FPNN	CNN2	800	2005	NONE	NCNE	NONE	799.95	0.900	396.77	149.860	9.390
FPC10063	FFNN	CNN2	1000	2C05	NONE	NCNE	NONF	999.94	0.880	479.29	170.651	7.074
FBC10064	FBNN	CNN2	1000	2005	NONE	NCAE	NONE	999.95	0.850	666.12	191.674	7.029
FBC15065	FBNN	CNN2	1500	2005	NONE	NCAE	NONE	1499.92	0.830	976.40	264.725	4.849
FBC20066	FBNN	CNN2	2000	2005	NCNE	NCAE	NONE	1999.90	0.800	1301.38	352.482	4.866
LWC10C67	LWU1	URO1	1000	2005	NCNE	ACAE	NONE	999.96	0.850	447.96	594.178	6.837
LWC15068	LWU1	URO1	1500	2005	NUNE	ACAE	NONE	1499.62	0.850	903.43	823.452	4.357
LW020069	LWU1	URO1	2000	2005	NONE	NCNE	NUNE	1999.98	0.800	1180.74	1075.328	6.229
GT1C1070	GTNN	CNN1	40C	2010	NCNE	NCNE	NONE	100.00	0.850	35.04	16.833	15.967
FP1C4C71	FPNN	CNN2	400	2010	NCNE	ACNE	NONE	399.97	0.920	220.84	92.055	10.453
FP1C8C72	FPNN	CNN2	800	2010	NONE	NCNE	NONE	799.95	0.930	407.65	150.078	9.648
FP210073	FPNN	ENN2	1000	2C10	NJNE	NJNE	NONE	999.94	0.880	492.89	170.924	9.332
FR110074	FBNN	CNN2	1000	2010	NONE	NCAE	NONE	999.95	0.850	686.64	192.082	7.245
FR115075	FBNN	CNN2	1500	2C10	NORL	ACAE	NONE	1499.92	0.830	1007.18	265.344	7.085
FB120076	FBNN	CNN2	2000	2010	NONE	NCAL	NONE	1999.90	0.800	1342.41	353.301	7.083
LW1CC77	LWU1	URO1	1000	2010	NCNE	NCAL	NONE	999.96	0.830	652.00	596.856	4.886
LW115078	LWU1	URO1	1500	2010	NONE	NCNL	NONE	1499.62	0.830	910.31	827.428	6.405
LW120079	LWU1	URO1	2000	2010	NONE	NONF	NUNE	1999.98	0.800	1189.82	1080.565	6.277
GT1C1080	GTNN	CNN1	100	2015	NCNE	ACNE	NONE	100.00	0.850	35.68	16.846	16.260
FP1C4C81	FPNN	CNN2	400	2015	NCNE	NCAE	NUME	399.97	0.920	226.28	92.164	10.711
FP110C82	FPNN	CNN2	800	2C15	NONE	NCAE	NUNE	799.95	0.900	418.53	150.295	9.905
FP110C83	FBNN	CNN2	1000	2C15	HUNE	NCNE	NUNE	999.94	0.880	506.49	171.195	5.589
FB110C84	FHNN	CNN2	1000	2015	NCNE	NCAL	MINE	999.95	0.850	707.15	192.494	7.462
FB115C85	FPNN	CNN2	1500	2015	NONE	NCAL	NUNE	1499.92	0.830	1037.95	265.959	7.302
FB120C86	LWU1	URO1	1000	2015	NCNE	NCAL	NUNE	1999.90	0.800	1383.45	354.123	7.299
LW11CC87	LWU1	URO1	1500	2015	NONE	NONL	NUNE	999.96	0.850	657.19	599.502	6.935
LW115088	LWU1	URO1	2000	2015	NONE	NONE	NUNE	1499.62	0.830	917.14	831.366	6.453
LW120C89	GTNN	CNN1	110	2020	NJNE	NONE	NONE	1999.98	0.800	1198.82	1085.759	6.325
GT2C1C90	FPNN	CNN4	400	2020	NONE	NCNE	NJNE	100.00	0.850	36.33	16.858	16.554
FP204C91	FENH	CNN7	800	2020	NCNE	NCNE	NJNE	399.97	0.920	231.72	92.273	10.968
FP2C8C92	FPNN	CNN2	1000	2C20	NONE	NCNL	NJNE	799.95	0.930	429.42	150.514	10.163
FP210C93	FBNN	CNN2	1000	2020	NONE	NCAE	NONE	999.94	0.880	520.10	171.468	5.847
FB210C94	FENN	CNN2	1500	2020	NCNE	NCAE	NONE	999.95	0.850	727.67	192.903	7.678
FB215C95	FENN	CNN2	1000	2023	NONE	NCAE	NONE	1499.92	0.830	1068.73	266.576	7.518
FB220CC96	LWU1	URO1	1500	2020	NCRE	NCRL	NJNE	1999.90	0.850	1424.48	354.943	7.516
LW215C97	LWU1	URO1	1500	2020	NONE	NCNL	NJNE	999.96	0.830	661.75	602.127	6.983
LW215058	LWU1	URO1	2000	2020	NCNE	NCNE	NONE	1499.62	0.830	923.93	835.270	6.127
LW220099	LWU1	URO1	2000	2020	NONE	NCNF	NONE	1199.98	0.800	1207.76	1090.901	6.372

CASE 1

THE BASE CASE

MFSX-PTF9   EXECUTCR. MPSX RELEASE 1 MCD LEVEL 3   PAGE   7 - 73/015

SECTICN 1 - RCWS

NUMBER	...ROW..	AT	...ACTIVITY...	SLACK ACTIVITY	..LOWER LIMIT.	..UPPER LIMIT.	.DUAL ACTIVITY
1	COST	BS	59850.86357	59850.86357-	NCNE	NCNE	1.00000
2	MAXLC1	LL	21000.0C000	.	21000.00000	NONE	.12753-
3	MAXLC2	LL	30855.8CC00	.	30855.80000	NONE	.02610-
4	MAXLC3	LL	45337.1C000	.	45337.10C00	NONE	.05337-
5	MAXLC4	LL	66614.9C000	.	66614.9C00	NONE	.07406-
6	MAXLC5	LL	57878.8C030	.	9787E.80CCC	NONE	.01422-
7	MAXLC6	LL	143816.0C000	.	143816.00003	NONE	.01439-
8	MAXLC7	LL	211312.0C000	.	211312.00C00	NCNE	.01093-
9	MAXLC8	LL	310486.CC000	.	310486.00CCC	NCNE	.00833-
10	MAXLC9	LL	456204.CC000	.	456204.00000	NCNE	.00671-
11	MAXL10	LL	670311.0C000	.	670311.00CCC	NCNE	.01868-
12	ED01	LL	5789399559.994	.	578999559.594	NCNE	.00000-
13	ED02	LL	8599995559.994	.	899999559.994	NONE	.00000-
14	ED03	LL	13213995939.79	.	1321995599.95	NONE	.00000-
15	ED04	LL	1940CCCC30.33	.	19400300C03.00	NONE	.00000-
16	ED05	LL	3C55995596.97	.	3059995599.57	NONE	.00000-
17	ED06	LL	4589599999.89	.	4589959999.85	NONE	.00003-
18	ED07	LL	6559555599.92	.	6599995999.92	NGNE	.00000-
19	ED08	LL	9699999599.89	.	9699959599.85	NCNE	.00000-
20	ED09	LL	14279955559.9	.	1427995999.9	NUNE	.00000-
21	ED10	LL	20549955555.9	.	2094999559.5	NCNE	.00000-

191

SECTION 2 - COLUMNS

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
22	GT601001	EQ	12.00000	.	12.00000	12.00000	22.10756-
23	FP608C02	EQ	6.00000	.	6.00000	6.00000	276.32336-
24	FB71C003	EQ	6.66000	.	6.66000	6.63000	519.81326-
25	LW71C004	EQ	1.00000	.	1.00030	1.00000	519.81748-
26	GT701005	BS	8.86725	36.53500		NONE	15.99558
27	FP704306	LL		182.75700	.	NONE	
28	FP708307	BS	10.96585	331.48200		NONE	
29	FB71CCC8	LL	.	543.32330	.	NONE	5.51565
30	LW71C009	LL	.	645.71200	.	NONE	112.23031
31	GT801010	Lt	.	22.68730	.	NONE	2.24007
32	FP804011	LL	.	136.94300	.	NONE	16.81768
33	FP808C12	LL	.	245.12200	.	NONE	9.28925
34	FP91CC13	BS	3.45773	235.26900		NONE	
35	FB81C014	LL	.	410.05900	.	NONE	6.88821
36	FB815015	BS	5.33183	598.51200		NONE	
37	FR82C016	LL	.	757.05900	.	NONE	15.76799
38	LW81C017	LL	.	471.62300	.	NONE	68.44893
39	LW815018	LL	.	657.57700	.	NONE	59.18626
40	LW82O019	LL	.	655.42900	.	NONE	77.50640
41	GT801020	BS	40.41100	16.84920		NONE	
42	FP804J21	LL	.	132.52800	.	NONE	13.38536
43	FP808022	LL	.	187.03600	.	NONE	9.60468
44	FP81CC23	LL	.	224.36500	.	NONE	4.24322
45	FB81C024	LL	.	3C5.2+400	.	NONE	4.02767
46	FB81C025	BS	8.37654	451.80300		NONE	
47	FB82C026	LL	.	602.14500	.	NONE	14.72704
48	LW810327	LL	.	242.34700	.	NONE	37.12819
49	LW815028	LL	.	477.25300	.	NONE	25.54130
50	LW82CC25	LL	.	623.73700	.	NONE	36.29539
51	GT9C1030	AS	75.99564	12.50340		NONE	10.02345
52	FP9J4031	LL	.	76.7J070	.	NONE	8.11951
53	FP9C8032	LL	.	140.20900	.	NONE	5.20619
54	FP91CC33	LL	.	168.93700	.	NONE	2.90472
55	FB910034	LL	.	234.92700	.	NONE	
56	FB915035	AS	11.84347	343.61333		NONE	10.11324
57	FB92O036	LL	.	453.96100	.	NONE	18.60584
58	LW91C037	LL	.	248.03300	.	NONE	6.01681
59	LW915O38	LL	.	346.56100	.	NONE	9.05761
60	LW92C039	LL	.	456.92300	.	NONE	2.37786
61	GT9J1040	LL	.	5.28221	.	NONE	6.41284
62	FP9J4041	LL	.	57.33680	.	NONE	3.51171
63	FP9U8042	LL	.	105.13200	.	NONE	
64	FP91C343	BS	16.95613	126.74103		NONE	
65	FB910044	LL	.	175.24100	.	NONE	6.35119
66	FB915045	LL	.	256.47500	.	NONE	5.33863
67	FB920046	LL	.	341.83000	.	NONE	12.55725
68	LW910047	LL	.	18C.77100	.	NONE	11.87981
69	LW915048	LL	.	251.96000	.	NONE	.87447
70	LW92CC49	BS	12.28644	325.28600		NONE	.

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
71	GTOO1050	BS	96.85210	6.88553	.	NONE	.
72	FP004051	LL	.	42.83110	.	NCNE	4.68167
73	FP0C8C52	LL	.	76.71970	.	NCNE	2.65117
74	FP015053	LL	.	54.99800	.	NCNE	.20013
75	FB010054	LL	.	131.70000	.	NCNE	8.38079
76	FB015055	LL	.	192.93333	.	NCNE	9.69580
77	FB020056	LL	.	257.10400	.	NCNE	17.26261
78	LW010057	LL	.	121.66300	.	NCNE	8.34280
79	LW015058	LL	.	183.52500	.	NCNE	.35489
80	LW020059	BS	22.84407	235.85100	.	NCNE	.
81	GTC1060	BS	321.70362	51.10581	.	NCNE	.
82	FP004061	LL	.	31.97380	.	NCNE	3.70746
83	FP008C62	LL	.	56.03590	.	NCNE	2.53816
84	FP015063	LL	.	71.11463	.	NONE	.91605
85	FB010064	LL	.	96.07740	.	NCNE	8.67779
86	FB015065	LL	.	144.93500	.	NCNE	10.97534
87	FB020066	LL	.	193.17406	.	NCNE	17.91407
88	LW010067	LL	.	96.18193	.	NCNE	5.98153
89	LW015068	LL	.	134.11300	.	NCNE	.17347
90	LW020069	BS	28.71109	175.26700	.	NCNE	.

193

CASE 2

INCREASING SYSTEM CAPACITY FACTOR

SECTION 2 - COLUMNS

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
22	GT601001	EQ	12.00000	.	12.00000	12.00000	23.43977-
23	FP608002	EQ	6.30300	.	6.00000	6.00300	286.36359-
24	FB710003	EQ	6.60000	.	6.60000	6.60000	524.99347-
25	LW710004	EQ	1.00000	.	1.00000	1.00000	524.99768-
26	GT701005	BS	55.22235	30.53500	.	NONE	
27	FP704306	LL	.	182.75700	.	NONE	17.01653
28	FP708007	LL	.	331.48200	.	NONE	1.43683
29	FB710008	BS	4.65289	543.02300	.	NONE	
30	LW710009	LL	.	649.71200	.	NONE	106.68464
31	GT801010	LL	.	22.68737	.	NONE	.84769
32	FP804011	LL	.	136.94300	.	NONE	16.60263
33	FP808012	LL	.	249.12200	.	NONE	9.07439
34	FP810013	BS	4.52205	299.26900	.	NONE	
35	FB810014	LL	.	410.05900	.	NONE	7.04854
36	FR815015	BS	4.49623	598.51200	.	NONE	
37	FB820016	LL	.	797.65900	.	NONE	14.85745
38	LW810017	LL	.	471.62300	.	NONE	68.67926
39	LW815018	LL	.	657.57700	.	NONE	59.18613
40	LW820019	LL	.	859.42900	.	NONE	76.59588
41	GT810120	BS	23.10866	16.84927	.	NONE	
42	FPR04021	LL	.	102.52800	.	NONE	15.11585
43	FP808022	LL	.	187.03600	.	NONE	13.75627
44	FP810223	LL	.	224.96500	.	NONE	10.29605
45	FB810024	LL	.	309.24400	.	NONE	4.83030
46	FR815125	BS	9.58410	451.31300	.	NONE	
47	FB820026	LL	.	602.14500	.	NONE	10.65201
48	LW810027	LL	.	342.34700	.	NONE	37.93078
49	LW815028	LL	.	477.25300	.	NONE	25.54117
50	LW820029	LL	.	623.73700	.	NONE	32.22048
51	GT901030	LL	.	12.5C849	.	NONE	3.43375
52	FP904031	LL	.	76.70070	.	NONE	19.38776
53	FP908032	LL	.	140.28900	.	NONE	26.63732
54	FP910033	LL	.	168.93700	.	NONE	28.21497
55	FB910034	LL	.	232.92700	.	NONE	4.57085
56	FR915035	BS	17.21872	340.61302	.	NONE	
57	FB920036	LL	.	453.96100	.	NONE	3.64954
58	LW910037	LL	.	248.63000	.	NONE	20.27194
59	LW915038	LL	.	346.56193	.	NONE	6.01688
60	LW920039	LL	.	452.92300	.	NONE	2.59375
61	GT901040	LL	.	5.28221	.	NONE	5.71365
62	FP904041	LL	.	57.33680	.	NONE	19.51662
63	FP908042	LL	.	105.13200	.	NONE	29.49170
64	FP910043	LL	.	126.74102	.	NONE	32.19058
65	FR910044	LL	.	175.24100	.	NONE	10.60454
66	FR915045	LL	.	256.47500	.	NONE	9.52089
67	FB920046	LL	.	341.83000	.	NONE	12.55721
68	LW910047	LL	.	180.77100	.	NONE	16.13316
69	LW915048	LL	.	251.96003	.	NONE	5.05593
70	LW920049	BS	22.52116	329.28600	.	NONE	

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
71	GT001050	LL	.	6.88553	.	NONE	3.69833
72	FP004051	LL	.	42.83110	.	NONE	15.01751
73	FP008052	LL	.	78.71970	.	NONE	23.09255
74	FP010053	LL	.	94.99800	.	NONE	25.46402
75	FR010054	LL	.	131.70000	.	NONE	11.77924
76	FR015055	LL	.	192.90300	.	NONE	13.02227
77	FR020056	LL	.	257.10400	.	NONE	17.26256
78	LW010057	LL	.	131.66300	.	NONE	11.74125
79	LW015058	LL	.	183.52500	.	NONE	3.68075
80	LW020059	BS	37.15262	239.85100	.	NONE	
81	GT001060	LL	.	5.05581	.	NONE	2.81682
82	FP004061	LL	.	31.97380	.	NONE	11.39178
83	FP008062	LL	.	58.89590	.	NONE	17.73187
84	FP010063	LL	.	71.14460	.	NONE	19.68959
85	FR010064	LL	.	98.87740	.	NONE	11.24737
86	FR015065	LL	.	144.93500	.	NONE	13.49026
87	FR020066	LL	.	193.17400	.	NONE	17.91408
88	LW010067	LL	.	96.18190	.	NONE	8.55109
89	LW015068	LL	.	134.13300	.	NONE	2.68493
90	LW020069	BS	41.19466	175.26700	.	NONE	

CASE 3

LIMITED SITES

SECTION 2 - COLUMNS

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
23	GT601001	FO	12.00000	.	12.00000	12.00000	22.10754-
24	FP630002	FO	6.00000	.	6.00000	6.00000	276.46949-
25	FB710003	FO	6.60000	.	6.60000	6.60000	519.87951-
26	LW711004	EQ	1.00000	.	1.00000	1.00000	519.87973-
27	GT701005	BS	8.86725	30.53500		NONE	15.99578
28	FP794006	LL	.	182.75700		NONE	.
29	FP730007	BS	10.96585	331.48200		NONE	5.42901
30	FB710108	LL		543.02300		NONE	112.11367
31	LW712009	LL		649.71200		NONE	2.23912
32	GT801010	LL		22.68730		NONE	16.81792
33	FP804311	LL		136.94300		NONE	9.28950
34	FP808012	LL		249.17200		NONE	.
35	FP810013	BS	3.45773	295.26900		NONE	6.88798
36	FB811314	LL		410.05900		NONE	.
37	FB815015	AS	5.33183	598.51200		NONE	.
38	FB820016	LL		747.65900		NONE	15.76920
39	LW810317	LL		471.62300		NONE	68.44870
40	LW815018	LL		657.57700		NONE	59.18626
41	LW820019	LL		859.42900		NONE	77.98785
42	GT801020	AS	40.41100	16.84920		NONE	.
43	FP804021	LL		102.52800		NONE	13.40142
44	FP808022	LL		187.03600		NONE	9.63673
45	FP810023	LL		224.96500		NONE	4.28322
46	FB810C24	LL		309.24400		NONE	4.02821
47	FB815025	AS	8.37654	451.80300		NONE	.
48	FH820026	LL		632.14500		NONE	14.72493
49	LW810327	LL		342.34700		NONE	37.12873
50	LW815028	LL		477.25300		NONE	25.54130
51	LW820029	LL		623.73700		NONE	36.77350
52	GT901030	AS	79.99564	12.50840		NONE	10.04511
53	FP904031	LL		76.70070		NONE	8.16817
54	FP938032	LL		140.28900		NONE	5.27370
55	FP910033	LL		168.93700		NONE	2.90519
56	FB910034	LL		232.97700		NONE	.
57	FB915035	AS	11.04347	340.61300		NONE	10.10464
58	FB920036	LL		453.96100		NONE	18.60631
59	LW910337	LL		248.63000		NONE	6.01681
60	LW915038	LL		346.56100		NONE	9.52924
61	LW920039	LL		452.92300		NONE	2.39446
62	GT901040	LL		9.28221		NONE	6.41699
63	FP904041	LL		57.33680		NONE	3.51586
64	FP908042	LL		105.13200		NONE	.
65	FP910043	AS	16.99613	126.74100		NONE	.
66	FB910044	LL		175.24100		NONE	6.13330
67	FB915045	LL		256.47500		NONE	4.99609
68	FB920046	LL		341.83200		NONE	12.07704
69	LW910047	LL		180.77100		NONE	11.65861
70	LW915048	LL		251.96000		NONE	.53200
71	LW920049	AS	12.28644	329.28600		NONE	

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
72	GT001050	BS	92.06092	6.88553	.	NONE	.
73	FP004051	LL	.	42.83110	.	NONE	4.63971
74	FP008052	LL	.	78.71970	.	NONE	2.56645
75	FP010053	LL	.	94.99800	.	NONE	.09323
76	FR010054	LL	.	131.73000	.	NONE	8.14613
77	FR015055	LL	.	192.93300	.	NONE	9.34084
78	FR020056	LL	.	257.10400	.	NCNE	16.78240
79	LW010057	LL	.	131.66300	.	NONE	8.10814
80	LW015058	BS	6.92224	183.52500	.	NONE	.
81	LW020059	BS	17.71356	239.85100	.	NONE	.
82	GT001060	BS	293.18733	5.10581	.	NONE	.
83	FP004061	LL	.	31.97380	.	NONE	3.68777
84	FP008062	LL	.	58.89593	.	NONE	2.49831
85	FP010063	LL	.	71.14460	.	NCNE	.86564
86	FR010064	LL	.	98.87740	.	NONE	8.56511
87	FR015065	LL	.	144.93500	.	NCNE	10.80483
88	FR020066	LL	.	193.17400	.	NCNF	17.68338
89	LW010067	LL	.	76.18190	.	NONE	5.86884
90	LW015068	BS	38.76632	134.10303	.	NCNF	.
91	LW020069	LL	.	175.26700	.	NONE	.24953

CASE 4

FORMULATION ONE

SECTION 2 - COLUMNS

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
195	G1C01601	FQ	12.00000	.	12.00000	12.00000	12.15074-
196	FP400002	EQ	6.00000	.	6.00000	6.00000	145.30237-
197	F0710603	FQ	6.60000	.	6.60300	6.60000	190.05064-
198	L4710004	EQ	1.00000	.	1.00000	1.00000	478.94842-
199	G1701005	BS	8.56725	16.74240	.	NONE	16.05019
200	FP704006	HS	10.56585	91.24360	.	NONE	
201	FP708007	LL		148.55500	.	NCNE	.11771
202	F8710028	LL		189.21500	.	NONE	111.19444
203	L4710005	EL		6C7.96200	.	NONE	1.74915
204	G1C01010	LL		12.10220	.	NCNC	16.52495
205	FP404011	LL		66.50930	.	NCNC	8.99623
206	FPC3012	LL		108.25400	.	NONE	
207	FP419013	HS	3.45773	123.14400	.	NONE	6.63222
208	FU410014	LL		137.43000	.	NONE	
209	FU15015	HS	5.37103	190.39100	.	NONE	
210	L4010017	LL		253.49800	.	NCNE	16.42257
211	F0710018	LL		639.75400	.	NGNF	74.57549
212	L4150018	LL		610.14730	.	NCNF	68.69334
213	L420019	LL		746.96460	.	NCNE	90.72787
214	G1C1320	LL		8.37047	.	NCNE	.26120
215	FP40421	LL		48.45120	.	NCME	11.75032
216	FP403022	LL		78.28670	.	NONE	6.27217
217	FP41323	HS	7.96537	89.77630	.	NONE	
218	FP410024	BS		100.61310	.	NCNE	4.25535
219	F410025	BS	5.47626	130.66430	.	NONF	
220	L4020026	LL		184.95330	.	NONE	13.09509
221	L41527	LL		118.09300	.	NCNF	42.73119
222	L410528	LL		441.17200	.	NJNE	33.54594
223	L41229	LL		576.17500	.	NONE	46.03604
224	G1C1030	BS	12.67200	6.46539	.	NONE	
225	FP404031	LL		35.24900	.	NCME	8.22542
226	FP410032	LL		57.44990	.	NONE	4.31611
227	FP410033	LL		65.44290	.	NCNE	.19217
228	L410034	LL		73.13300	.	NJNE	3.05394
229	L415035	HS	12.24925	101.24200	.	NONE	
230	FP429036	LL		134.85300	.	NONE	9.77639
231	L410037	LL		319.10930	.	NONF	25.97410
232	L415038	LL		319.15400	.	NONE	16.81729
233	L420C39	LL		416.74920	.	NONE	73.07861
234	G1C1040	LL		4.70817	.	NCNE	1.39869
235	FP404041	LL		25.71560	.	NCNF	6.30279
236	FPC8042	HS	13.30055	41.85080	.	NCNE	3.40219
237	FP13043	HS		47.60800	.	NCNE	
238	FP910044	HS		53.05500	.	NONE	2.68203
239	FU150045	HS	18.01648	73.97050	.	NONE	
240	F420046	LL		98.35700	.	NONC	5.74300
241	L410047	LL		160.60100	.	NONC	17.93970
242	L415048	LL		231.10500	.	NCNE	10.11471
243	L420049	LL		301.90300	.	NONE	12.60663

NUMBER	..COLUMN..	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT..	..UPPER LIMIT.	.REDUCED COST.
244	CIUCI050	LL	.	3.42854	.	NONE	.23104
245	PPUO4051	LL	.	18.73450	.	NONE	4.57653
246	PPUC8052	BS	.	30.52640	.	NONE	2.46588
247	PPO10053	LL	13.75857	34.7765C	.	NONE	1.94408
248	IbJ10054	BS	.	39.01680	.	NONE	
249	IbJ15055	BS	26.03413	53.97010	.	NONE	4.19467
250	PPJ20056	LL	.	71.73CM0	.	NONE	13.14070
251	PPU20057	LL	.	121.03400	.	NONE	.51841
252	LbJ15058	LL	.	167.85730	.	NONE	.43056
253	PPU25059	LL	.	219.13310	.	NONE	.09757
254	CIUCI06C	LL	.	2.44669	.	NONE	3.32221
255	PPUO4061	LL	.	13.64030	.	NONE	1.78641
256	PPUC8062	LL	.	22.24493	.	NONE	
257	PPU10063	LL	4.57937	25.33110	.	NONE	1.41967
258	IbJ10064	LL	.	28.42160	.	NONE	
259	IbJ15065	BS	20.02852	39.25500	.	NONE	3.02301
260	LbJ10J67	LL	.	52.42150	.	NONE	12.04334
261	Lb15068	LL	.	86.15640	.	NONE	9.19121
262	LbJ20069	LL	.	122.21100	.	NONE	11.80696
263	CIUCI070	LL	.	1.61011	.	NONE	.02530
264	FP104071	LL	.	9.64300	.	NONE	2.40942
265	PP1C8072	LL	.	16.21000	.	NONE	1.79181
266	PP110073	BS	53.34817	18.46160	.	NONE	
267	PP110074	BS	4C.46C59	20.74730	.	NONE	1.04761
268	PP115075	LL	.	28.66010	.	NONE	
269	Pb120076	LL	.	30.16643	.	NONE	2.13063
270	Pb110077	LL	.	64.46690	.	NONE	12.33688
271	Lb115078	BS	91.50314	89.37130	.	NONE	12.03442
272	LbJ20079	LL	65.06324	116.71160	.	NONE	15.66987
273	CIUCI080	BS	.	1.32397	.	NONE	1.74017
274	PP104081	LL	.	7.24360	.	NONE	.92701
275	PP108082	BS	.	11.61240	.	NONE	
276	PP110083	BS	.	13.45530	.	NONE	.78729
277	PPU20084	LL	.	15.12930	.	NONE	
278	Pb115085	LL	92.57470	20.5C290	.	NONE	1.43508
279	Lb120086	LL	104.54171	27.63210	.	NONE	14.24279
280	PP110087	LL	.	47.11750	.	NONE	16.61906
281	Lb115098	LL	.	65.34070	.	NONE	21.77638
282	Lb120J99	LL	.	95.33460	.	NONE	.01901
283	CI2CI050	LL	.	.96412	.	NONE	1.15090
284	PP104051	LL	.	5.27704	.	NONE	.55920
285	PPUC8052	BS	.	8.60770	.	NONE	
286	PP210053	BS	92.57470	9.8CC17	.	NONE	.61374
287	Lb110094	LL	.	11.03203	.	NONE	
288	Lb215095	BS	104.54171	15.24540	.	NONE	.73538
289	Lb220056	LL	.	20.29900	.	NONE	16.67529
290	Lb21C057	LL	.	34.43630	.	NONE	21.79254
291	Lb15058	LL	.	47.7686C	.	NONE	28.46566
292	Lb220J99	LL	.	62.34800	.	NONE	
293	U253JC	EC	.				

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
225	U25301	BS	.	.	.	NONE	.
226	U25302	BS	.	.	.	NONE	.
227	U25303	BS	.	.	.	NONE	.
228	U25304	BS	.	.	.	NONE	.
299	U25305	BS	.	.	.	NONE	.
300	U25306	BS	.	.	.	NONE	.
301	U25307	BS	.	.	.	NONE	.
302	U25308	BS	.	.	.	NONE	.
303	U25309	BS	.	.	.	NONE	.
304	U25310	BS	.	.	.	NONE	.
305	P5P100	EQ	.	.	.	NONE	.
306	P5P101	BS	.92025	.	.	NONE	.
307	P5P102	BS	1.23001	.	.	NONE	.
308	P5P103	BS	2.54900	.	.	NONE	.
309	P5P104	BS	3.73012	.	.	NONE	.
310	P5P105	BS	4.45349	.	.	NONE	.
311	P5P106	BS	5.23416	.	.	NONE	.
312	P5P107	BS	5.90292	.	.	NONE	.
313	P5P108	BS	6.16371	.	.	NONE	.
314	P5P109	BS	5.35215	.	.	NONE	.
315	P5P110	BS	5.74390	.	.	NONE	.
316	TAIL00	EQ	.	.	.	NONE	.
317	TAIL01	BS	.67034	.	.	NONE	.
318	TAIL02	BS	1.45549	.	.	NONE	.
319	TAIL03	BS	2.03403	.	.	NONE	.
320	TAIL04	BS	2.74333	.	.	NONE	.
321	TAIL05	BS	3.21403	.	.	NONE	.
322	TAIL06	BS	3.71334	.	.	NONE	.
323	TAIL07	BS	4.17341	.	.	NONE	.
324	TAIL08	BS	4.34543	.	.	NONE	.
325	TAIL09	BS	4.33953	.	.	NONE	.
326	TAIL10	BS	4.34632	.	.	NONE	.
327	NFP0101	LL	.	13.04690	.	NONE	13.64690
328	NFP0102	LL	.	10.61050	.	NONE	10.61050
329	NFP0103	LL	.	8.21555	.	NONE	8.21555*
330	NFP0104	LL	.	6.33795	.	NONE	6.33795
331	NFP0105	LL	.	4.87358	.	NONE	4.87358
332	NFP0106	LL	.	3.73665	.	NONE	3.73665
333	NFP0107	BS	.32594	2.85745	.	NONE	2.85745
334	NFP0108	LL	.	2.17994	.	NONE	
335	NFP0109	LL	.	1.65949	.	NONE	1.65949
336	NFP0110	LL	.		.	NONE	1.26080
337	NFP0101	BS	.79010		.	NONE	
338	NFP0102	BS	.97074		.	NONE	
339	NFP0103	BS	.65741		.	NONE	
340	NFP0104	BS	.57900		.	NONE	
341	NFP0105	BS	.52767		.	NONE	
342	NFP0106	BS	.74471		.	NONE	2.17994
343	NFP0107	BS	.63233		.	NONE	
344	NFP0108	LL	.		.	NONE	
345	NFP0109	BS	.		.	NONE	

MPSX-PIF?   EXECUTOR. MPSX RELEASE 1 MOD LEVEL ?

NUMBER	COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
346	Nt P01110	BS	622482.24027	1.24340	.	NONE	.
347	Nt P02101	BS	1241968.80237	.C0203	.	NONE	.
348	Nt P02102	BS	1691050.51760	.0C157	.	NONE	.
349	Nt P02103	BS	2718528.53889	.C0121	.	NONE	.
350	Nt P02104	BS	434364.52641	.00093	.	NONE	.
351	Nt P02105	BS	6669617.34793	.00071	.	NONE	.
352	Nt P02106	BS	5833762.73326	.0C054	.	NONE	.
353	Nt P02107	BS	1442331.1026	.0C041	.	NONE	.
354	Nt P02108	BS	2142721.2044	.00032	.	NONE	.
355	Nt P02109	BS	3129057.5950	.00024	.	NONE	.
356	Nt P02110	BS	756564.56670	.00018	.	NONE	.
357	Nt P03101	BS	250560.58670	.00767	.	NONE	.
358	Nt P03102	BS	35050.58067	.00592	.	NONE	.
359	Nt P03103	BS	1869592.55443	.00152	.	NONE	.
360	Nt P03104	BS	1860993.56772	.00116	.	NONE	.
361	Nt P03105	BS	1229318.56772	.00088	.	NONE	.
362	Nt P03106	BS	1229313.56772	.0C066	.	NONE	.
363	Nt P03107	BS	1238389.56772	.00050	.	NONE	.
364	Nt P03108	BS		.0C038	.	NONE	.
365	Nt P03109	BS	.	.00024	.	NONE	.
366	Nt P03110	LL	.	.0C022	.	NONE	.

CASE 5

FORMULATION ONE

with

HIGH FOSSIL FUEL COSTS

SECTION 2 - COLUMNS

NUMBER	.COLUMN.	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
		EQ	12.C0000		12.00000	12.C0000	12.39178-
		EQ	6.00000		6.00000	6.C0000	141.26870-
		EQ	6.0000		6.0000	6.0000	191.69655-
		BS	9.C5720		1.0000	1.C0000	537.61025-
		LL		16.74200		NONE	15.59437
		LL	11.	51.29000		NONE	1.50052
		LL		145.55430		NONE	61.46673
		LL		157.94230		NONE	1.85062
		LL		12.12270		NONE	16.61704
		BS		66.59500		NONE	9.08836
		LL	1.49773	153.27430		NONE	6.48730
		LL		123.11430		NONE	17.12702
		BS	4.77113	137.63090		NONE	12.37566
		LL				NONE	5.0412
		LL		253.46800		NONE	7.24632
		LL				NONE	
		BS	13.41057	36.74967		NONE	12.64824
		LL		42.44321		NONE	8.15687
		LL		78.01671		NONE	7.47692
		LL		45.71993		NONE	...6696
		LL		130.01330		NONE	12.41969
		LL		136.86430		NONE	31.41659
		LL		154.93190		NONE	70.10363
		BS	9.37125	216.01330		NONE	2.23342
		LL		641.17230		NONE	10.19362
		BS	75.05424	6.49035		NONE	8.07873
		LL		55.29500		NONE	4.67815
		LL		57.64550		NONE	12.44319
		LL		73.71530		NONE	14.31577
		BS	11.84530	134.21230		NONE	29.71573
		LL		134.35130		NONE	14.61855
		BS		319.15430		NONE	1.45378
		LL		416.75230		NONE	.56594
		LL		4.70217		NONE	6.11490
		BS	14.76304	26.71500		NONE	3.21620
		LL		41.86040		NONE	
		LL		47.61890		NONE	10.C8770
		LL		53.55500		NONE	11.67038
		LL		73.87050		NONE	22.56654
		BS	17.37240	60.35700		NONE	10.83205
		LL		166.80190		NONE	
		LL		241.18530		NONE	
		LL		301.93530		NONE	.34891

NUMBER	COLUMN	AT	...ACTIVITY...	..INPUT COST..	..LOWER LIMIT.	..UPPER LIMIT.	.REDUCED COST.
244	GIU01050	BS	94.76748	3.42854	.	NONE	5.07214
245	FPUC4051	LL		18.73450	.	NONE	3.53252
246	FPU08052	LL		30.52640	.	NONE	1.42757
247	FPU10053	LL		34.75650	.	NONE	5.86355
248	FU013054	LL		39.01680	.	NONE	6.05857
249	FBU15055	LL		53.87810	.	NONE	12.73666
251	FBU20056	LL		71.73680	.	NONE	8.09380
252	LWU10057	LL		121.09300	.	NONE	.13378
253	LWU15058	LL		157.8C700	.	NONE	
254	LWU21059	BS	22.75997	219.13300	.	NONE	
256	GIU01063	LL		2.49069	.	NONE	.03113
255	FPU34061	LL		13.64830	.	NONE	3.30531
256	FPU08062	LL		22.24490	.	NONE	1.76951
257	FPU10063	BS	57.62121	25.31110	.	NONE	
258	FU010364	LL		28.45160	.	NONE	1.37437
259	FBU15365	BS	19.13991	39.29540	.	NONE	
201	FBU20066	LL		52.32150	.	NONE	3.19300
201	LWU13067	LL		98.19940	.	NONE	6.21495
202	LWU15069	LL		122.23130	.	NONE	.64806
203	LWU20069	LL		155.61900	.	NONE	.53012
204	GILC1070	BS	375.73896	1.01811	.	NONE	
205	FPU04071	LL		9.94300	.	NONE	2.43750
207	FPIC3072	LL		16.21000	.	NONE	1.35894
207	FPI1-3073	LL		10.46160	.	NONE	.09761
208	FU113074	LL		20.74700	.	NONE	1.02343
209	FU123075	BS	65.12507	28.6C010	.	NONE	
210	FBU10077	LL		38.16040	.	NONE	2.21359
211	LWU13077	LL		64.46690	.	NONE	9.59224
212	LWU23079	LL		89.37130	.	NONE	7.93395
213	GILOT130	BS	401.61165	116.71310	.	NONE	10.23673
214	FPL04JE1	LL		1.32397	.	NONE	
216	FPIC8JJ2	LL		7.24360	.	NONE	1.79508
217	FPI13133	LL		11.01240	.	NONE	1.01859
218	FU110384	LL		14.45590	.	NONE	.11668
218	FBU13385	BS	90.35295	15.12930	.	NONE	.77681
220	LWU13087	LL		20.90290	.	NONE	
261	LWU15388	LL		27.63210	.	NONE	1.47475
262	LWU23135	LL		47.11720	.	NONE	12.09430
263	GI2C1090	BS	114.71219	65.34070	.	NONE	14.29886
266	FP204051	LL		85.33460	.	NONE	18.69759
269	FP209J92	BS	90.09532	.96412	.	NONE	.01224
290	FP210033	LL		5.27704	.	NONE	1.14429
200	FU210094	LL		8.6C779	.	NONE	.55259
201	FU215J75	LL		9.6C617	.	NONE	
292	FU223096	LL		11.03200	.	NONE	.60547
293	LW210067	LL		15.24540	.	NONE	
294	LW215C99	LL		20.29900	.	NONE	.76017
	LW220099	LL		34.41530	.	NONE	15.78048
	U23330	EQ		47.76860	.	NONE	20.16337
				62.38800	.	NONE	26.31729